Dark Matter Detection in the Light of Recent Experimental Results

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KAIST-KIAS Cosmology Workshop, Daejeon (Korea)

June 12-21, 2002

- ♣ 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

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

   - The MSSM
   - Superstring scenarios

4. RELIC DENSITY

THE PROBLEM OF ROTATION CURVES

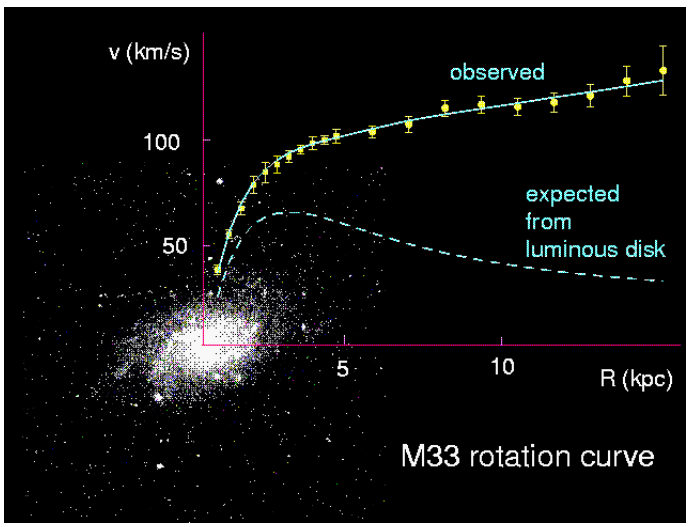
- One can compute the rotational velocity of isolated stars or hydrogen clouds in the outer parts of Galaxies simply using Newton's law

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

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.



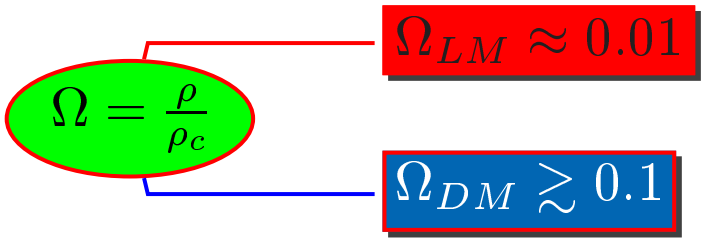
(Roy, 2000 using data from Corbelli,Salucci, 1999)

A SOLUTION

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

Dark Matter

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



  - 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

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

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...

- Axions

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

- Lightest Supersymmetric Particle (LSP)

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

- Strongly Interacting Massive Particles (SIMPs)

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

- CHArged Massive Particles (CHAMPs)

  De Rújula, Glashow, Sarid; Dimopoulos et al., 90

- Self-Interacting Dark Matter (SIDM)

  Spergel, Steinhardt, 00

- WIMPzillas

  Kolb, Chung, Riotto, 1998

- String inspired candidates

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

  Ellis, Lopez, Nanopoulos, 90

  Faraggi, Pospelov, 00

- Axinos

  Covi, Kim, Roszkowski, 99

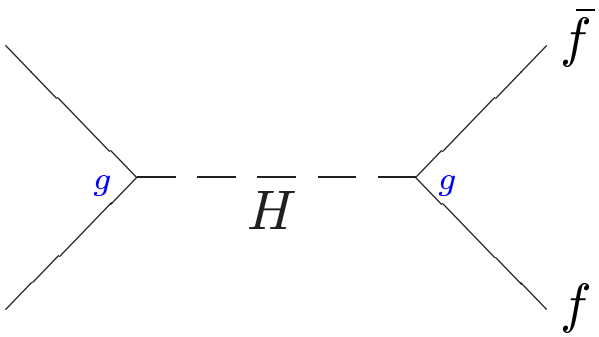
KEY QUESTION: THE RELIC DENSITY

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

- WIMPs fulfil this condition naturally since

$$\Omega \approx \frac{3\times 10^{-27} cm^3 s^{-1}}{\sigma_{\text{annihilation}}\ v}$$

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

- However axions need to have $m_a \approx 10^{-5}$ eV to produce $\Omega \approx 1$

DETECTION

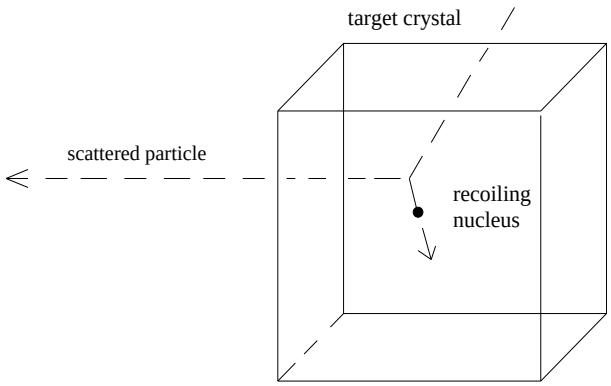
Since the detection will be in the Earth we only need to know the properties of our Galaxy

- 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

$$E_{\mathrm{W}} \approx \tfrac{1}{2}\ (100\ \mathrm{GeV/c^2})\ (300\ \mathrm{km/s})^2 \approx 100\ \mathrm{keV}$$

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,...

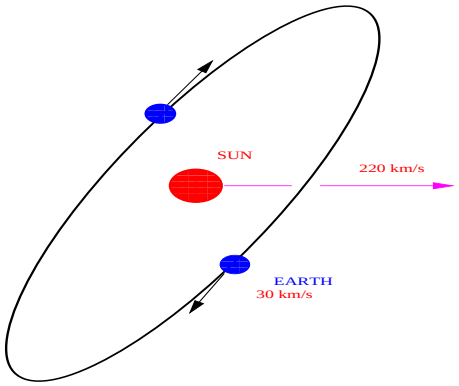
  (using $\rho_{\mathrm{W}} \sim 0.3$ GeV/cm^3 and $v_{\mathrm{W}} \sim 300$ km/s)

$$\Downarrow$$

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

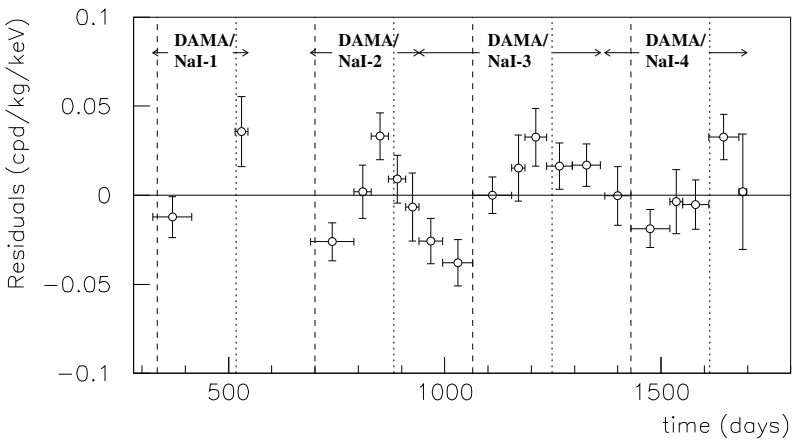
- However, there are recent intriguing results in UKDMC, DAMA

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

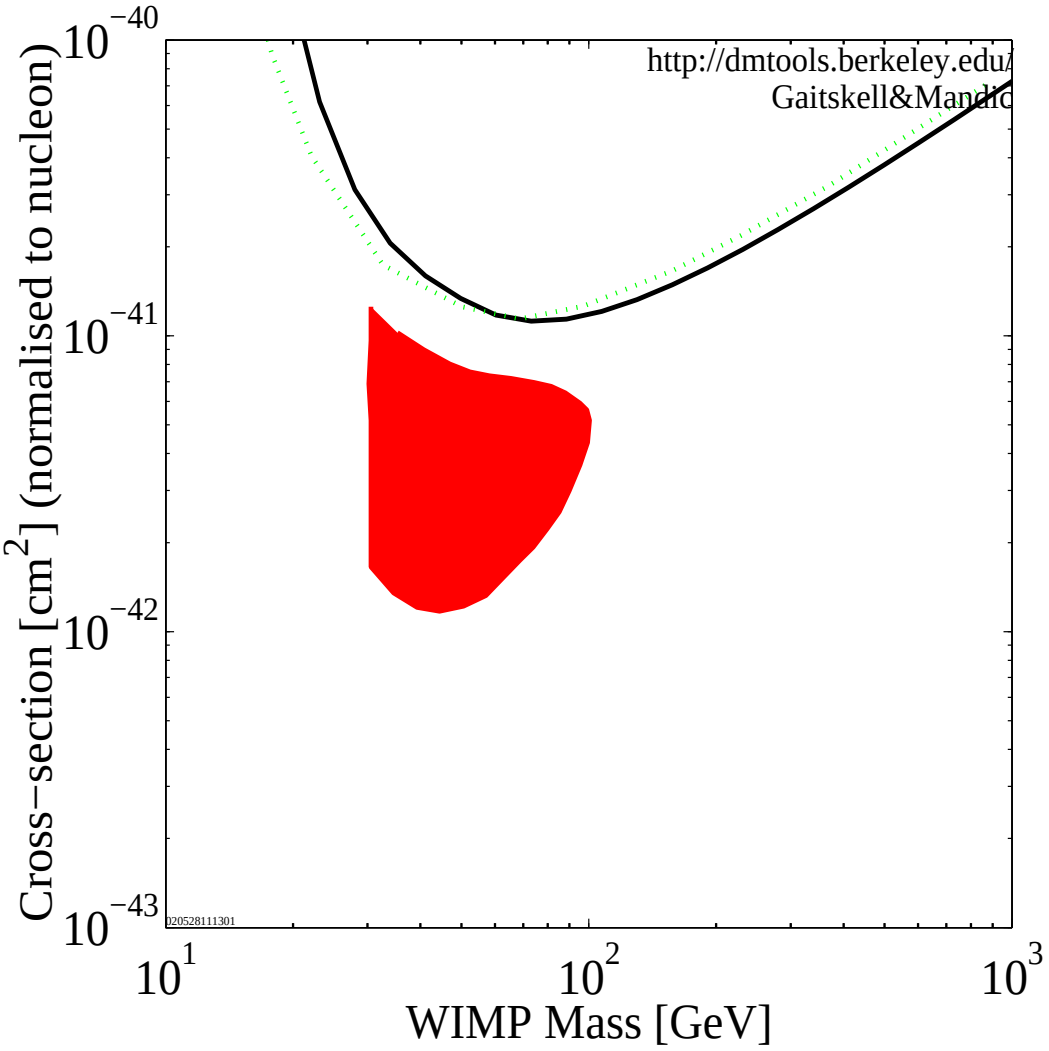


because of the Earth's motion around the Sun: Fluctuation in the dark matter flux $\rightarrow$ A rate variation of $\approx 7\%$ (summer versus winter)

The data collected over four yearly cycles favour at 4σ C.L. **the presence of a yearly modulation**

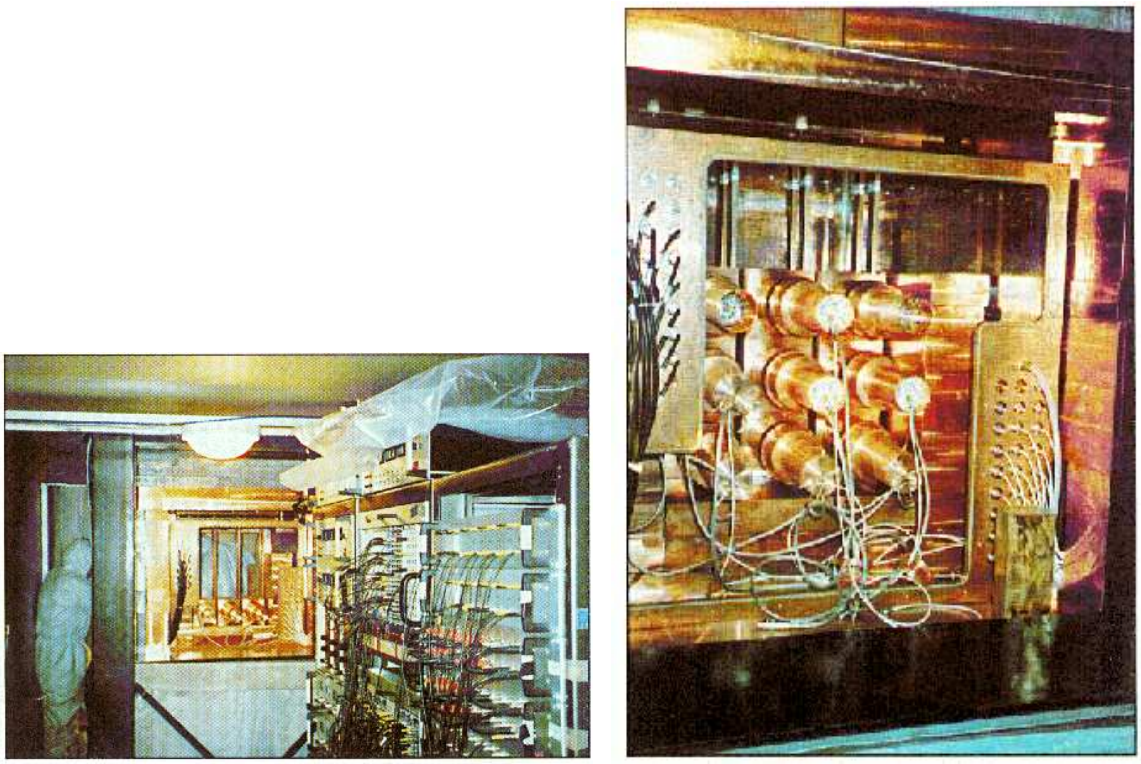


$\sigma_{\text{WIMP-nucleon}} \approx 10^{-6} - 10^{-5}$ pb



DATA listed top to bottom on plot
IGEX exclusion limit
Heidelberg Moscow, 1998
DAMA 2000 58k kg−days NaI Ann. Mod. 3sigma w/DAMA 1996
020528111301

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



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

- **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

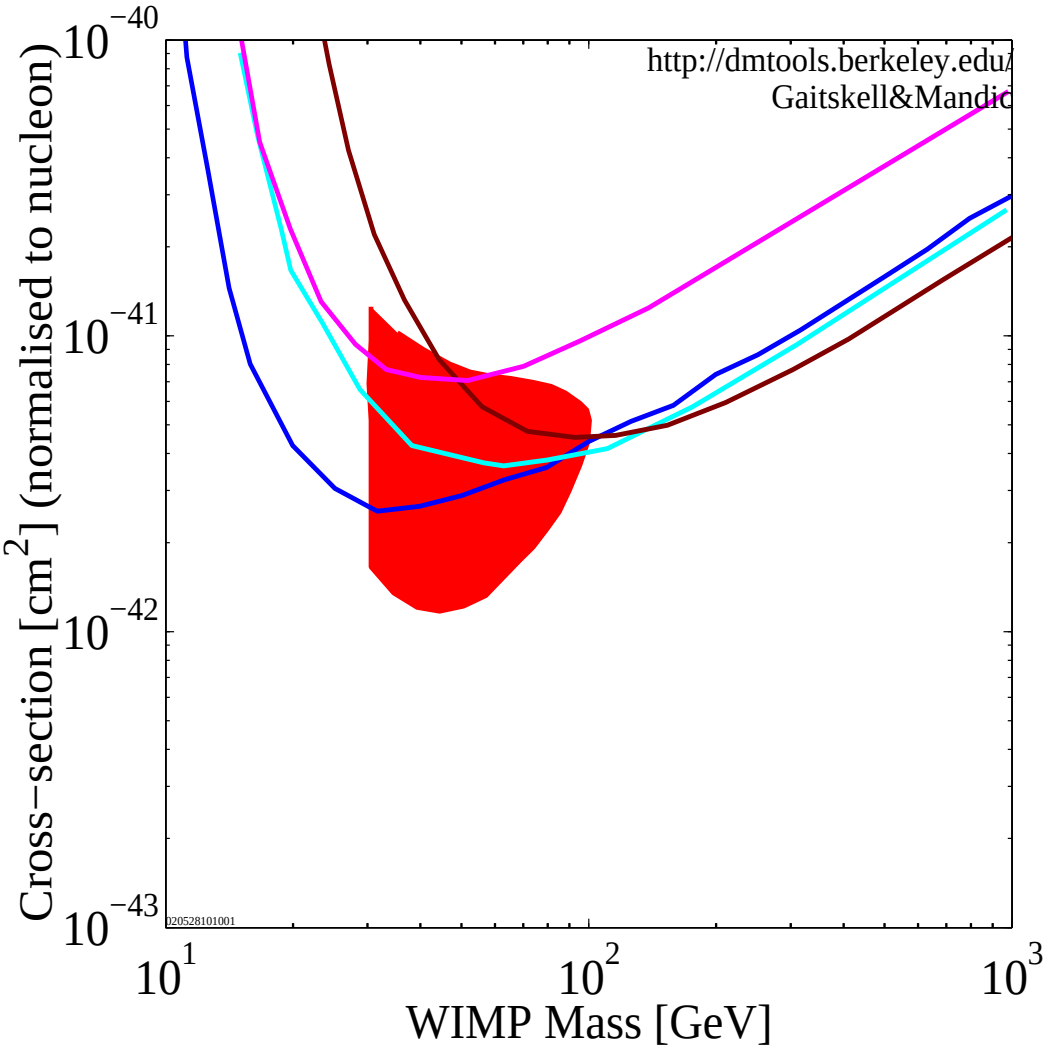
  After 96 days taking data they observed ~ 60 nuclear recoils

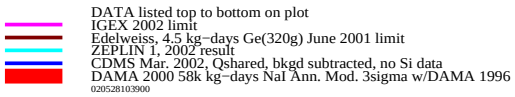
They are not due to WIMPs

$\Downarrow$

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

Part of the region excluded by CDMS has also been excluded by IGEX, EDELWEISS, ZEPLIN


http://dmtools.berkeley.edu/
Gaitskell&Mandic
Cross−section [cm^2] (normalised to nucleon)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^1
10^2
10^3
WIMP Mass [GeV]
020528101001


DATA listed top to bottom on plot
IGEX 2002 limit
Edelweiss, 4.5 kg−days Ge(320g) June 2001 limit
ZEPLIN 1, 2002 result
CDMS Mar. 2002, Qshared, bkgd subtracted, no Si data
DAMA 2000 58k kg−days NaI Ann. Mod. 3sigma w/DAMA 1996
020528103900

The DAMA region ($\sigma \approx 10^{-6} - 10^{-5}$ pb) will be tested by 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

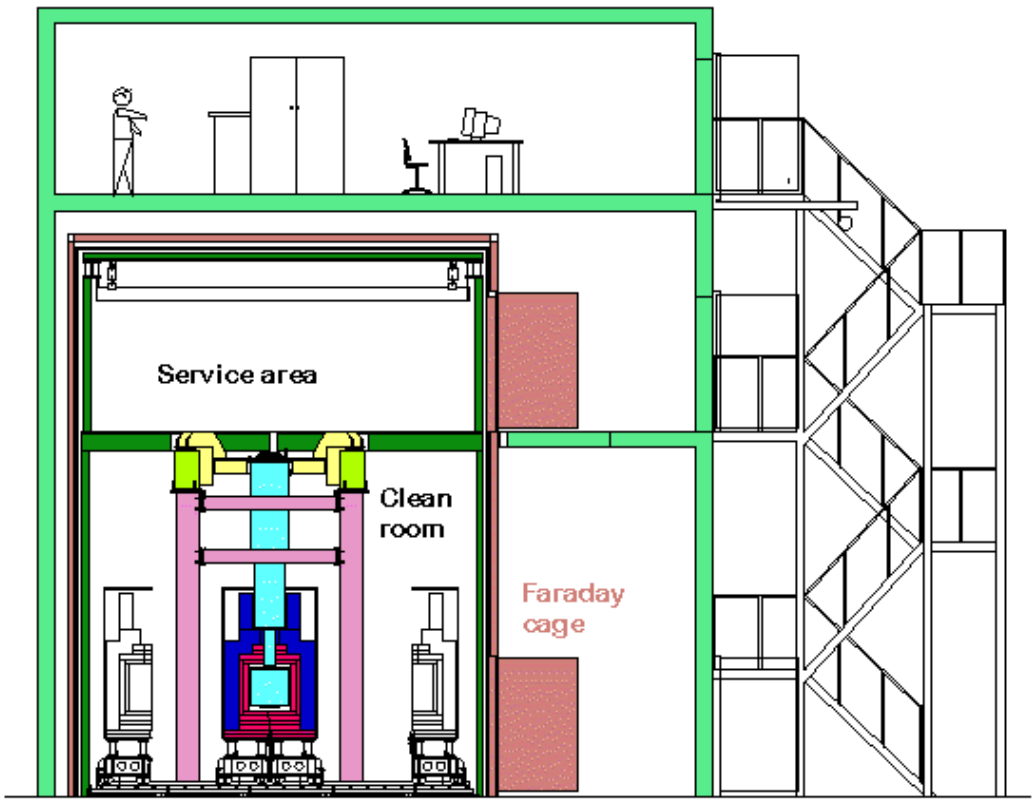
Future dark matter searches

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

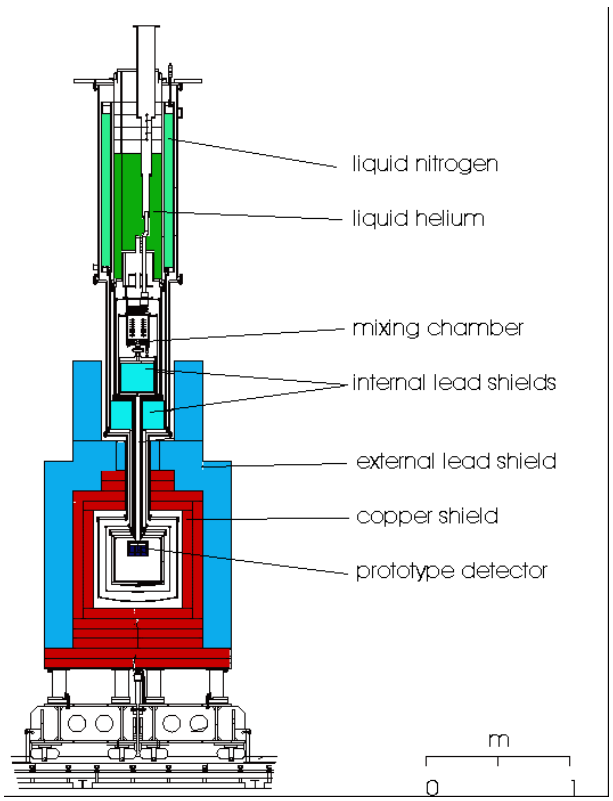
CRESST, CUORE, GENIUS, GEDEON, EDELWEISS, MACHe3, PICASSO, ORPHEUS, ZEPLIN, DRIFT,...

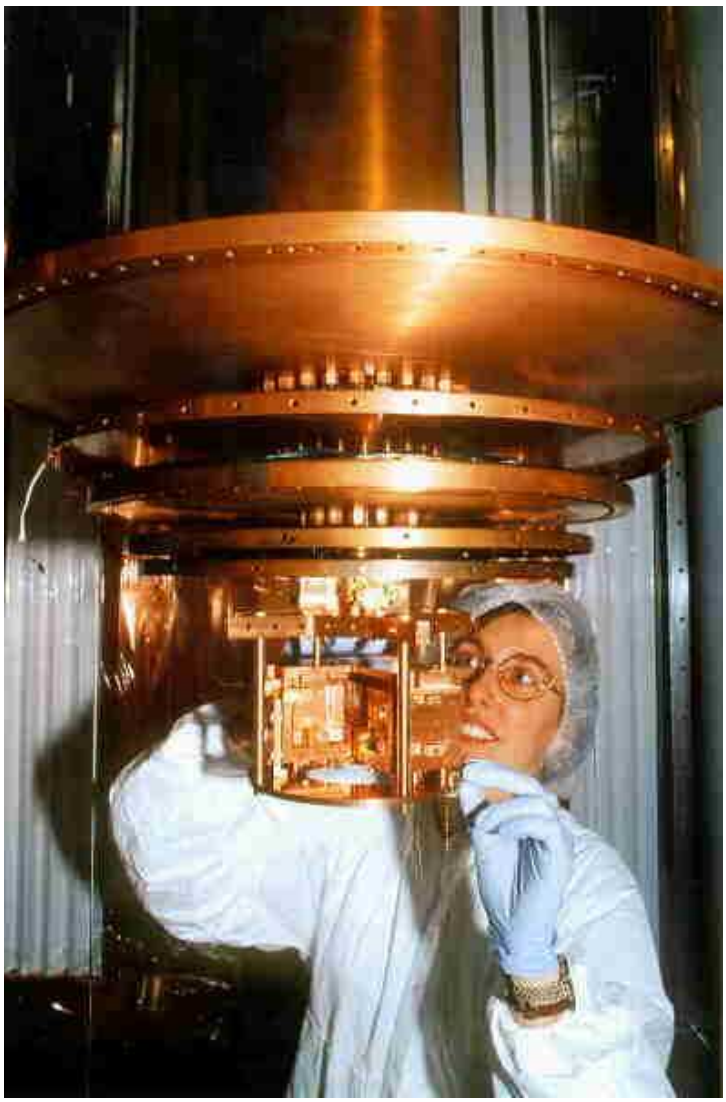
e.g. CRESST experiment, located in Gran Sasso, measures simultaneously phonons and scintillation light distinguishing the nuclear recoils from the electron recoils cause by background radioactivity

CRESST Setup: Outside View

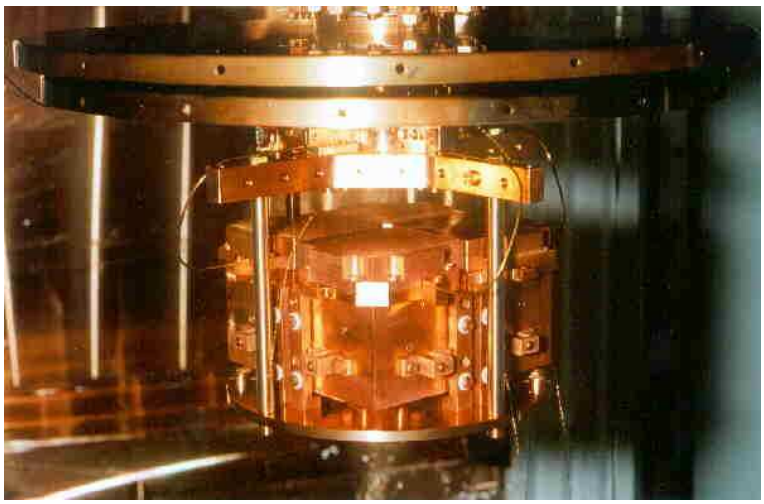


CRESST Setup

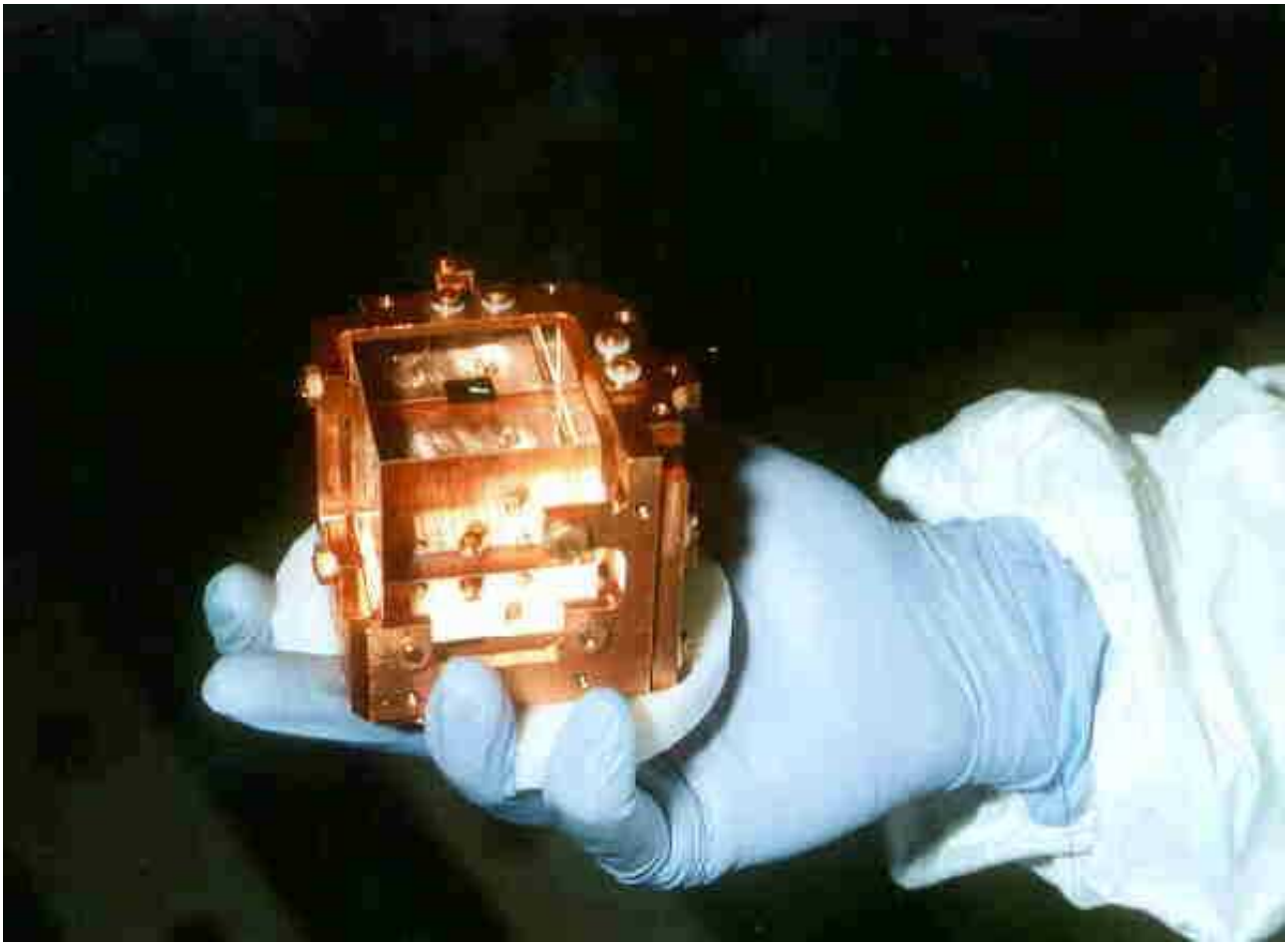




Assembling the Detectors

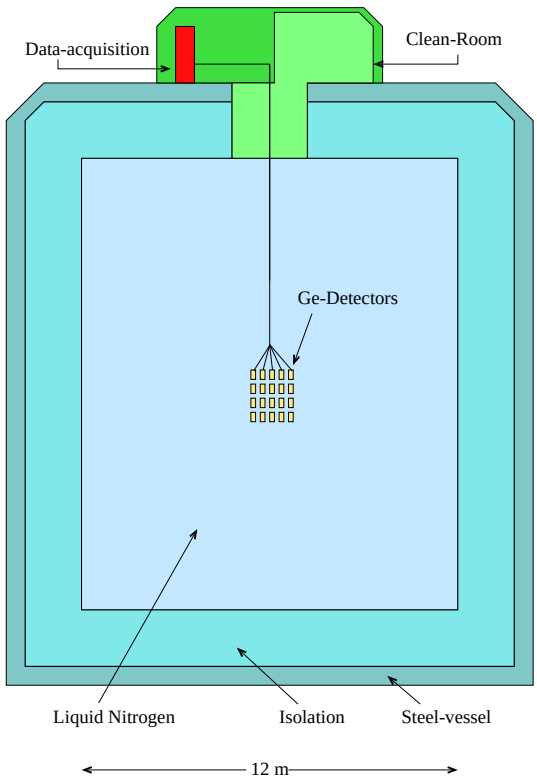


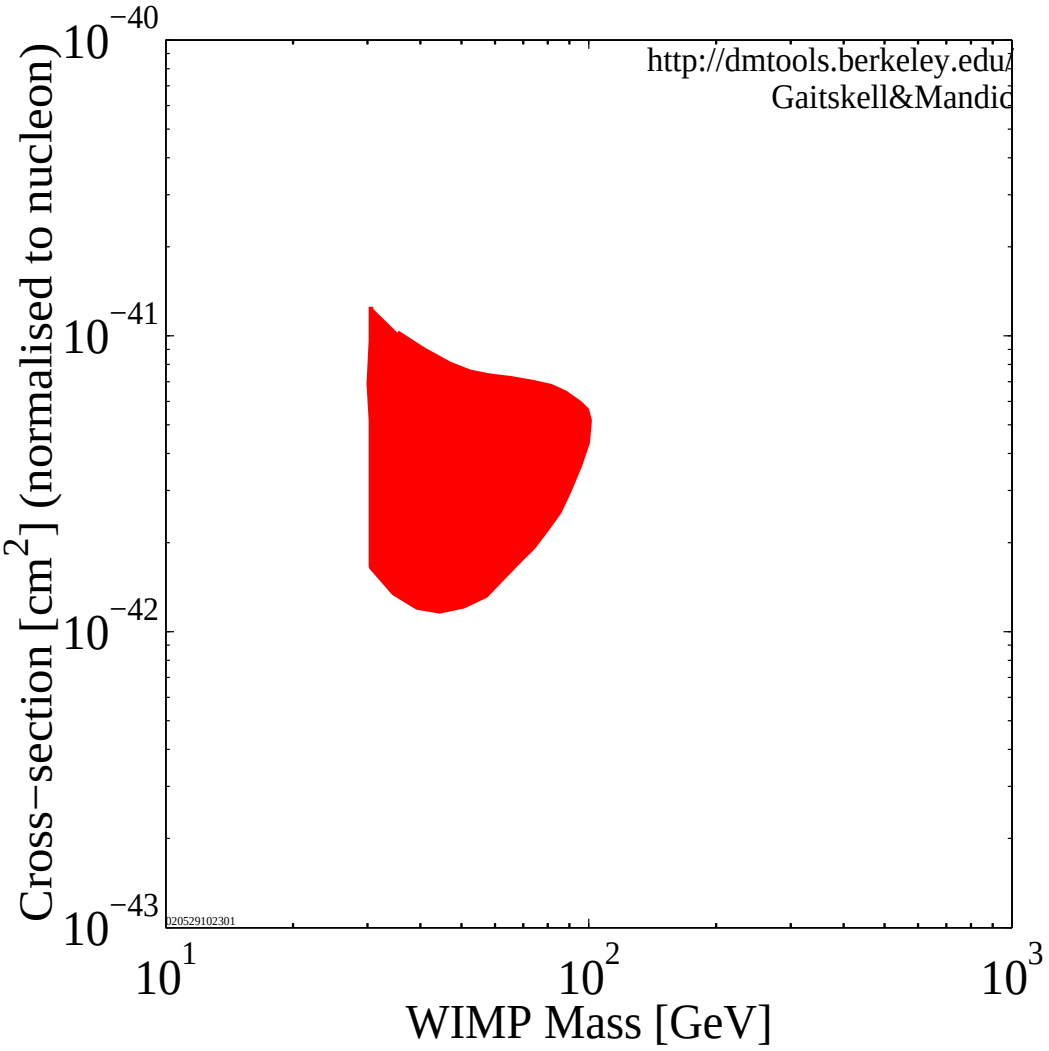
Prototype Detectors (1 kg Sapphire)



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 almost the full range of the parameter space of susy models with neutralinos as dark matter




http://dmtools.berkeley.edu/
Gaitskell&Mandic
020529102301
Cross−section [cm^2] (normalised to nucleon)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^1
10^2
10^3
WIMP Mass [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

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

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 since 1993:

Drees, Nojiri

Kelley, Lopez, Nanopoulos, Pois, Yuan

Arnowitt, Nath

Kane, Kolda, Roszkowski, Wells

Berezinsky, Bottino, Ellis, Fornengo, Mignola, Scopel

Baer, Brhlik

Chen, Drees, Gunion

Barger, Kao

Kamionkowski, Kinkhabwala

Bailin, Kraniotis, Love

Sadoulet

Belli, Bernabei, Bottino, Donato, Fornengo, Prosperi, Scopel

Ellis, Falk, Olive, Srednicki

Moroi, Randall

Chattopadhyay, Ibrahim, Nath

Khalil, Lazarides, Pallis

Feng, Matchev, Wilczek

...

In the MSSM there is a mixing of neutral gauginos and higgsinos $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$

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

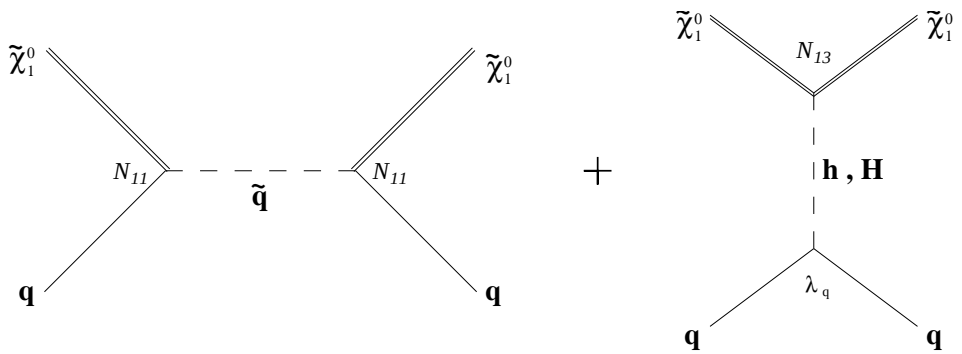
This implies that the lightest mass eigenstate (lightest neutralino) is

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

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

$\mu >> \Rightarrow \tilde{\chi}_1^0 \sim \tilde{B}^0 \Rightarrow$ small cross section

since the scattering channels through Higgs exchange are suppressed (N_{13}, $N_{14} \approx 0$)

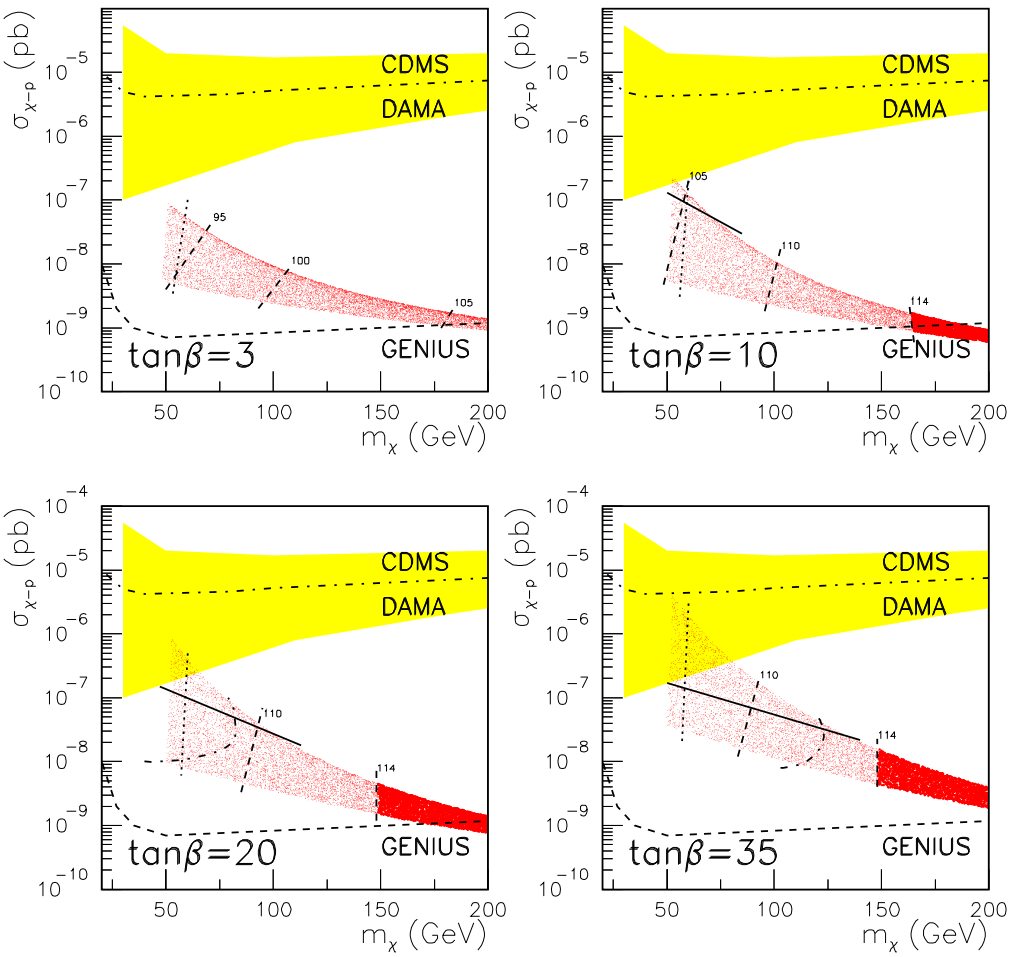


In the MSSM: $\mu^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2$

Working in the supergravity framework with universal soft terms (m, M, A), for low and moderate values of $\tan\beta$, μ turns out to be large

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

This result is **not** compatible with DAMA



♣ Decreasing μ, the Higgsino components of $\tilde{\chi}_1^0$ become important $\Rightarrow$ Larger cross sections

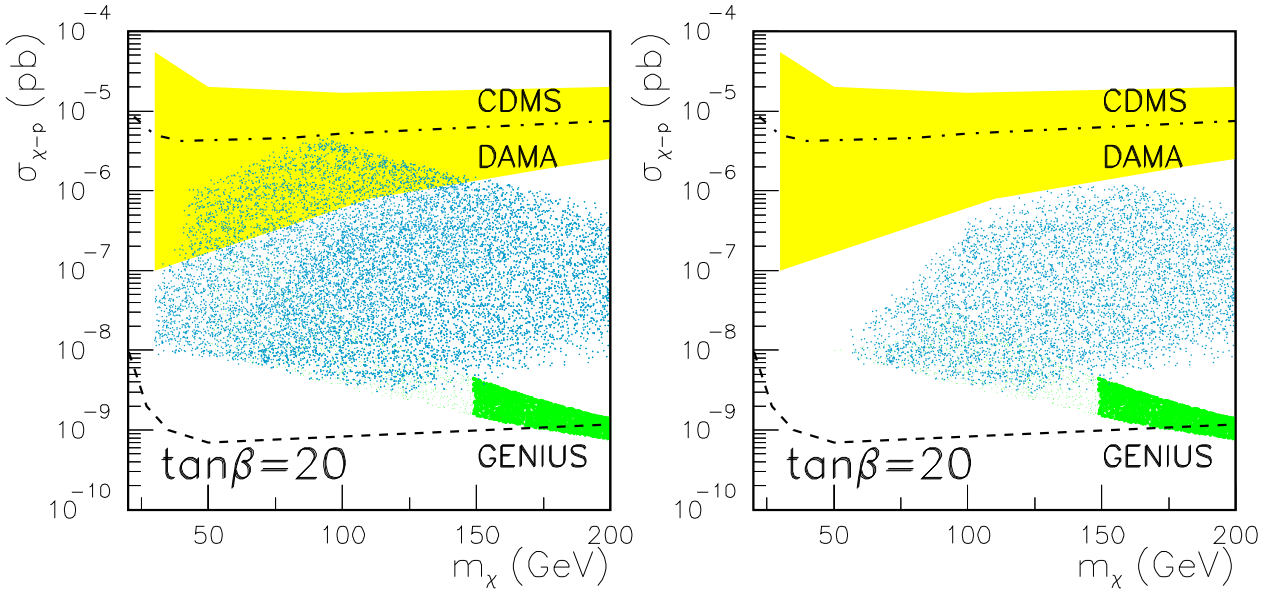
Recently, several proposals have been made in this sense:

- To work with non-universal scalar masses m_α

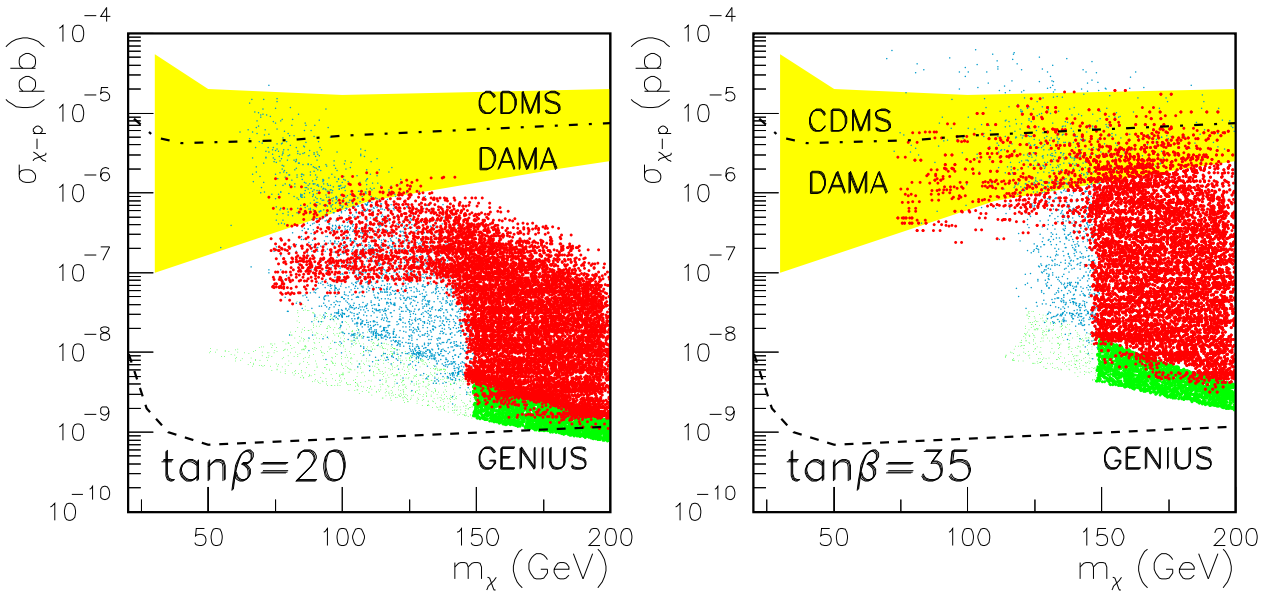
  Bottino, Donato, Fornengo, Scopel
  Accomando, Arnowitt, Dutta, Santoso

- Non-universal gaugino masses M_i

  Corsetti, Nath
  Cerdeño, Khalil, C.M.



Scatter plot using non-universal soft gaugino masses

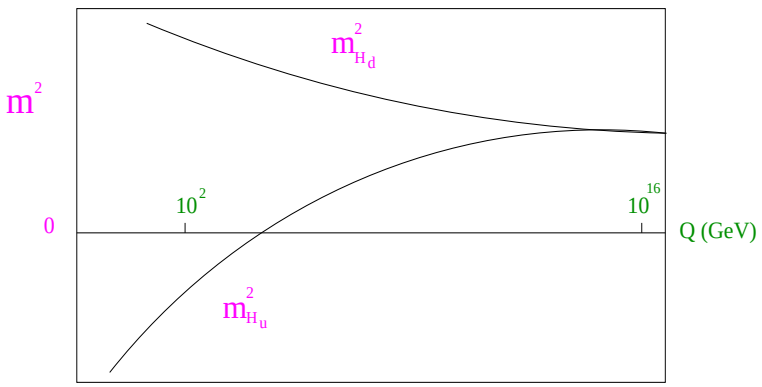


Using non-universal scalar masses: $m \leq m^2_{Hu} \leq 2m$, $0 \leq m^2_{H_d,Q_L,u_R} \leq m$

Unification scale and cross section

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

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



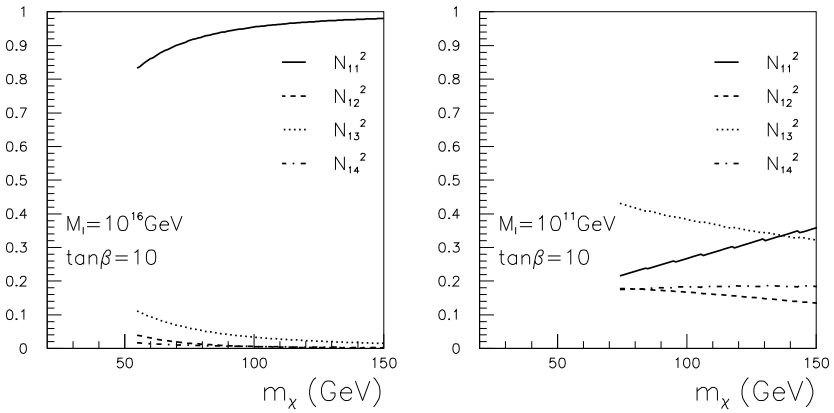
For $\tan\beta$ fixed, the smaller the initial scale for the running is, the smaller the value of μ becomes.

$$\mu^2 = \frac{m^2_{H_d^0} - m^2_{H_u^0} \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2$$

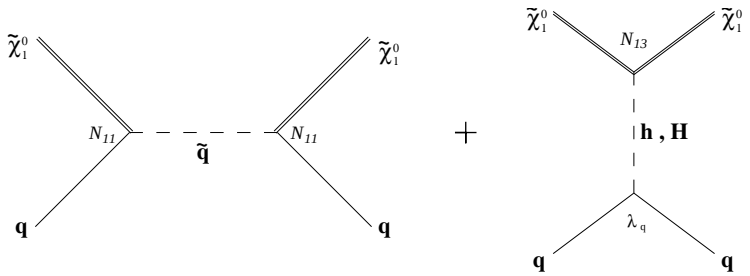
since $\mathcal{L} \sim \mu \tilde{H}_u^0 \tilde{H}_d^0 +$ h.c., the lightest neutralino $\tilde{\chi}_1^0$ will have an important Higgsino component

$\Downarrow$

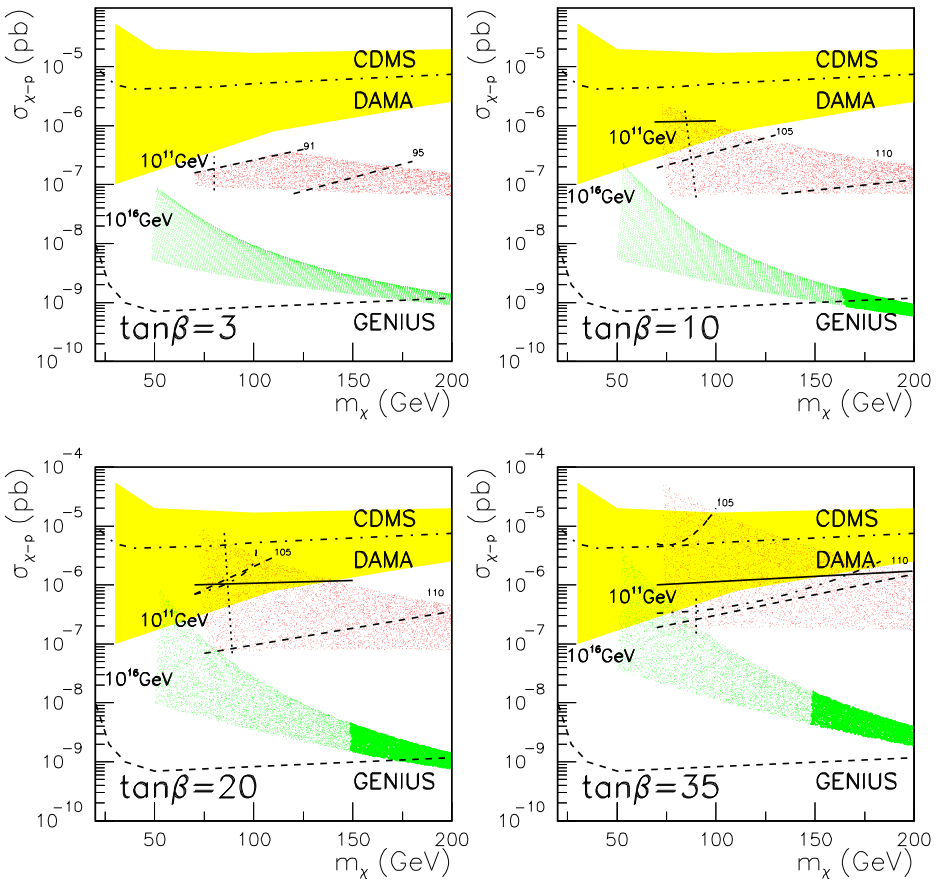
larger $\sigma_{\tilde{\chi}_1^0-nucleon}$



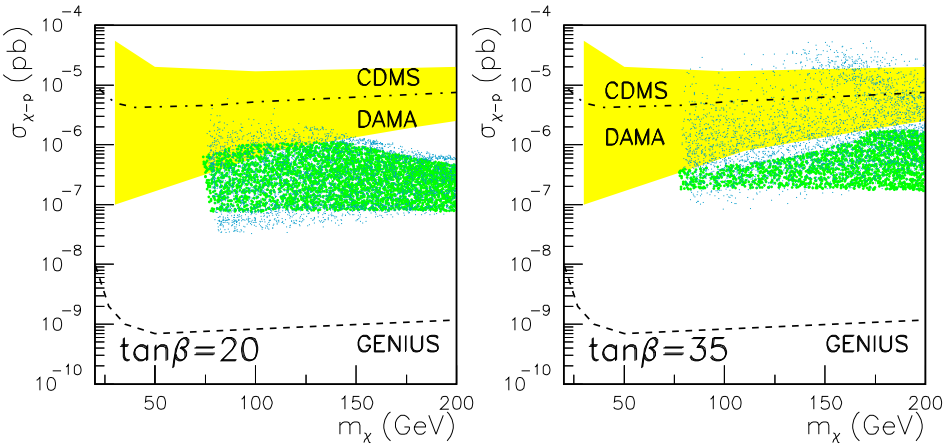
Gaugino-Higgsino components-squared of the lightest neutralino as a function of its mass



Feynman diagrams contributing to neutralino-nucleon cross section.



Scatter plot showing the MSSM with $M_I = 10^{11}$ GeV. The M_{GUT} case (green region) is also shown, for comparison.



Scatter plot showing the MSSM with $M_I = 10^{11}$ GeV and nonuniversal scalar masses. The universal case (green region) is also shown, for comparison.

Cerdeño, Gabrielli, C.M., 02

A PHOTOGRAPH EXPLAINING 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

Antoniadis

Lykken

Arkani-Hamed, Dimopoulos, Dvali,

Bachas, Shiu, Tye, Kakushadze, Pioline, Benakli, Oz, ...

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

Phenomenologically, "intermediate" initial scales $M_I \approx 10^{10-14}$ GeV are specially attractive

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

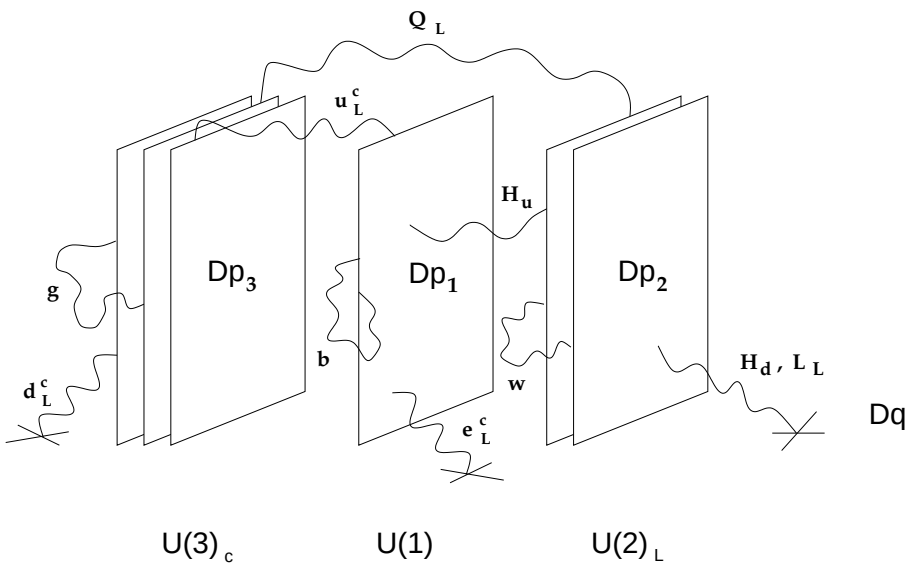
Abel, Allanach, Quevedo, Ibañez, Klein, 00

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, large cross sections, even in the small $\tan\beta$ regime, can be obtained

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



$$U(3)_c \times U(2)_L \times U(1) \to (SU(3)_c \times U(1)_3) \times \left(SU(2)_L \times U(1)_2\right) \times U(1)_1$$

α_3 α_2 α_1

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

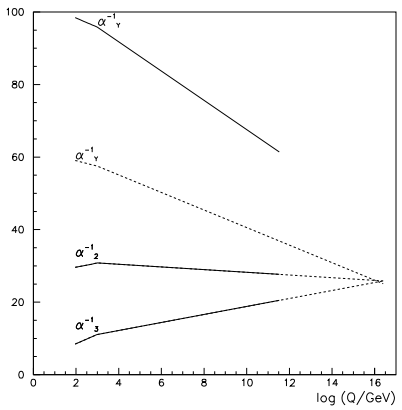
$$\frac{1}{\alpha_Y(M_I)} = \frac{2}{\alpha_1(M_I)} + \frac{1}{\alpha_2(M_I)} + \frac{2}{3\alpha_3(M_I)}$$

$$\Downarrow$$

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

$$\Downarrow$$

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

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

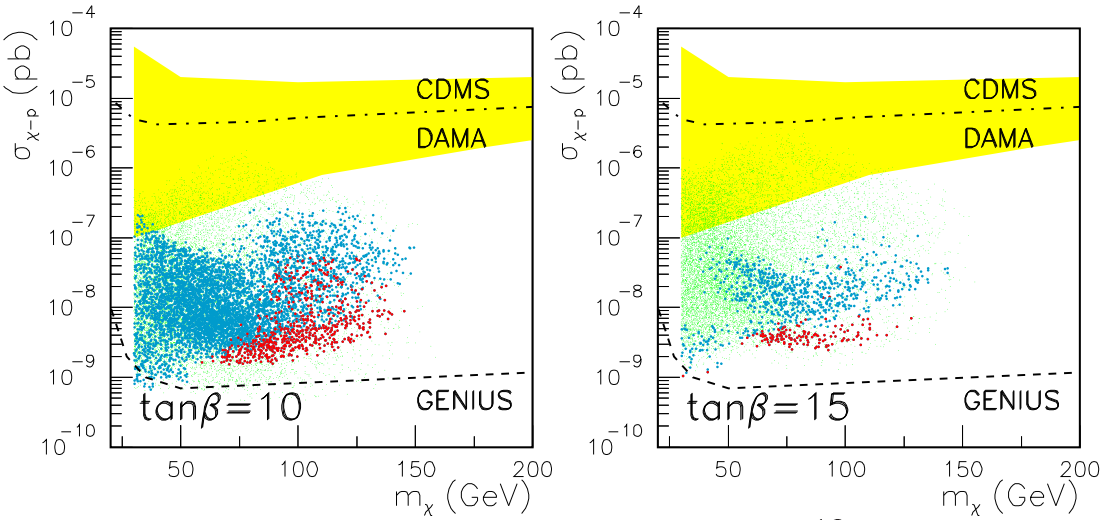
$$M_3 = \sqrt{3}m_{3/2}\sin\theta$$
$$M_2 = \sqrt{3}m_{3/2}\,\Theta_1\cos\theta$$
$$M_Y = \sqrt{3}m_{3/2}\,\alpha_Y(M_I)\left(\frac{2\,\Theta_3\cos\theta}{\alpha_1(M_I)}+\frac{\Theta_1\cos\theta}{\alpha_2(M_I)}+\frac{2\,\sin\theta}{3\alpha_3(M_I)}\right)$$

$$m^2_{Q_L} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(1-\Theta_1^2\right)\cos^2\theta\right]$$
$$m^2_{d_R} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(1-\Theta_2^2\right)\cos^2\theta\right]$$
$$m^2_{u_R} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(1-\Theta_3^2\right)\cos^2\theta\right]$$
$$m^2_{e_R} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(\sin^2\theta+\Theta_1^2\cos^2\theta\right)\right]$$
$$m^2_{L_L} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(\sin^2\theta+\Theta_3^2\cos^2\theta\right)\right]$$
$$m^2_{H_u} = m^2_{3/2}\left[1-\tfrac{3}{2}\left(\sin^2\theta+\Theta_2^2\cos^2\theta\right)\right]$$
$$m^2_{H_d} = m^2_{L_L}$$

$$A_u = \frac{\sqrt{3}}{2}m_{3/2}\left[(\Theta_2-\Theta_1-\Theta_3)\cos\theta-\sin\theta\right]$$
$$A_d = \frac{\sqrt{3}}{2}m_{3/2}\left[(\Theta_3-\Theta_1-\Theta_2)\cos\theta-\sin\theta\right]$$
$$A_e = 0$$

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.



D-brane scenario with the string scale $M_I = 10^{12}$ GeV

However, most of the regions consistent with DAMA limits are forbidden because of the experimental constraints

In the analysis the parameters θ and Θ_i are varied in the whole allowed range, $0 \leq \theta \leq 2\pi$, $-1 \leq \Theta_i \leq 1$. For the gravitino mass, $m_{3/2} \leq 300$ GeV is taken

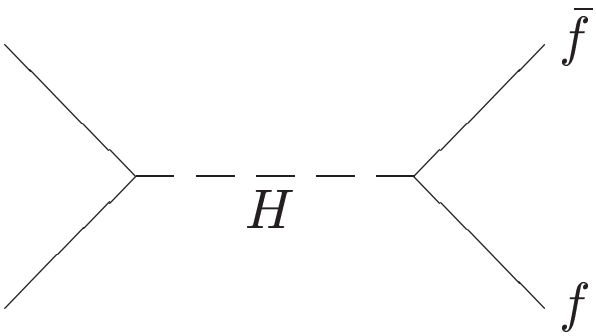
RELIC DENSITY

- We were interested in the possibility of obtaining large $\sigma_{\tilde{\chi}_1^0 - nucleon}$.
  In order to compute it, *no cosmological assumptions about the early Universe need to be used*

- Such cosmological assumptions indeed must be taken into account when computing the amount of relic neutralino density $\Omega_{\tilde{\chi}_1^0}$.
  Observations imply that one should obtain: $0.1 \lesssim \Omega_{\tilde{\chi}_1^0}\, h^2 \lesssim 0.3$

  - Thermal production of neutralinos:

    $$\Omega_{\tilde{\chi}_1^0}\, h^2 \propto 1/\sigma_{\text{annihilation}}$$

    thus it is expected that high $\sigma_{\tilde{\chi}_1^0 - nucleon}$ will correspond to low $\Omega_{\tilde{\chi}_1^0}$

- Moduli decays can produce neutralinos

Moroi, Randall, 99

We can apply this mechanism to the case with intermediate scales

Khalil, C.M., Torrente-Lujan, 02

The decay width $\Gamma_\phi \sim \frac{m_\phi^3}{M^2}$ is usually too small and therefore $T_{RH} \lesssim$ 1 MeV

However, if $M = M_I \rightarrow T_{RH} \gtrsim 1$ MeV

e.g. 10^{12} GeV $\lesssim M_I \lesssim 10^{14}$ GeV
$\Rightarrow 6$ MeV $\lesssim T_{RH} \lesssim 0.3$ GeV

An example with $M = M_I$ is the case of the twisted moduli in type I strings

Since $\Omega \propto 1/T$, and $T_R << T_f \sim m_\chi/20 \sim 5$ GeV, the relic neutralino density can be larger

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, GEDEON, 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

  - $\sigma_{\tilde{\chi}_1^0 - nucleon}$ in the MSSM with universality is not compatible with DAMA

  - Larger $\sigma_{\tilde{\chi}_1^0 - nucleon}$ may be obtained with: non-universality, intermediate scales

  - Theoretical relic neutralino density and observations may also be compatible