INITIAL SCALES, SUPERSTRINGS, DARK MATTER

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OUTLINE

1. INTRODUCTION TO DARK MATTER
   - The problem of rotation curves in Galaxies
   - A solution: dark matter
   - A natural candidate is the lightest neutralino

2. DETECTION: PRESENT SITUATION
   - Elastic scattering with nuclei in a material
   - DAMA (CDMS) collaboration claims (not) to have detected WIMPs

3. THEORETICAL MODELS
   - The simplest MSSM is in contradiction with DAMA results
   - Inspired by superstring scenarios we will vary the initial scale obtaining larger cross sections

THE PROBLEM OF ROTATION CURVES

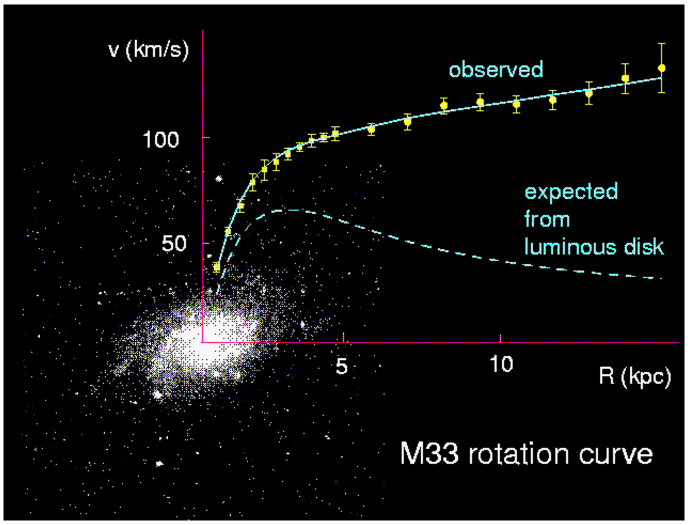
♣ One can compute the rotational velocity of isolated stars or hydrogen clouds in the outer parts of Galaxies simply using Newton's law

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

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

♣ The most common explanation to rotation curves is to assume that there is non-luminous matter in and around the Galaxies

Zwicky, 1933

Dark Matter

♣ Supersymmetry gives us a natural candidate for dark matter: the lightest

neutralino

- It is usually the **LSP** and therefore stable
- It is a WIMP

Goldberg, 83
Ellis, Hagelin, Nanopoulos, Olive, Srednicki, 84

DETECTION

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

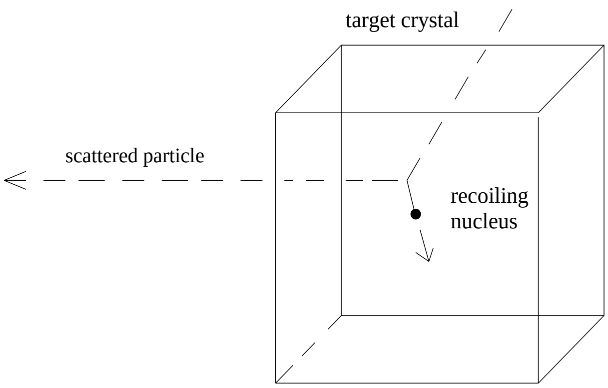
♡ The local mass density necessary to reproduce the rotation curve of our Galaxy is $\rho \sim 0.3\ GeV/cm^3$

♡ 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



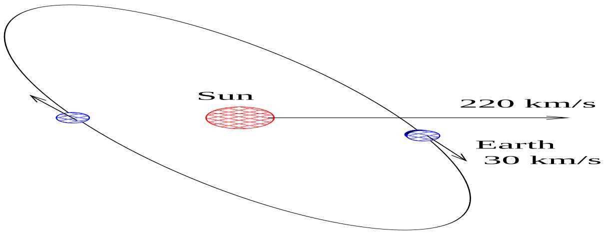
EXPERIMENTS

♣ CDMS collaboration (since 1998)

Using a 10 kg Ge detector during 96 days they did not observe nuclear recoils due to dark matter particles (the method is basically calorimetric) $\Rightarrow \sigma \lesssim 10^{-5}$ pb

♣ DAMA collaboration (since 1996)

The Earth's motion around the Sun $\Rightarrow$ fluctuation in the dark matter flux $\Rightarrow$ a rate variation of $\approx 7\%$



Using nine 9.70 kg NaI crystal scintillators located at the deep underground, they have reported that the data collected over four yearly cycles favour at 4σ C.L. **the presence of a yearly modulation** $\Rightarrow \sigma \approx 10^{-6} - 10^{-5}$ pb

THEORETICAL MODELS

It is then crucial to analyze the compatibility of the neutralino as a dark matter candidate, with the sensitivity of current dark matter detectors, DAMA and CDMS.

In the MSSM there is a mixing of neutral gauginos and higgsinos

$$\mathcal{L} \sim -\frac{1}{2}(\psi^0)^T \mathcal{M} \psi^0 + \text{h.c.},$$

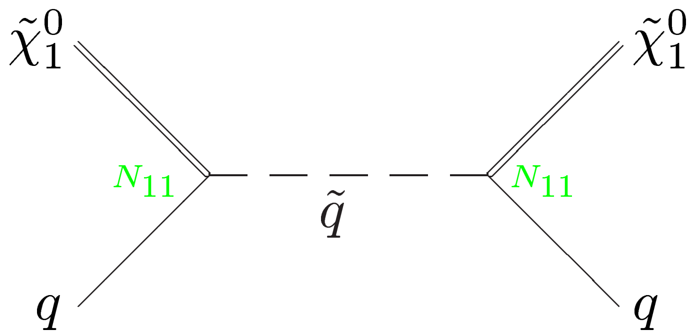
where $\psi^0 = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$

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

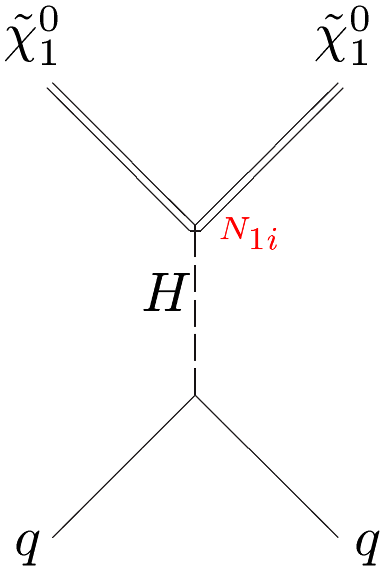
This implies that the lightest mass eigenstate (lightest neutralino) is

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

The lightest neutralino has interactions with nucleons, e.g.



$$\Rightarrow \quad \sigma_{\tilde{\chi}_1^0 - p} \propto \frac{m_r^2}{4\pi} \left(\frac{g'^2 \sin\theta}{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2} \right)^2 |N_{11}|^4$$



$$\Rightarrow \quad \sigma_{\tilde{\chi}_1^0 - p} \propto \frac{m_r^2}{4\pi} \frac{\lambda_q^2}{m_H^4} |N_{1i} \left(g' N_{11} - g N_{12} \right)|^2$$

$$i = 3, 4$$

Working in the supergravity framework for the MSSM with universal soft terms (m, M, A) one obtains generically

$$\sigma_{\tilde{\chi}_1^0 - p} < 10^{-6} \text{ pb}$$

which is compatible with CDMS but **not** with DAMA

see e.g. Ellis, Ferstl, Olive, 2000

Previous works analyzing neutralino-nucleon cross section:

M. Drees and M.M. Nojiri, Phys. Rev. D48 (1993) 3483.

S. Kelley, J. Lopez, D. Nanopoulos, H. Pois and K. Yuan, Phys. Rev. D47 (1993) 246; R. Arnowitt and P. Nath, Phys. Rev. D70 (1994) 3696; Phys. Rev. D54 (1996) 2374, 56 (1997) 2820; Phys. Lett. B437 (1998) 344; G. Kane, C. Kolda, L. Roszkowski and J. Wells, Phys. Rev. D49 (1994) 6173; V. Berezinsky, A. Bottino, J. Ellis, N. Fornengo, G. Mignola and S. Scopel, Astropart. Phys. 5 (1996) 1, 6 (1996) 333; H. Baer and M. Brhlik, Phys. Rev. D53 (1996) 597, 55 (1997) 3201, 57(1998) 567; V. Barger and C. Kao, Phys. Rev. D57 (1998) 3131; M. Kamionkowski and A. Kinkhabwala, Phys. Rev. D57 (1998) 3256; B. Sadoulet, Nucl. Phys. Proc. Suppl. 77 (1999) 389; M. Brhlik and L. Roszkowski, Phys. Lett. B464 (1999) 303; P. Belli, R. Bernabei, A. Bottino, F. Donato, N. Fornengo, D. Prosperi and S. Scopel, Phys. Rev. D61 (2000) 023512; A. Corsetti and P. Nath, hep-ph/9904497; J. Ellis, T. Falk, K. Olive and M. Srednicki, hep-ph/9905481; T. Moroi and L. Randall, hep-ph/9906527; A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. Rev. D59 (1999) 095003; hep-ph/9909228; U. Chattopadhyay, T. Ibrahim and P. Nath, hep-ph/0005109.

H. Baer and M. Brhlik, Phys. Rev. D57 (1998) 567.

C.-H. Chen, M. Drees and J.F. Gunion, Phys. Rev. D55 (1997) 330; D. Bailin, G.V. Kraniotis and A. Love, Phys. Lett. B432 (1998) 90; Nucl. Phys. B556 (1999) 23; S. Khalil, G. Lazarides and C. Pallis, hep-ph/0005021.

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

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

μ turns out to be large and therefore the lightest neutralino is mainly Bino since $N_{11} \approx 1$

$$\Downarrow$$

The scattering channels through Higgs exchange are suppressed (N_{13}, $N_{14} \approx 0$) and therefore the cross section is small.

- The scattering channels through squark exchange are also suppressed by the mass of squarks

Several proposals have been made to modify this result:

- 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

Then $\sigma_{\tilde{\chi}_1^0-p} \approx 10^{-6}$ pb may be reached:

- with $\tan\beta \gtrsim 25$ in the universal case
- with $\tan\beta \gtrsim 4$ in the non-universal case if the m_α's fulfil some relations

Accomando, Arnowitt, Dutta, Santoso, 2000

see also Gómez, Vergados, 2000

non-universal gaugino masses M_i may also be helpful

Corsetti, Nath, 2000

SUPERSTRINGS

The analyses of $\sigma_{\tilde{\chi}_1^0-p}$ were performed assuming the unification scale, $M_{GUT} \approx 10^{16}$ GeV

However, it has been realized that the string scale may be anywhere between the weak scale and the Planck scale Lykken, 96

- 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

- to explain experimental observations as neutrino masses or the scale for axion physics

Benakli, 99

- in order to attack the hierarchy problem

$$m_{3/2} \approx \frac{F}{M_{Planck}} \approx \frac{M_I^2}{M_{Planck}} \approx \frac{\left(10^{10-12}\right)^2}{M_{Planck}} \approx M_W$$

Burgess, Ibañez, Quevedo, 99

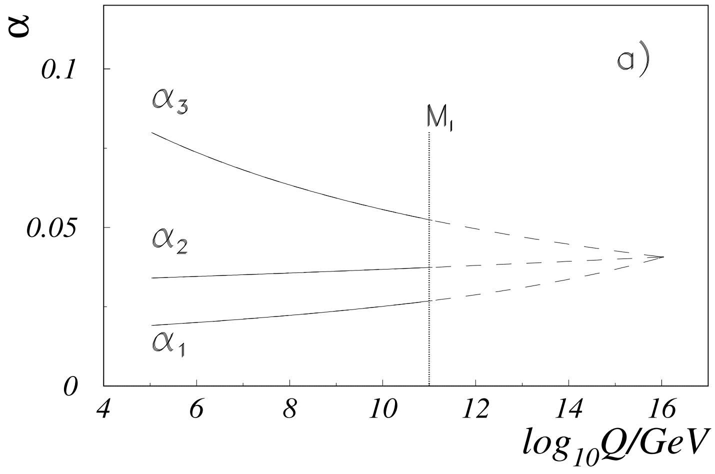
- might also explain the observed ultra-high energy ($\approx 10^{20}$ eV) cosmic rays as products of long-lived massive string mode decays

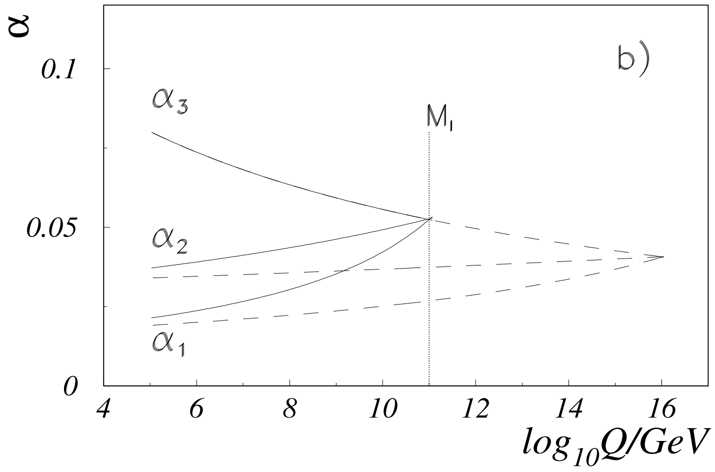
- several models of chaotic inflation favour also these initial scales

Kaloper, Linde, 99

- charge and color breaking constraints become less important

Abel, Allanach, Quevedo, Ibañez, Klein, 2000





Running of the gauge couplings with energy if the initial scale is $M_I = 10^{11}$ GeV (solid lines). For comparison the usual running of the MSSM couplings is also shown with dashes lines.

(a) non universality of couplings

Similar scenarios have been obtained assuming that the groups of the standard model come from different sets of Dp-branes

Cerdeño, Gabrielli, Khalil, Muñoz, Torrente-Lujan, 2001

(b) universality of couplings

Similar models have been built explicitely using the same set of Dp-branes

Aldazabal, Ibañez, Quevedo, Uranga, 2000

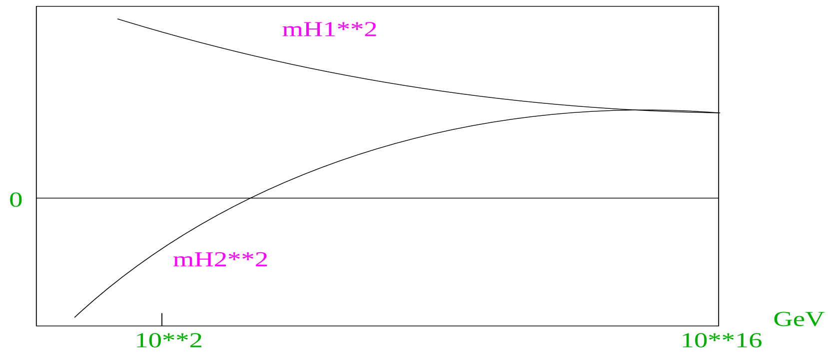
Bailin, Kraniotis, Love, 2000

INITIAL SCALES AND CROSS SECTIONS

Inspired by superstring scenarios we studied how much the analysis of $\sigma_{\tilde{\chi}_1^0-p}$ is modified by taking a scale M_I smaller than M_{GUT}

see also Bailin, Kraniotis, Love, 2000

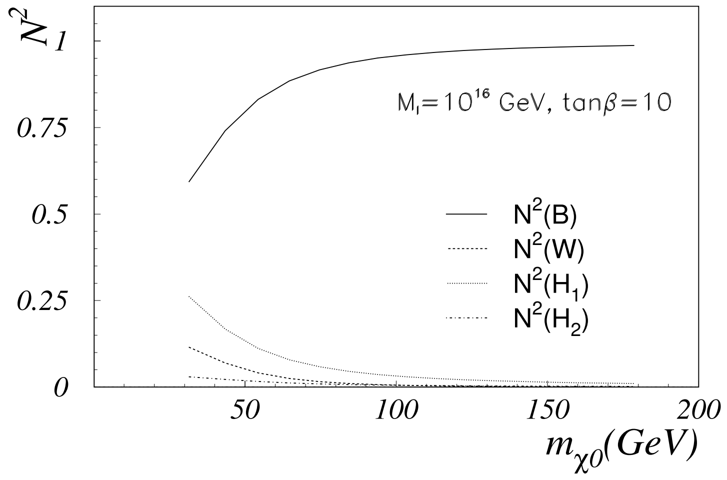
Smaller initial scales, as for example $M_I \approx 10^{11}$ GeV, will imply larger $\sigma_{\tilde{\chi}_1^0-p}$

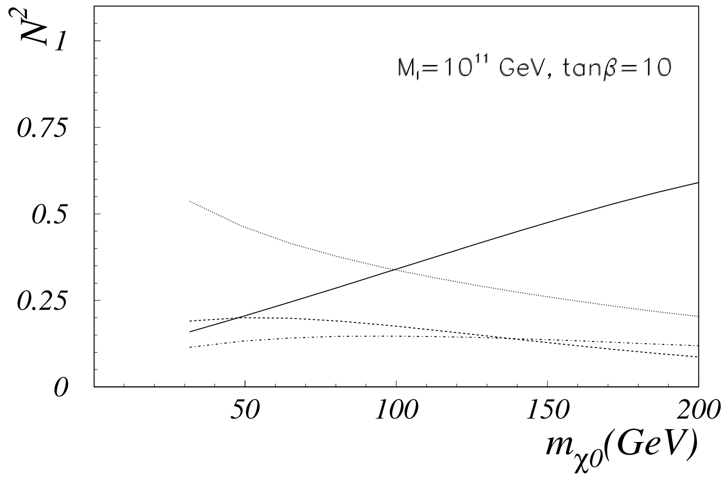


For $\tan\beta$ fixed, the smaller the initial scale for the running is, the smaller the value of μ becomes.

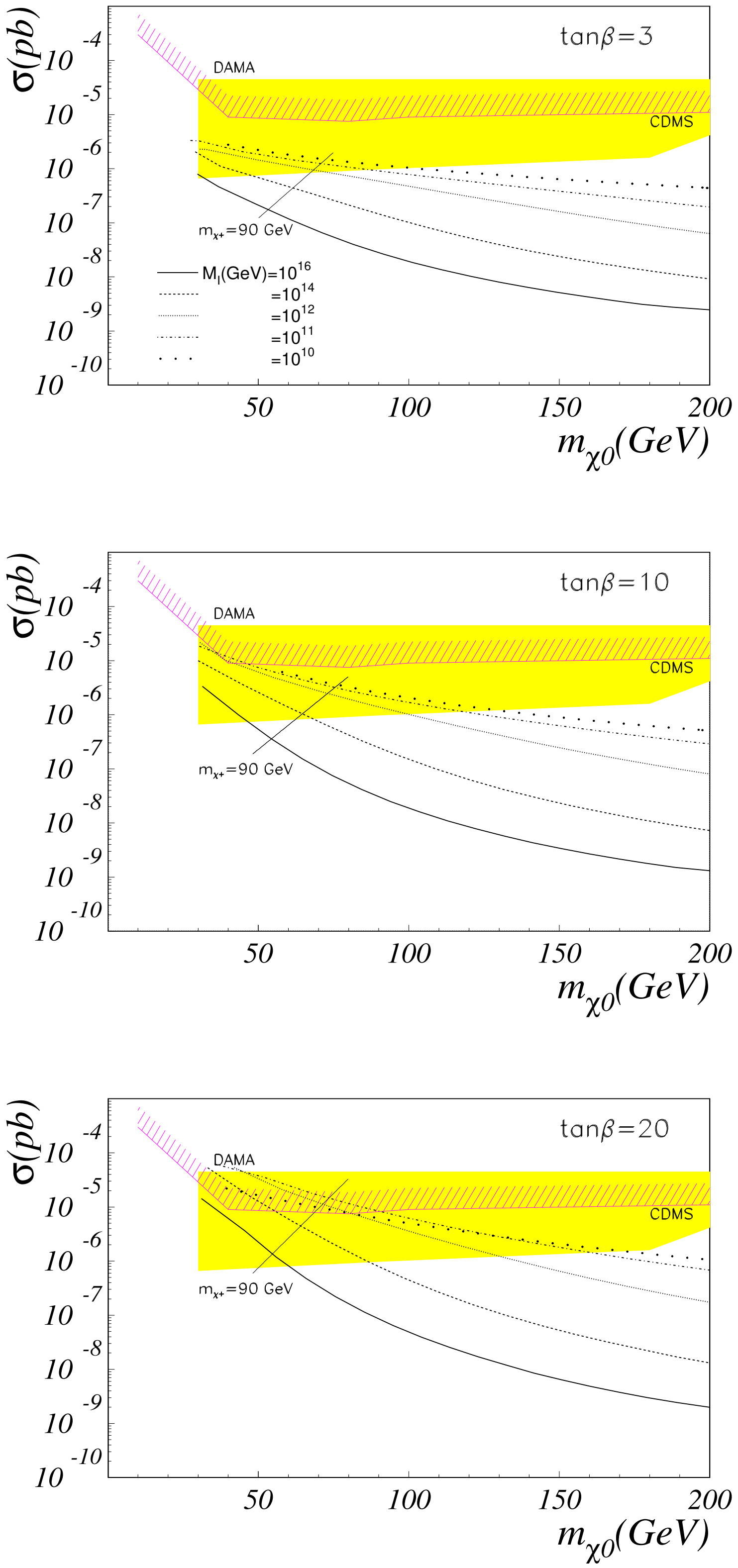
$$\mu^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2$$

and therefore the larger the Higgsino components of the lightest neutralino become





Gaugino-Higgsino components-squared N_{1i}^2 of the lightest neutralino as a function of its mass, for the case $\tan\beta = 10$. Scattering channels through Higgs exchange are now important.



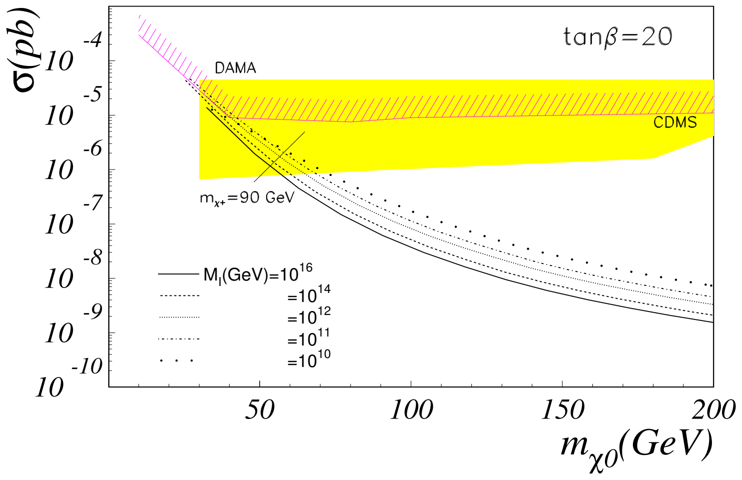
Cross section as a function of the neutralino mass. Current experimental limits, DAMA and CDMS, are shown. The region on the left of the line denoted by $m_{\tilde{\chi}_1^{\pm}} = 90$ GeV is excluded.

For instance, when $m_{\tilde{\chi}_1^0} = 100$ GeV, $\sigma_{\tilde{\chi}_1^0-p}$ for $M_I = 10^{11}$ GeV is two orders of magnitude larger than for M_{GUT}.

In particular, for $\tan\beta = 3$, one finds $\sigma_{\tilde{\chi}_1^0-p} < 10^{-6}$ pb if the initial scale is $M_I = 10^{16}$ GeV. However $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-6}$ GeV is possible if M_I decreases. For $M_I \lesssim 10^{12}$ GeV, taking into account the experimental lower bound on the lightest chargino mass $m_{\tilde{\chi}_1^\pm} = 90$, the range 70 GeV $\lesssim m_{\tilde{\chi}_1^0} \lesssim$ 100 GeV is even consistent with the DAMA limits.

For $\tan\beta = 10$ we see that the range 60 GeV $\lesssim m_{\tilde{\chi}_1^0} \lesssim$ 130 GeV is now consistent with DAMA limits. This corresponds to $M_I \lesssim 10^{14}$ GeV.

Finally, we show the case $\tan\beta = 20$. Then the above range increases 50 GeV $\lesssim m_{\tilde{\chi}_1^0} \lesssim$ 170 GeV, corresponding now to $M_I \lesssim 10^{16}$ GeV.



Cross section as a function of the neutralino mass in the case of gauge coupling unification at M_I. Current experimental limits, DAMA and CDMS, are shown. The region on the left of the line denoted by $m_{\tilde{\chi}_1^{\pm}} = 90$ GeV is excluded.

Again the cross section increases when M_I decreases. However, this increment is less important than in the previous case.

Only with $\tan\beta \gtrsim 20$ we obtain regions consistent with DAMA limits

CONCLUSIONS

There is **now** a large amount of experimental efforts in order to obtain a direct detection of dark matter

Not only CDMS and DAMA but also:

- UKDMC
- Heidelberg-Moscow
- DAMA 250 kg (projected)
- CDMS Soudan (projected)
- GENIUS (projected)
- . . .

And may be, as a by-product, supersymmetry (recall that LHC will not work until 2005)

We have noted that the neutralino-nucleon cross section in the MSSM is quite sensitive to the value of the initial scale for the running of the soft breaking terms

$$\downarrow$$

The smaller the scale is, the larger the cross section becomes

- Taking $M_I \approx 10^{10-12}$ GeV rather than $M_{GUT} \approx 10^{16}$ GeV we find that the cross section is compatible with the sensitivity of current dark matter experiments $\sigma_{\tilde{\chi}_1^0-p} \approx 10^{-6}$–$10^{-5}$ pb, for $\tan\beta \gtrsim 3$

- For larger values of the initial scale, as e.g. $M_I = 10^{14}$ GeV, the compatibility is obtained for $\tan\beta \gtrsim 10$