Dark Matter Detection in the Light of Recent Experimental Results

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Milano, November 6 (2003)

- One of the great enigmas still unsolved is the existence of dark matter

- A natural candidate for dark matter is a Weakly Interacting Massive Particle

- In principle, detecting WIMPs directly, by experiments on the Earth, is possible
  - WIMP searches has been carried out since 1987
  - One of the collaborations claims that the first direct evidence for dark matter has recently been observed
  - In the light of this (polemical) result $\sim$ 20 experiments has been proposed all over the world

A natural candidate for WIMP is a susy particle:
neutralino

$\Downarrow$

Competition between these (simple) experiments
and the LHC, in the hunt for the first susy particle ?

OUTLINE

1. INTRODUCTION TO DARK MATTER

   - The problem of flat rotation curves in Galaxies
   - Solution: dark matter
   - Dark matter candidates

2. DETECTION

   - Elastic scattering with nuclei in a material
   - Experiments around the world

3. THEORETICAL MODELS

   Supersymetric Scenarios:

   - Supergravity
   - Superstrings

THE PROBLEM OF ROTATION CURVES

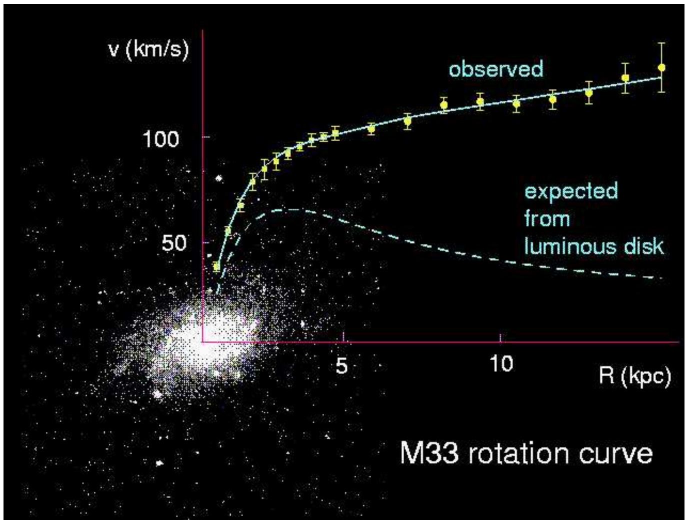
- ♣ One can compute the rotational velocity of isolated stars or hydrogen clouds in the outer parts of Galaxies simply using Newton's law

$$\frac{v_{\text{rot}}^2}{r} = \frac{G\ M(r)}{r^2} \Rightarrow \boxed{v_{\text{rot}} = \sqrt{\frac{G\ M(r)}{r}}}$$

Thus for $r > r_{\text{luminous disk}}$,

$$M(r) = M_{\text{luminous disk}} = constant \rightarrow v_{\text{rot}} \propto \frac{1}{\sqrt{r}}$$

- ♣ However, astronomers observe e.g.



(Roy, 2000 using data from Corbelli,Salucci, 1999)

A SOLUTION

- To assume that there is non-luminous matter in and around the Galaxies Zwicky, 1933

Dark Matter

- Flat rotation curves ⇒ at least 90% of the matter on galactic halo scales is dark

$$\Omega = \frac{\rho}{\rho_c}$$

$$\Omega_{LM} \approx 0.01$$

$$\Omega_{DM} \gtrsim 0.1$$

- ρ is the density averaged over the Universe
- $\rho_c = 1.88\ h^2 \times 10^{-29}$ g/cm^3 $=10^{-5} h^2$ GeV/cm^3

- Analyses of dark matter in cluster of Galaxies favour

$$\boxed{\Omega_{DM} \approx 0.2 - 0.3}$$

ZOO OF DARK MATTER CANDIDATES

Now the problem is to decipher the nature of the dark matter

♠ BARYONIC matter as Gas, MACHOs, is not sufficient

♠ Particle Physics provides NON–BARYONIC candidates:

- The only ones which are known to exist, Neutrinos, are basically excluded
- Axions with a mass $\sim 10^{-5}$ eV
- WIMPs
  Neutralino is usually the LSP $\rightarrow$ stable
  It is a WIMP with a mass $\sim 10^{2-3}$ GeV
- SIMPs, CHAMPs, SIDM, WIMPzillas, String inspired, Axinos, ...

- Strongly Interacting Massive Particles (SIMPs)

  Wolfram; Dover, Gaisser, Steigman, 79; Witten, 84

- Axions

  Ipser, Sikivie; Stecker, Shafi; Turner, Wilczek, Zee, 83

- Lightest Supersymmetric Particle (LSP)

  Goldberg; Ellis, Hagelin, Nanopoulos, Olive, Srednicki, 83

- String inspired candidates

  Gross, Harvey, Martinec, Rohm; Kolb, Secker, Turner, 85

  Ellis, Lopez, Nanopoulos, 90

  Faraggi, Pospelov, 00

  Cembranos, Dobado, Maroto, 03

- CHArged Massive Particles (CHAMPs)

  De Rújula, Glashow, Sarid, 90

- Axinos

  Rajagopal, Turner, Wilczek, 91

- WIMPzillas

  Kolb, Chung, Riotto, 98

- Self-Interacting Dark Matter (SIDM)

  Spergel, Steinhardt, 00

- Scalar Dark Matter

  Burgess, Pospelov, ter Veldhuis, 01

  Birkedal-Hansen, Wacker, 03

  Boehm, Fayet, 03

- superWIMPs

  Feng, Rajaraman, Takayama, 03

- ...

- ...

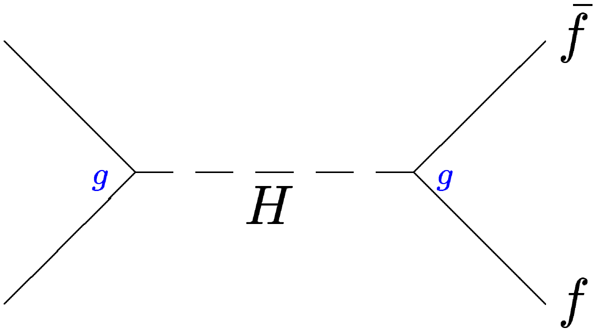
KEY QUESTION: THE RELIC DENSITY

A good dark matter candidate must fulfil $\Omega \approx 1$

- WIMPs fulfil this condition naturally since

  $$\Omega \propto \frac{1}{\sigma_{\text{annihilation}}}$$

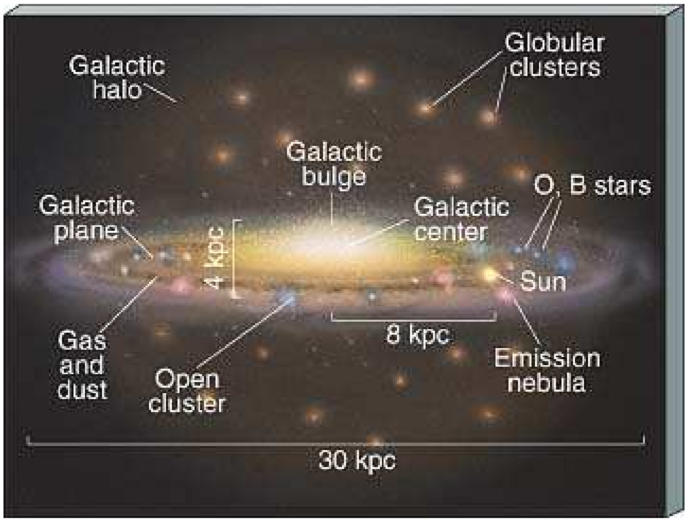
  and a particle with weak-scale interactions has the appropriate value of the annihilation cross section to obtain $\Omega \approx 1$



This is a striking coincidence

DETECTION

Since the detection will be in the Earth we only need to know the properties of our Galaxy

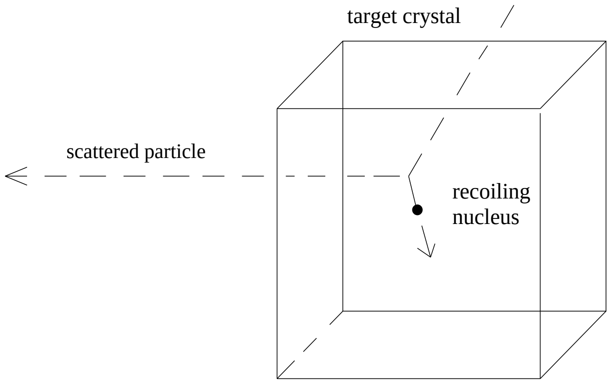


- ♢ The local mass density necessary to reproduce the rotation curve of our Galaxy is $\rho \sim 0.3\ GeV/cm^3$
- ♢ The velocity dispersion of dark matter particles is $v \sim 300\ km/s$

For $m \sim 100$ GeV this implies $J \approx 10^5\ \frac{particles}{cm^2\ s}$

Therefore direct detection through elastic scattering with nuclei in a detector is possible

Goodman, Witten, 85; Wasserman, 86



For $\sigma_{\text{WIMP-nucleon}} \approx 10^{-8} - 10^{-6}$ pb

a material with nuclei composed of about 100 nucleons, i.e. $m_N \sim 100$ GeV

$\Rightarrow R \sim J\sigma_{\text{WIMP-nucleus}}/m_N \approx 10^{-2} - 1$ events per day per kilogram

EXPERIMENTS

$$E_{\rm W} \approx \frac{1}{2}\,(100 \text{ GeV}/c^2)\,(300 \text{ km/s})^2 \approx 100 \text{ keV}$$

Thus the experiments must have an extremely good background discrimination

e.g. cosmic rays with energies $\sim$ keV-MeV occur at $\gtrsim \frac{100\ events}{kg\ day}$

♣ Ge ionization detectors with masses $\lesssim 1$ kg has been applied to WIMP searches since 1987

Negative search results + last data from Heidelberg-Moscow, IGEX,...

(using $\rho_{\rm W} \sim 0.3$ GeV/cm^3 and $v_{\rm W} \sim 300$ km/s)

$$\Downarrow$$

$$\boxed{\sigma_{\text{WIMP-nucleon}} < 10^{-4} - 10^{-5} \text{ pb}}$$

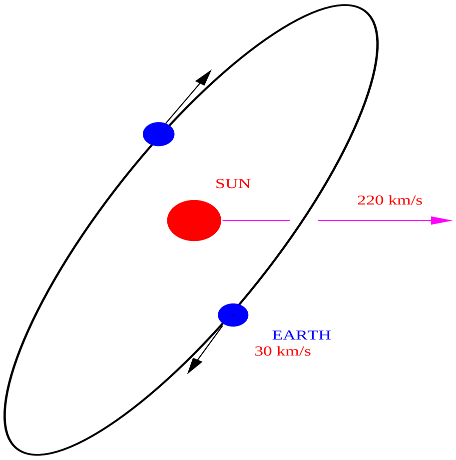
♣ However, there are recent intriguing results in DAMA

Annual modulation signature, is a different method for discriminating a dark matter signal from background

Drukier, Freese, Spergel 86

Freese, Frieman, Gould, 88

Griest, 88



Because of the Earth's motion around the Sun

$$v_E = v_0 \left\{ 1.05 + 0.07 \cos\left[\frac{2\pi(t-t_m)}{1\ year} \right] \right\}$$

$t_m \approx$ June 2

$\Downarrow$

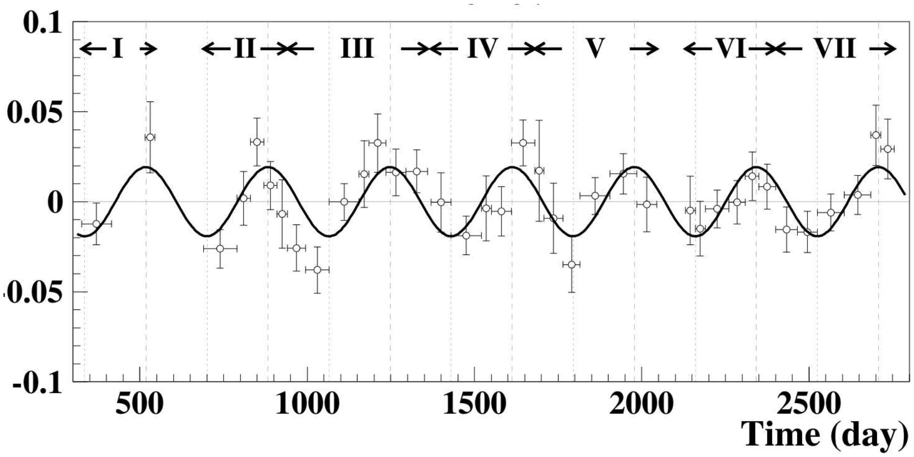
Fluctuation in the dark matter flux

$\downarrow$

A rate variation of $\approx 7\%$ (summer versus winter)

- **DAMA**: 100 kg NaI crystal scintillators located at the deep underground (Gran Sasso), measure the annual modulation effect

  The data collected over seven yearly cycles, 1995-2002, favour **the presence of a yearly modulation**



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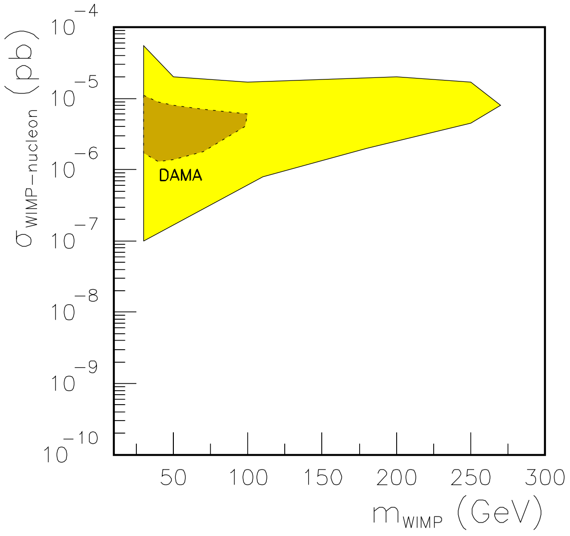
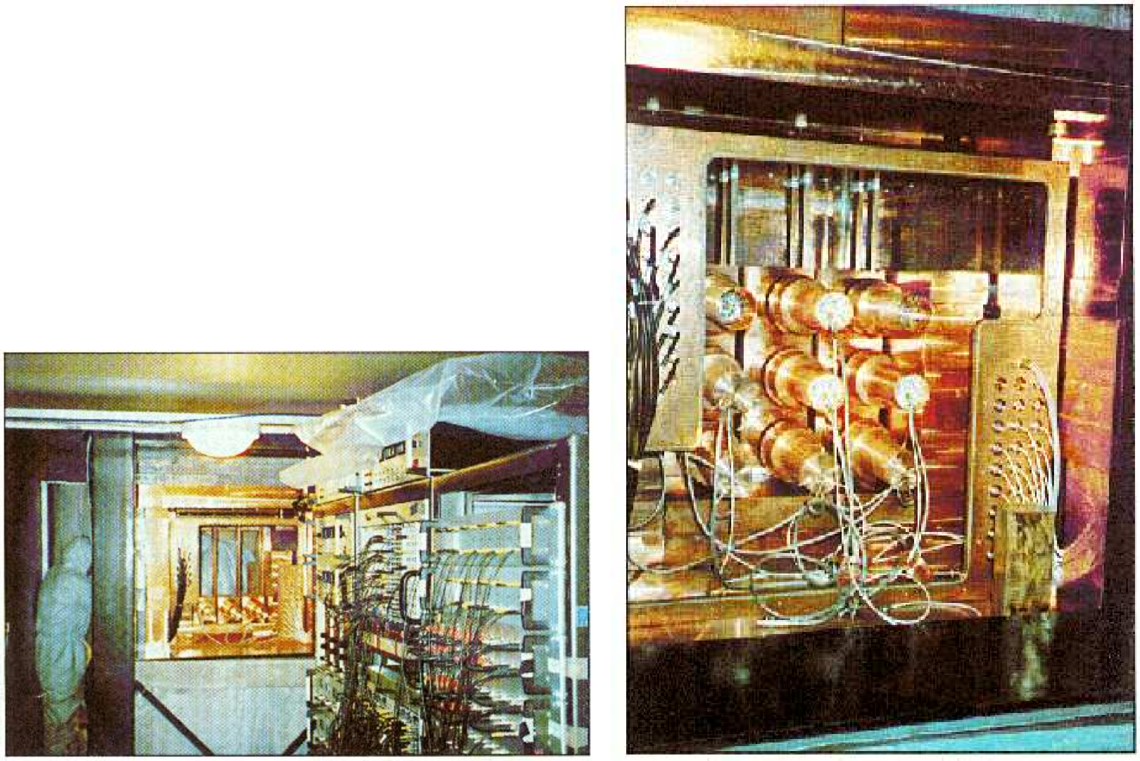


$$\boxed{\sigma_{\text{WIMP-nucleon}} \approx 10^{-6} - 10^{-5}\ \text{pb}}$$

DAMA experiment: Installing the detectors inside the copper box and shield



View of some detectors in the copper box in progress of installation

On the contrary:

- **CDMS**: 0.5 kg Ge detector measuring both ionization and temperature rise produced during a recoil, and located 10 metres below ground at Stanford University

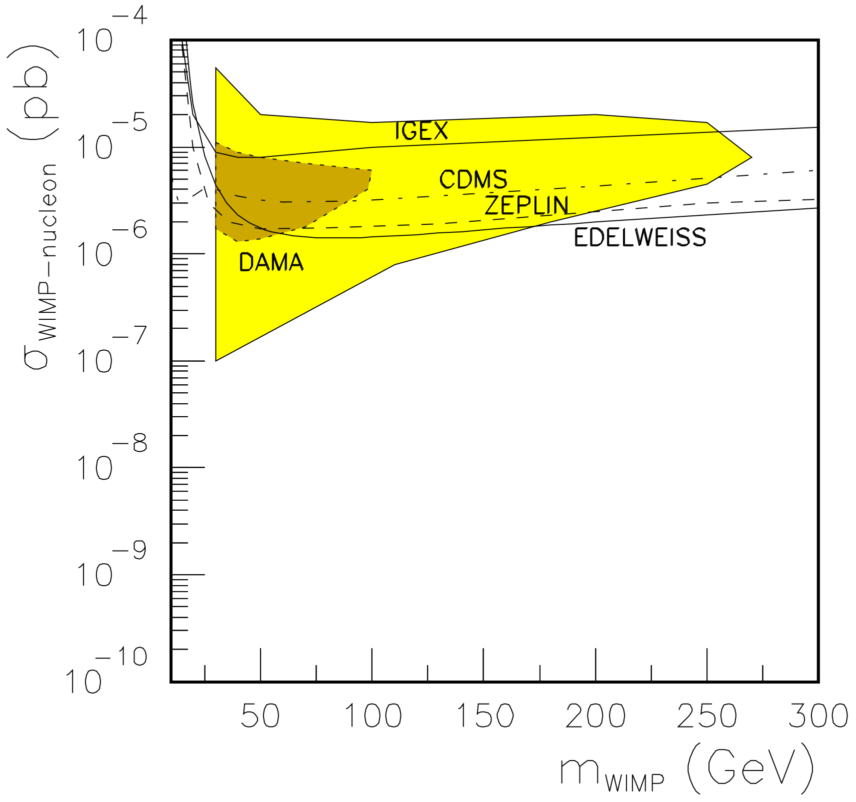
  After 96 days taking data they observed ~ 60 nuclear recoils

They are not due to WIMPs

$$\Downarrow$$

$$\boxed{\sigma_{\text{WIMP-nucleon}} < 10^{-5}\ \text{pb}}$$

- In addition, there are very recent results from EDELWEISS (June 2002), and also ZEPLIN (september 2002), excluding even larger regions than CDMS



The DAMA region ($\sigma \approx 10^{-6} - 10^{-5}$ pb) will also be tested by other current detectors, e.g. upgraded IGEX detectors, HDMS experiment

In addition, DAMA and CDMS will expand their experiments to DAMA 250 kg and CDMS 10 kg Soudan

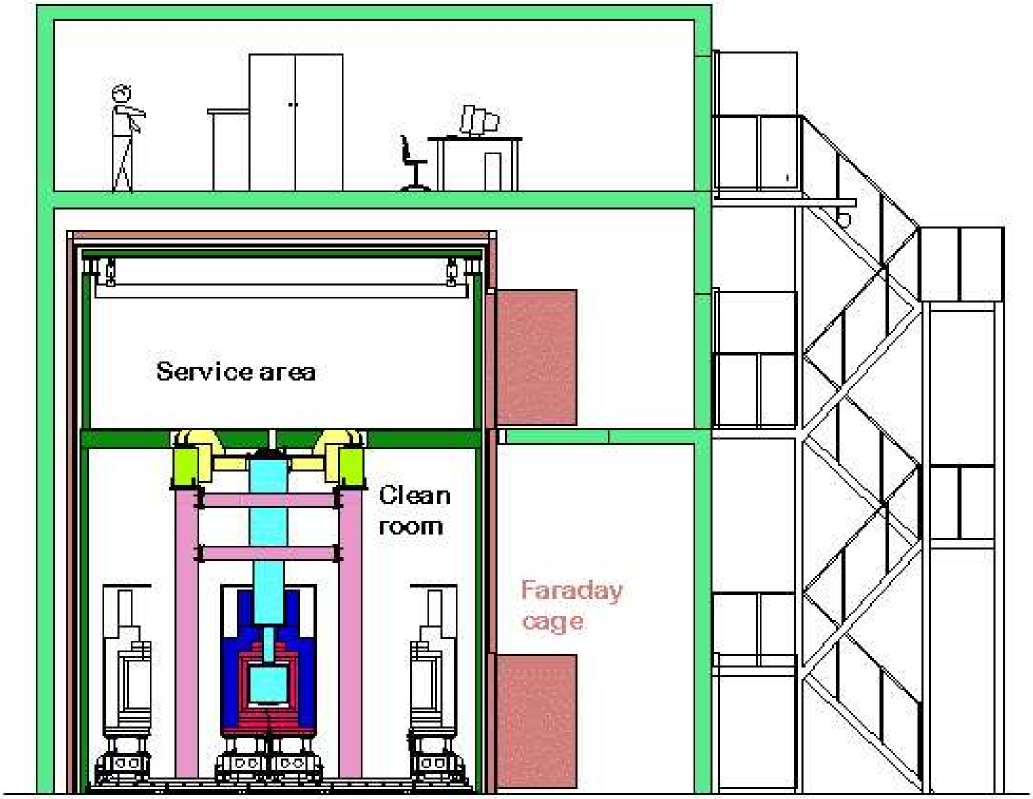
Future dark matter searches

In the light of the polemical results, DAMA versus CDMS/EDELWEISS collaborations, a new generation of very sensitive experiments have been proposed all over the world:

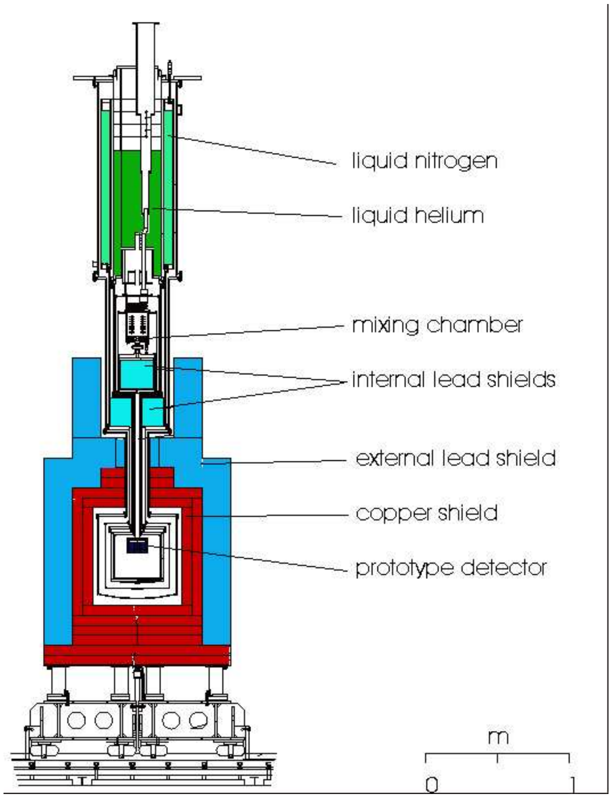
CRESST, CUORE, GENIUS, GEDEON, MACHe3, PICASSO, ORPHEUS, DRIFT,...

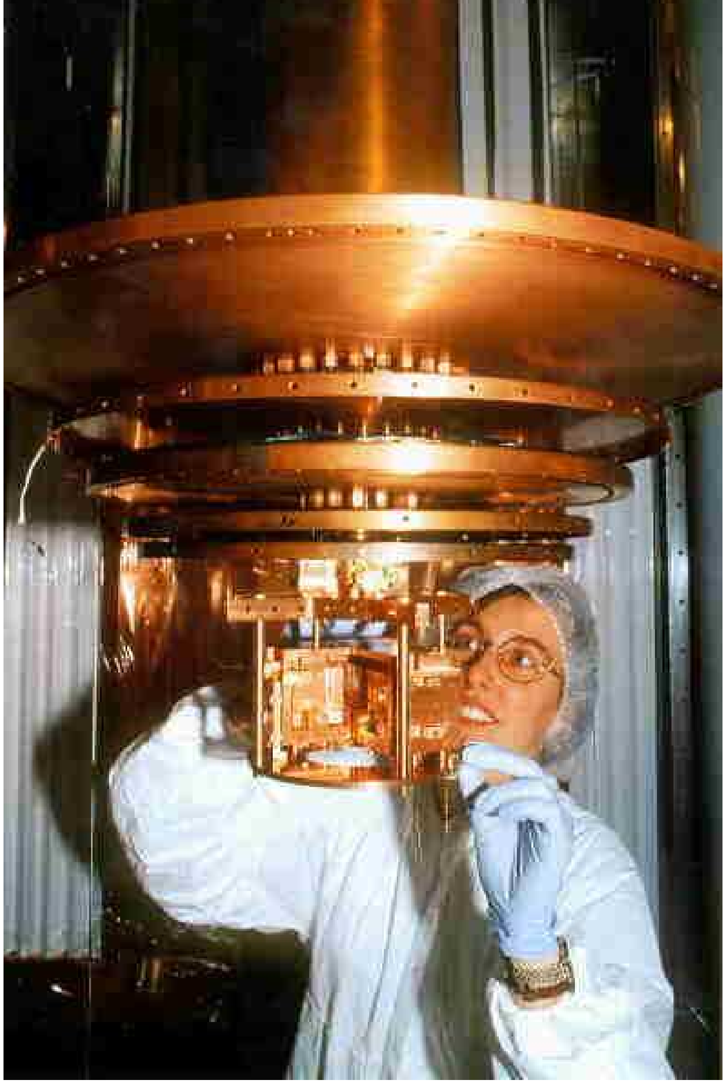
e.g. CRESST experiment, located in Gran Sasso, measures simultaneously phonons and scintillation light distinguishing the nuclear recoils from the electron recoils cause by background radioactivity

CRESST Setup: Outside View

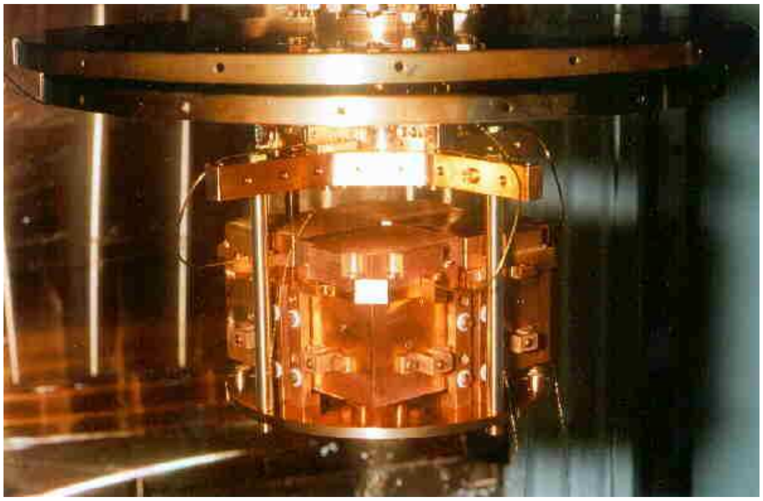


CRESST Setup

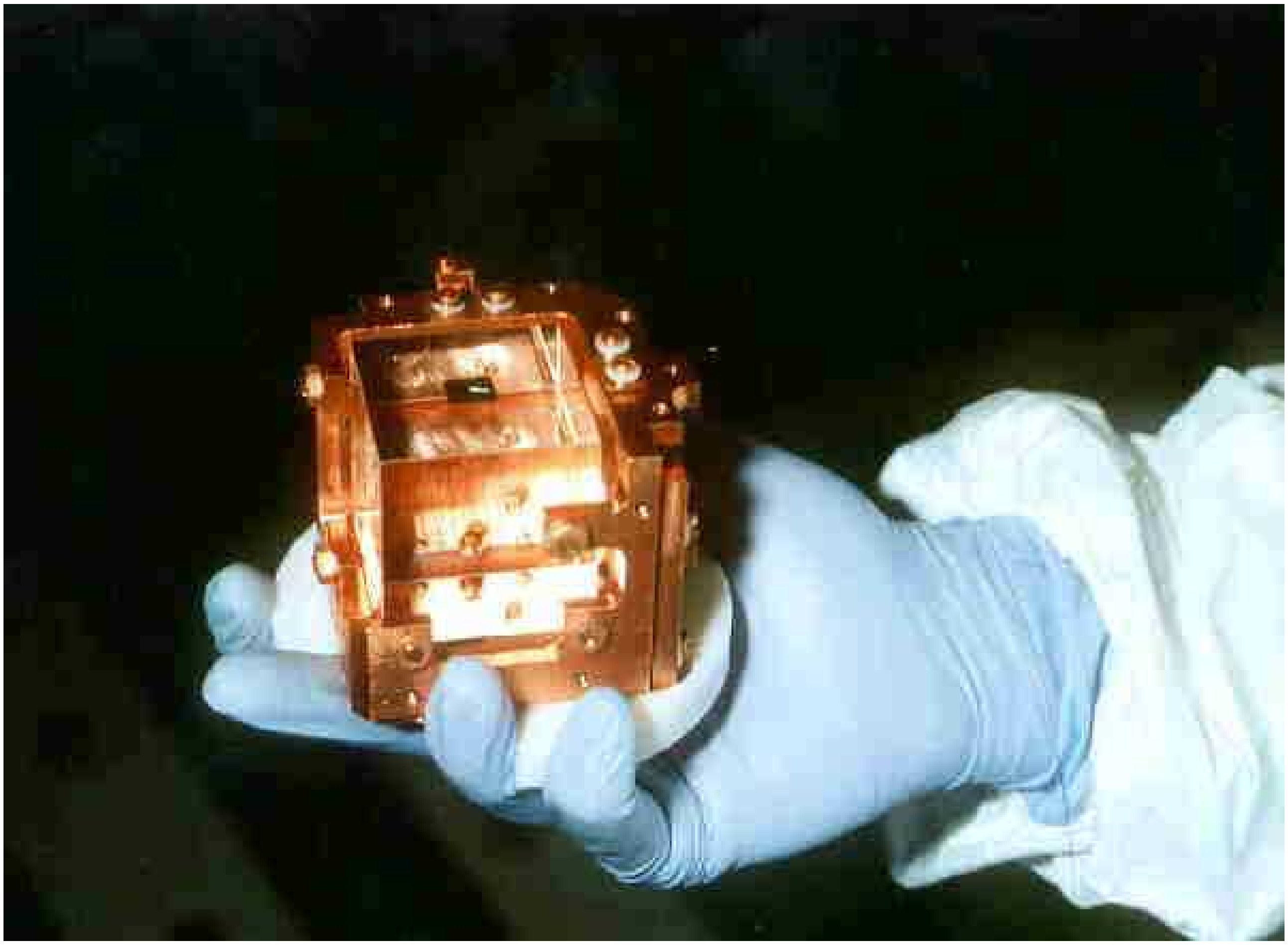




Assembling the Detectors

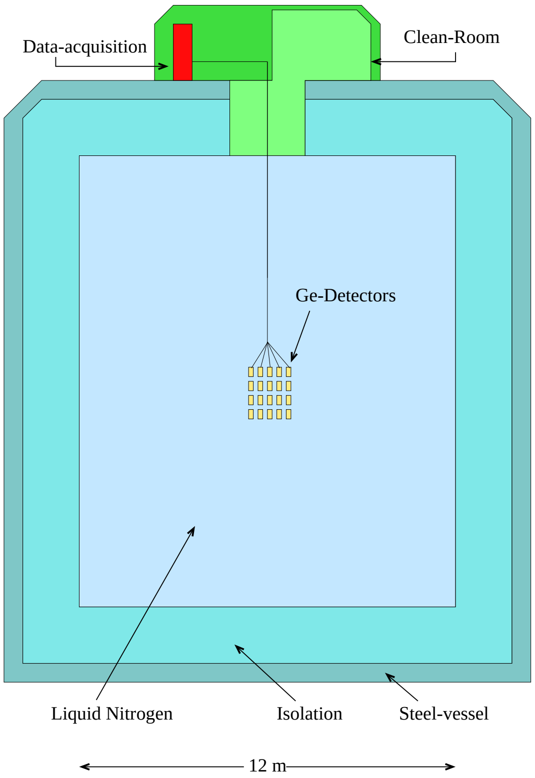


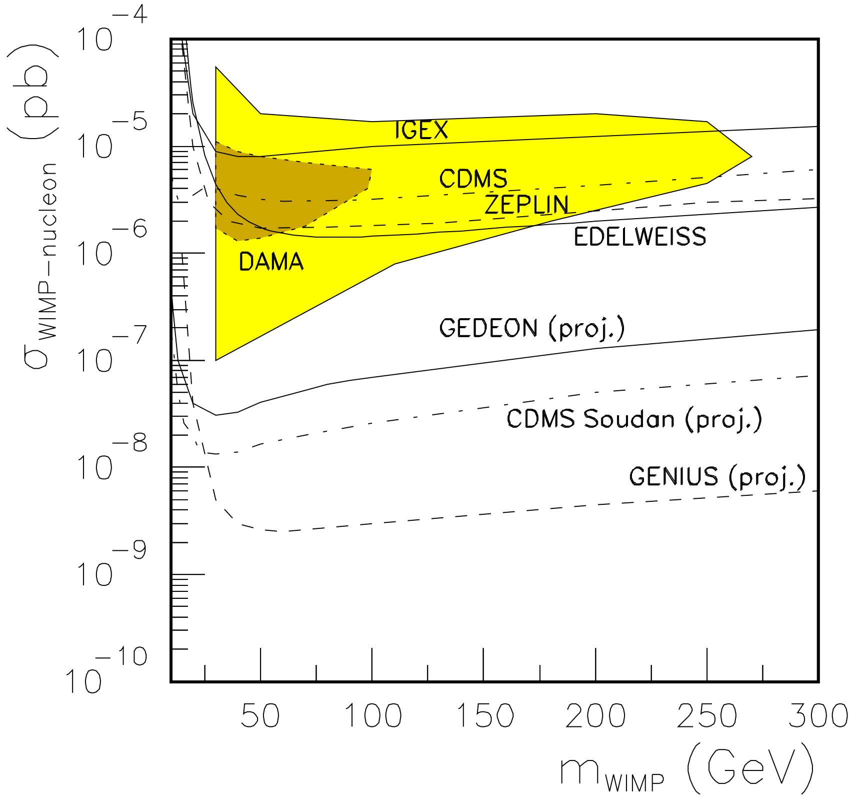
Prototype Detectors (1 kg Sapphire)



Single 262 g detector

GENIUS with an array of 100 kg of Ge crystals directly in liquid nitrogen, will be able to test a cross section as low as $\sigma \approx 10^{-9}$ pb, covering an important range of the parameter space of supersymmetric models with neutralinos as dark matter

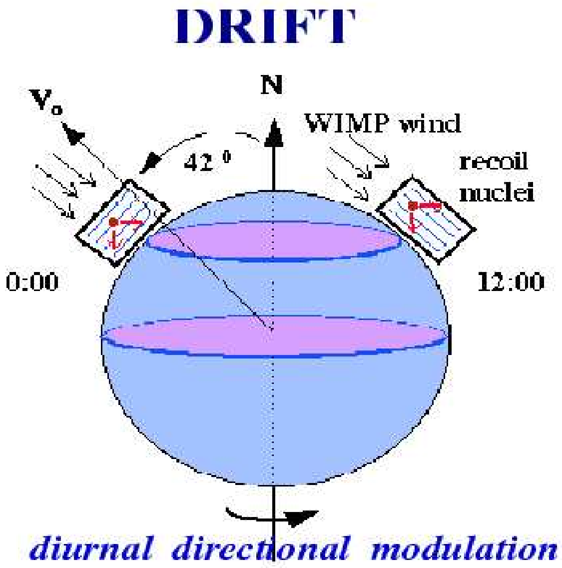




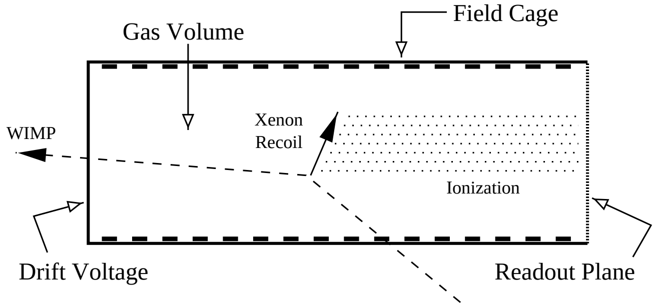
$\sigma_{WIMP-nucleon}$ (pb)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
IGEX
CDMS
ZEPLIN
EDELWEISS
DAMA
GEDEON (proj.)
CDMS Soudan (proj.)
GENIUS (proj.)
50
100
150
200
250
300
m_{WIMP} (GeV)

Efforts to build detectors sensitive to the directional dependence, are also being carried out. This is an extension of the idea of annual modulation.

As the Earth moves through the galactic halo, the large preponderance of the recoils are in the opposite direction The detector will see the mean recoil direction rotate and back again over one day.

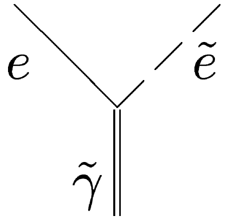


DRIFT is a project of an ionization xenon-gas detector. The arrival time of the ionization signal will be used to reconstruct the event in three dimensions



THEORETICAL MODELS

The LSP is stable since e.g.:



Thus it is a candidate for dark matter

In most of the parameter space of the MSSM the LSP is a neutralino

The neutralino is the leading candidate for WIMP:

- It is a WIMP (with a mass $\sim 10^{2-3}$ GeV)
- It is a neutral particle.

  This is welcome since otherwise it would bind to nuclei and would be excluded as a candidate for dark matter from unsuccessful searches for exotic heavy isotopes

It is then crucial to analyze the compatibility of the neutralino as a dark matter candidate, with the sensitivity of detectors

Analyses neutralino-nucleon cross section:

Goodman, Witten, 85
Wasserman, 86
Griest, 88
Raby, West, 88
Srednicki, Watkins, 89
Barbieri, Frigeni, Giudice, 89
Ellis, Flores, 91
Kamionkowski, 91
Gelmini, Gondolo, Roulet, 91
Engel, Pittel, Vogel, 92
Ressell et al., 93
Drees, Nojiri, 93
Bednyakov, Klapdor-Kleingrothaus, Kovalenko, 94
Kamionkowski, Krauss, Ressell, 95

L. Bergström and P. Gondolo, 95

S. Khalil, A. Masiero and Q. Shafi, 97

A. Bottino, F. Donato, N. Fornengo and S. Scopel, 98
U. Chattopadhyay, T. Ibrahim and P. Nath, 98
D. Bailin, G.V. Kraniotis and A. Love, 98

R. Arnowitt and P. Nath, 99 S. Khalil and Q. Shafi, 99
T. Falk, A. Ferstl and K.A. Olive, 99
P. Gondolo and K. Freese, 99
S.Y. Choi, 99
V.A. Bednyakov and H.V. Klapdor-Kleingrothaus, 99
A. Bottino, F. Donato, N. Fornengo and S. Scopel, 99
Khalil, 99

J. Ellis, A. Ferstl and K.A. Olive, 00
E. Accomando, R. Arnowitt, B. Dutta and Y. Santoso, 00
A. Corsetti and P. Nath, 00
J.L. Feng, K.T. Matchev and F. Wilczek, 00
E. Gabrielli, S. Khalil, C. Muñoz and E. Torrente-Lujan, 00
J. Ellis, A. Ferstl and K.A. Olive, 00
D. Bailin, G.V. Kraniotis and A. Love, 00
V. Mandic, A.T. Pierce, P. Gondolo and H. Murayama, 00
A. Bottino, F. Donato, N. Fornengo and S. Scopel, 00
V.A. Bednyakov and H.V. Klapdor-Kleingrothaus, 00

M. Drees, Y.G. Kim, T. Kobayashi and M.M. Nojiri, 01
M.E. Gomez and J.D. Vergados, 01
J. Ellis, T. Falk, G. Ganis, K.A. Olive and M. Srednicki, 01
D.G. Cerdeño, E. Gabrielli, S. Khalil, C. Muñoz and E. Torrente-Lujan, 01
D. Bailin, G.V. Kraniotis and A. Love, 01
Y.G. Kim and M.M. Nojiri, 01
J. Ellis and K.A. Olive, 01
D.G. Cerdeño, S. Khalil and C. Muñoz, 01
A. Djouadi, M. Drees, P. Fileviez Perez and M. Muhlleitner, 01
A. Bottino, F. Donato, N. Fornengo and S. Scopel, 01
J. Ellis, A. Ferstl and K.A. Olive, 01
R. Arnowitt and B. Dutta, 01

V.A.Bednyakov, 02
J. Ellis, K. A. Olive and Y. Santoso, 02
D.G. Cerdeño, E. Gabrielli and C. Muñoz, 02
A.B. Lahanas, D.V. Nanopoulos and V.C. Spanos, 02

E.A. Baltz and P. Gondolo, 02
D.G. Cerdeño and C. Muñoz, 02
A. Bottino, F. Donato, N. Fornengo and S. Scopel, 02
Y.G. Kim, T. Nihei, L. Roszkowski and R. Ruiz de Austri, 02
V. Bertin, E. Nezri and J. Orloff, 02
J. Ellis, T. Falk, K.A. Olive and Y. Santoso, 02
R. Arnowitt and B. Dutta, 02
A. Birkedal-Hansen and B.D. Nelson, 02
A. Bottino, N. Fornengo and S. Scopel, 02

A. Birkedal-Hansen, 03
J. Ellis, A. Ferstl, K.A. Olive and Y. Santoso, 03
J. Ellis, K.A. Olive, Y. Santoso, V.C. Spanos, 03
H. Baer and C. Balazs, 03
A.B. Lahanas and D.V. Nanopoulos, 03
U. Chattopadhyay, A. Corsetti, P. Nath, 03
J.D. Vergados, 03
A. Bottino, F. Donato, N. Fornengo and S. Scopel, 03
R. Dermisek, S. Raby, L. Roszkowski, R. Ruiz De Austri, 03
U. Chattopadhyay and D.P. Roy, 03
D.G. Cerdeño, E. Gabrielli, M.E. Gómez and C. Muñoz, 03
H. Baer, C. Balazs, A. Belyaev and J. O'Farril, 03
J. Ellis, K.A. Olive, Y. Santoso and V.C. Spanos, 03

The MSSM allows a large number of free parameters

$$-\mathcal{L}_f = Y_{\alpha\beta\gamma}\Phi^\alpha\tilde{\Phi}^\beta\tilde{\Phi}^\gamma + \mu\tilde{H}_u\tilde{H}_d + h.c.$$

$$-\mathcal{L}_{soft} = m^2_\alpha\Phi^{*\overline{\alpha}}\Phi^\alpha$$

$$+M_a\lambda^a\lambda^a + A_{\alpha\beta\gamma}Y_{\alpha\beta\gamma}\Phi^\alpha\Phi^\beta\Phi^\gamma + B\mu H_u H_d + h.c.$$

$$\Phi^\alpha = Q_L, u^c_L, d^c_L, L_L, e^c_L, H_u H_d$$

But, when the electroweak symmetry breaking is imposed, μ and B are determined:

minimizing the Higgs effective potential

$$V_H = \tfrac{1}{8}(g_2^2 + g'^2)(|H_u|^2 - |H_d|^2)^2 + (m^2_{H_u} + \mu^2)|H_u|^2$$

$$+(m^2_{H_d} + \mu^2)|H_d|^2 + B\mu(H_u H_d + h.c.)$$

one gets

$$\mu^2 = \frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{\tan^2\beta - 1} - \tfrac{1}{2}M_Z^2 \approx -m^2_{H_u} - \tfrac{1}{2}M_Z^2$$

and higgsinos (B^0, W^0, H_1^0, H_2^0)

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -\frac{g'\nu_1}{\sqrt{2}} & \frac{g'\nu_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g\nu_1}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} \\ -\frac{g'\nu_1}{\sqrt{2}} & \frac{g\nu_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g'\nu_2}{\sqrt{2}} & -\frac{g\nu_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

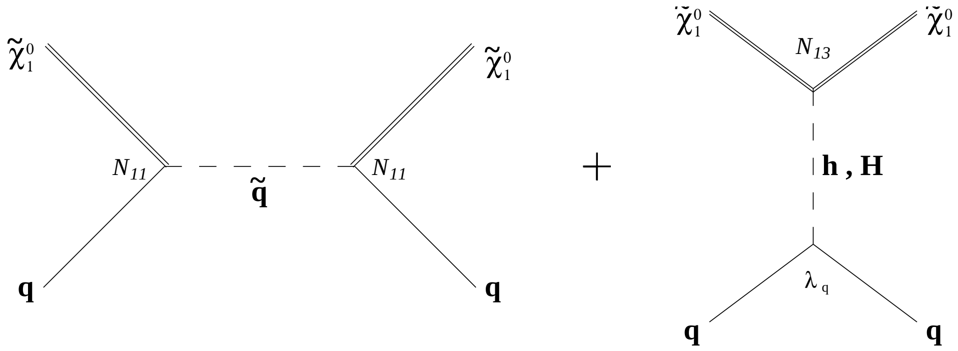
This implies that the lightest mass eigenstate (lightest neutralino) is

$$\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

The crucial parameter in this discussion is μ, since the cross section is very sensitive to its value

e.g. $\mu >>$ $\Rightarrow \tilde{\chi}_1^0 \sim$ gaugino $\Rightarrow$ small cross section

since the scattering channels through Higgs exchange are not so important (N_{13}, $N_{14} <<$)



In addition, $m_A^2 = m_{H_d}^2 + m_{H_u}^2 + 2\mu^2$ will be large

SUPERGRAVITY

Working in the framework of Supergravity:

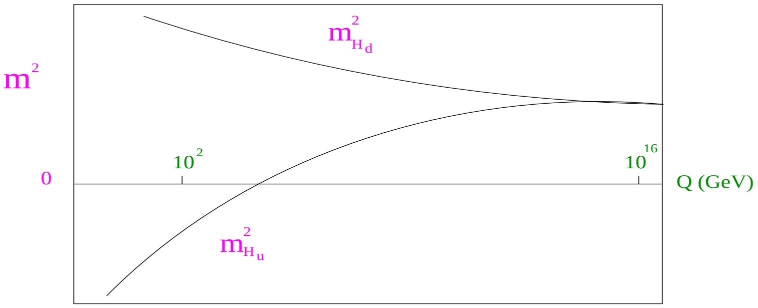
- M_a, m_α, $A_{\alpha\beta\gamma}$, B are generated at high energy once supersymmetry is broken through gravitational interactions (can be computed!)

  E.g. in minimal supergravity

  $$M_a = M,\ m_\alpha = m,\ A_{\alpha\beta\gamma} = A$$

- The RGEs are used to derive the low-energy soft parameters

  E.g., with $M_{GUT} \approx 2 \times 10^{16}$ GeV, $m^2_{H_u}$ evolves towards large and negative values

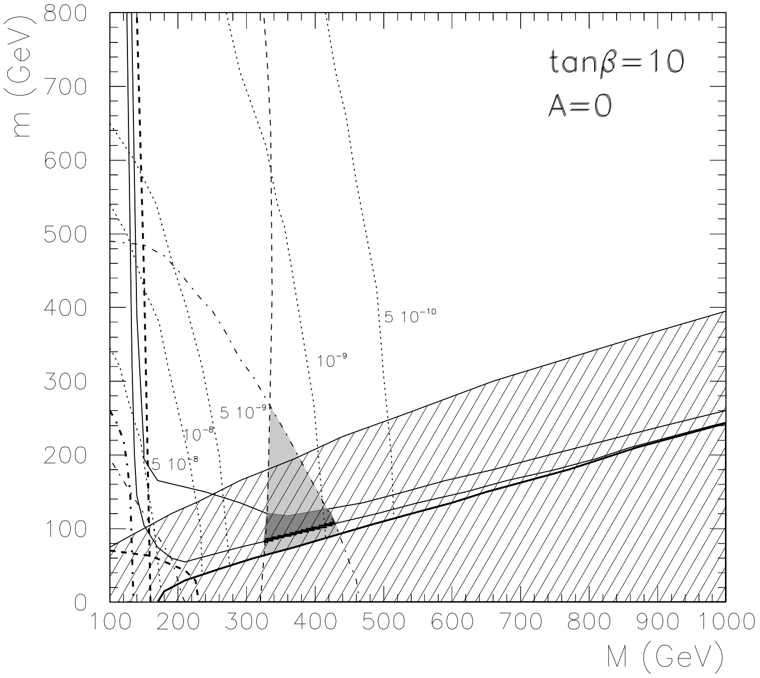


Thus in minimal supergravity

$$\mu^2 \approx -m^2_{H_u} - \frac{1}{2}M_Z^2 \quad >> \Rightarrow \tilde{\chi}^0_1 \sim \tilde{B}^0$$

(since $M_1(M_Z) \approx 0.5 M_2(M_Z)$)

Minimal Supergravity with a GUT scale



* $m_h \gtrsim 114$ GeV (region to the right of the near-vertical dashed line)

* $2 \times 10^{-4} \leq BR(b \to s\gamma) \leq 4.1 \times 10^{-4}$ (right of the double dot-dashed line)

* $11.3 \times 10^{-10} \leq a_\mu \leq 56.1 \times 10^{-10}$ (region bounded by dot-dashed lines)

* $\tilde{\chi}_1^0$ is the LSP (region above the double solid line)

The light shaded area, with $\sigma_{\tilde{\chi}_1^0 - n} \approx 10^{-9}$ pb, is favoured by all the phenomenological constraints, while the dark one fulfills in addition: $0.1 \lesssim \Omega_{\mathrm{DM}} h^2 \lesssim 0.3$. The black region on top of this indicates the WMAP range: $0.094 \lesssim \Omega_{\mathrm{DM}} h^2 \lesssim 0.129$

The ruled region bounded by the upper solid line is excluded because of the Charge and Colour Breaking constraint

$$V_{\mathrm{UFB-3}} \approx (m^2_{H_u} + m^2_{L_i})|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}}(m^2_{L_j} + m^2_{e_j} + m^2_{L_i})|H_u|$$

$\tan\beta \lesssim 20$ is excluded for any A. Larger values can also be forbidden depending on A

Cerdeño, Gabrielli, Gomez, C.M., 03

In supersymmetry there are scalar fields with colour and electric charge

$$\Phi^{\alpha} = \tilde{u}\ ,\tilde{d}\ ,\tilde{c}\ ,\tilde{s}\ ,\tilde{t}\ ,\tilde{b}\ ,\tilde{e}\ ,\tilde{\mu}\ ,\tilde{\tau}$$

$$\Downarrow$$

Enormous complexity of V

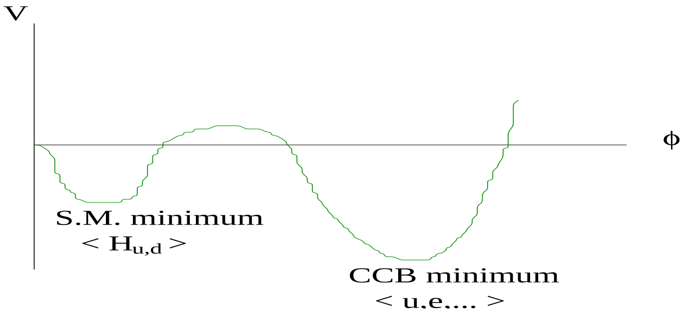
$$V = m_{\alpha}^{2}\Phi^{*\overline{\alpha}}\Phi^{\alpha}$$

$$+A_{\alpha\beta\gamma}Y_{\alpha\beta\gamma}\Phi^{\alpha}\Phi^{\beta}\Phi^{\gamma} + B\mu H_u H_d + h.c.$$

$$+V_F$$

$$+V_D$$

This induces the possible existence of dangerous Charge and Colour Breaking (CCB) Minima:



several mechanisms were proposed in the past to increase the cross section:

- to work in the large $\tan\beta$ regime
- to work with non-universal soft scalar masses m_α

Bottino, Donato, Fornengo, Scopel, 99

Arnowitt, Nath, 99

Accomando, Arnowitt, Dutta, Santoso, 00

- to work with non-universal gaugino masses

Corsetti, Nath, 00

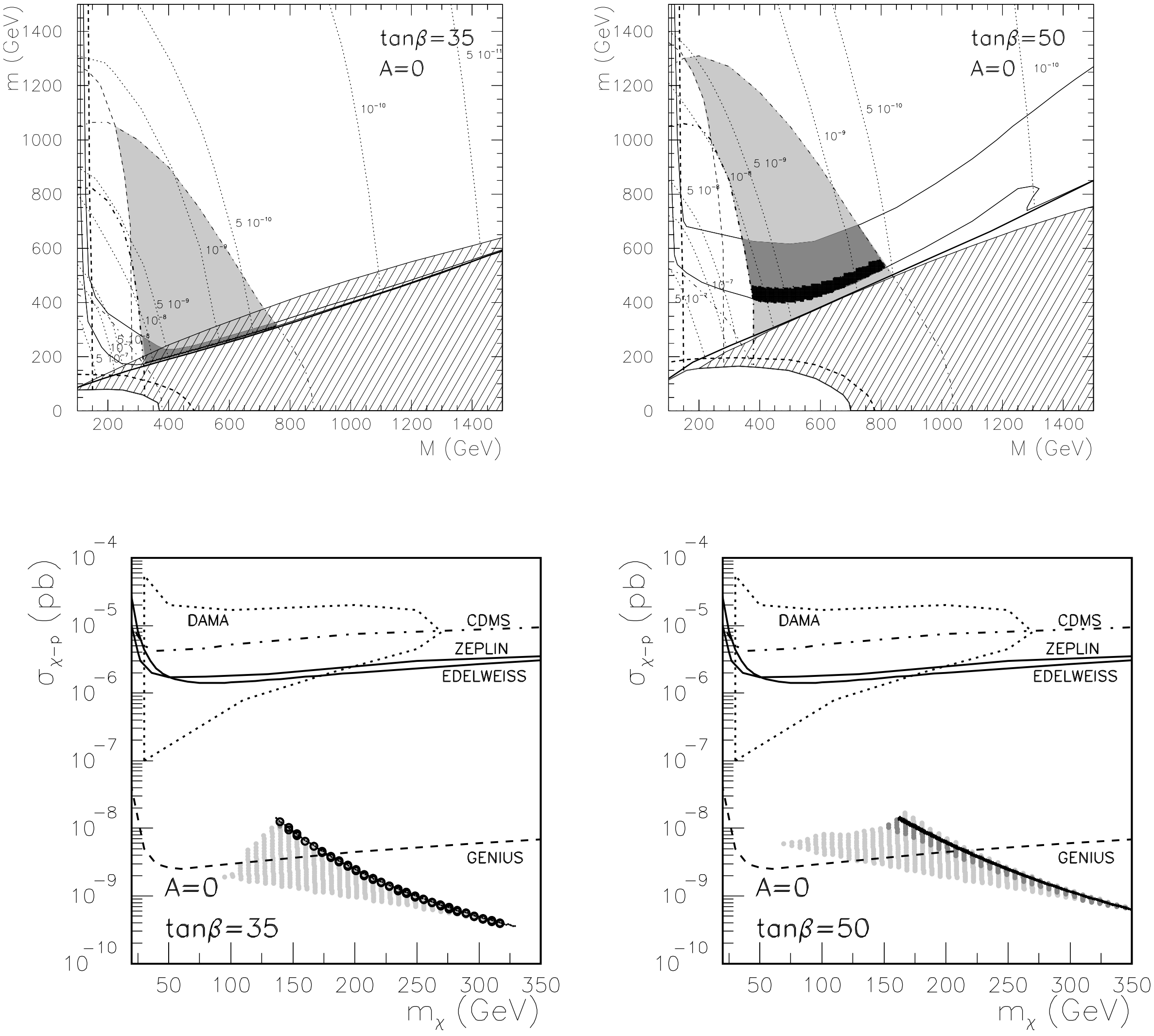
Cerdeño, Khalil, C.M., 01

- Focus point supersymmetry scenario

Feng, Matchev, Wilczek, 00

- to work with an intermediate scale

Gabrielli, Khalil, C.M., Torrente-Lujan, 00



For example, for $\tan\beta = 35$ and $A = M$ essentially the whole dark shaded area is allowed by CCB constraint, whereas for $A = -M, -2M$ this is forbidden

$$\boxed{\sigma_{\tilde{\chi}_1^0-n} \lesssim 3\times 10^{-8}\ \text{pb}}$$

♠ There are several interesting phenomenological arguments in favour of Supergravity scenarios with scales $M_I \approx 10^{10-14}$ GeV.

Benakli, 99
Burgess, Ibañez, Quevedo, 99

- In order to explain experimental observations such as neutrino masses or the scale for axion physics
- In order to ameliorate the hierarchy problem
$$m_{3/2} \approx \frac{F}{M_{Planck}} \approx \frac{M_I^2}{M_{Planck}} \approx \frac{\left(10^{10-12}\right)^2}{M_{Planck}} \approx M_W$$
- Might also explain the observed ultra-high energy cosmic rays as products of long-lived massive ($\approx 10^{12}$ GeV) string mode decays
- Inflation in models with large internal dimensions might favour also these initial scales

  Kaloper, Linde, 99
- Charge and color breaking constraints become less strong

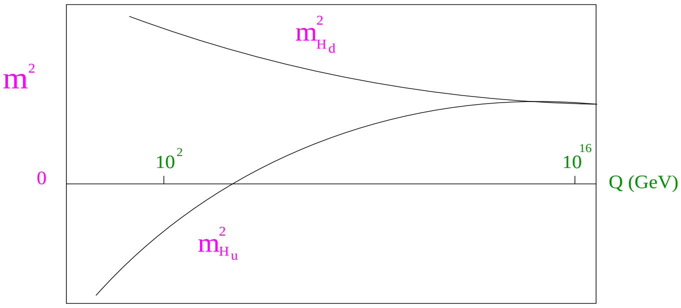
  Abel, Allanach, Quevedo, Ibañez, Klein, 00

♠ In addition, the string scale may be anywhere between the weak and the Planck scale.

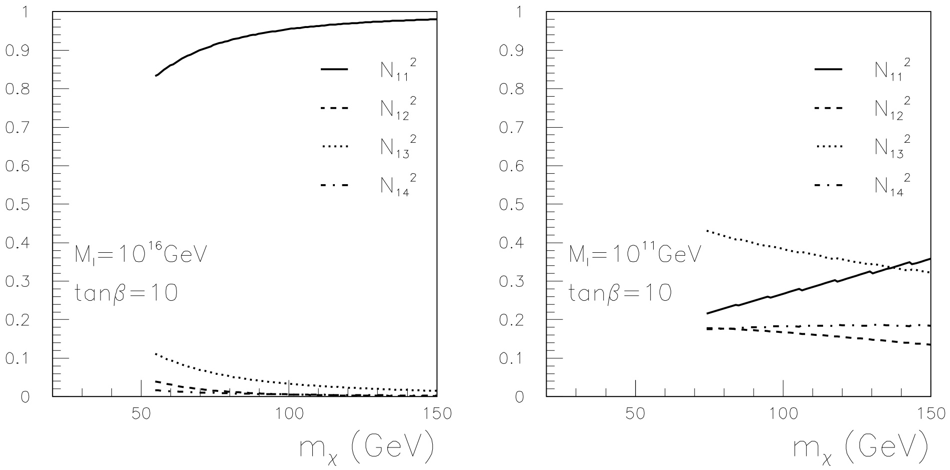
Minimal Supergravity with an intermediate scale

The analysis of $\sigma_{\tilde{\chi}_1^0-n}$ is modified by taking a scale M_I smaller than $M_{GUT} \approx 10^{16}$ GeV,

because $\mu^2 \approx -m_{H_u}^2 - \frac{1}{2}M_Z^2$ decreases:



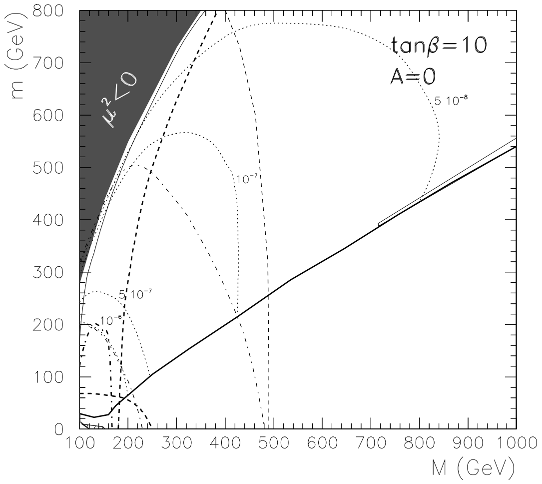
Since $\mathcal{L} \sim \mu \tilde{H}_u^0 \tilde{H}_d^0$ + h.c., the lightest neutralino $\tilde{\chi}_1^0$ will have an important Higgsino component:



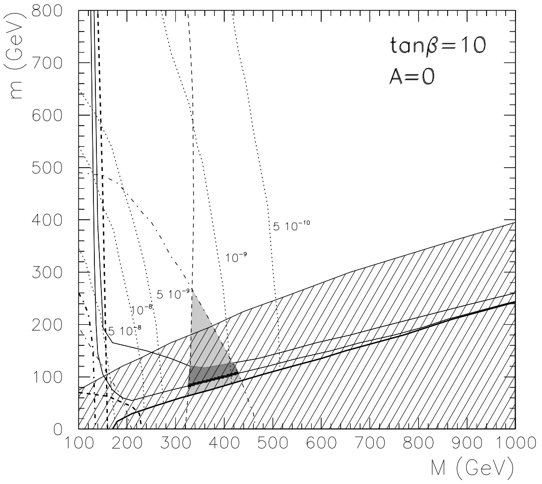
In addition, $m_A^2 = m_{H_d}^2 + m_{H_u}^2 + 2\mu^2$ also decreases

$$\Rightarrow \text{larger } \sigma_{\tilde{\chi}_1^0-n}$$

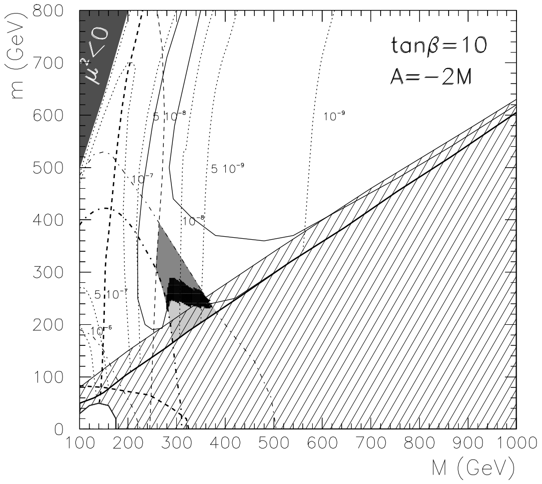
$M_I = 10^{11}$ GeV

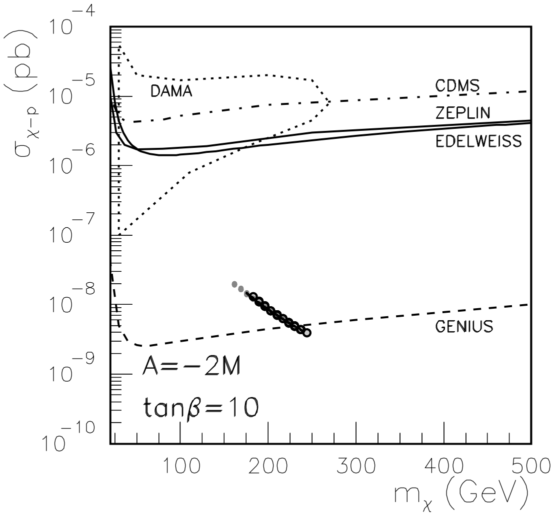


M_{GUT}



$M_I = 10^{11}$ GeV





Regions excluded by the CCB constraint are much smaller than in those cases where the initial scale is the GUT one, since $m_{H_u}^2$ is less negative. Recall that

$$V_{\mathrm{UFB-3}} \approx (m_{H_u}^2 + m_{L_i}^2)|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}}(m_{L_j}^2 + m_{e_j}^2 + m_{L_i}^2)|H_u|$$

$$\boxed{\sigma_{\tilde{\chi}_1^0-n} \lesssim 10^{-7}\ \text{pb}}$$

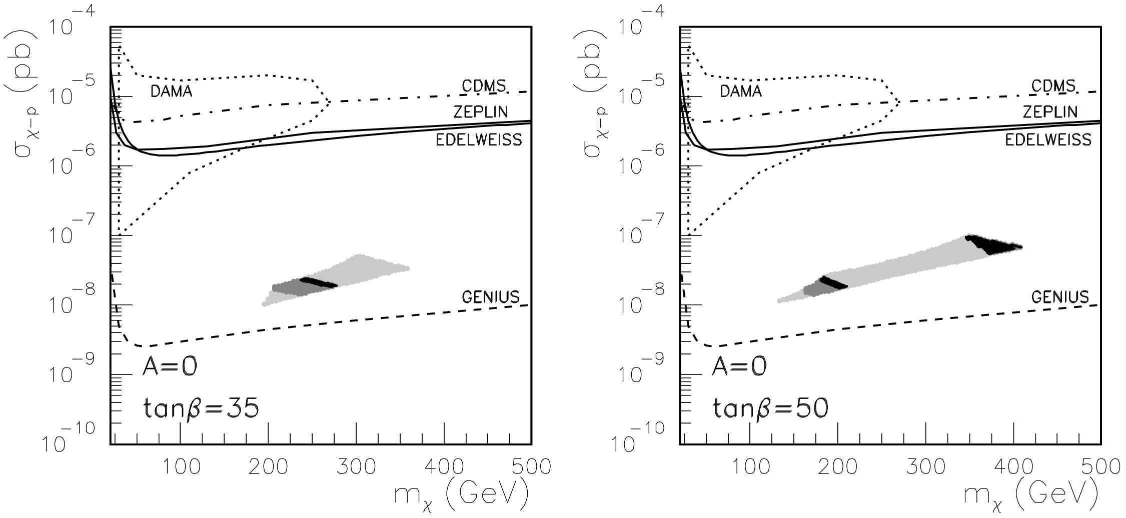
Supergravity with non-universal gaugino masses

$$M_1 = M(1+\delta_1),\ M_2 = M(1+\delta_2),\ M_3 = M(1+\delta_3)$$

For example, if M_3 is small, $m_{H_u}^2$ at low energy will be less negative, and then μ^2 will become smaller $\Rightarrow$ larger cross section

However, small values of M_3 also lead to an important decrease in the Higgs mass

For instance, using $\delta_{1,2} = 0, \delta_3 = -0.5$:



Regions excluded by the CCB constraint are not very relevant

$$\boxed{\sigma_{\tilde{\chi}_1^0-n} \lesssim 10^{-7}\ \text{pb}}$$

$$m_{H_d}^2 = m^2(1+\delta_d)\ , \quad m_{H_u}^2 = m^2(1+\delta_u)$$

One can increase the cross section:

- ♣ reducing μ through $\delta_u > 0$
- ♣ decreasing $m_A^2 = m_{H_d}^2 + m_{H_u}^2 + 2\mu^2$ through $\delta_d < 0$

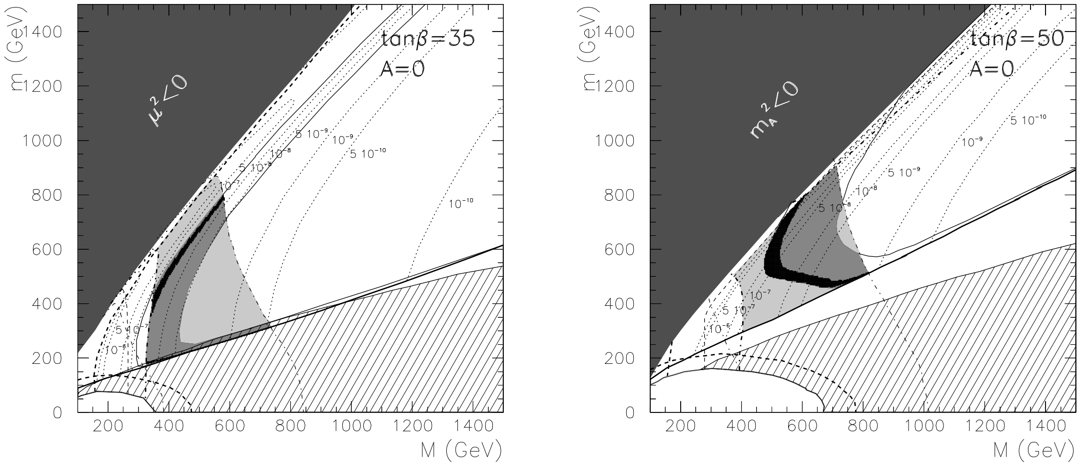
Three representative cases:

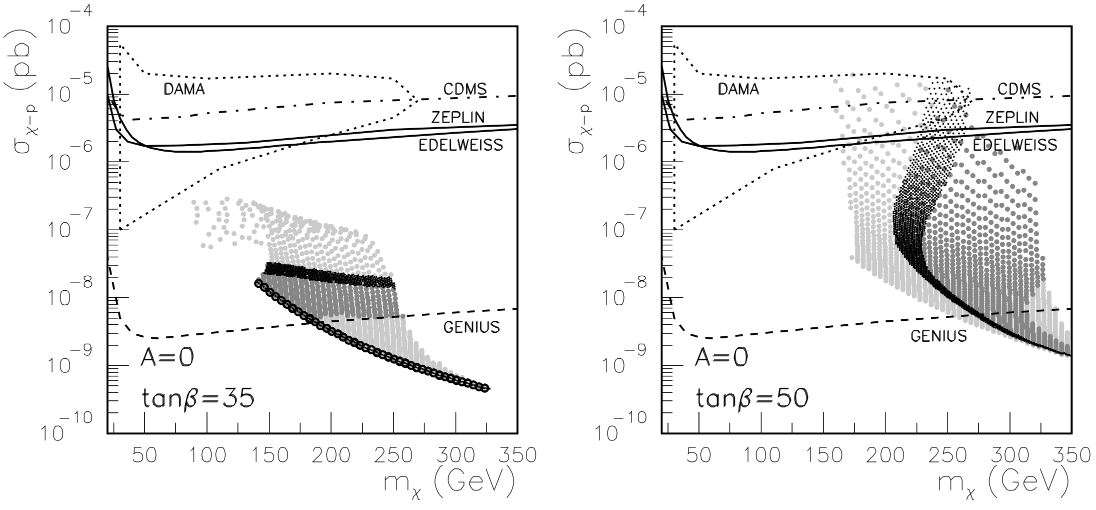
a) $\delta_d = 0\ ,\ \delta_u = 1$

b) $\delta_d = -1\ ,\ \delta_u = 0$

c) $\delta_d = -1\ ,\ \delta_u = 1$

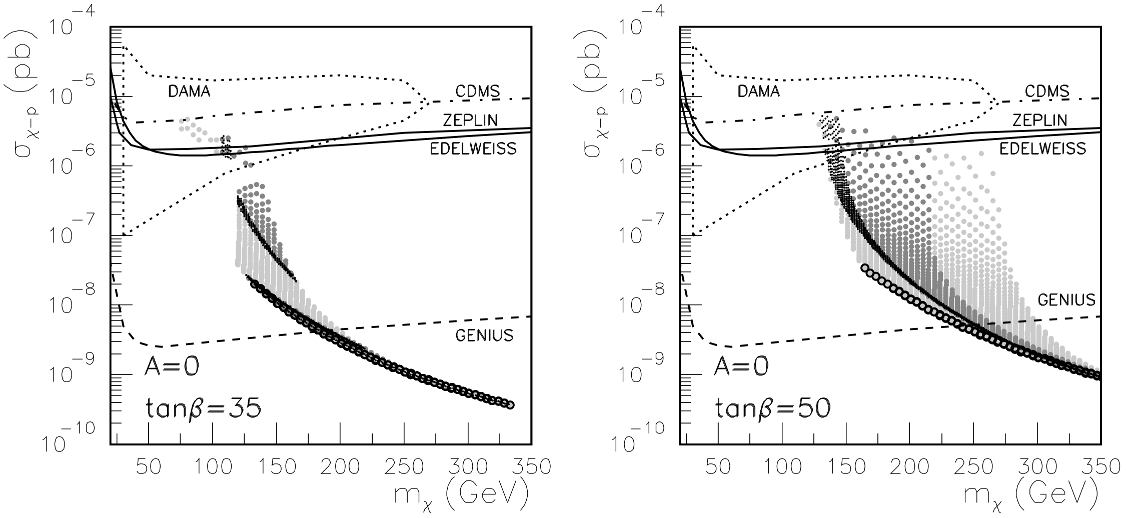
Case a)





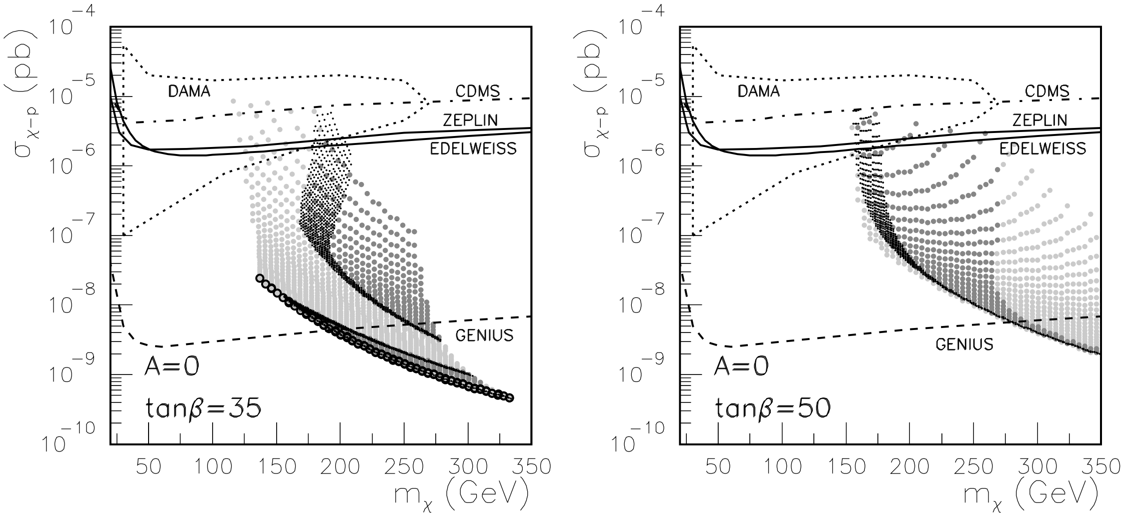
$\delta_u > 0.85$ is sufficient to enter in DAMA fulfilling all constraints

Case b) $\delta_d = -1$, $\delta_u = 0$



For $\tan\beta = 50$, $\delta_d \lesssim -0.4$ is sufficient to enter in DAMA fulfilling all constraints

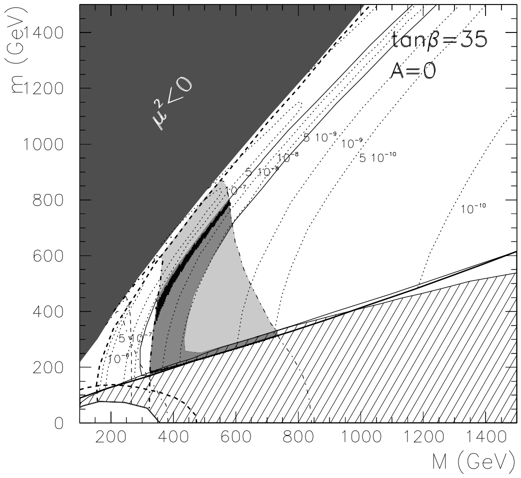
Case c) $\delta_d = -1$, $\delta_u = 1$



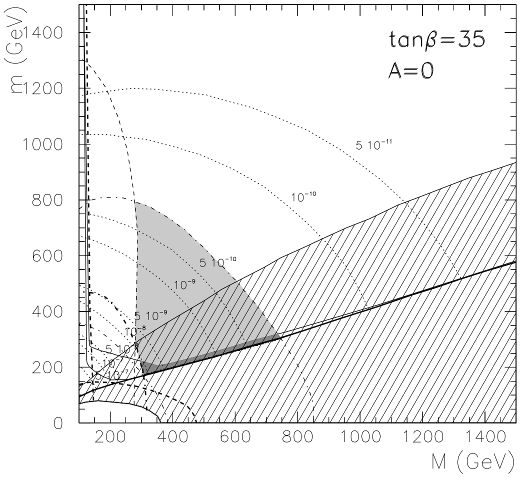
Large regions accesible for experiments are present

Concerning the restrictions coming from the CCB constraint, these are slightly less important than in the universal scenario

This is not a general result, and different choices of the δ's can modify the situation. For example, for the same case as before, a) $\delta_d = 0\ ,\delta_u = 1$, but using the opposite choice for the sign of the δ parameters, not only the cross section is smaller, $\sigma_{\tilde{\chi}_1^0 - n} < 10^{-8}$ pb, but also the CCB constraint is very restrictive, forbidding all points which are allowed by the experimental and astrophysical constraints.



a) $\delta_d = 0\ ,\delta_u = 1$



$\delta_d = 0\ ,\delta_u = -1$

$$m_{H_u}^2 = m^2(1+\delta_u)$$

$$V_{\rm UFB-3} \approx (m_{H_u}^2 + m_{L_i}^2)|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}}(m_{L_j}^2 + m_{e_j}^2 + m_{L_i}^2)|H_u|$$

Since the low-energy limit of superstring theory is 4-dimensional Supergravity, the neutralino is also a candidate for dark matter in superstring constructions.

Taking into account that the soft terms can in principle be computed in these constructions, one can study the associated $\tilde{\chi}_1^0$-nucleon cross section.

A PHOTOGRAPH EXPLAINING WHAT IS STRING THEORY WILL BE READY SOON HERE

A SECOND PHOTOGRAPH EXPLAINING ALSO WHAT IS STRING THEORY WILL BE READY SOON HERE

SUPERSTRINGS

It has been realized that the string scale may be anywhere between the weak scale and the Planck scale

Lykken, 96

Arkani-Hamed, Dimopoulos, Dvali,

Antoniadis, Bachas, Shiu, Tye, Kakushadze,...

For example, embedding the standard model inside D3-branes in type I strings,

$$M_I^4 = \frac{\alpha M_{\text{Planck}}}{\sqrt{2}} M_c^3$$

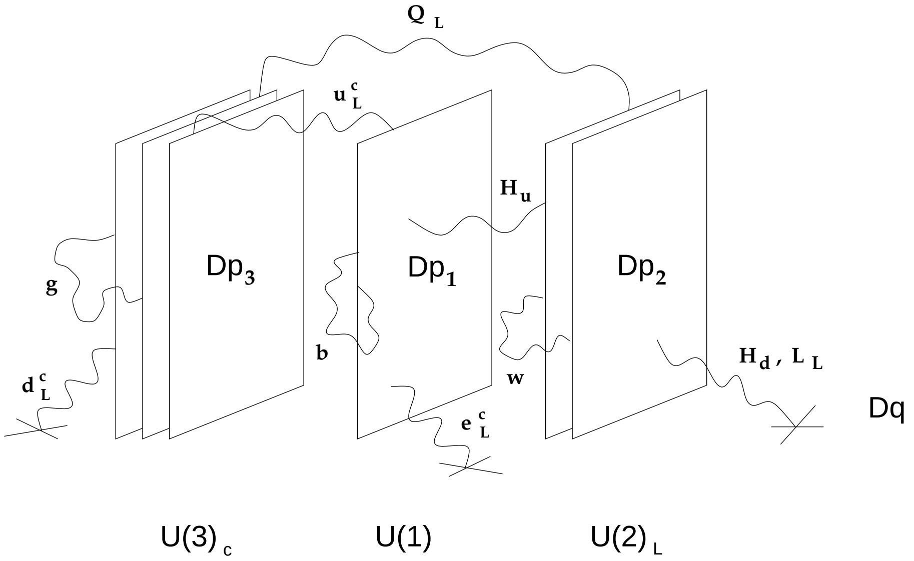
Thus one gets $M_I \approx 10^{10-12}$ GeV with $M_c \approx 10^{8-10}$ GeV

D-brane scenarios with the gauge group and particle content of the SUSY standard model lead naturally to intermediate values for the string scale, in order to reproduce the value of gauge couplings deduced from experiments

In addition, the soft terms turn out to be generically non universal

Due to these results, the cross section can be increased

Cerdeño, Gabrielli, Khalil, C.M., Torrente-Lujan, 01



$$U(3)_c \times U(2)_L \times U(1) \rightarrow (SU(3)_c \times U(1)_3) \times (SU(2)_L \times U(1)_2) \times U(1)_1$$

α_3 α_2 α_1

$$\Rightarrow Y = -\frac{1}{3}\, Q_3 - \frac{1}{2}\, Q_2 + Q_1$$

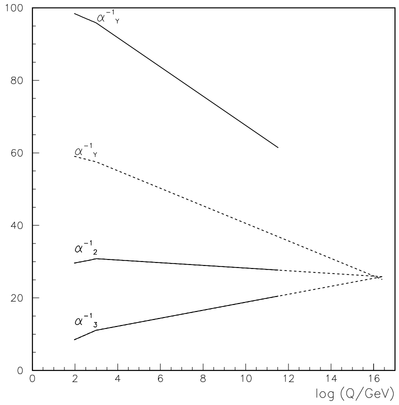
$$\frac{1}{\alpha_Y(M_I)} = \frac{2}{\alpha_1(M_I)} + \frac{1}{\alpha_2(M_I)} + \frac{2}{3\alpha_3(M_I)}$$

$$\Downarrow$$

$$\ln \frac{M_I}{M_Z} = \frac{2\pi\left(\frac{1}{\alpha_Y(M_Z)} - \frac{2}{\alpha_1(M_I)} - \frac{1}{\alpha_2(M_Z)} - \frac{2}{3\alpha_3(M_Z)}\right)}{\left(\frac{2}{3}b_3 + b_2 - b_Y\right)}$$

$$\Downarrow$$

M_I is fixed to intermediate values



Running of the gauge couplings of the MSSM with energy Q embedding the gauge groups within different sets of Dp-branes (solid lines). For comparison the running of the MSSM couplings with the usual normalization factor for the hypercharge, $3/5$, is also shown with dashed lines.

Soft terms using the parameterization

$$F^S = \sqrt{3}(S+S^*)m_{3/2}\sin\theta$$

$$F^i = \sqrt{3}(T_i+T_i^*)m_{3/2}\cos\theta\;\Theta_i$$

$$M_3 = \sqrt{3}m_{3/2}\sin\theta$$

$$M_2 = \sqrt{3}m_{3/2}\;\Theta_1\cos\theta$$

$$M_Y = \sqrt{3}m_{3/2}\;\alpha_Y(M_I)\left(\frac{2\;\Theta_3\cos\theta}{\alpha_1(M_I)}+\frac{\Theta_1\cos\theta}{\alpha_2(M_I)}+\frac{2\;\sin\theta}{3\alpha_3(M_I)}\right)$$

$$m^2_{Q_L} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(1-\Theta_1^2\right)\cos^2\theta\right]$$

$$m^2_{d_R} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(1-\Theta_2^2\right)\cos^2\theta\right]$$

$$m^2_{u_R} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(1-\Theta_3^2\right)\cos^2\theta\right]$$

$$m^2_{e_R} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(\sin^2\theta+\Theta_1^2\cos^2\theta\right)\right]$$

$$m^2_{L_L} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(\sin^2\theta+\Theta_3^2\cos^2\theta\right)\right]$$

$$m^2_{H_u} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(\sin^2\theta+\Theta_3^2\cos^2\theta\right)\right]$$

$$m^2_{H_d} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(\sin^2\theta+\Theta_2^2\cos^2\theta\right)\right]$$

$$m^2_{H_d} = m^2_{L_L}$$

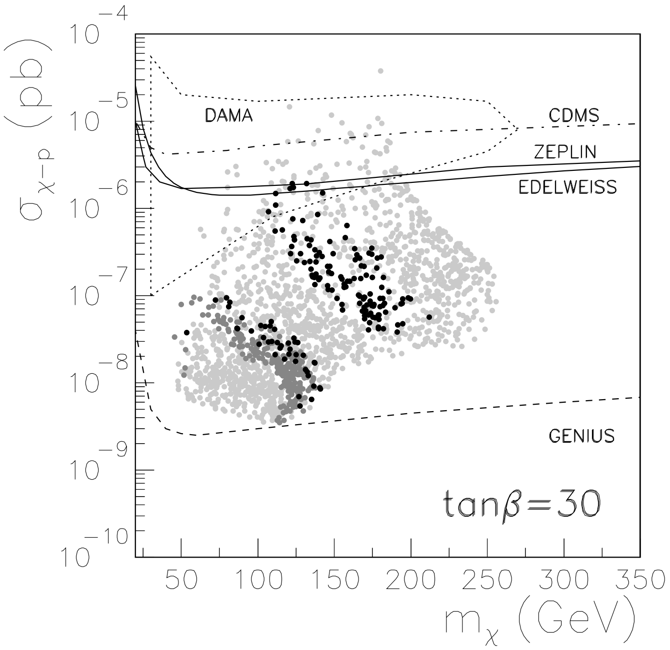
$$A_u = \frac{\sqrt{3}}{2}m_{3/2}\left[(\Theta_2-\Theta_1-\Theta_3)\cos\theta-\sin\theta\right]$$

$$A_d = \frac{\sqrt{3}}{2}m_{3/2}\left[(\Theta_3-\Theta_1-\Theta_2)\cos\theta-\sin\theta\right]$$

$$A_e = 0$$

4 free parameters, $m_{3/2}$, θ and two Θ_i's since $\sum_{i=1,2,3}|\Theta_i|^2 = 1$

These soft terms are generically **non-universal**. For example in the overall modulus limit ($\Theta_{1,2,3} = 1/\sqrt{3}$) universality cannot be obtained. The dilaton limit ($\sin^2\theta = 1$) would give rise to tachyonic states e_R and L_L.



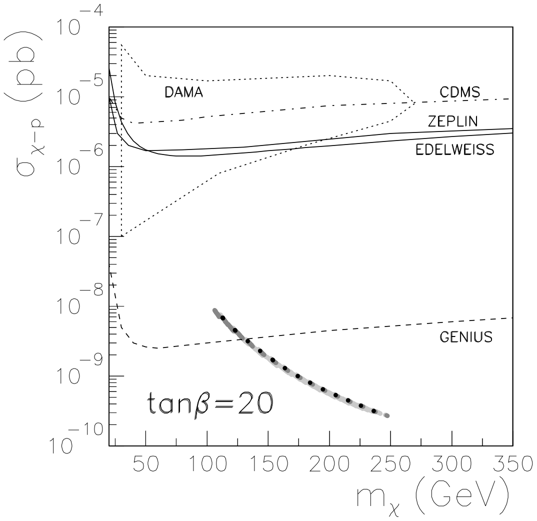
Cerdeño, C.M., in preparation

Orbifold scenarios of the Heterotic String have generically non-universal soft terms

In order to reproduce the value of gauge couplings deduced from experiments, they have

$$M^2 \approx 3m_{3/2}^2\left(1-\cos^2\theta\right)$$
$$m_{Q_L}^2, m_{d_R}^2 = m_{3/2}^2\left(1-\cos^2\theta\right)$$
$$m_{u_R}^2 = m_{3/2}^2\left(1-2\cos^2\theta\right)$$
$$m_{L_L}^2, m_{e_R}^2 = m_{3/2}^2\left(1-3\cos^2\theta\right)$$
$$m_{H_u}^2 = m_{3/2}^2\left(1-\cos^2\theta\right)$$
$$m_{H_d}^2 = m_{3/2}^2\left(1-4\cos^2\theta\right)$$

$M > m$ produces:



Cerdeño, C.M., in preparation

In addition, the CCB constraint excludes all these points

CONCLUSIONS

- ♣ Impressive experimental efforts in order to obtain a direct detection of WIMPs ...Heidelberg-Moscow, IGEX, UKDMC, DAMA, CDMS, upgraded IGEX, HDMS, DAMA 250 kg, CDMS Soudan, CRESST, CUORE, GENIUS, EDELWEISS, MACHe3, PICASSO, ORPHEUS, ZEPLIN, DRIFT,...

- ♣ From the theoretical point of view, there are also efforts analyzing the compatibility of different models with the sensitivity of experiments

  - The absence of dangerous charge and colour breaking minima imposes interesting constraints on the computation of $\sigma_{\tilde{\chi}_1^0-nucleon}$
  - $\sigma_{\tilde{\chi}_1^0-nucleon}$ in Minimal Supergravity is not compatible with present experiments
  - Larger $\sigma_{\tilde{\chi}_1^0-nucleon}$ can be obtained with intermediate scales, non-universal gaugino and non-universal scalar masses → Large regions accesible for experiments are present
  - D-brane constructions are explicit scenarios where intermediate scales and non-universal soft terms arise naturally → Regions compatible with current experiments