Theory of WIMPs

4^{th} Patras Meeting

DESY, Hamburg, 2008

David G. Cerdeño

UNIVERSIDAD AUTONOMA DE MADRID

WIMPs: a Bestiary

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Contents

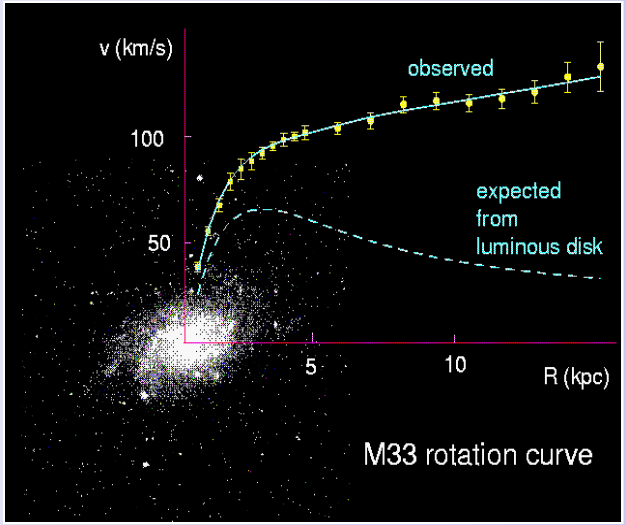
- WIMPs?
  - Thermal production
  - Direct searches for WIMPs
- Bestiary
  - Lightest SUSY particle (LSP), e.g., the NEUTRALINO, the SNEUTRINO
  - Little Higgs Models (LTP)
  - Lightest Kaluza-Klein particle (LKP)
- Conclusions

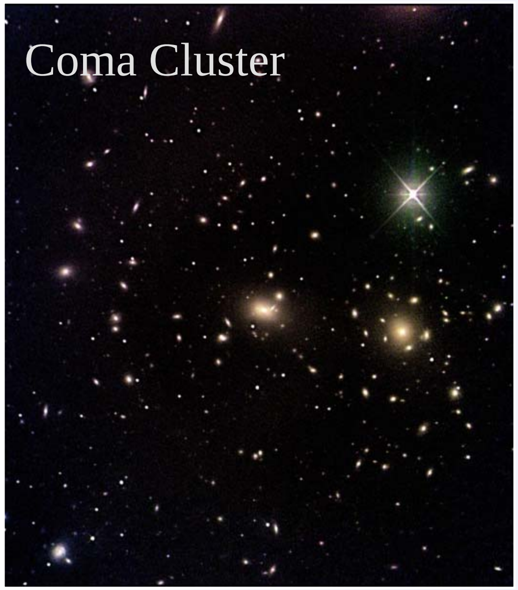
Motivation for Dark Matter

• The motivation for dark matter arises from gravitational effects in astronomical observations at various scales. Luminous (visible) matter is insufficient to account for the observed effects.

At the galactic scale:

- Rotation curves of spiral galaxies
- Gas temperature in elliptic galaxies





Clusters of galaxies

- Peculiar velocities
- Gas temperature (X-ray measurements)
- Gravitational lensing

So WHAT is the Dark Matter? ... WHAT DO WE KNOW...

- We have a good idea of what we are looking for:

- However, the number of suspects is large, all postulated in **modern Particle Physics.**

Axions with a small mass $m_a \approx 10^{-5}$ eV

Weakly Interacting Massive Particles (WIMPs)

Lightest Supersymmetric Particle

Lightest Kaluza-Klein Particle

SIMPs, CHAMPs, SIDM, WIMPzillas, Scalar DM, Light DM ...

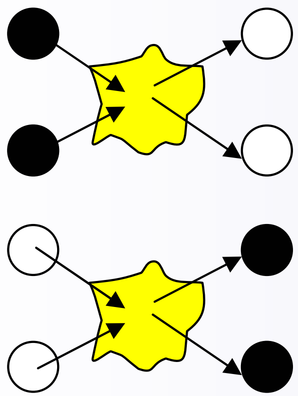
NEW PHYSICS BEYOND THE STANDARD MODEL OF PARTICLE PHYSICS

How is Particle Dark Matter produced?

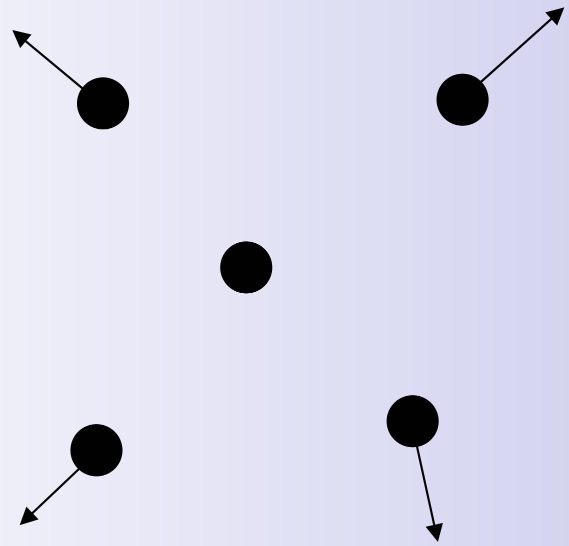
time — Today t~13.6 Gyr

Temperature — T~3K

Thermal equilibrium



Due to the expansion of the Universe DM particles fall out of equilibrium and cannot annihilate any more.



A Relic Density of DM is obtained which remains constant.

The number density, n, of DM decreases with T.

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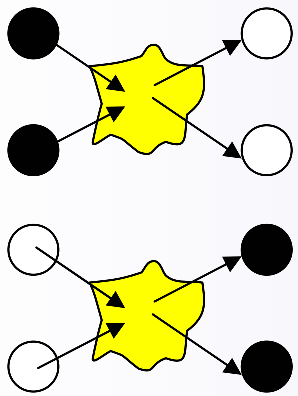

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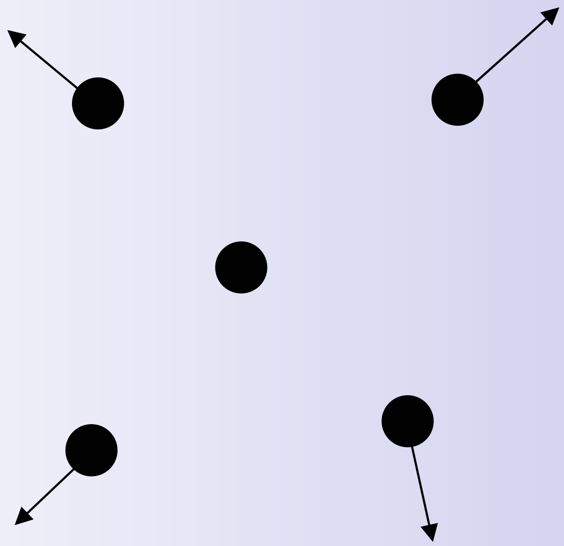


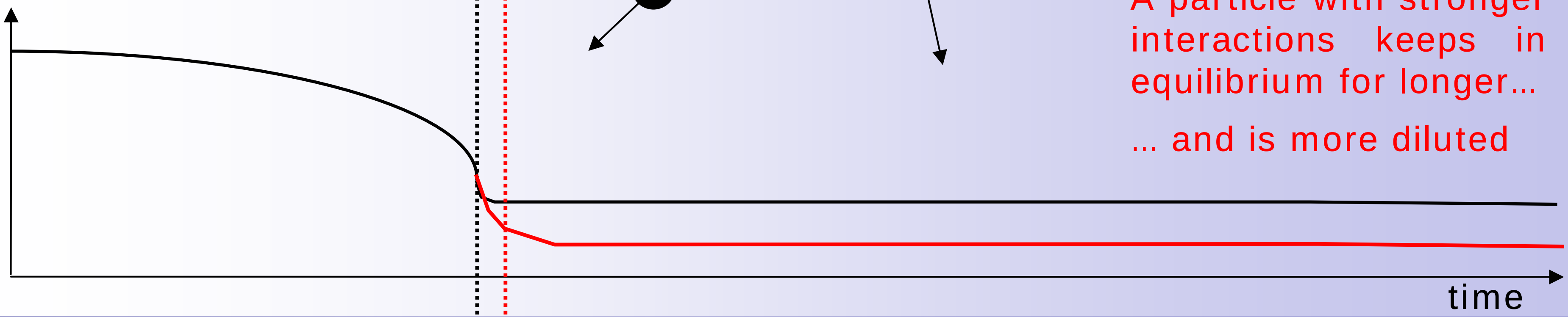
A Relic Density of DM is obtained which remains constant.

How much dark matter remains depends on its interaction rate

A particle with stronger interactions keeps in equilibrium for longer…

… and is more diluted

The number density, n, of DM decreases with T.



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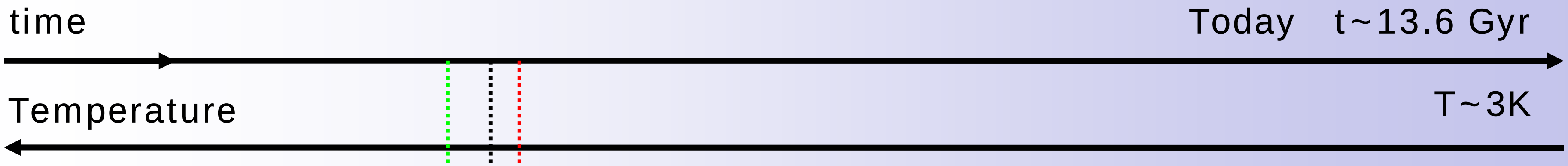
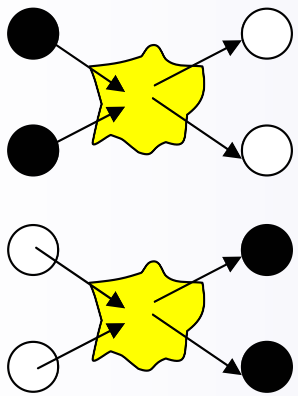


Thermal equilibrium



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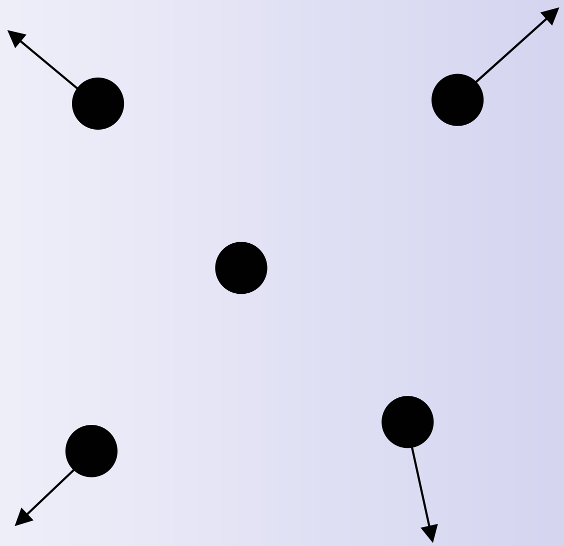
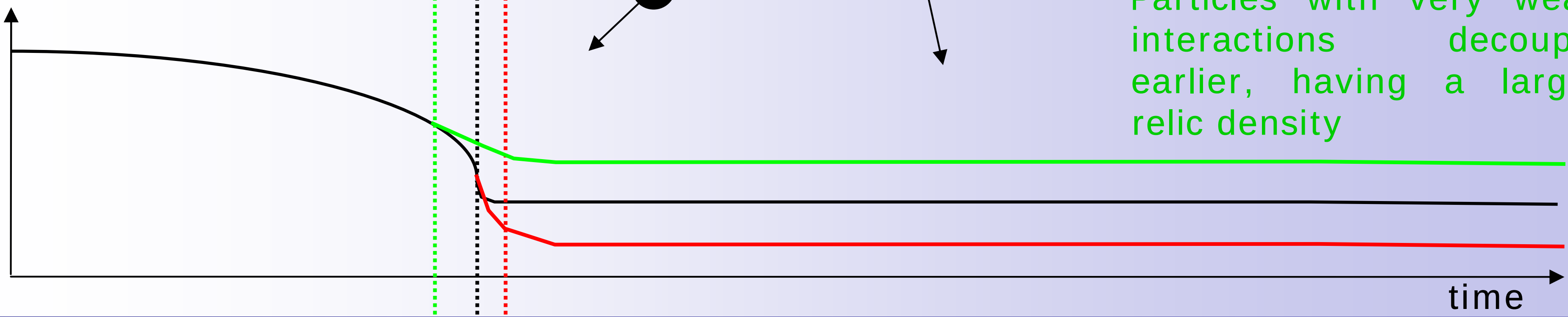


A Relic Density of DM is obtained which remains constant.

How much dark matter remains depends on its interaction rate

Particles with very weak interactions decouple earlier, having a larger relic density

The number density, n, of DM decreases with T.



How is Particle Dark Matter produced?

- The resulting WIMP relic density

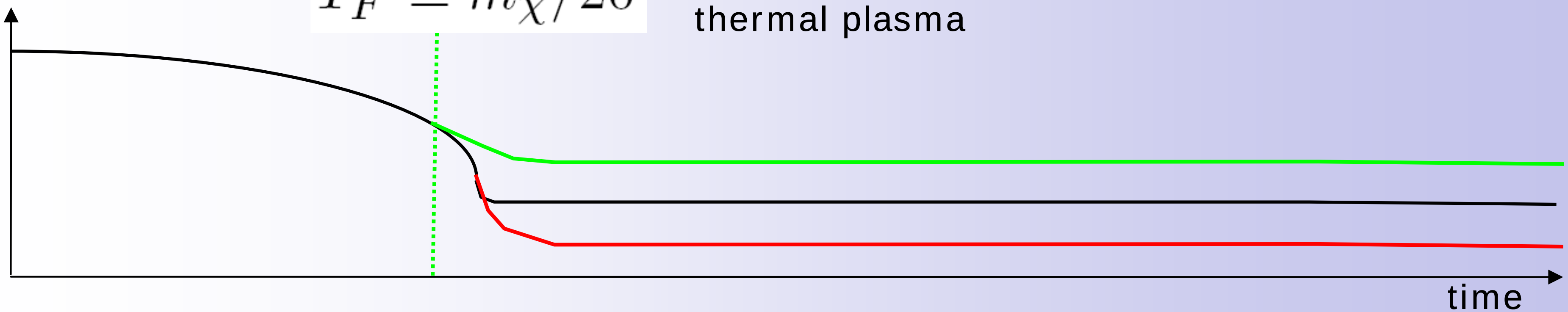
$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}$$

is naturally of order 0.1 when the annihilation cross section is of “weak scale”

$$\sigma \sim 10^{-9}\ \mathrm{GeV}$$

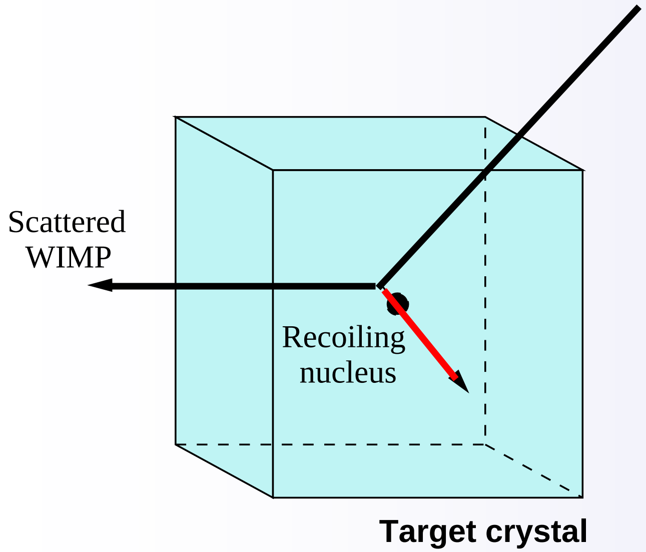
$$T_F \simeq m_\chi / 20$$

Non-relativistic when they decoupled from the thermal plasma



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

WIMP-nucleus interaction

- The interaction of a generic WIMP with nuclei has several contributions $\sigma_{\chi-N}$

Axial-Vector

$$L_A \sim \bar{\chi}\gamma^\mu\gamma_5\chi\,\bar{q}\gamma^\mu\gamma_5 q$$

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

- Adds incoherently

SPIN-DEPENDENT

(Nucl. Angular mom)

Scalar

$$L_S \sim \bar{\chi}\chi\,\bar{q}q$$

$$A^2$$

SPIN-INDEPENDENT

(Nucleon #)

Vector

$$L_V \sim \bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma^\mu q$$

$$A^2$$

- Adds coherently
- Only for non-Majorana WIMPs

SPIN-INDEPENDENT

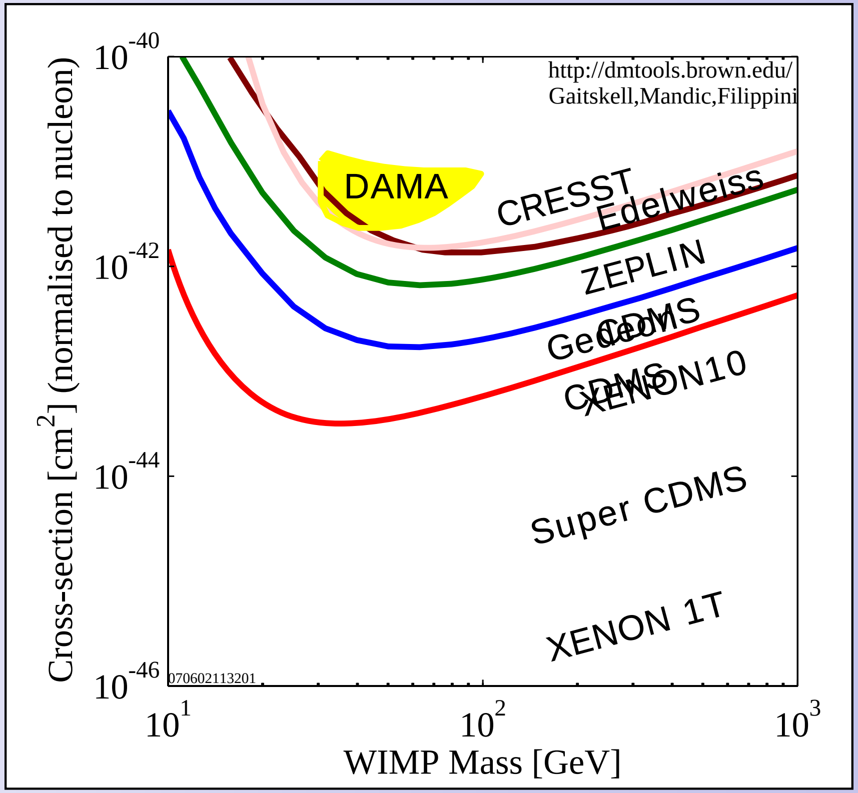
Spin-independent cross section

• 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)

• How large can the WIMP detection cross section be?

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



Calculate the theoretical predictions for WIMP-nucleus cross section

WIMPs: a (biased) Bestiary

WIMPs

- 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)
- Heavy Majorana neutrinos (Minimal Technicolor Theories)

(Kainulainen, Tuominen, Virkajärvi '06; Kouvaris '07)

And some "phenomenologically motivated" toy models

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

Heavy neutrinos as dark matter

- Heavy (Dirac or Majorana) 4th generation neutrino

(Lee, Weinberg ’77)

LEP limits on the invisible Z width imply $m_\nu > M_Z/2$

Such neutrinos would have a too small relic density

(Lee, Weinberg ’77; Hut ’77; Vysotsky, Dolgov, Ya, Zeldovich ’77; Enqvist, Kainulainen, Maalampi ‘89)

Direct and indirect searches rule out $m_\nu < 1$ TeV

(e.g., Germanium detectors ’87-’92; Kamiokande ’92)

These problems are due to the SU(2) coupling to the Z boson being too large

Solution: consider mixing with “sterile” singlet neutrino… but <u>not stable</u>!

E.g., right-handed neutrinos

(Dodelson, Widrow, ‘94)

…in B-L extensions [illegible] can be very light without being in conflict with LEP (and only decays through mixing with left-handed)

(e.g., Khalil, Seto ‘08)

NOT WIMPS

Heavy neutrinos as dark matter

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Direct and indirect searches rule out $m_\nu < 1$ TeV

(e.g., Germanium detectors '87-'92; Kamiokande '92)

These problems are due to the SU(2) coupling to the Z boson being too large

They become too weakly-interacting to be detected directly (not WIMPs)

WIMPs

- Heavy (Dirac or Majorana) 4^{th} generation neutrino

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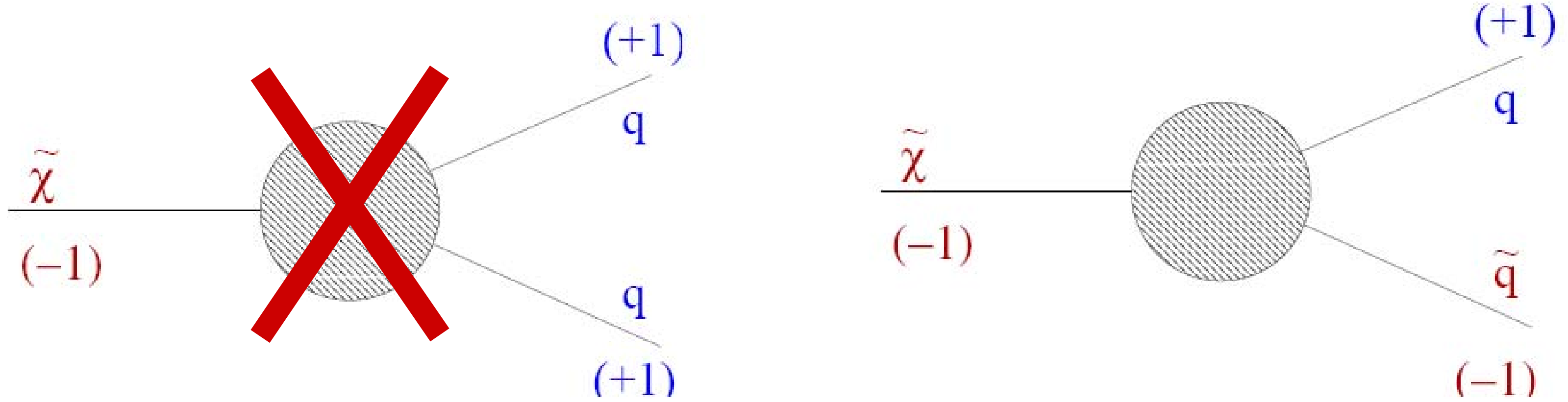
Lightest Supersymmetric Particle

• 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.

Lightest Supersymmetric Particle

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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	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
Charginos	$\tilde{W}^\pm$, $\tilde{H}^\pm_{1,2}$
Gluino	$\tilde{g}$
Gravitino	$\tilde{G}$
Axino	$\tilde{a}$

Lightest squark or slepton: charged and therefore excluded by searches of exotic isotopes

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

Lightest neutralino: WIMP

Gravitino: Present in Sup[…] theories. Can also be the LSP and a goo[…] candidate

Axino: SU[…]ner of the axion. Extremely weak interactions

NOT WIMPS

Lightest Supersymmetric Particle

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Lightest sneutrino: Possible in extensions of the MSSM by reducing its mixing with the Z boson: WIMP

Lightest neutralino: WIMP

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

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

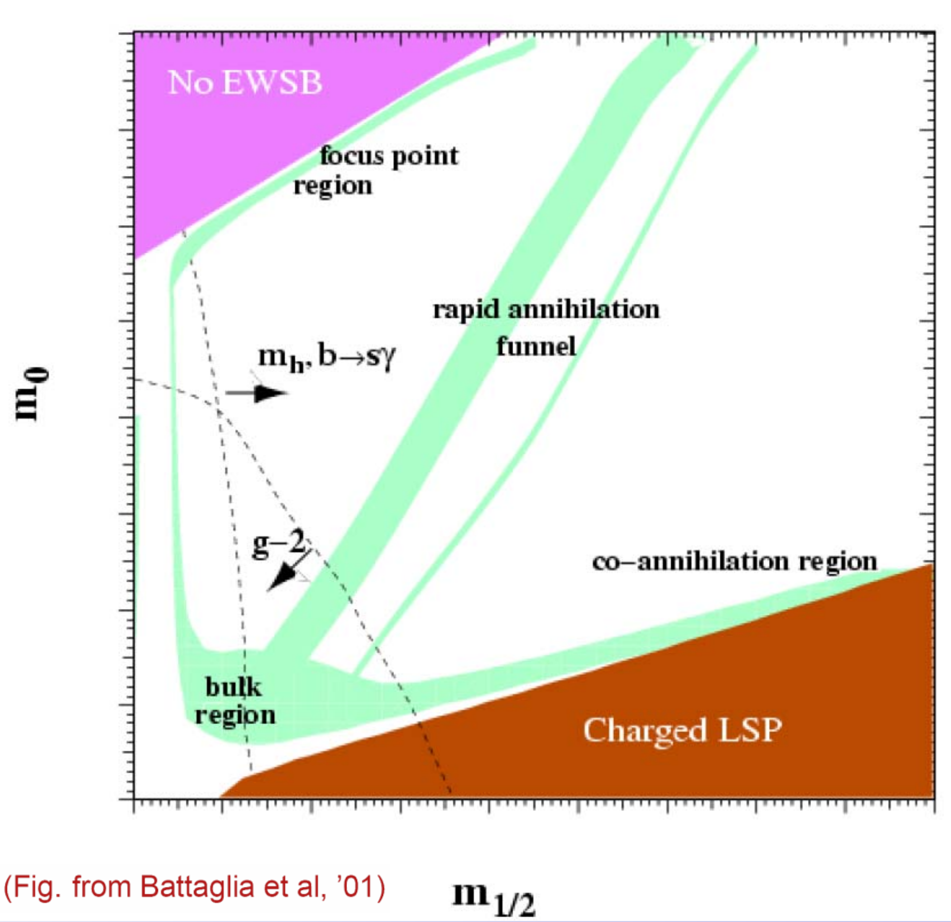
The neutralino in the MSSM

- The requirement of having a correct relic density is very constraining

- Coannihilations with NLSP

- Rapid annihilation due to resonance with CP-odd Higgs

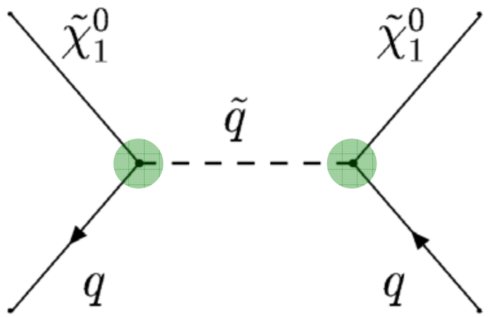
- Focus Point (large Higgsino composition)



(Fig. from Battaglia et al, '01)

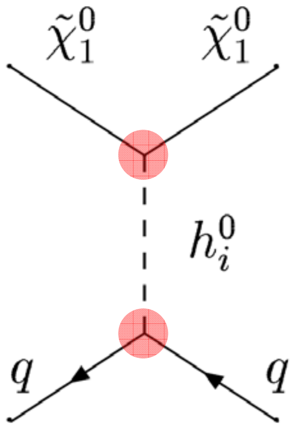
Spin-independent cross section

- 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

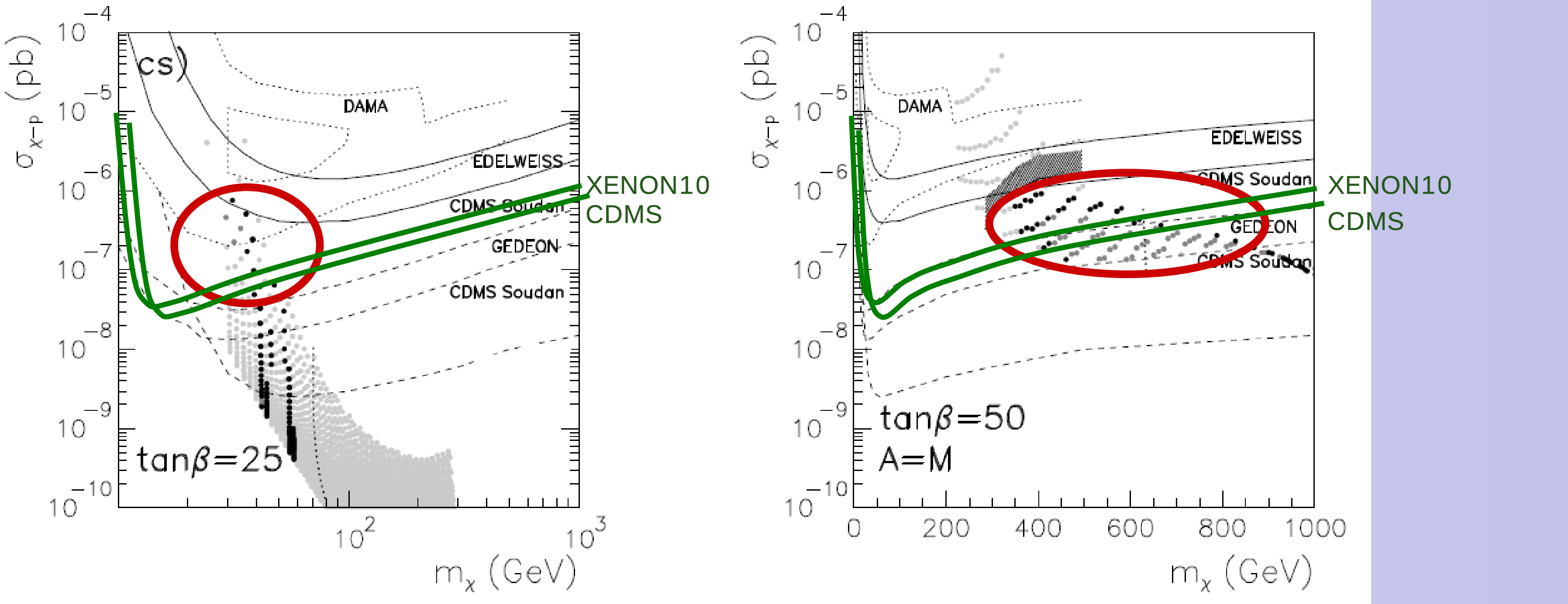
It is the leading contribution, and increases when

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

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

Neutralino in the MSSM

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



$M_1 = \frac{1}{4} M_{2,3}$ $M_1 = \frac{4}{3} M_{2,3}$

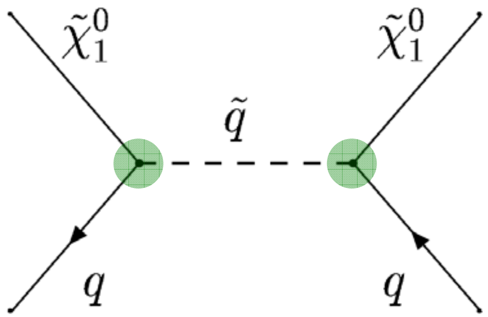
Very light **Bino-like** neutralinos with masses ~10 GeV.

Heavy **Higgsino-like** neutralinos with masses ~500 GeV.

(S.Baek, D.G.C., G.Y.Kim, P.Ko, C.Muñoz ´05)

Spin-dependent cross section

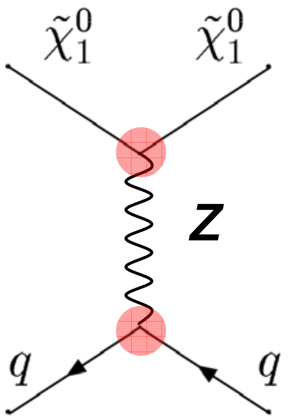
- Contributions from **squark-** and **Z-**exchanging diagrams:



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

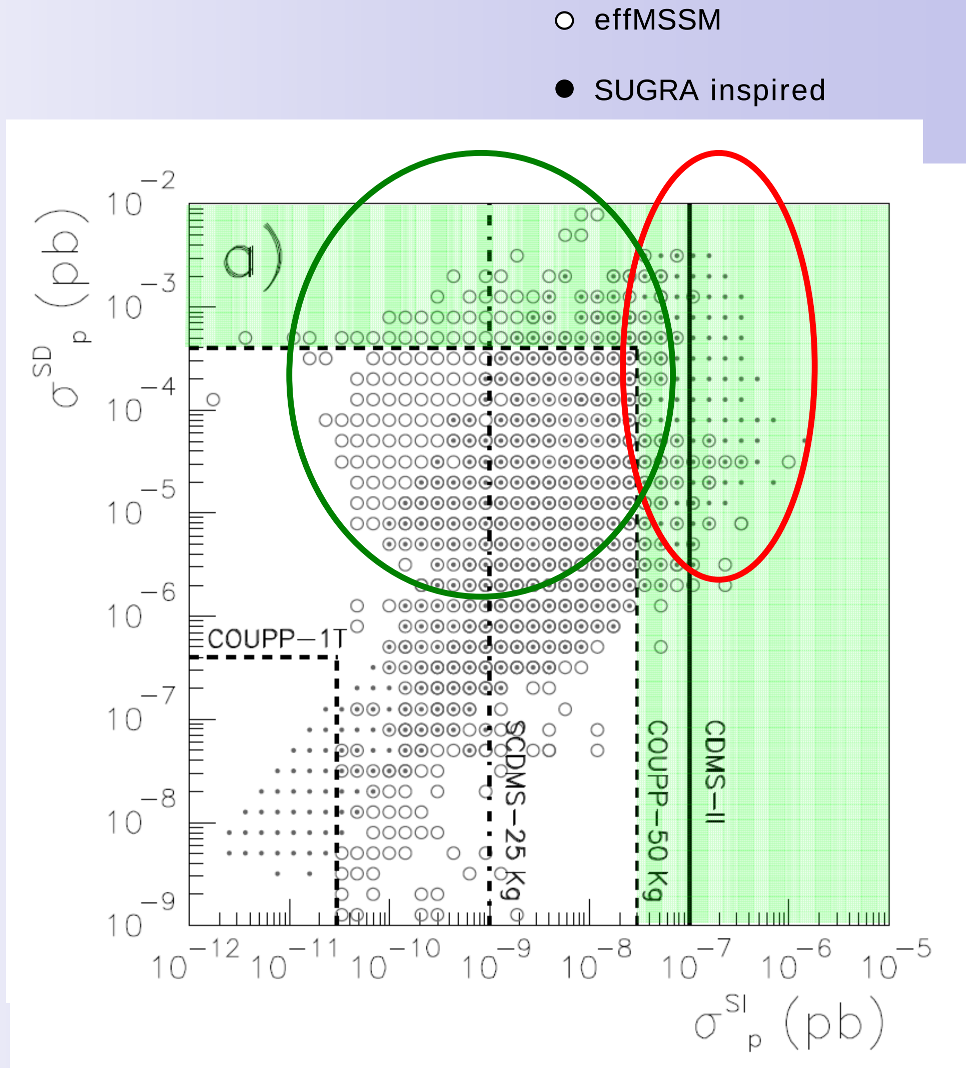
- Overall theoretical predictions in the MSSM:

Enhancement of Z-exchange

Through a decrease in the μ parameter

Enhancement of q̃-exchange

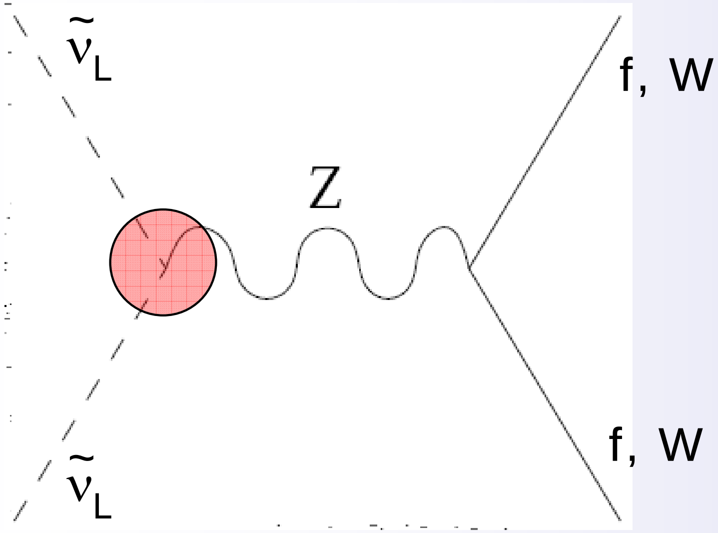
$$(m_{\tilde{u},\tilde{d},\tilde{s}} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} \lesssim 0.1$$



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

Sneutrino DM in the MSSM

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



Sneutrino (left-handed) coupling with Z boson is rather large, leading to

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

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

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

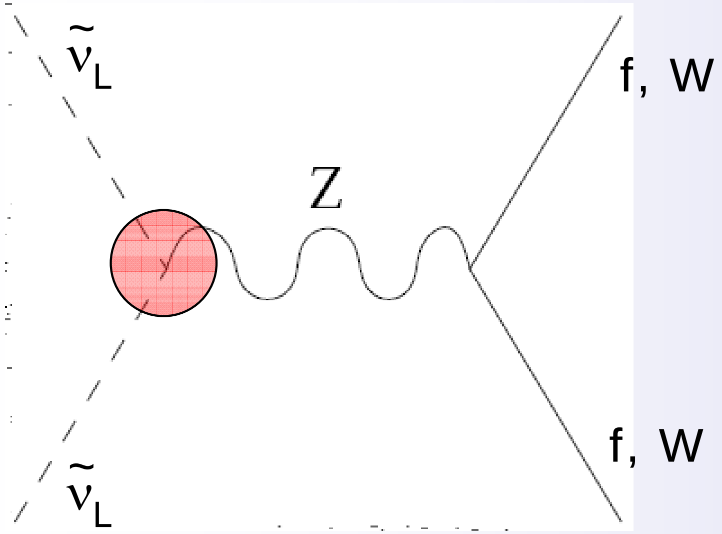
(Falk, Olive, Srednicki '94)

Sneutrino DM in the MSSM

- These problems alleviated by reducing the Zνν coupling

This can be done by including a “sterile” (e.g., right-handed) component with which the left-handed sneutrino can mix.

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



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

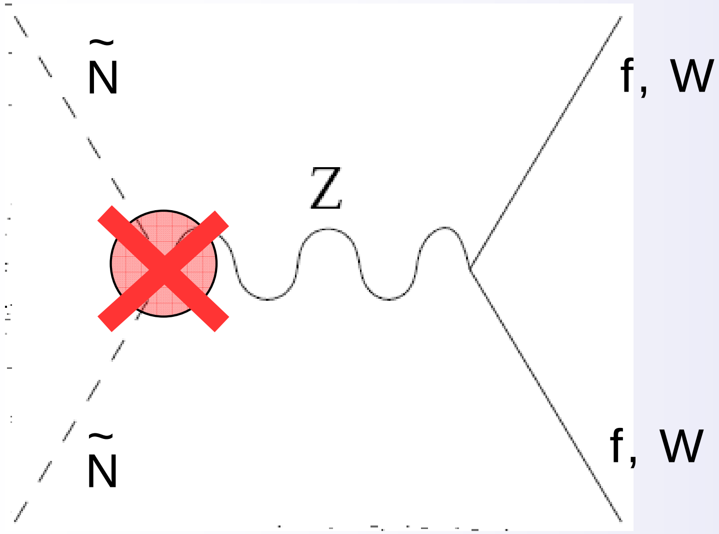
- Smaller annihilation cross section
- Smaller detection cross section

BUT: sneutrino mixing is proportional to the value of the neutrino Yukawa coupling → a large mixing is difficult to reconcile with see-saw generation of neutrino masses (unless the trilinear A is very large)

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

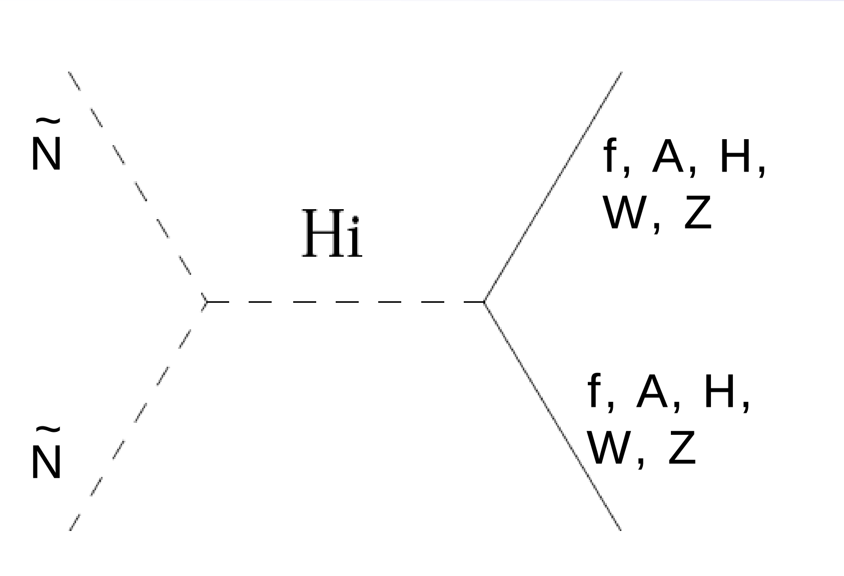
BUT: very small detection cross section (would not account for a WIMP observation)

Sneutrino DM in the MSSM

- (Right-handed) sneutrinos in the NMSSM: with a new coupling to the Higgses

(Cerdeño, Seto, Muñoz – in preparation)

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



- Thermally produced with the correct relic density
- Not excluded (yet) by direct detection experiments but with large detection cross section

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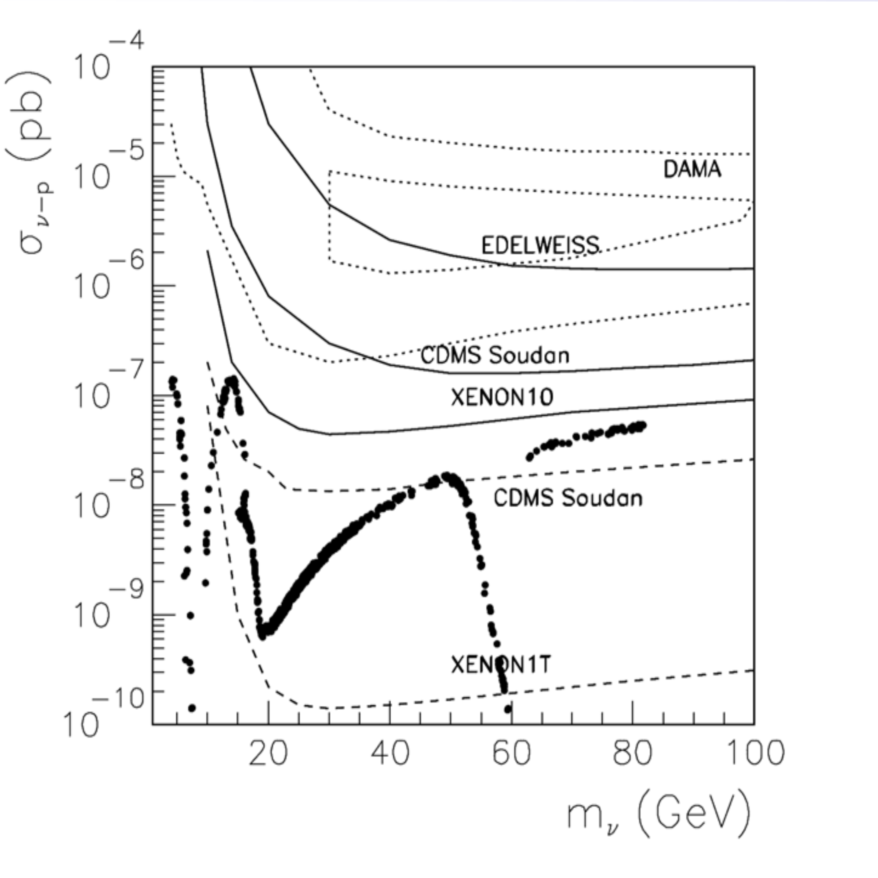

$$\tilde{\nu} = \tilde{N}$$

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LTP

Little Higgs Theories

• TeV extension of the SM in which the Higgs (possibly composite) is a pseudo Nambu-Goldstone boson, corresponding to a global symmetry spontaneously broken at a scale ~1 TeV.

(Arkani-Hamed, Cohen, Katz, Nelson '02; J. Hubisz, P. Meade '03)

Additional gauge bosons appear at the TeV scale which contribute to low-energy observables

Extremely constrained from precision electroweak fits → include a discrete Z_2 (T) parity.

The lightest T-odd particle is stable

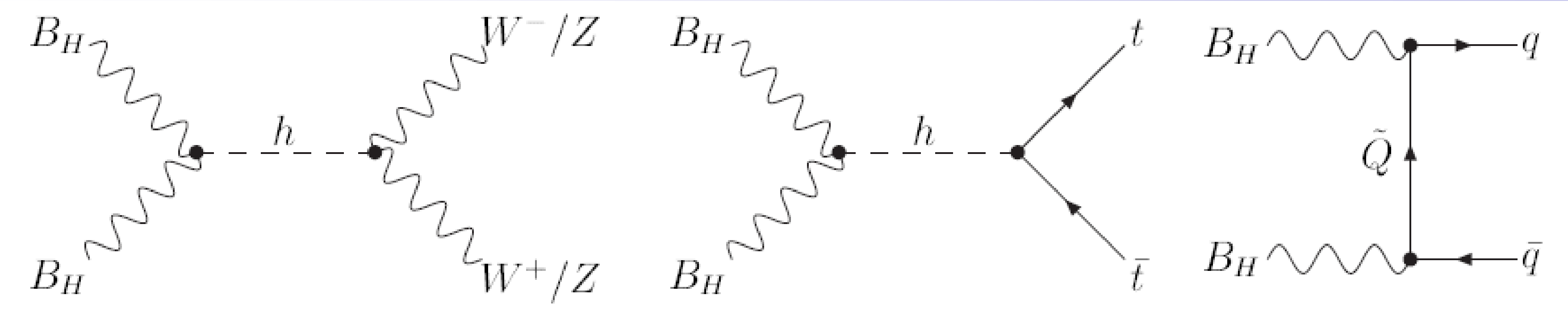
LTP

Little Higgs Theories

• In a T-parity conserving model a “heavy photon” can play the role of WIMP dark matter

(Arkani-Hamed, Cohen, Katz, Nelson ’02; J. Hubisz, P. Meade ‘03)

The only direct coupling to the SM fields is through the Higgs, resulting in weak scale interactions



(A. Birkedal, A. Noble, M. Perelstein, A. Spray ‘06)

The correct relic density is only obtained near the resonant annihilation through the Higgs or via coannihilation effects with another T-odd particle.

Little Higgs Theories

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(Arkani-Hamed, Cohen, Katz, Nelson '02; J. Hubisz, P. Meade '03)

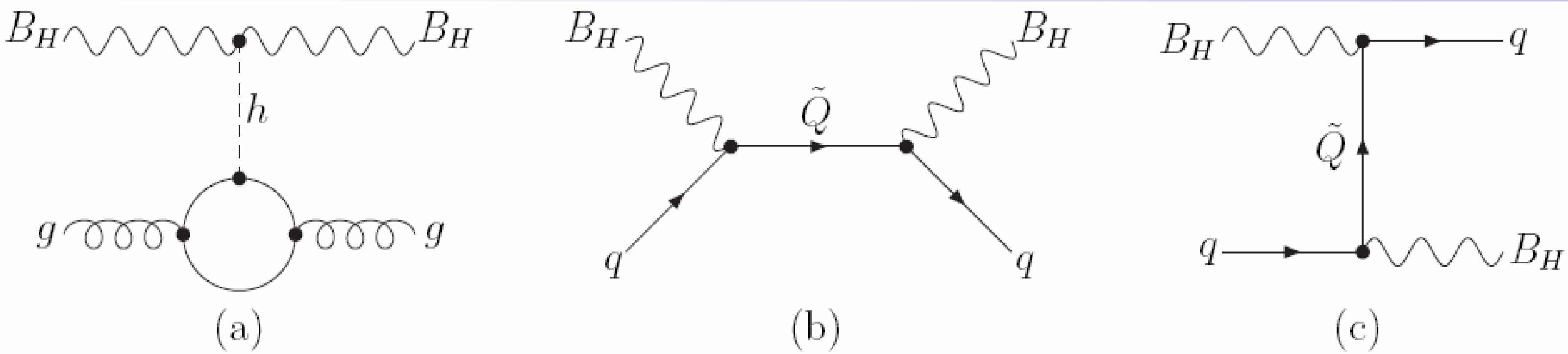


Figure 3: The leading processes which contribute to the heavy photon–nucleon elastic scattering cross section relevant for direct dark matter detection experiments.

(A. Birkedal, A. Noble, M. Perelstein, A. Spray '06)

Little Higgs Theories

- The (direct) detection cross section increases as the Higgs mass decreases

(A. Birkedal, A. Noble, M. Perelstein, A. Spray '06)

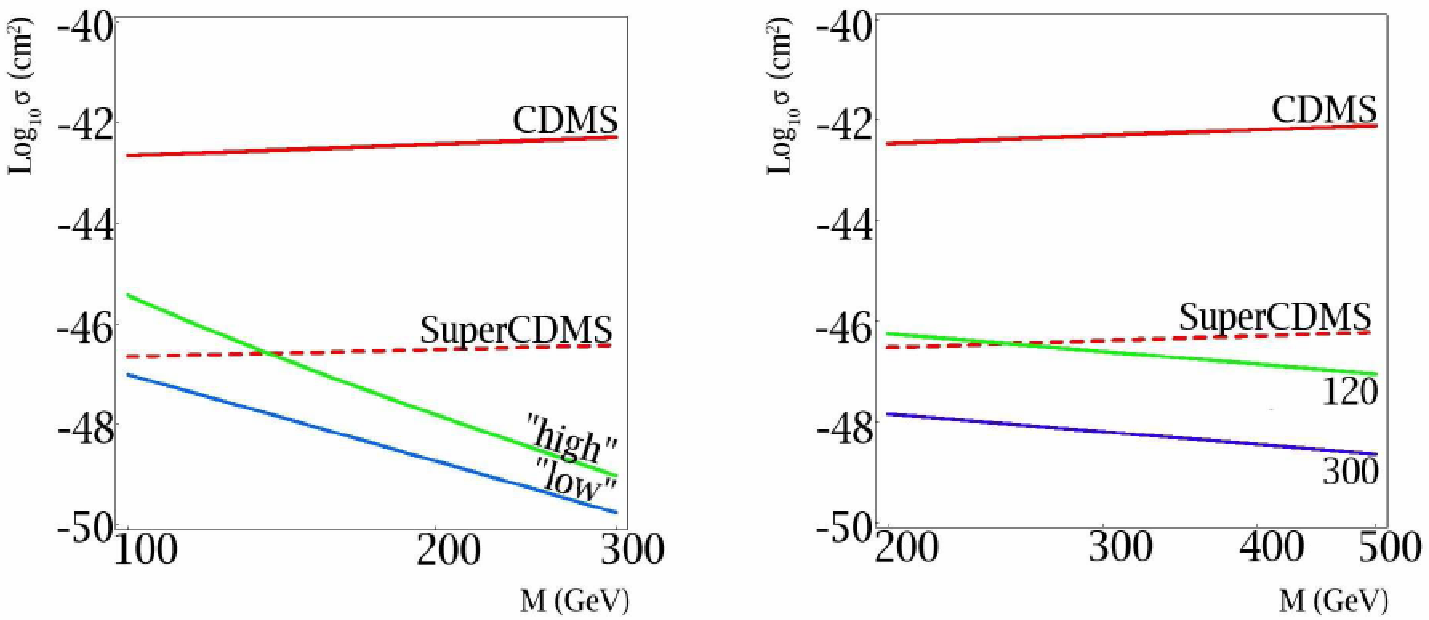
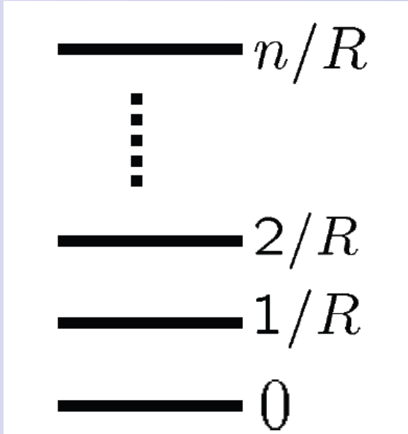


Figure 4: The spin-independent (SI) WIMP-nucleon elastic scattering cross section in the pair-annihilation bands (left panel) and in the coannihilation region, for two values of m_h, 120 and 300 GeV (right panel). The present [26] and projected [27] sensitivities of the CDMS experiment are also shown.

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

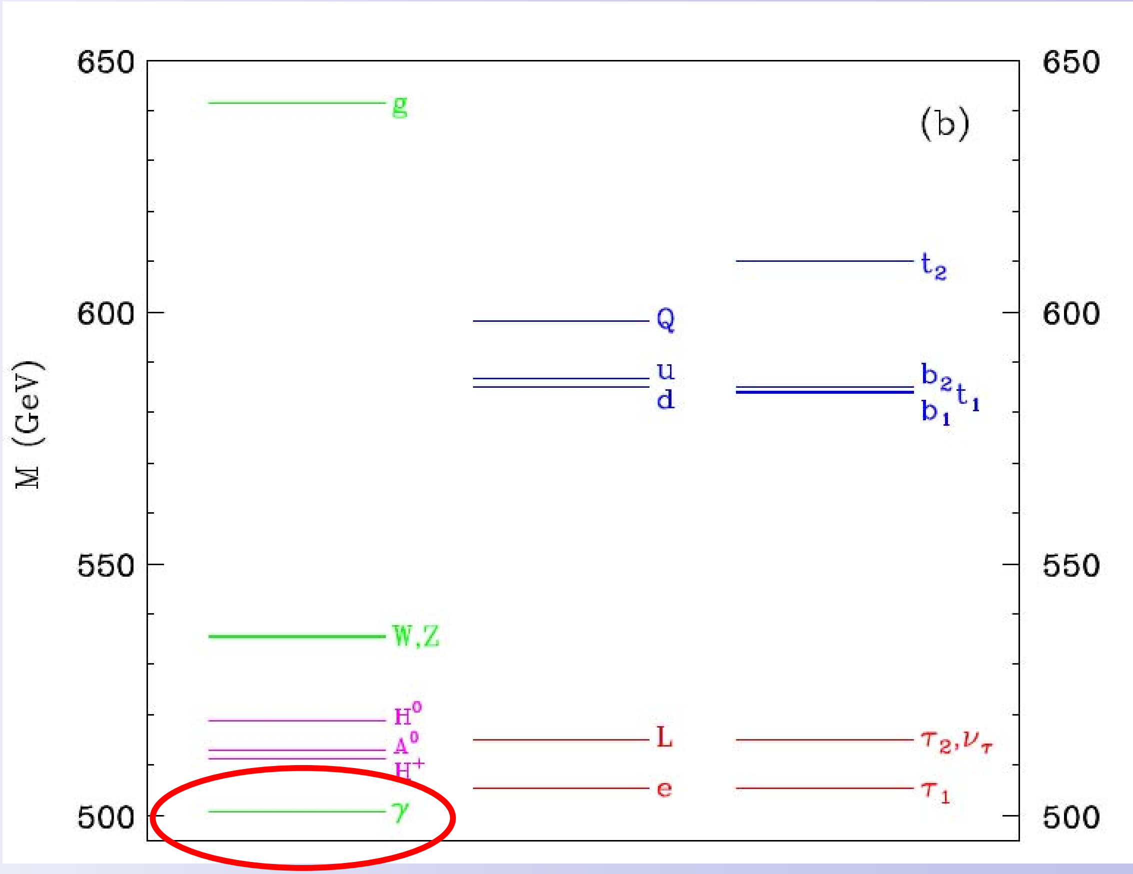
- In order to obtain Chiral fermions the extra dimension has to be orbifolded, leading to conservation of KK-Parity

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

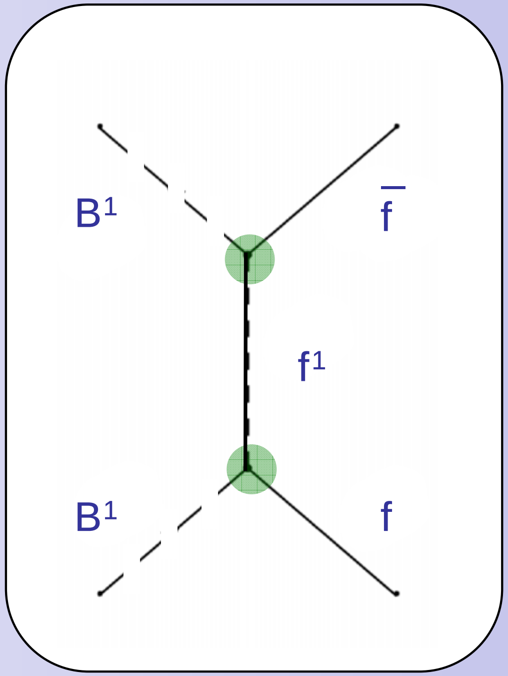
KK dark matter

- 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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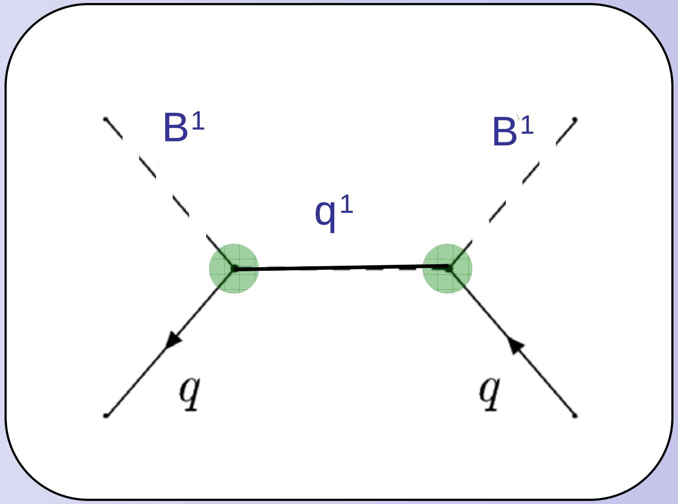
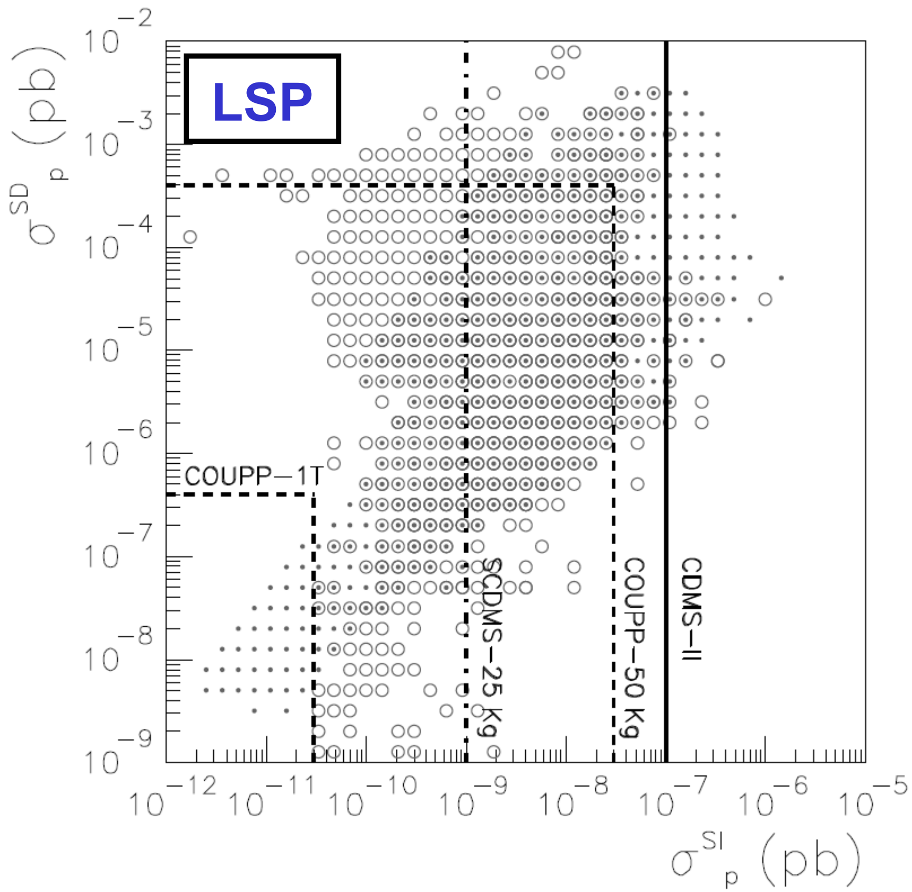
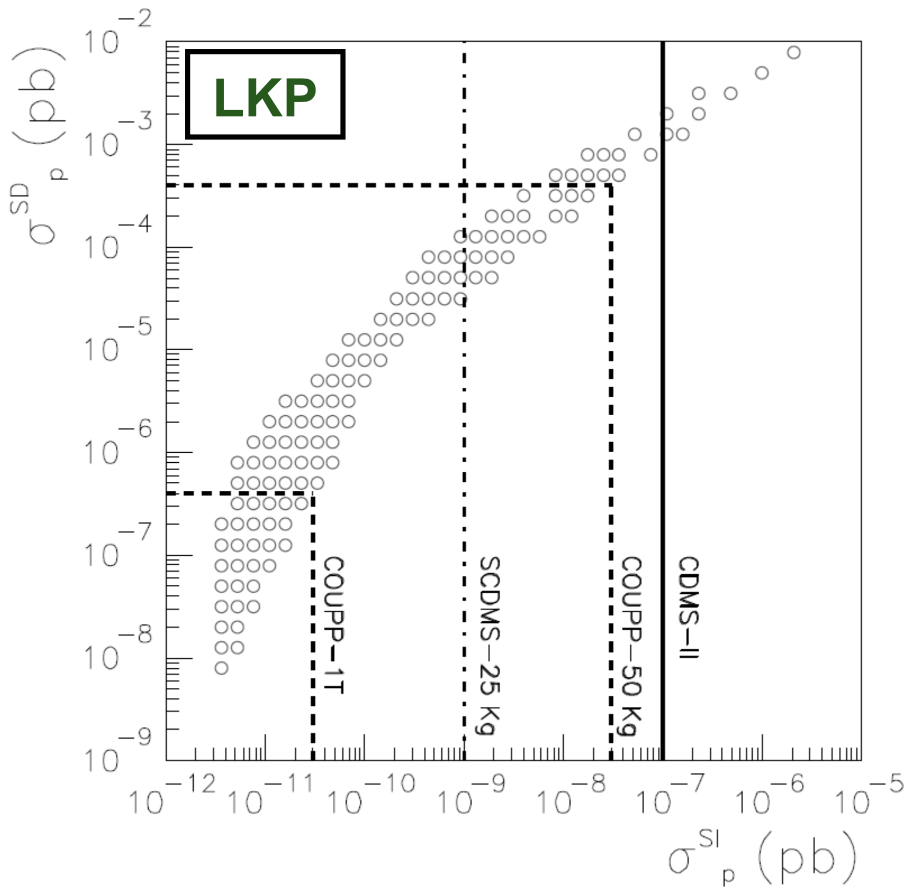


• B(1) interaction with quarks also dominated by s-channel with KK-quark exchange

Discriminating Neutralino vs LKP

- Complementarity of spin-dependent and independent searches

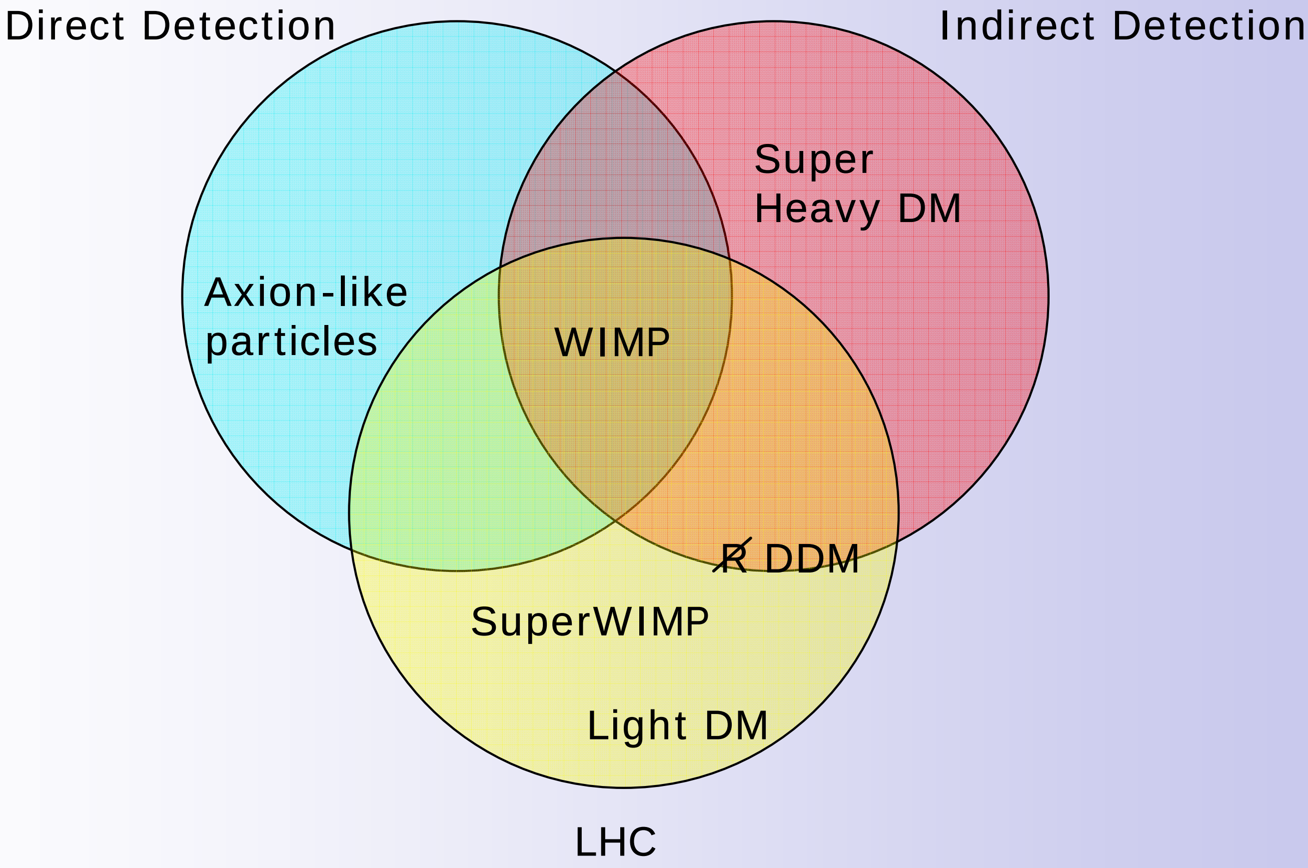




(G.Bertone, D.G.C., J.I.Collar, B.Odom´07)

Conclusions / Complementarity of DM searches

- We are attacking the DM in various fronts:



Probing WIMP dark matter implies probing new physics at the TeV scale.

Conclusions

• Dark Matter is a necessary ingredient in the present models of our Universe... but we have not identified it yet.

Experiments in the near future (direct, indirect, LHC) might have enough sensitivity to probe WIMP candidates.

• WIMP dark matter related to phy

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

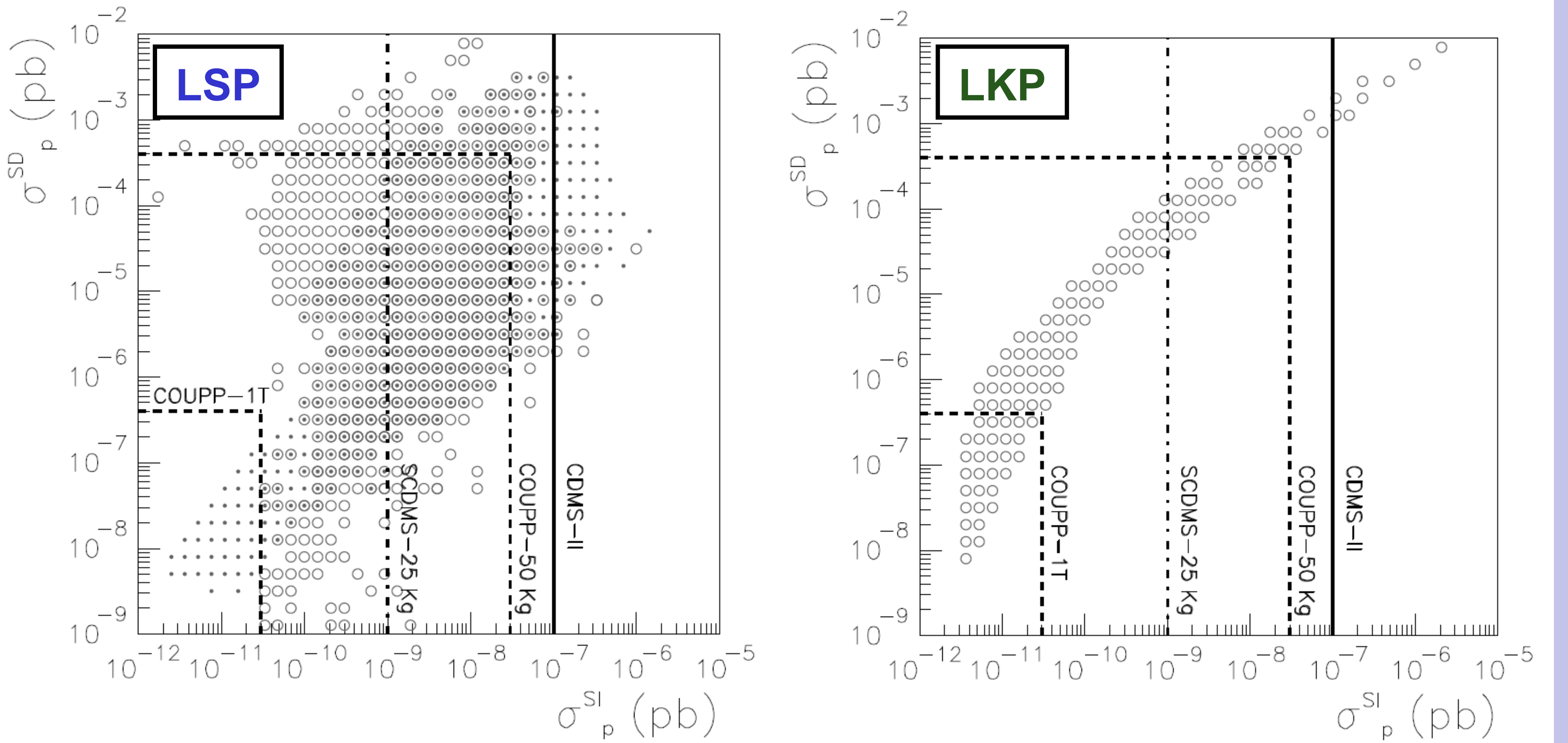
- The lightest neutralino
- The LKP in UED models

• 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.

Discriminating Neutralino vs LKP

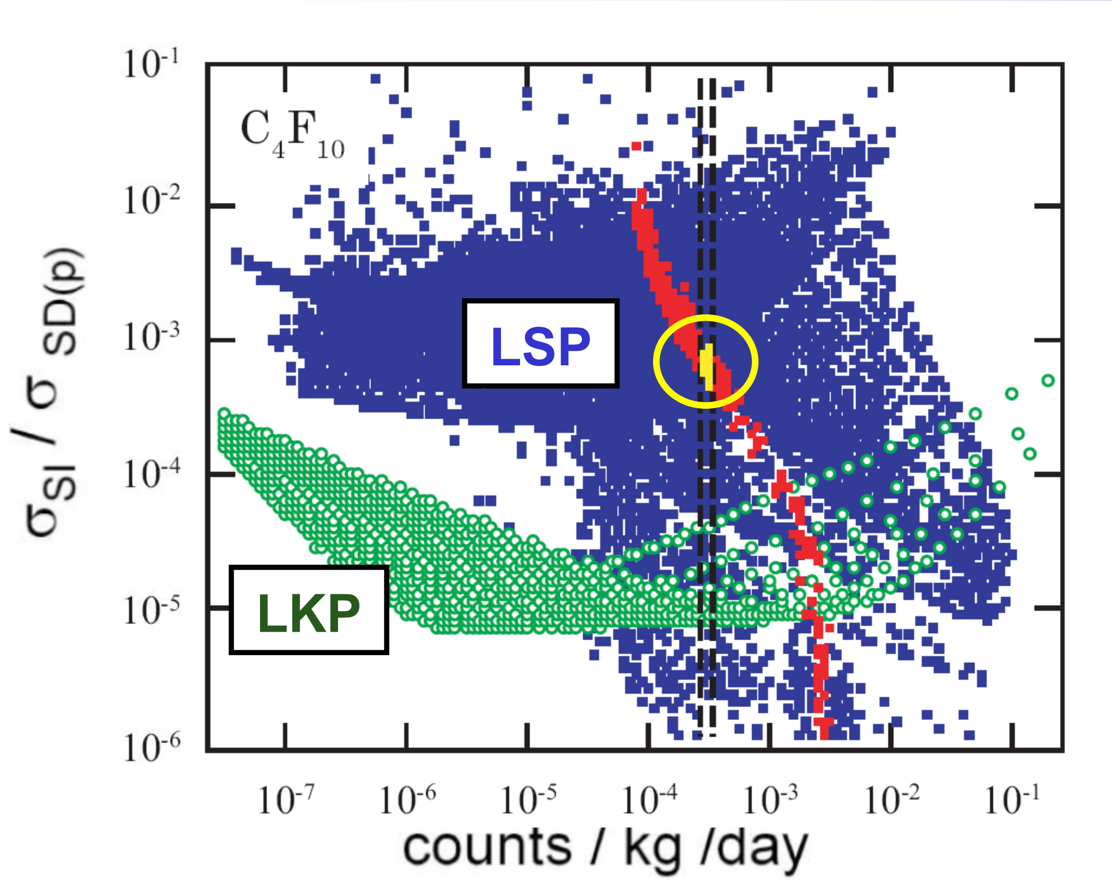
- Complementarity of spin-dependent and independent searches



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

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



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.

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

Identification

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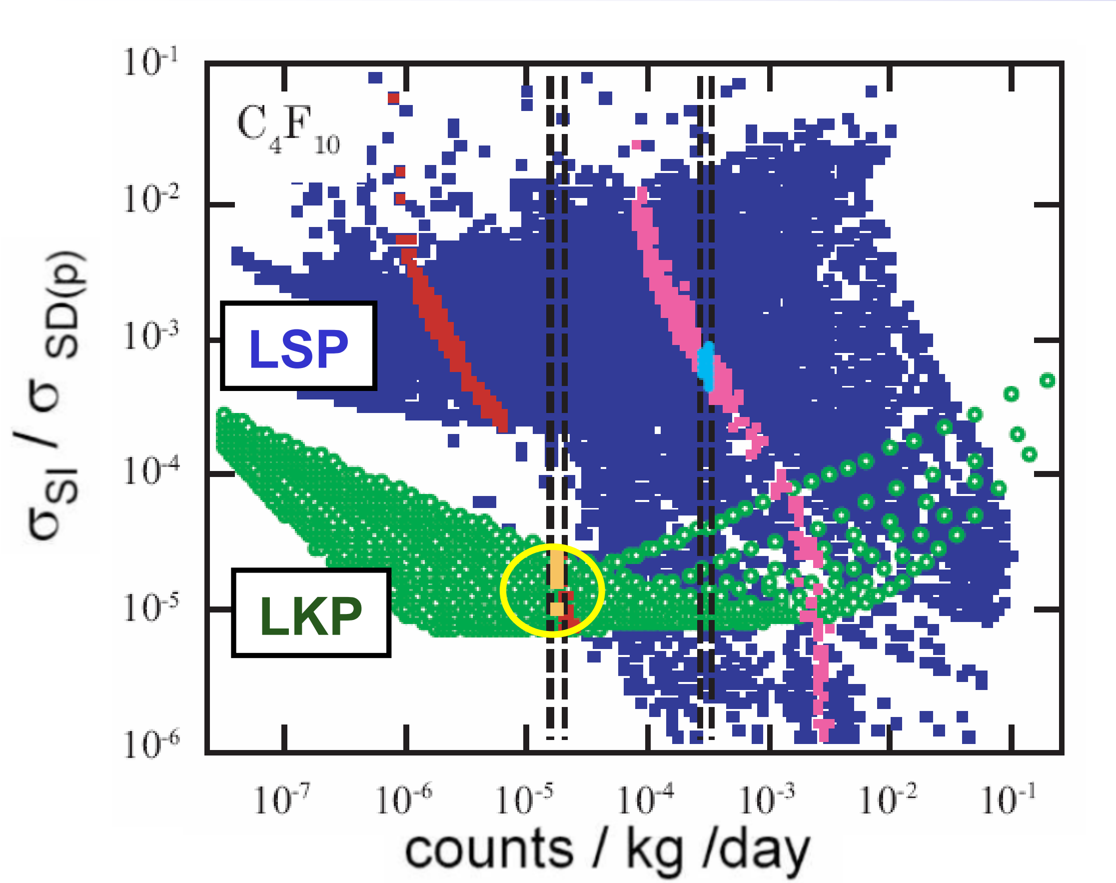

(G.Bertone, D.G.C., J.I.Collar, B.Odom´07)

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Conclusions

• Dark Matter is a necessary ingredient in the present models of our Universe... but we have not identified it yet.

Experiments in the near future (direct, indirect, LHC) might have enough sensitivity to probe WIMP candidates.

• 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:

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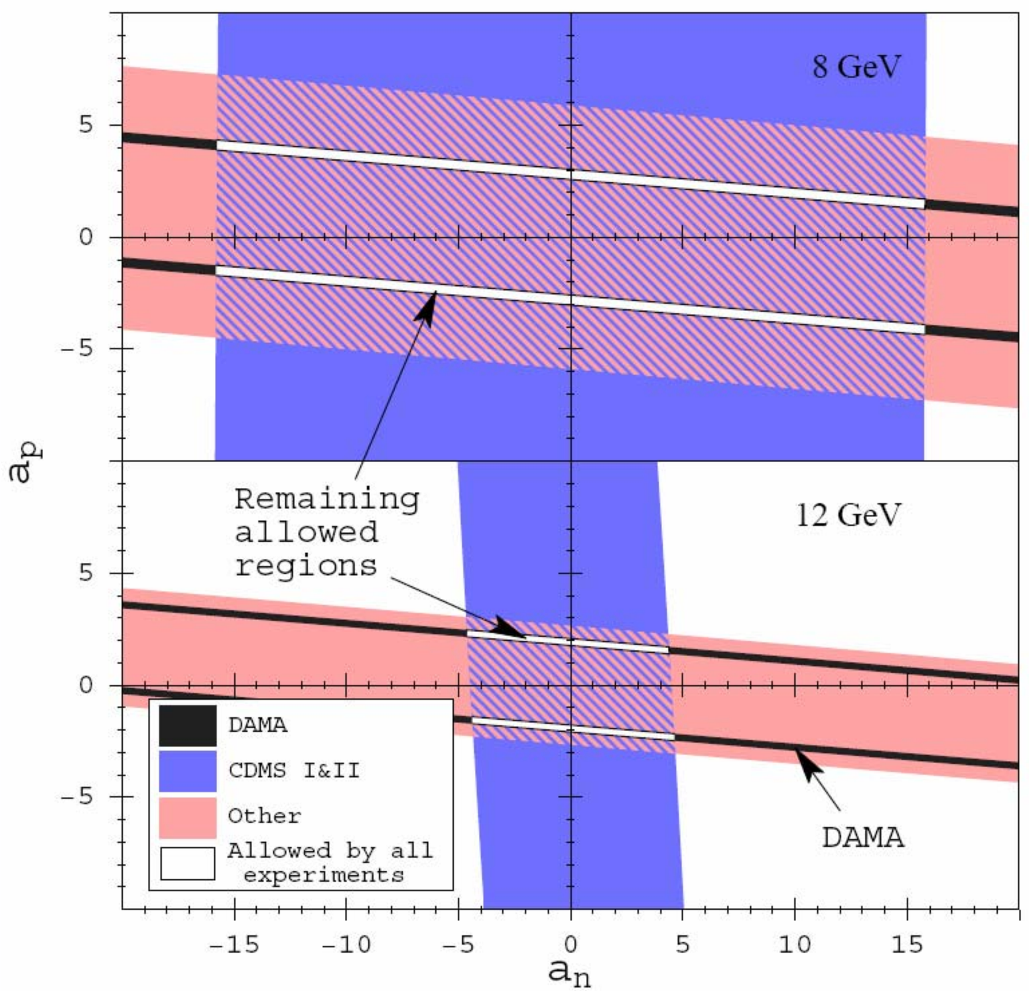
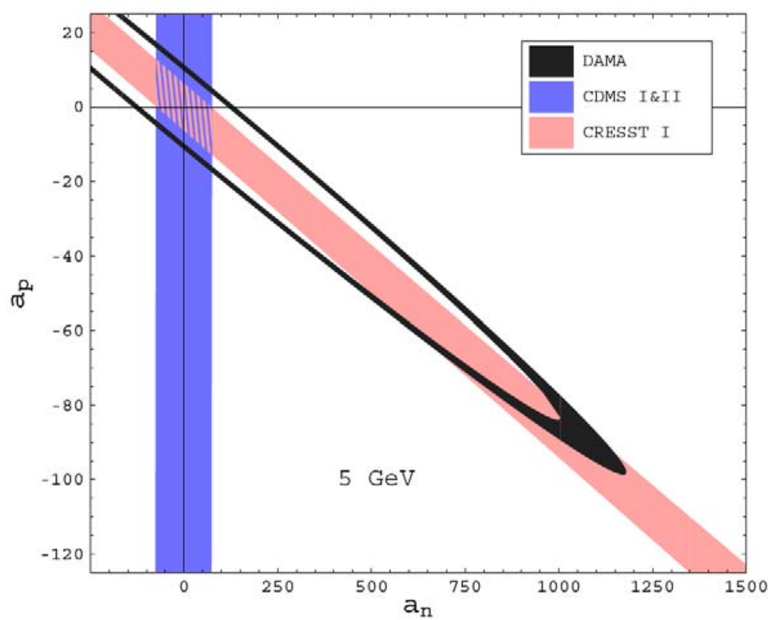
Compatibility with DAMA result

Comparison with DAMA result

- Compatibility with DAMA observation?

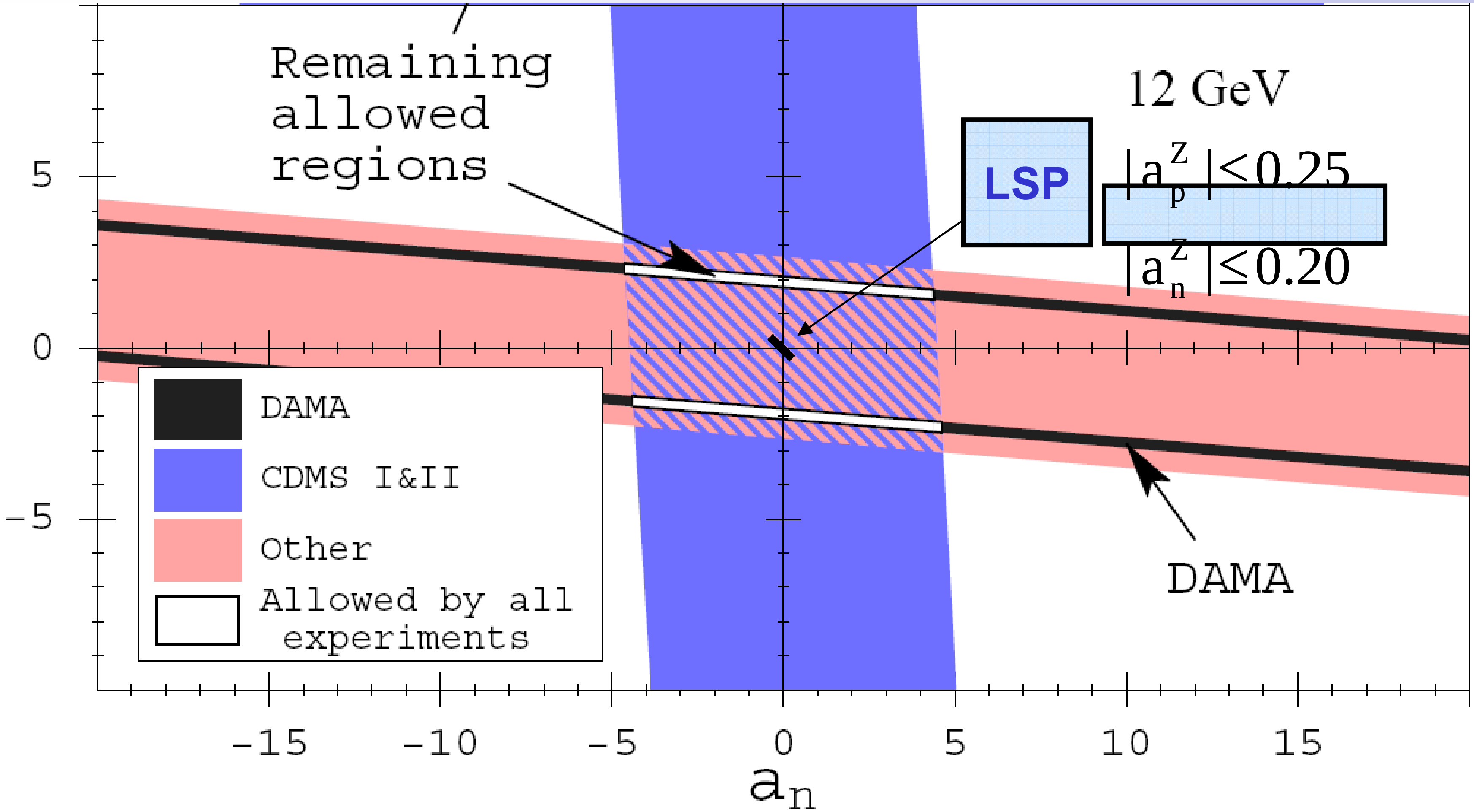




Savage, Gondolo, Freese ´06

Comparison with DAMA result

- The predicted Spin-dependent cross section is insufficient to explain DAMA´s result with neutralinos or KK dark matter



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.

Projected DM experiments

Projected and/or developing experiments

- These experiments and other projected ones are going to cover wider areas of the WIMP DM parameter space

Direct detection experiments

- ArDM

CIEMAT - ETH/Zurich – U. Granada – U. Sheffield - Soltan Institute Warszawa – U. Zurich

Initiated in 2004

Bi-phase ≅1 ton Argon detector with independent ionization and scintillation readout, to demonstrate the feasibility of a noble gas ton-scale experiment with the required performance to efficiently detect and sufficiently discriminate backgrounds for a successful WIMP detection.

1st phase Placed at CERN, 2nd phase Canfranc?

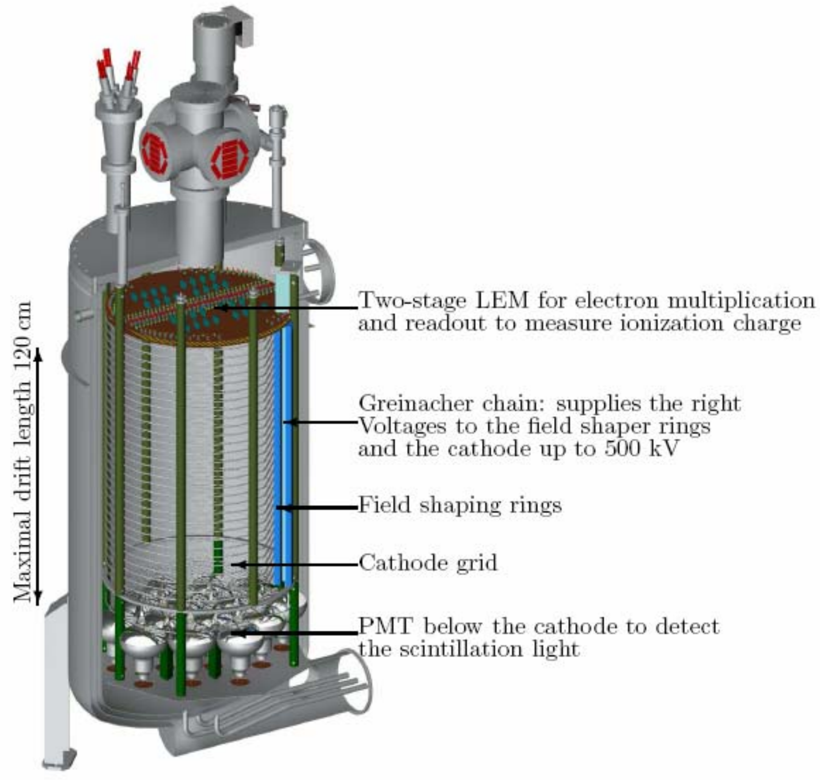


Figure 1. Setup of the ArDM detector.

Direct detection experiments

- WARP

U. degli Studi di Pavia, INFN, LNGS, U. degli Studi dell'Aquila, Napoli, Padova, Princeton U., IFJ PAN Krakow,

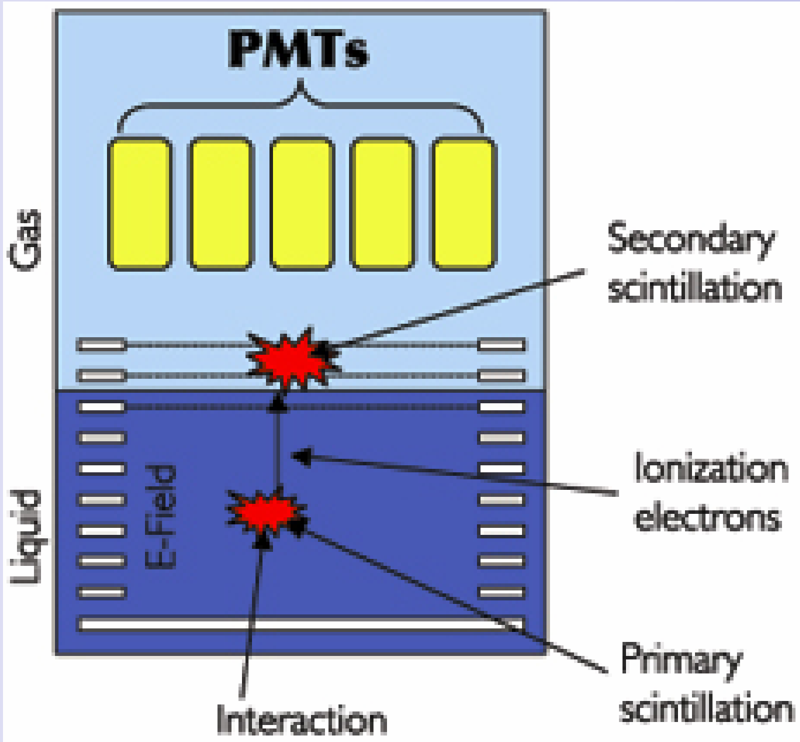
Gran Sasso National Laboratory (LNGS)

Detection in noble liquids. Started with Xenon, now switched to Argon (mostly due to previous experience with ICARUS)

Inner double phase argon. When a particle interacts in the liquid region excitation and ionization occur.

A primary scintillation signal due to disexcitation of argon is produced and detected by the photomultipliers positioned in the gaseous phase.

If electric fields are applied, some ionization electrons produced in the interaction processes drift towards the gas phase, where they are accelerated in order to produce, through collisions with atoms, the emission of photons (proportional to ionization) in a secondary scintillation.



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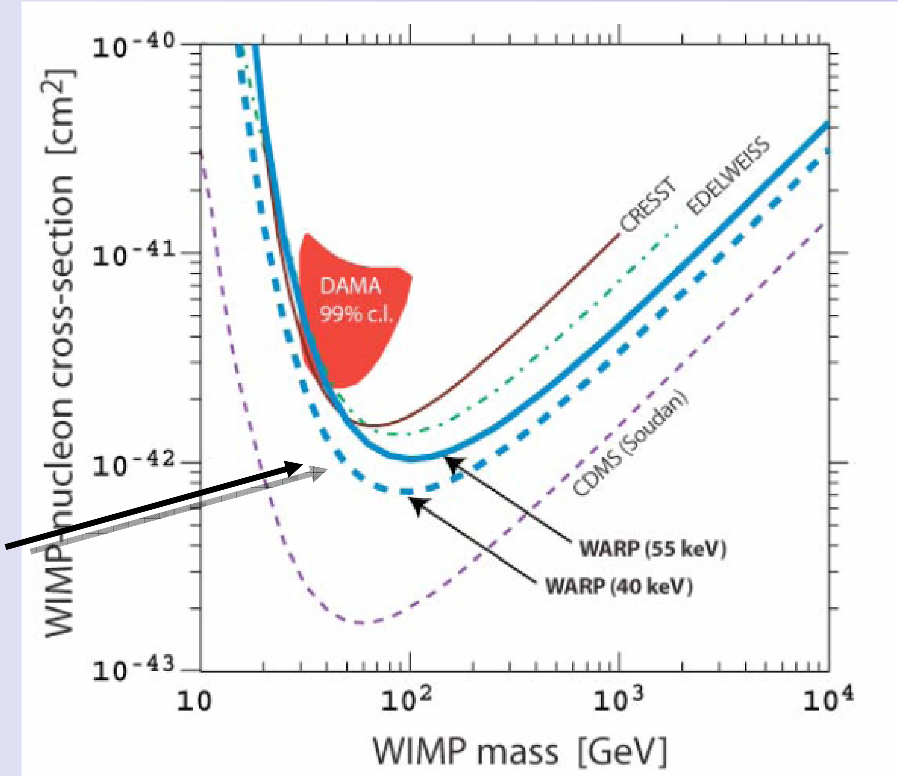
Detection in noble liquids. Started with Xenon, now switched to Argon (mostly due to previous experience with ICARUS)

Inner double phase argon. When a particle interacts in the liquid region excitation and ionization occur.

Jan. 2007: Results based on a test chamber with 2.3 litre of liquid Ar (started 2004)

Next step: 100 litres (140 Kg) detector



Direct detection experiments

- ZEPLIN

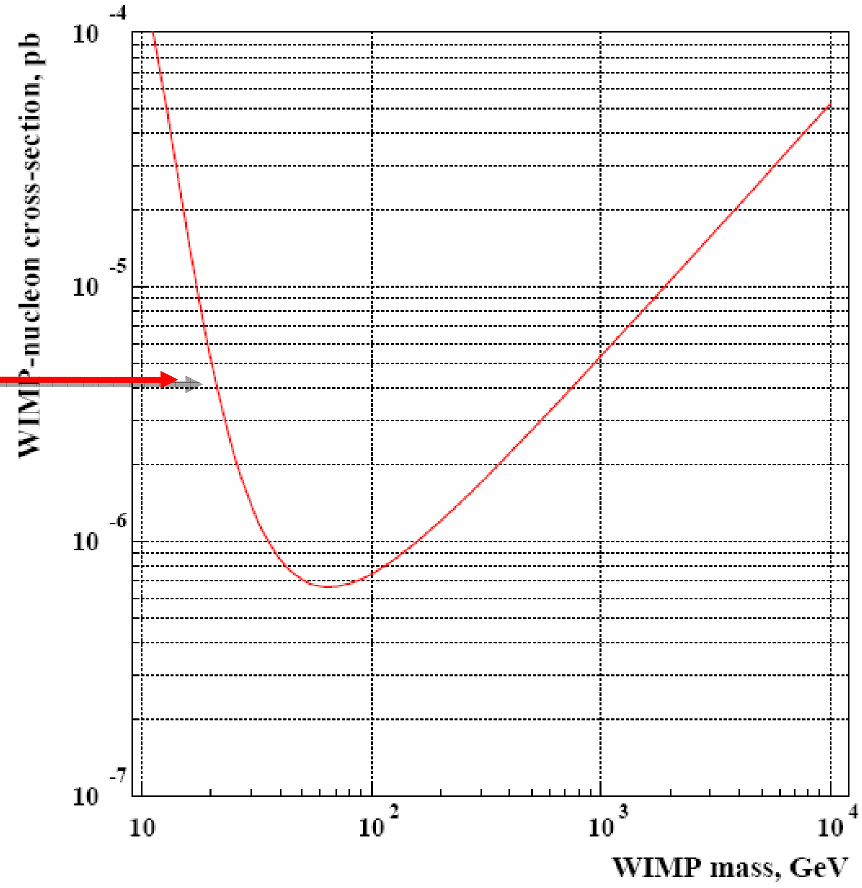
UCLA, UKDMC (1987-2007), Texas A&M, CERN, Torino, Padova, UMSHN Mexico, CINVESTAV Mexico

Boulby mine (UK)

ZEPLINII: two-phase liquid Xe detector.

Started 2005

First run results from Mar. 2007



ZEPLINIII: Proposed a multi-ton liquid Xenon experiment.

ZEPLINIV: 1ton upgrade of ZEPLINII

Direct detection experiments

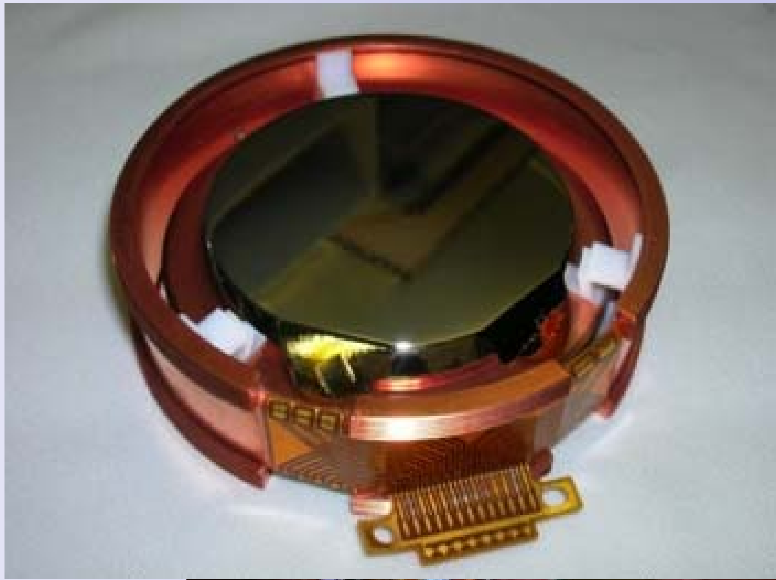
- EDELWEISS

CNRS, CEA, Karlsruhe, Dubna

Modane Undergound Laboratory (LSM)

2005: Final results for EDELWEISS
Measurement of ionization and phonons

EDELWEISSII currently starting taking data



Direct detection experiments

- ANAIS

University of Zaragoza

Canfranc Underground Laboratory

Initiated 2000

ANAIS is a large mass scintillators experiment (10x10.7 kg NaI(Tl)) planned to look for an annual modulation in the WIMP signal.

10.7 kg prototype tested and started taking data in summer 2005. Aimed at background and threshold reduction.

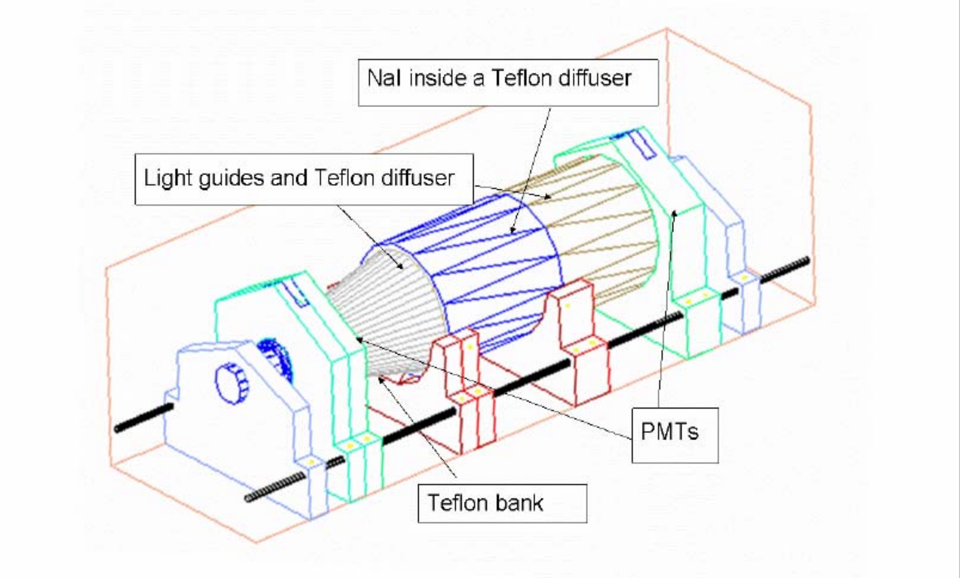


Figure 2. Schematic view of the second prototype of the ANAIS experiment.

Direct detection experiments

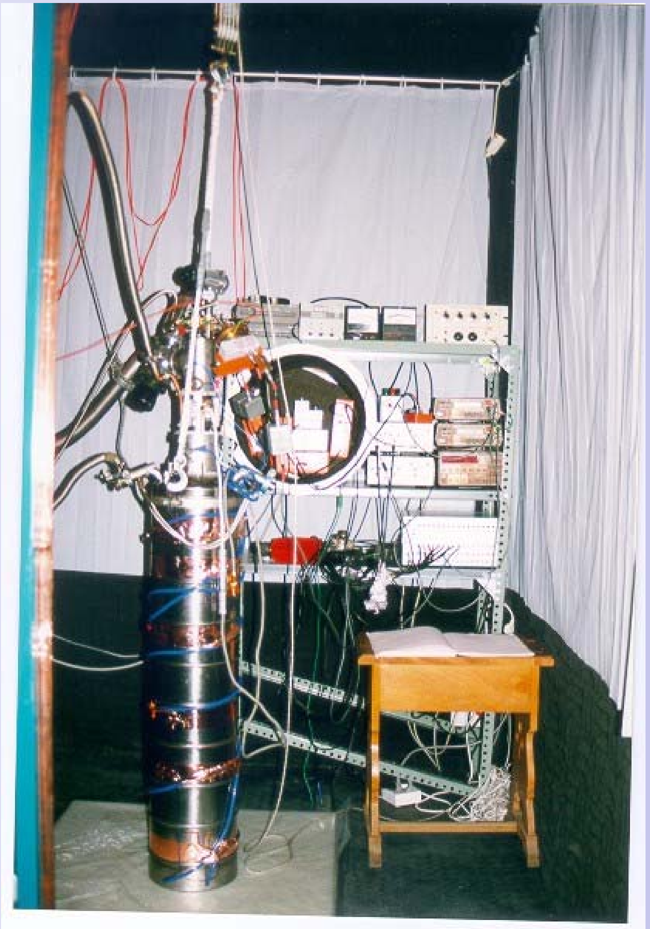
- ROSEBUD

University of Zaragoza, Institut d'Astrophysique Spatiale, Orsay (IAS)

Canfranc Underground Laboratory

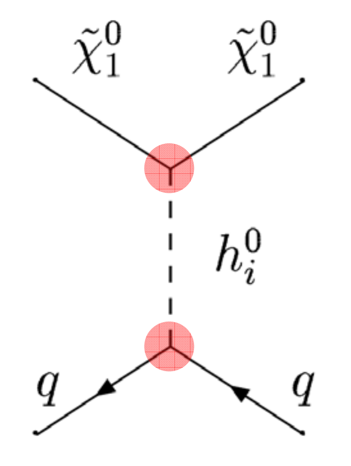
1998-1999: First phase of the experiment only sapphire (25 and 50 g) was used as absorber.

2000-: Second phase of the experiment operating bolometers of Germanium (67g), sapphire (50g) and Calcium Tungstate (54g).



Non-universal soft masses

Non-universal soft terms



Higgs-exchange

Leading contribution. It can increase when

- The Higgsino components of the neutralino increase

$$\mu \downarrow$$

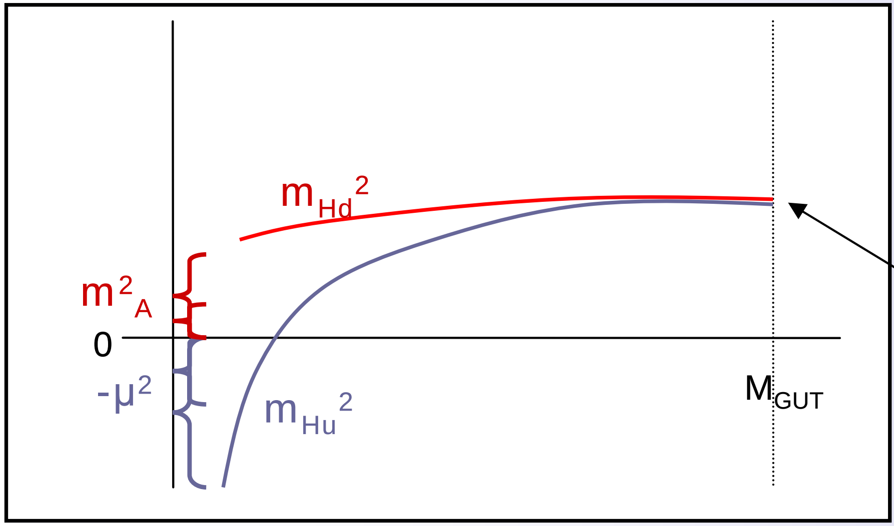
- The Higgs masses decrease

$$m_h,\ m_{H^0}\ m_{A^0} \downarrow$$

In terms of the mass parameters in the RGE

$$m_A{}^2 \approx m_{H_d}^2 - m_{H_u}^2 - M_Z^2$$

$$\mu^2 \approx -m_{H_u}^2 - \tfrac{1}{2} M_Z^2$$



Non-universal soft terms (e.g., in the Higgs sector)

$m_{Hu}{}^2 \Uparrow$

$m_{Hd}{}^2 \Downarrow$

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.

The neutralino in the NMSSM

The neutralino in the NMSSM

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

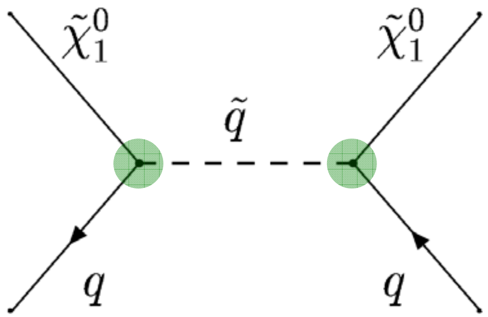
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta & 0 \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta & 0 \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu & -\lambda v_2 \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu &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

The lightest neutralino has now a singlino component

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

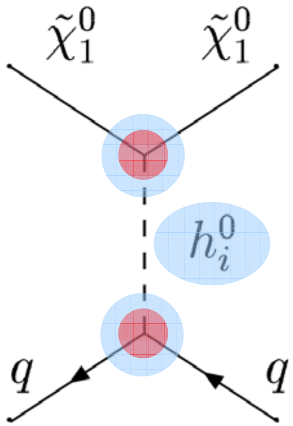
Spin-independent cross section

- 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

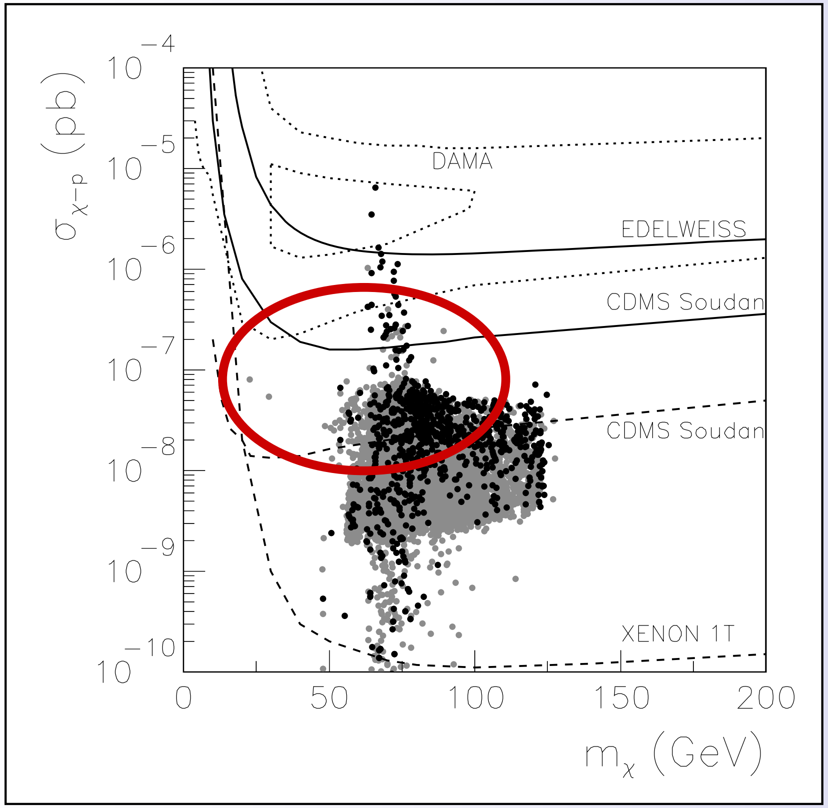
It is the leading contribution, and increases when

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



This is due to the Higgs masses being very small. These results correspond to 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

Detectability

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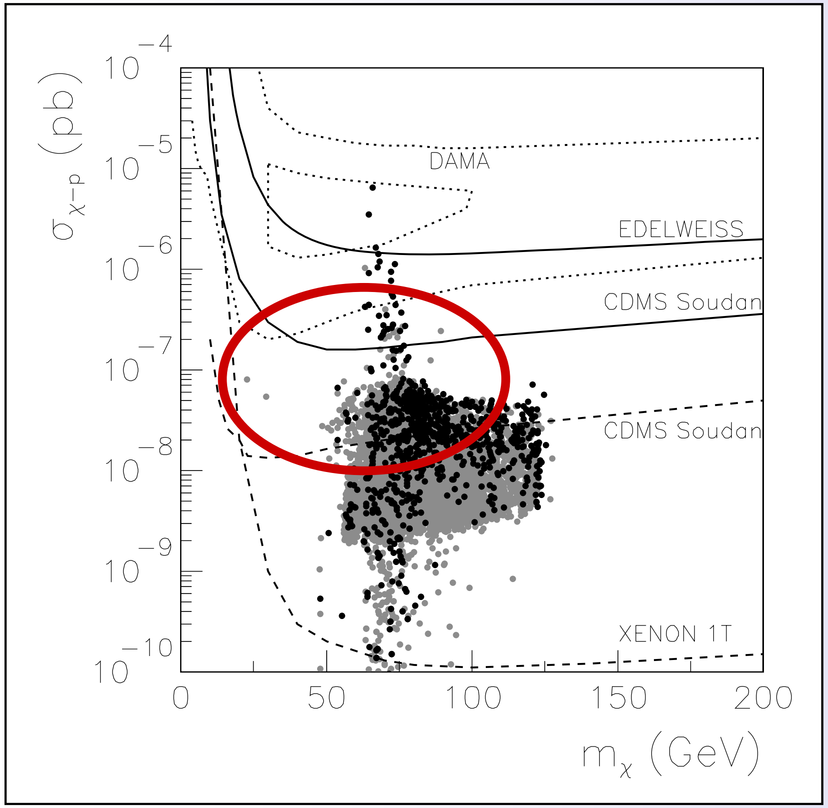
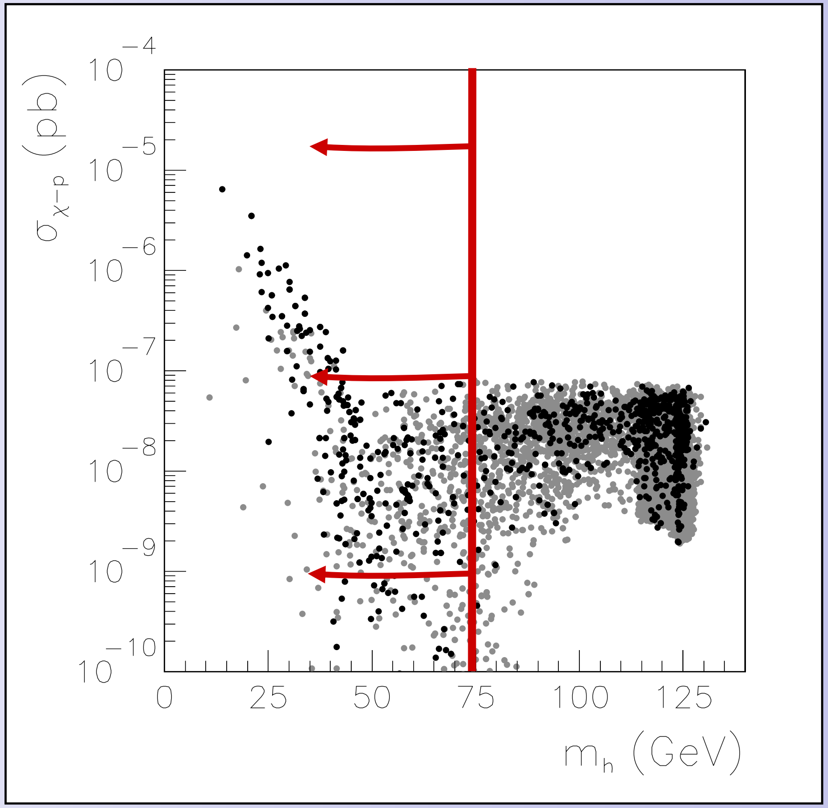
Higgses lighter than 70 GeV and mostly singlet-like





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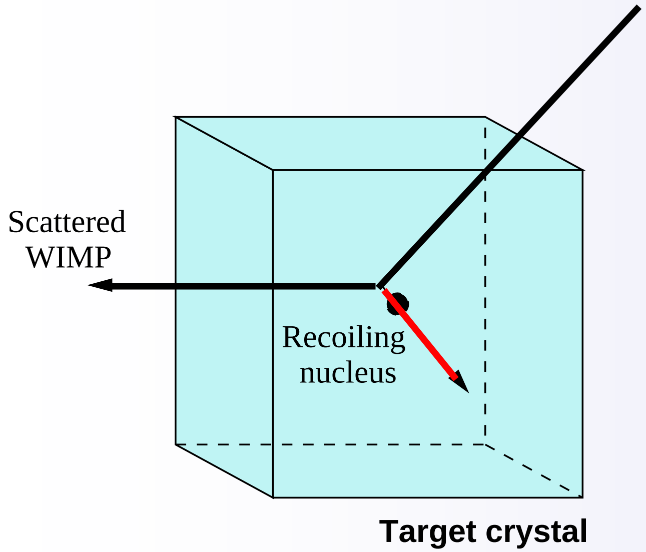
(D.G.C., E. Gabrielli, D.López-Fogliani, A.Teixeira, C.Muñoz ´07)

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

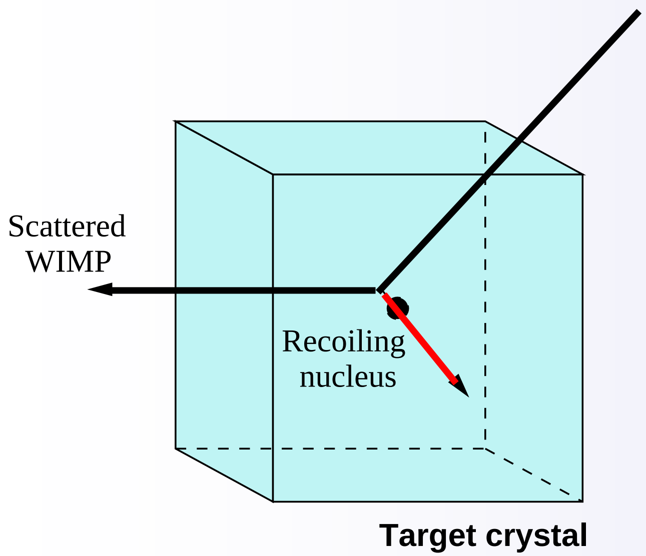
- Ionization on solids
- Ionization in scintillators (measured by the emmited photons)
- Temperature increase (measured by the released phonons)

Problems

- Very small interaction rate
- Large backgrounds (experiments must be deep underground)
- Uncertainties in the DM properties in our galaxy

WIMP direct detection

• The direct detection of WIMPS can take place through their elastic scattering 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)

Modern and projected detectors use a combination of these techniques

Ionization + phonons: **CDMS, EDELWEISS**

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

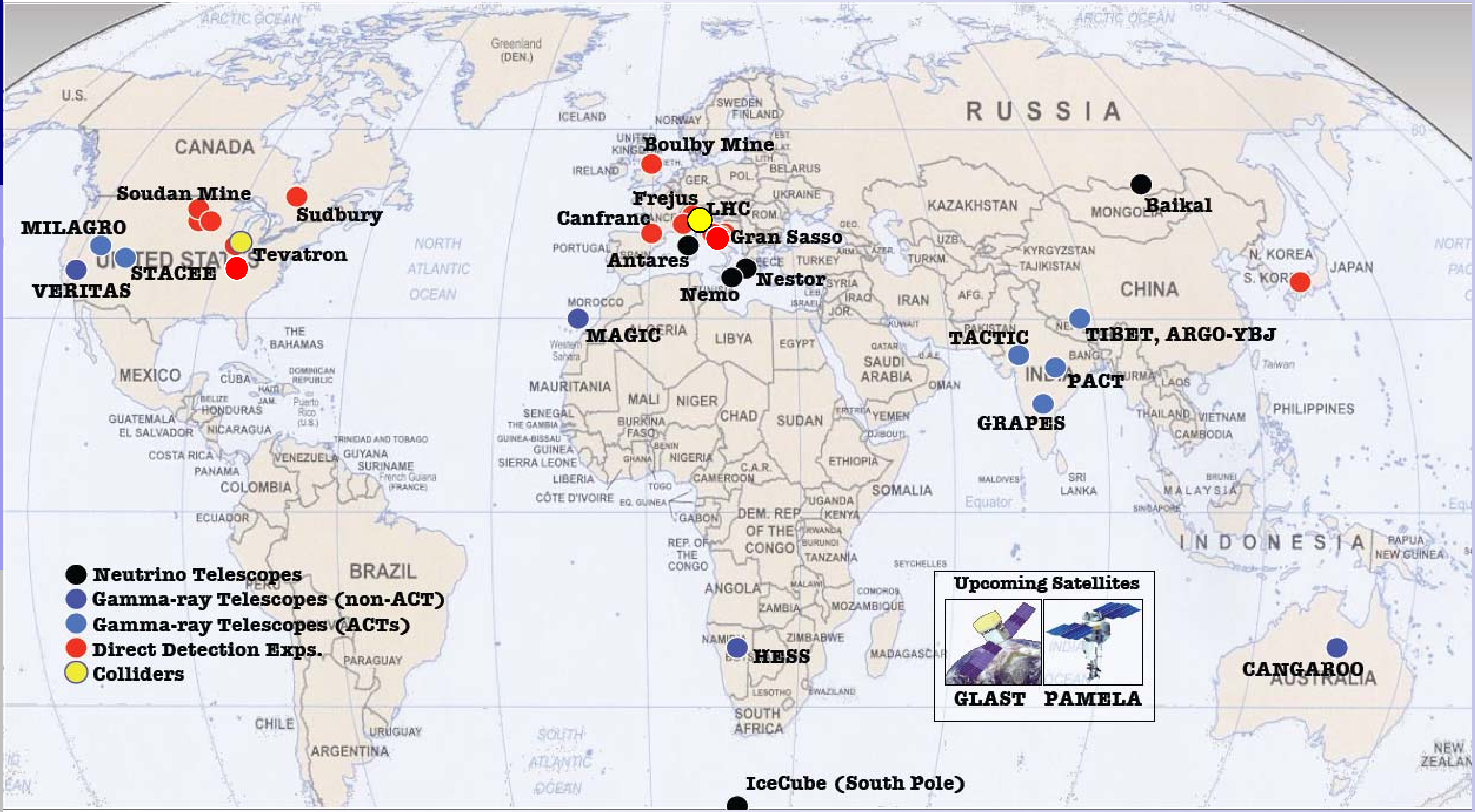
Scintilation + phonons: **CRESST II, ROSEBUD**

Dark matter related experiments around the world (2007)

Experiment	Technology	β,γ rejection	Comments
CDMS	Cryo Ge/Si	ionization/phonon	surface β's, timing helps
Edelweiss	Cryo Ge	ionization/thermal	surface β's, NbSi helps
CRESST, Rosebud	Cryo $CaWO_4$	scintillation/thermal	low light for WIMP on W
Zeplin, XENON,	LXe 2-phase	charge/scintillation	low light, PMT radioactivity
WArP, ArDM,	LAr 2-phase	charge/scintillation	purification (^{39}Ar,^{42}Ar,^{85}Kr)
XMASS	LXe	scint,self-shielding,	No E-field, good scaling
CLEAN	LAr/LNe	scint,pulse shape disc.	also solar ν, no E-field
Majorana, Gerda	HPGe counting	energy resolution	primarily $\beta\beta$-decay
Genius, GEDEON	HPGe counting	extreme purity	large mass, ann mod.
Cuoricino	Cryo TeO_2	stat. subtraction	
DAMA,LIBRA, ANAIS	NaI scint.	pulse shape disc. extreme purity	large mass, ann mod. also $\beta\beta$-decay
Picasso, COUPP	bubble chambers	nucleation thresh	large mass, alpha bkgd
DRIFT	drift chmbr (gas)	track length	directionality/low density

(P.B. Cushman '07)

Dark matter related experiments around the world (2007)



WIMP-nucleus interaction

- The interaction of a generic WIMP with nuclei has several contributions $\sigma_{\chi-N}$

Axial-Vector

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

- Adds incoherently

SPIN-DEPENDENT (Nucl. Angular mom)

Scalar

$$L_S \sim \bar{\chi}\chi\ \bar{q}q \qquad A^2$$

SPIN-INDEPENDENT (Nucleon #)

Vector

$$L_V \sim \bar{\chi}\gamma^\mu\chi\ \bar{q}\gamma^\mu q \qquad A^2$$

- Adds coherently
- Only for non-Majorana WIMPs

SPIN-INDEPENDENT

Spin-independent cross section

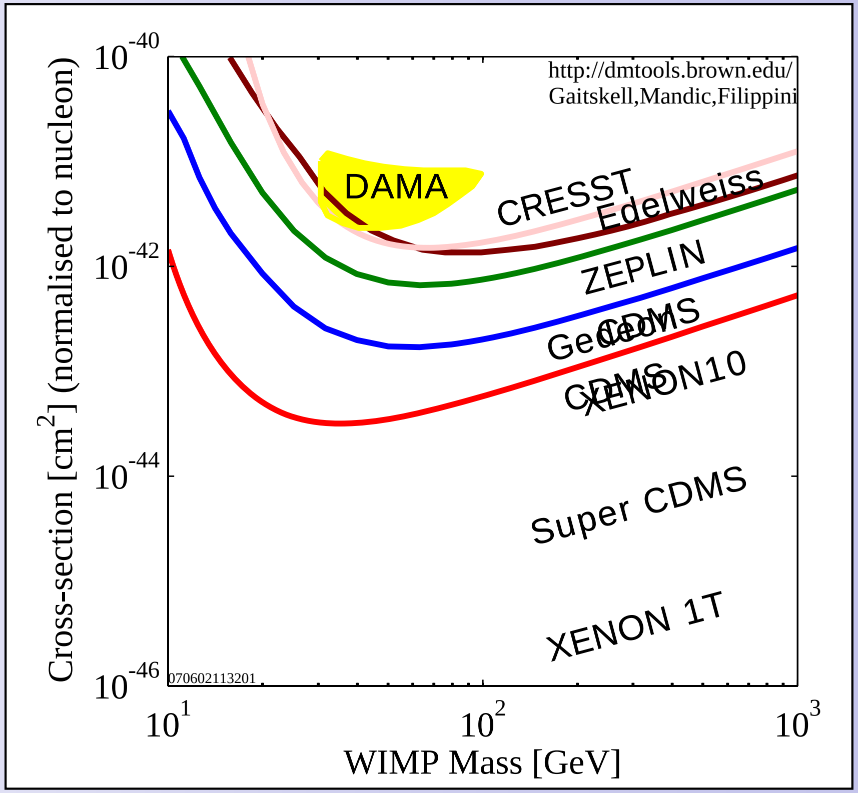
• Most of the experiments nowadays are mostly sensitive to the scalar (spin-independent) part of the WIMP-nucleon cross section (using, e.g., with Iodine or Germanium).

(Dominant for nuclei with A ≥ 20)

• How large can the WIMP detection cross section be?

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

Calculate the theoretical predictions for WIMP-nucleus cross section



Heavyweights...

- Two heavyweights have taken over in the last years...

Direct detection experiments

- CDMS

Brown U., Caltech. Case Western Reserve U., FNAL, MIT, RWTH-Aachen, Santa Clara U. Stanford, Berkeley, Santa Barbara, U. Of Colorado, U. Of Florida, U. Of Minessotta.

Soudan Underground Laboratory

Initiated 2000

Simultaneous measurement of ionization and temperature increase.

Sep. 2005: 6x250g Ge and 6x100g Si solid state detectors operated at 50 mK

Direct detection experiments

- CDMS

Brown U., Caltech. Case Western Reserve U., FNAL, MIT, RWTH-Aachen, Santa Clara U. Stanford, Berkeley, Santa Barbara, U. Of Colorado, U. Of Florida, U. Of Minessotta.

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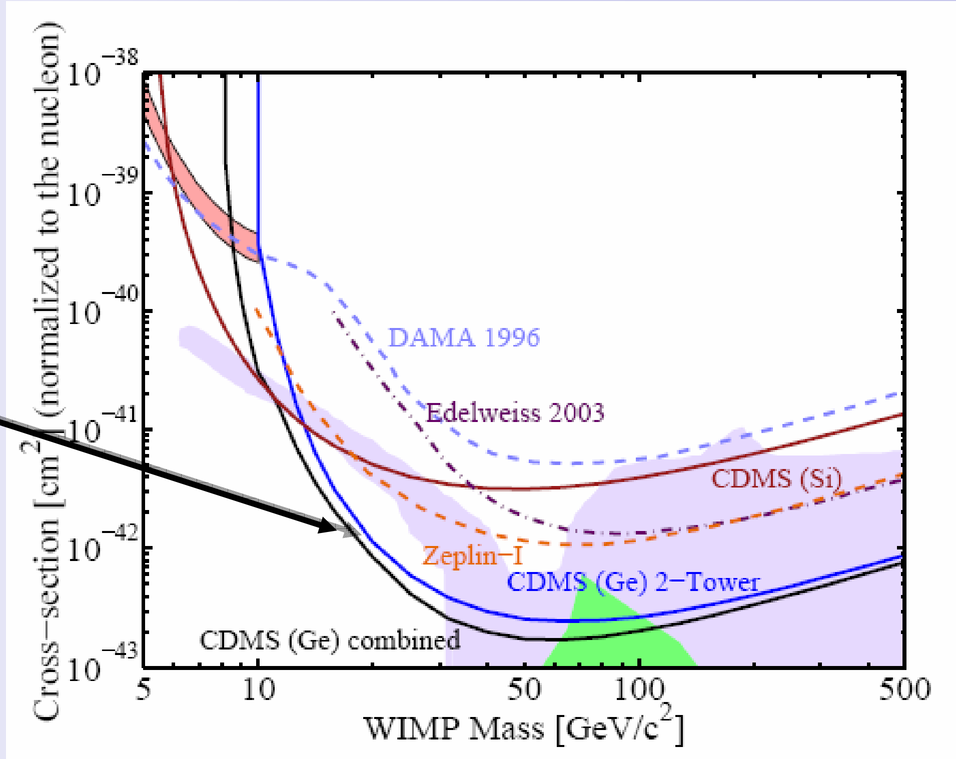
Initiated 2000

Simultaneous measurement of ionization and temperature increase.

Sep. 2005: 6x250g Ge and 6x100g Si solid state detectors operated at 50 mK



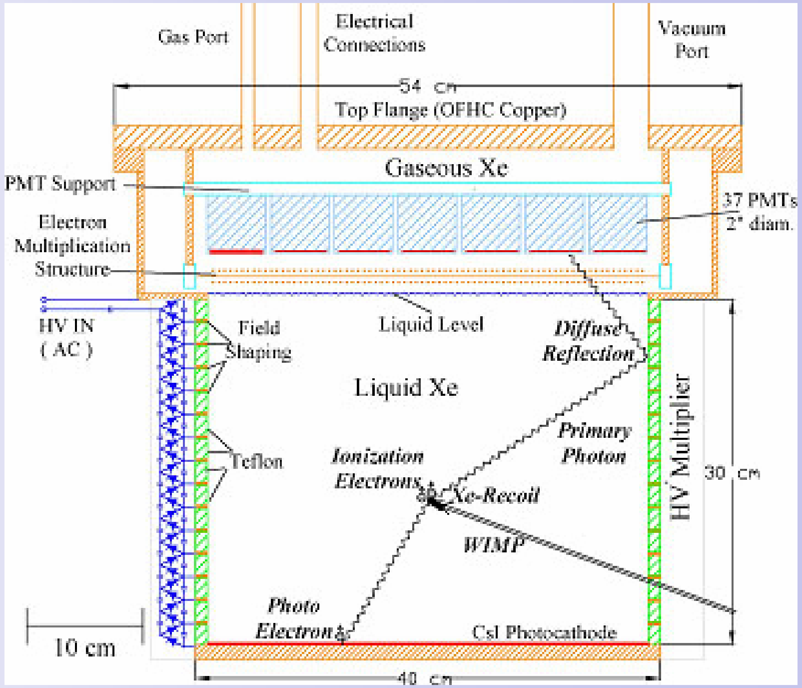
Direct detection experiments

- XENON

Columbia U., Brown U., Rice U., Case Western Reserve U., RWTH-Aachen U., Yale U., Lawrence Livermore National Lab., LNGS, U. Of Coimbra

Gran Sasso National Laboratory (LNGS)

Measurement of scintillation and ionization



Direct detection experiments

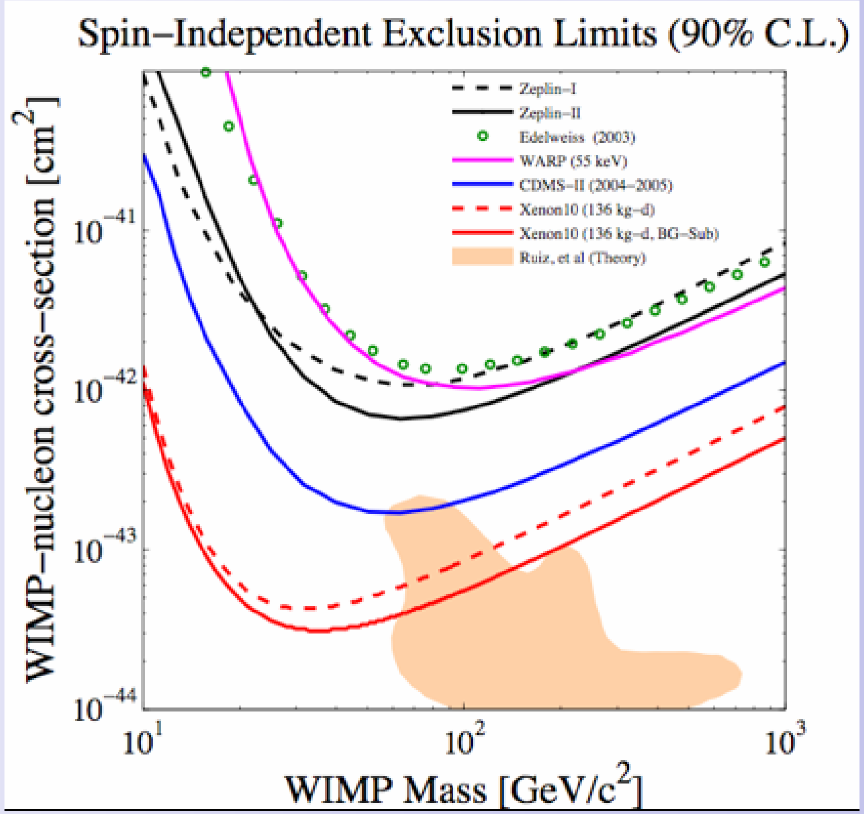
- XENON

Columbia U., Brown U., Rice U., Case Western Reserve U., RWTH-Aachen U., Yale U., Lawrence Livermore National Lab., LNGS, U. Of Coimbra

Gran Sasso National Laboratory (LNGS)

Measurement of scintillation and ionization

June 2007: XENON10 results from a 10 month WIMP search run



Direct detection experiments

- CDMS

Brown U., Caltech. Case Western Reserve U., FNAL, MIT, RWTH-Aachen, Santa Clara U. Stanford, Berkeley, Santa Barbara, U. Of Colorado, U. Of Florida, U. Of Minessotta.

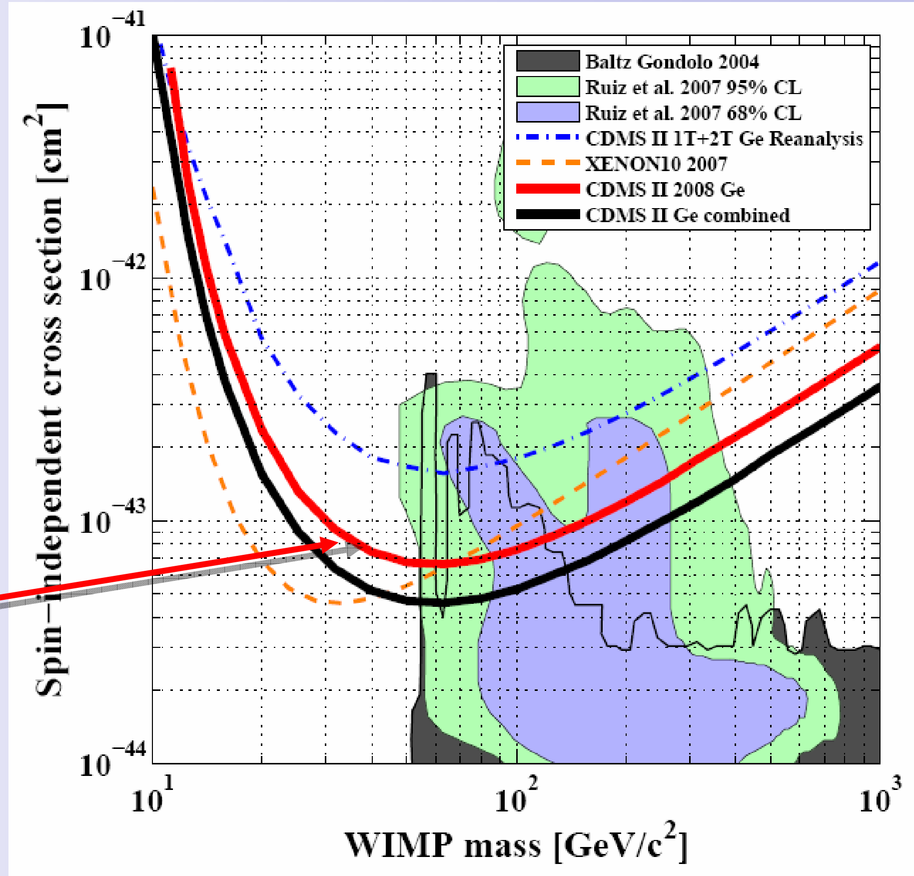
Soudan Underground Laboratory

Initiated 2000

Simultaneous measurement of ionization and temperature increase.

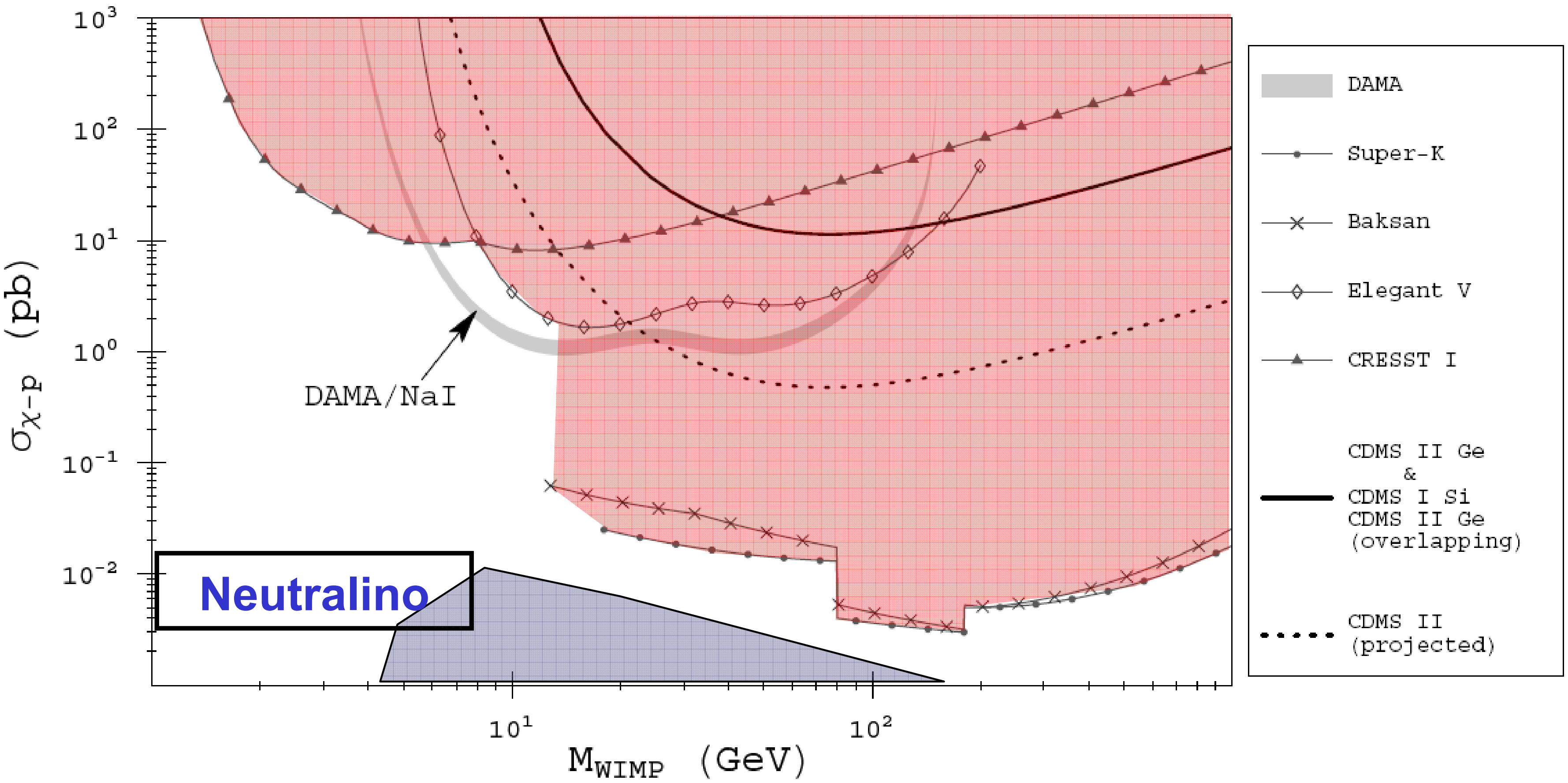
Feb. 2008: 19x250g Ge and 11x100g Si solid state detectors operated at 50 mK (18 additional detectors since 2006, improved cryogenic stability, increased exposure)

NEW DATA FROM 15 DETECTORS



Spin-dependent cross section

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

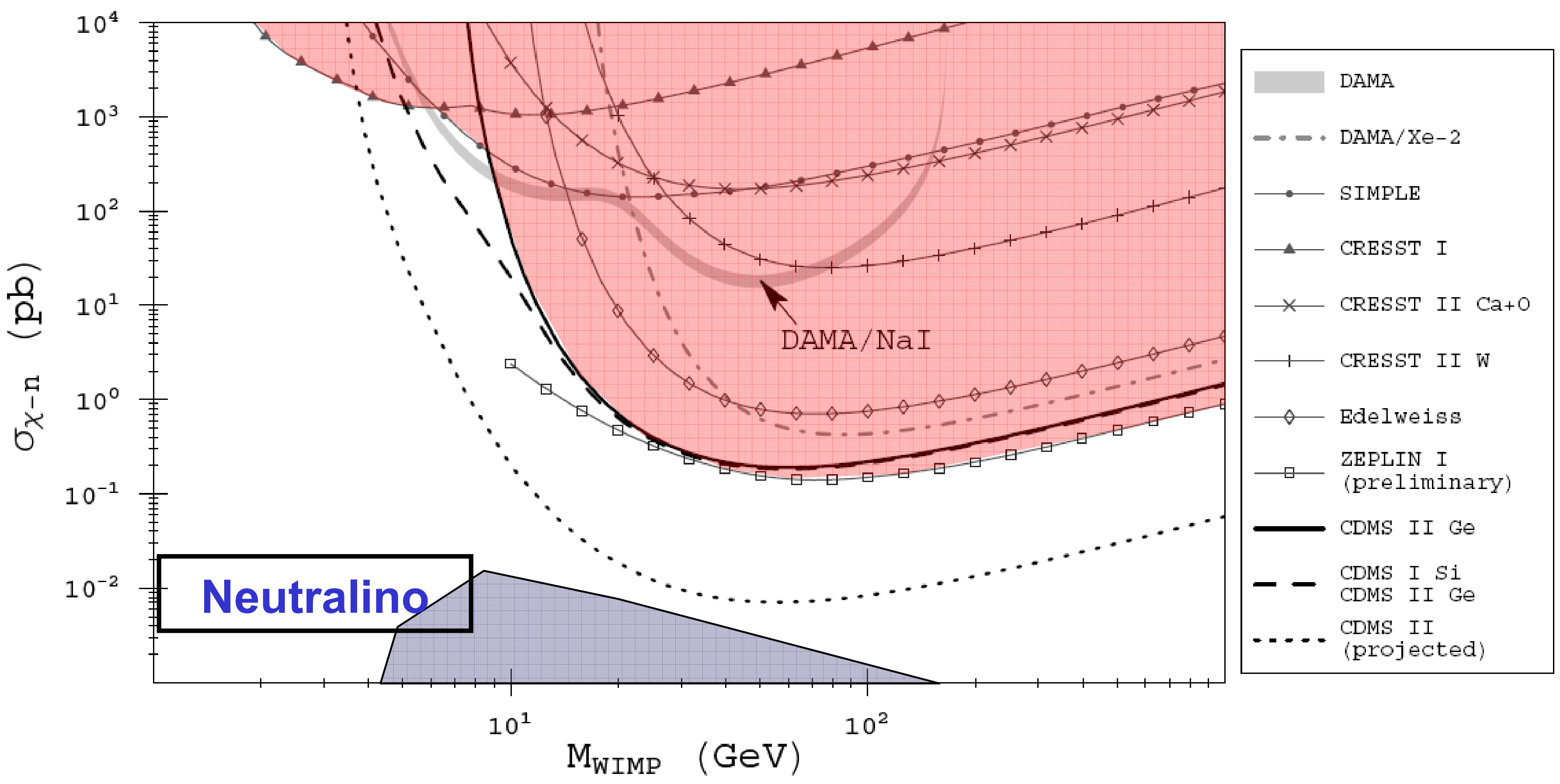


Savage, Gondolo, Freese ´06

Spin-dependent cross section

Detectability

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



Savage, Gondolo, Freese ´06

Direct detection experiment

- PICASSO

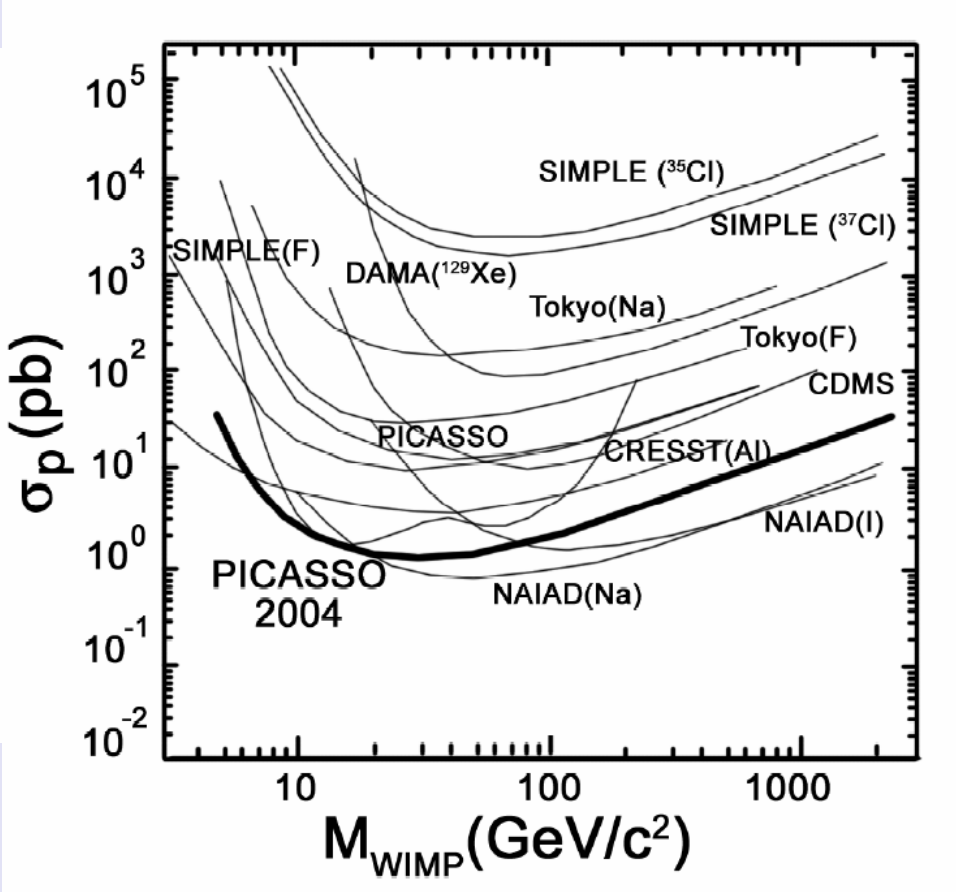
U. degli Studi di Pavia, INFN, LNGS, U. degli Studi dell'Aquila, Napoli, Padova, Princeton U., IFJ PAN Krakow,

SNOLAB, Sudbury (Canada)

4.5l modules with 80g of active mass of C_4F_{10}. Droplets are suspended in elastic polymer.

Feb. 2005: Results

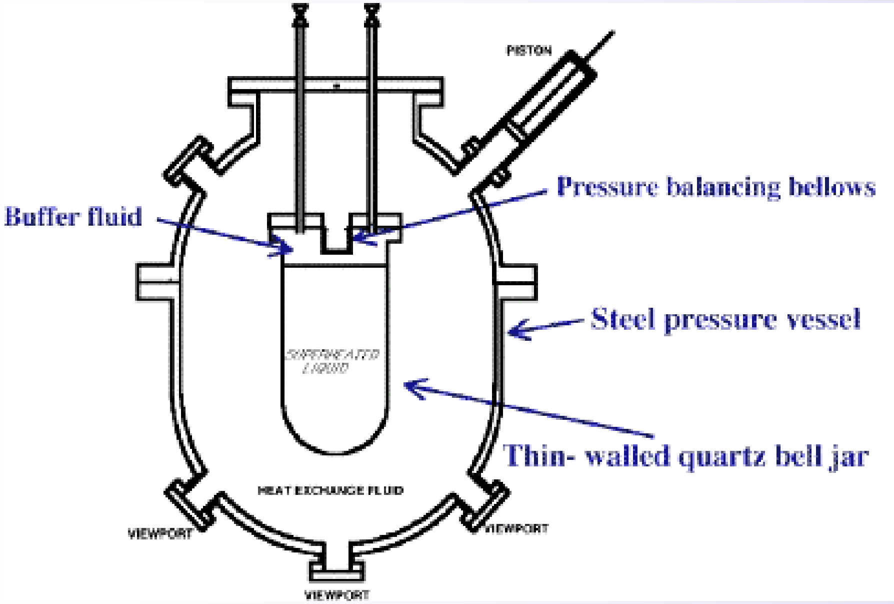
Presently PICASSO is installing a new experiment with 32 detector modules and with an active mass of 2.6 kg.

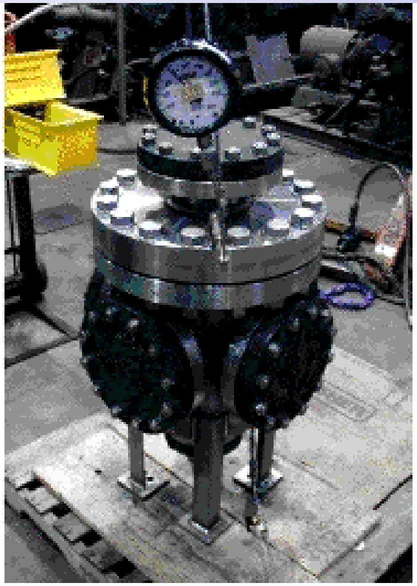


COUPP (Chicagoland Observatory for Underground Particle Physics)

- COUPP

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

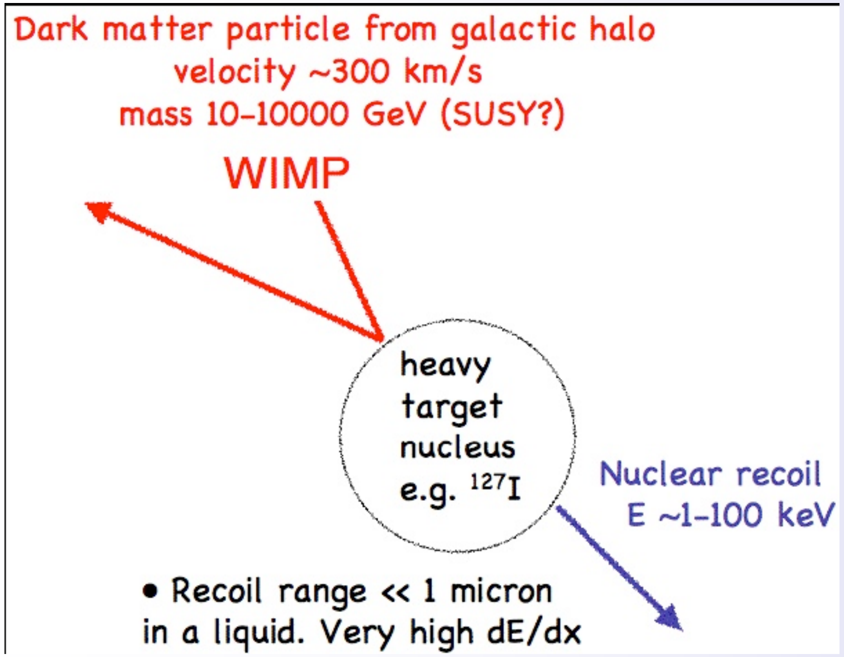


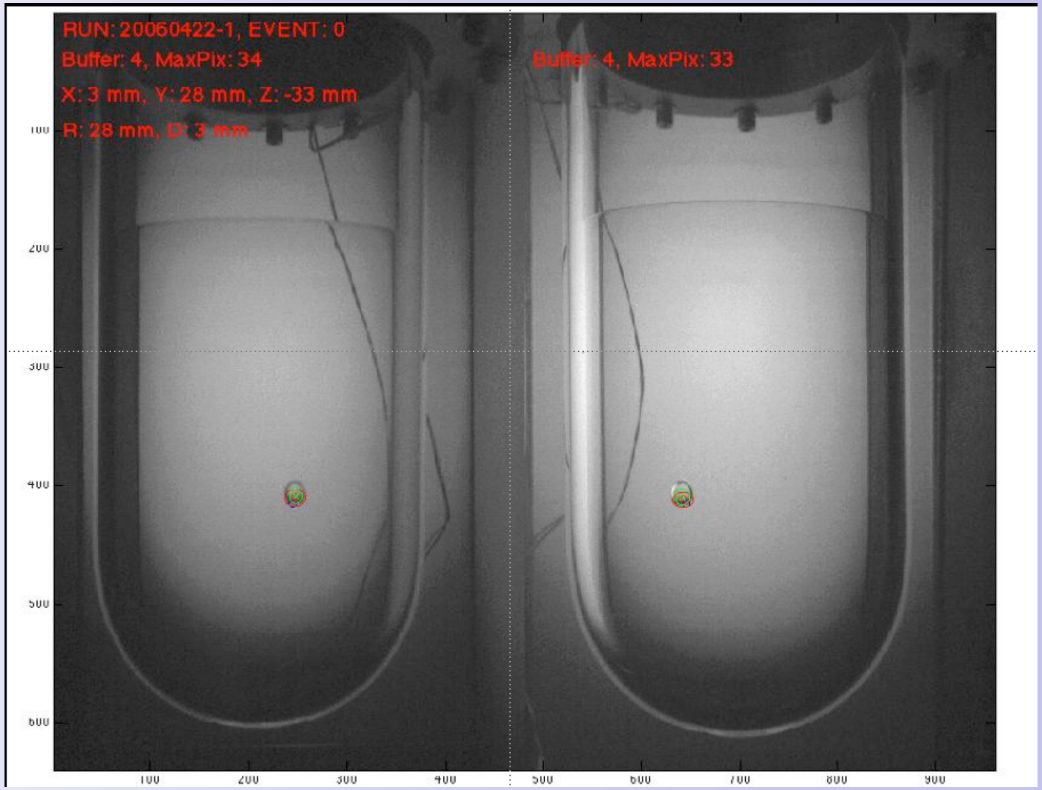


http://collargroup.uchicago.edu/news/coupp.html

COUPP

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

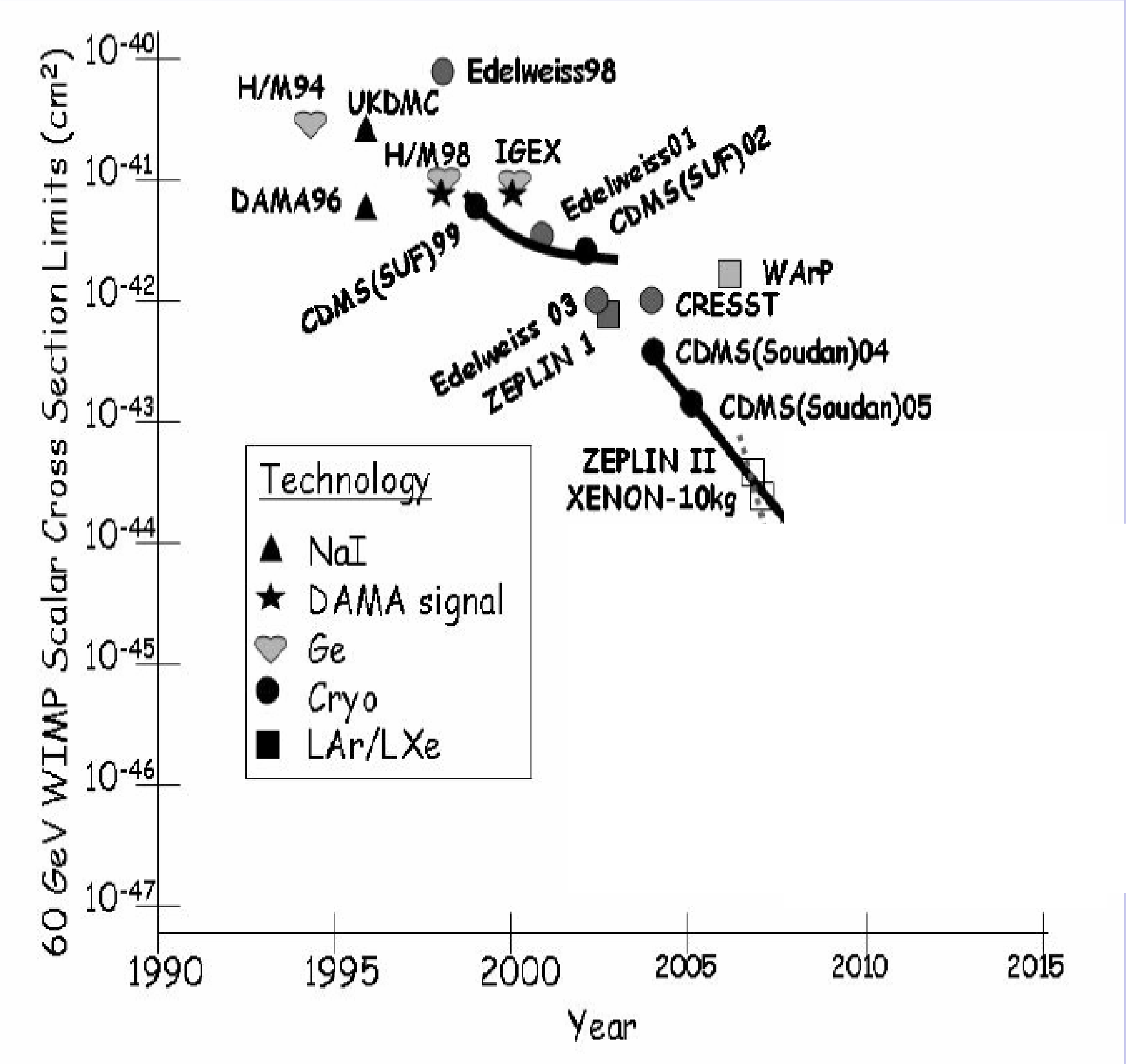




Stereo view of a typical event in 2 kg chamber

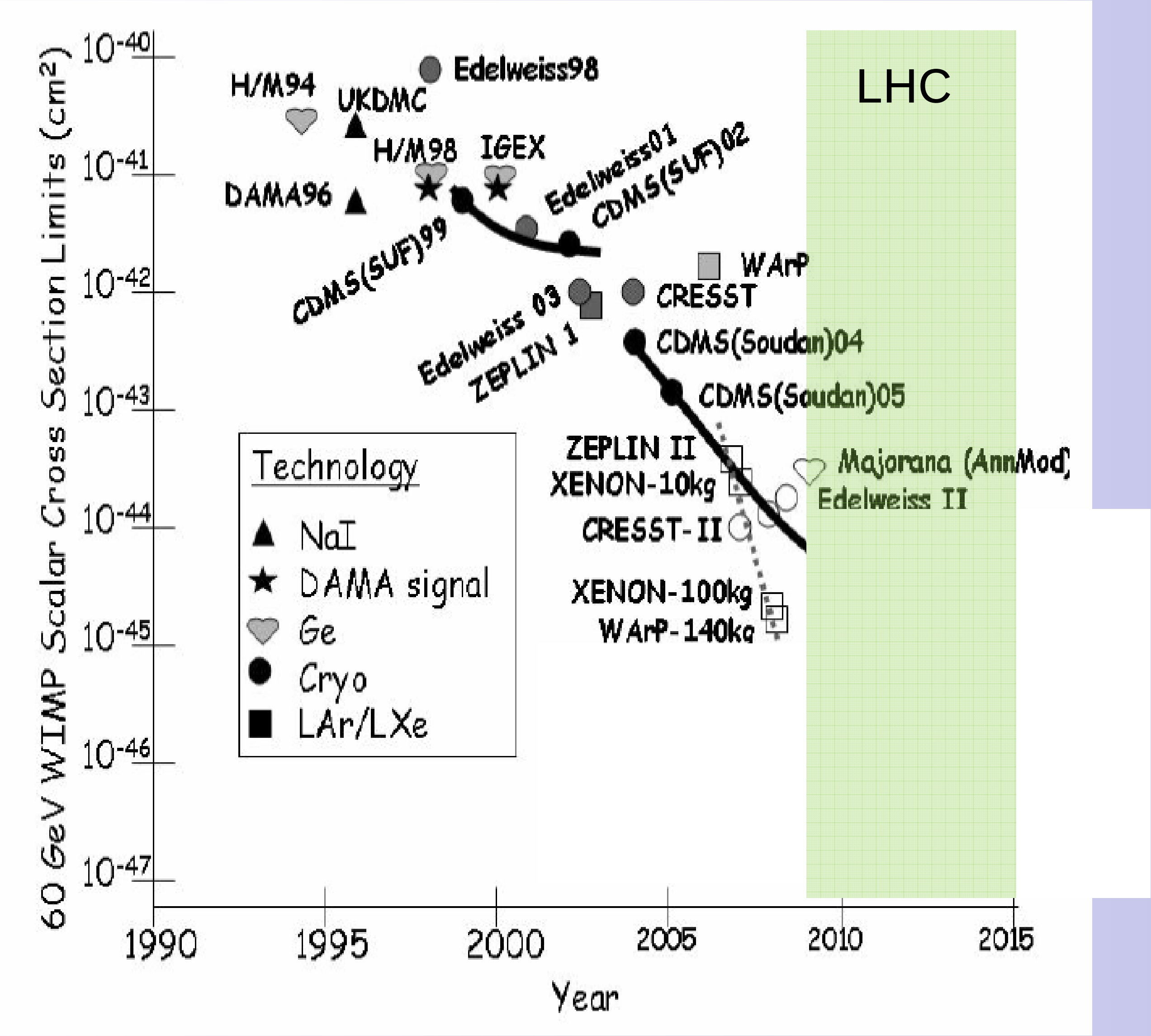
• Choice of three triggers: pressure, acoustic, motion

Experimental Timeline



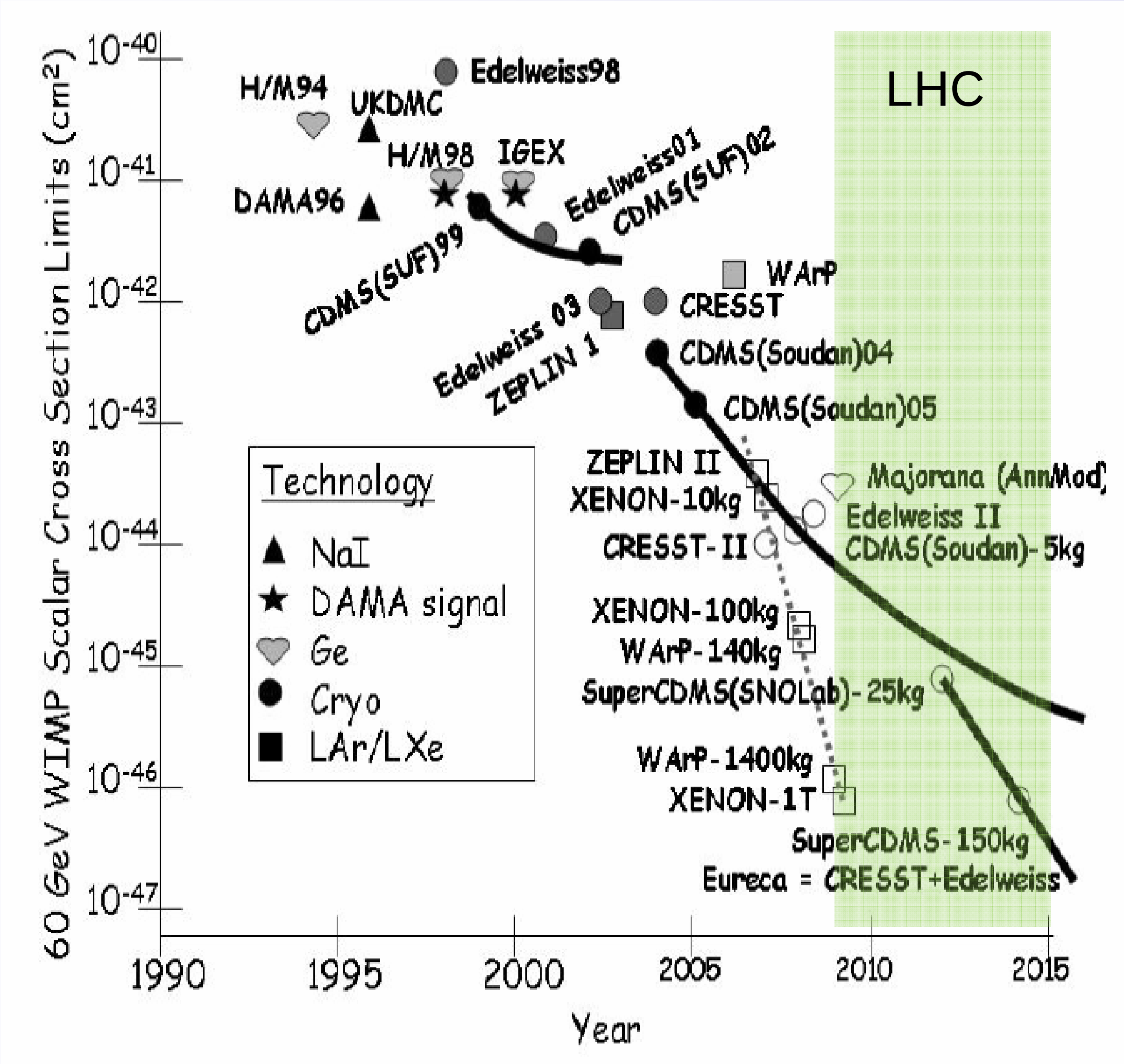
(P.B. Cushman '07)

Experimental Timeline



(P.B. Cushman '07)

Experimental Timeline



(P.B. Cushman '07)

What do we (theorists) need to provide?

- In order to determine the feasibility of direct detection of WIMP DM

Evaluate the theoretical predictions for the WIMP-nucleon scattering cross section ...

Lightest Supersymmetric Particle (Neutralinos)

Lightest Kaluza-Klein Particle

... and compare the with experimental sensitivities

... in both the spin-dependent and independent channels

- **Compatibility with an LHC hypothetical signal**
- **Compatibility with indirect DM searches**