DARK MATTER DETECTION

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OUTLINE

1. INTRODUCTION TO DARK MATTER

   - The problem of flat rotation curves in Galaxies
   - Solution: dark matter
     (*another solution: non-Newtonian gravity ?*)
   - Dark matter candidates
   - The relic density
     $\Rightarrow$ best candidates are WIMPs (neutralinos)

2. DETECTION

   - Elastic scattering with nuclei in a material
     (*another possibility: indirect detection*)
   - 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 equation of motion

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

$$\Downarrow$$

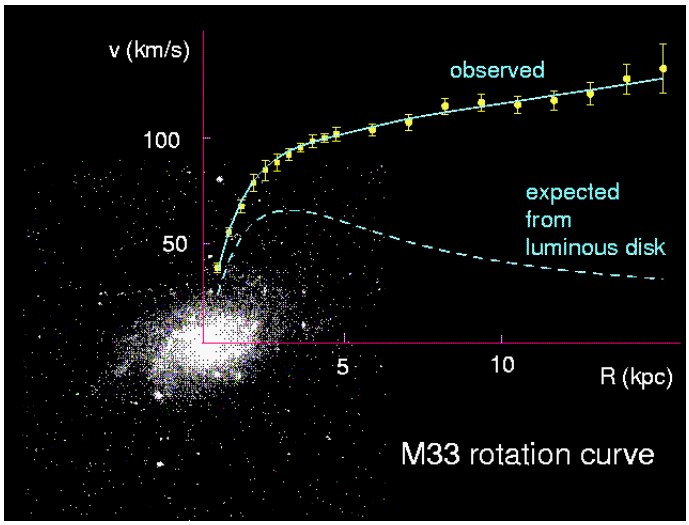
$$v_{\text{rot}} = \sqrt{\frac{G\ M(r)}{r}}$$

- r is the distance from the center of the Galaxy
- $M(r)$ is the mass enclosed within this distance

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

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

♣ However, astronomers observe $v_{\text{rot}} = constant$



Observed rotation curve of the nearby dwarf spiral galaxy M33, superimposed on its optical image (Roy, 2000 using data from Corbelli,Salucci, 1999)

- 1 pc=3.26 light years

♣ v_{rot} rises towards a constant value, beyond the visible disk

♣ This has been observed for about a thousand Galaxies, including the Milky Way

SOLUTION

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

Zwicky, 1933

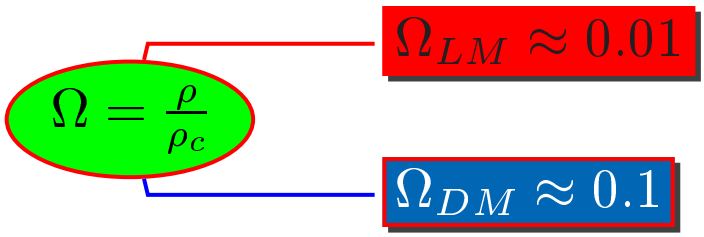
Dark Matter

(it has gravitational interaction but no electromagnetic interaction)

$$M(r) \propto r \;\Rightarrow\; v_{\text{rot}} = \sqrt{\frac{G\ M(r)}{r}} = constant$$

- This hypothesis is not so odd if we remember that the existence of Neptune was suggested on the basis of the irregular motion of Uranus

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



- ρ is the density averaged over the Universe

- $\rho_c = 3H_0^2/8\pi G = 1.88\ h^2 \times 10^{-29}\ g/cm^3$
  $= 10^{-5} h^2\ GeV/cm^3$; $h \approx 0.7$

♣ New evidence from large scale ($\sim$ Mpc) measurements, as e.g. the motions of cluster member Galaxies, fauvored

$$\boxed{\Omega_{DM} \lesssim 0.5}$$

♣ As often remarked, this would lead to another Copernican revolution:

we are not the center of the Universe

+

we are not made of what most of the Universe is made of

ANOTHER SOLUTION

Inspired by the fact that the precession of the perihelion of Mercury yielded the revision of Newtonian gravity and its replacement by General Relativity, a small number of authors suggested the modification of Newton's law at large scales

Classical Theory

- $V \to -r^{-1/2}$ Finzi, 63
- $V \to \ln r$ Bekenstein, Milgrom, 84
- $V = -\frac{GM}{r}(1 + \alpha\ e^{-r})$ Sanders, 86

Relativistic Theory

Higher-derivative gravity

- $S = -\beta \int dx^4 \sqrt{-g}\; C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma}$

  $= -2\beta \int dx^4 \sqrt{-g}\; \left(R_{\mu\nu} R^{\mu\nu} - \frac{1}{3} R^2\right)$

  $\Rightarrow V = -\frac{GM}{r} + \gamma r + \ldots$

Mannheim, Kazanas, 89

- $S = -\int dx^4 \sqrt{-g}\; \left(\frac{1}{2k^2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu}\right)$

  $\Rightarrow V = -GM[\, \frac{1}{r} + \frac{1}{3}\left(\frac{\cos \mu r}{r} + y\, \frac{\sin \mu r}{r}\right)]$

Kenmoku, Kitajima, Okamoto, Shigemoto, 92

Gravity with cosmological constant

- $V = -\left(\frac{GM}{r} + \Lambda r^2\right)$

Whitehouse, Kraniotis, 99

5 dimensional gravity inspired in strings (D-branes)

- $V = -\frac{GM}{r} + f(r) \ln r$

Vollick, 2000

These attempts are rather **ad hoc** in general

They require special values of the parameters and special functions to reproduce the flat rotation curves

"If a new theory of gravity is required, it will ultimately be accepted because of its beauty and unifying properties rather than because it eliminates the need for dark matter"

Binney, Tremaine, 87

ZOO OF DARK MATTER CANDIDATES

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

♠ BARYONIC

- Gas
- MAssive Compact Halo Objects (MACHOs)

  Paczynski, 86; Carr, 90; Shaham, Dekel, 79

  brown and white dwarfs, jupiters, neutron stars
- Stellar black-hole remnants

measured abundances of helium, deuterium and lithium in the scenario of big-bang nucleosynthesis

$$\Rightarrow \Omega_{BM} \lesssim 0.04$$

also gravitational lensing for MACHOs
$\Rightarrow 0.01 \approx \Omega_{LM} < \Omega_{BM} < \Omega_{DM} \approx 0.5$

Thus baryons must be components of the dark matter but **more candidates are needed**

♠ NON-BARYONIC

Depending on whether the candidates were relativistic or non relativistic at the time the Galaxies started to form, they can be classified as:

♢ hot

- Light neutrinos

  However, simulations of structure formation are not very successful at reproducing the observed structure of our Universe

  Besides, their masses are too small ($\lesssim$ eV) to account the required Ω_{DM}

♢ cold

There are no presently known particles which could be candidates

However, extensions of the Standard Model predict stable particles

Zel'dovich, 65; Zel'dovich, Okun, Pikelner, 65; Chiu, 66

- Axions

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

- Weakly Interacting Massive Particles (WIMPs)

  - Heavy ($m_\nu \gtrsim$ GeV) fourth-generation neutrino

    Lee, Weinberg, 77
    Hut, 77
    Vysotskii, Dolgov, Zel'dovich, 70

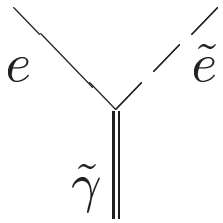
    Why is it stable ?

    Excluded by direct detection experiments

  - Lightest Supersymmetric Particle (LSP)

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

The LSP in the MSSM is stable since e.g.



Usually the LSP is a neutralino

Other possibilities are excluded:

- sneutrino

  Ibañez, 84

  Hagelin, Kane, Raby, 84

  Excluded by direct detection experiments

- slepton

  Unsuccessful searches for exotic heavy isotopes

  $\Rightarrow$ the relic LSP should be electrically neutral (also with no strong interactions), otherwise it will bind to nuclei

These particles would exist as a background density throughout the Universe but would also cluster with stellar matter to form the principal component of the galactic halos

Perhaps it is not a coincidence that
particles which may solve crucial problems in particle physics may also solve the Dark Matter problem

- Axions

  Peccei, Quinn, 77

  which may solve the strong CP problem

- Supersymmetric particles

  Gol'fand, Likhtman, 71

  Volkov, Akulov, 72

  Wess, Zumino, 74

  which may solve:

  the gauge hierarchy problem

  the origin of the Higgs potential

  the unification of the gauge couplings

  the combination of general relativity with QFT (supergravity)

Clearly, the original motivation for Supersymmetry has nothing to do with the Dark Matter problem

However, Supersymmetry give us a natural ($\Omega \approx 1$) Dark Matter candidate

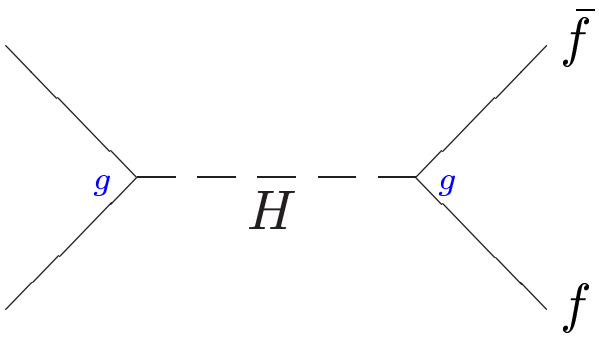
KEY QUESTION: THE RELIC DENSITY

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 $\Omega \approx 1$

OTHER (EXOTIC) CANDIDATES

- Strongly Interacting Massive Particles (SIMPs)

  Dover, Gaisser, Steigman, 79

  Wolfram, 79

  Witten, 84

  e.g. bound state of ordinary quarks and gluons with a heavy stable quark, scalar quark, gluino, or colored technibaryon

- CHArged Massive Particles (CHAMPs)

  De Rújula, Glashow, Sarid, 90

- Self-Interacting Dark Matter (SIDM)

  Spergel, Steinhardt, 2000

  Dark matter is self-interacting with a large scattering cross section but negligible annihilation

- WIMPzillas

  Kolb, Chung, Riotto, 1998

  nonthermal WIMPs with masses in the range 10^{12} to 10^{16} GeV

String inspired candidates

$$SU(3) \times SU(2) \times U(1)_Y \times G_H$$

- Shadow world

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

  "the audience could be living in the middle of a shadow mountain or at the bottom of a shadow ocean"

- Cryptons, which are stable bound states of matter in a hidden sector of string theory

  Ellis, Lopez, Nanopoulos, 90

- Glueballs of the hidden-sector non-Abelian gauge group as candidates for SIDM

  Faraggi, Pospelov, 2000

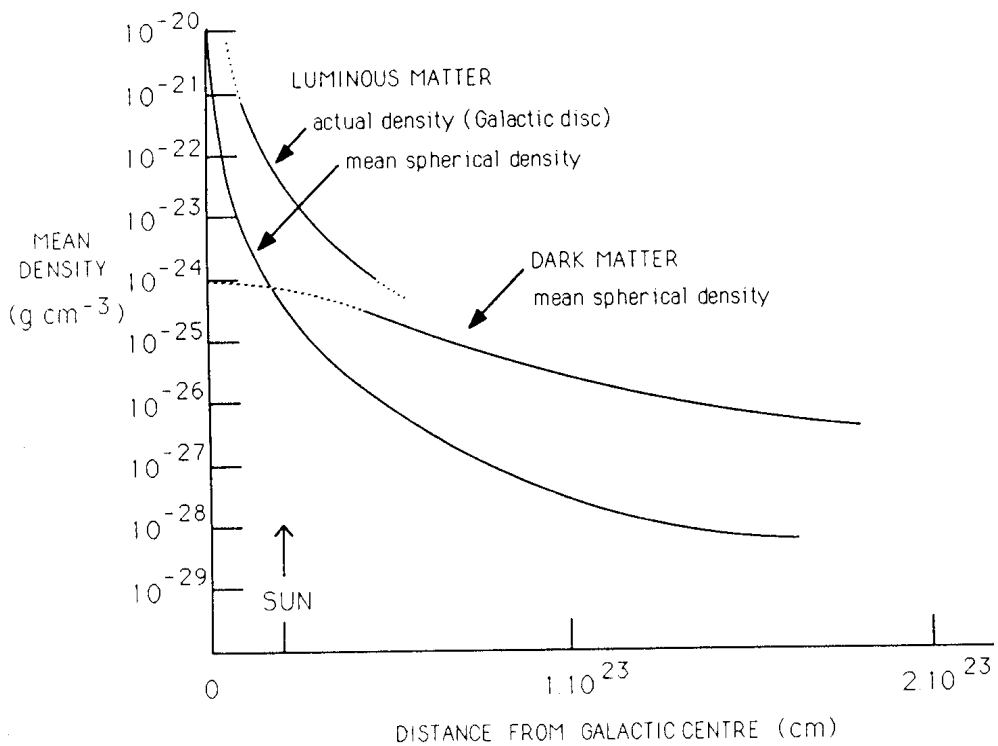
- . . .
- . . .

Many of these candidates are **ephemeral**

DETECTION

Studies of the possibility of dark matter detection began ~ 1982

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



Radial distribution of luminous and dark matter in the Galaxy.

(Smith, Lewin, 1990)

♡ The local mass density necessary to reproduce the flat rotation curve of our Galaxy is

$$\rho_0 \sim 0.3\ GeV/cm^3 = 5 \times 10^{-25}\ gr/cm^3$$

- even taking into account the MACHO observations the most likely density for a non-baryonic dark matter candidate is close to this canonical value

♡ The velocity dispersion of dark matter particles

$$v_0 \sim 220\ km/s$$

This means

$$n_{\mathrm{W}} \approx 0.3\ \frac{GeV}{cm^3}\ \frac{1\ WIMP}{100\ GeV} = \frac{3\ WIMPS}{(10\ cm)^3}$$

$$J_{\mathrm{W}} = n_{\mathrm{W}}\ v_{\mathrm{W}} \approx \frac{3\ WIMPS}{(10\ cm)^3}\ 200 \times 10^5\ cm/s$$

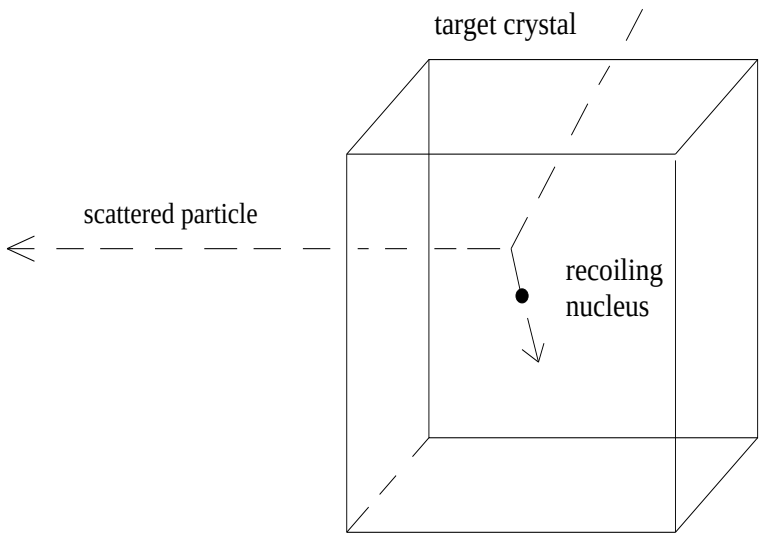
$$= 60000\ \frac{WIMPS}{cm^2\ s}$$

WIMPs have couplings to ordinary particles

⇒ Direct experimental detection through elastic scattering with nuclei in a detector is possible

Goodman, Witten, 85; Wasserman, 86

DIRECT DETECTION



- This technique rules out heavy neutrinos and sneutrinos

- However, the neutralino has cross section considerably smaller

$$\boxed{\sigma_{\text{ neutralino-nucleon}} \lesssim 10^{-5}\ pb = 10^{-41}\ cm^2}$$

e.g mean free path:

$$l = \frac{1}{n_{\text{ earth}}\ \sigma_{\text{ neutralino-nucleus}}} \approx \frac{1}{10^{22}\ \frac{nuclei}{cm^3}\ 10^{-33}\ cm^2}$$

$$= 10^6 \text{ km}$$

INDIRECT DETECTION

- Annihilation of WIMPs accumulated in the Sun and/or Earth due to gravitational effects, produces neutrinos which can be detected in underground detectors, specially through the muons produced by their interactions in the rock

- Annihilation of WIMPs in the Galactic halo can produce anomalous cosmic rays

EXPERIMENTS

$$E_{\mathrm{W}} \approx \frac{1}{2}\,\frac{100GeV}{c^2}\,(200\ km/s)^2 \approx 20\ \text{keV}$$

Thus the experiments must have an extremely good background discrimination

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

- **C**ryogenic **D**ark **M**atter **S**earch collaboration (since 1998)

  The method is basically calorimetric:

  - using a Si detector they observed $\frac{4\ nuclear\ recoils}{0.1\ kg\ 33\ days}$
  - using a Ge detector they observed $\frac{13\ nuclear\ recoils}{10\ kg\ 96\ days}$

They are not due to WIMPs

Using $\rho_{\mathrm{W}} = 0.3\ GeV/cm^3$ and $v_{\mathrm{W}} = 220\ km/s$ they deduce an upper bound for the cross section

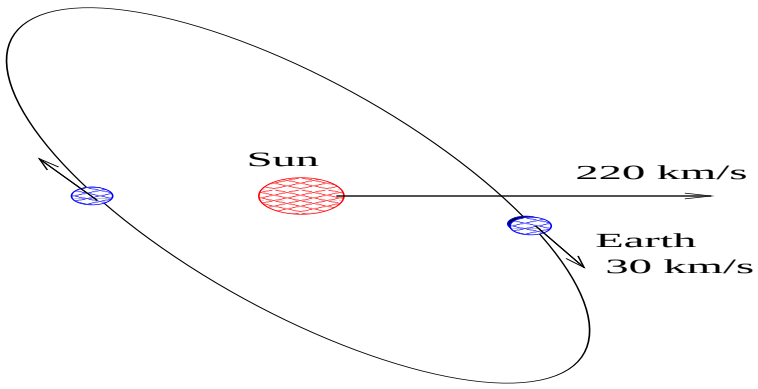
$$\sigma_{\mathrm{W}-p} \lesssim 10^{-5}\ \text{pb}$$

A different method for discriminating a signal from background is **the annual modulation signature**

Druckier, Freese, Spergel, 86; Freese, Frieman, Gould, 88

♣ **DA**rk **MA**tter collaboration (since 1996)

This is due to the Earth's motion around the Sun



the orbital plane inclined at $\gamma = 60^o$ to the galatic one

$$v_{\,\text{Earth}}(t) = v_{\,\text{Sun}} + v_{\,\text{Earth}} \;\; \cos\gamma \;\; \cos\frac{2\pi(t-t_0)}{1year}$$

$t_0 = 2^{nd}$ June

⇓

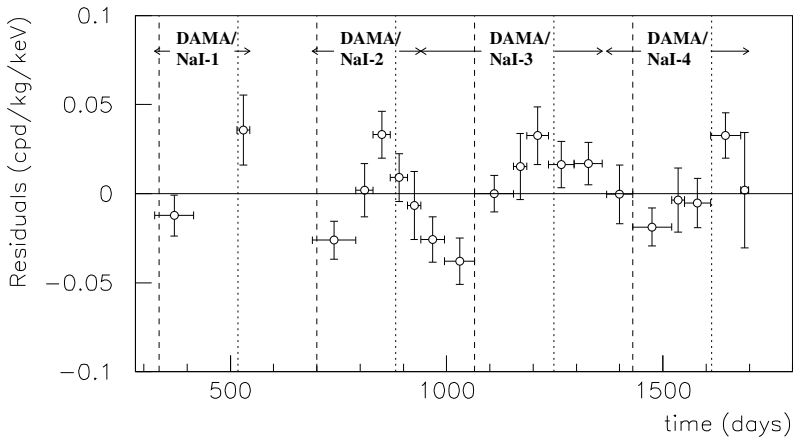
Fluctuation in the dark matter flux

⇓

A rate variation of $\approx 7\%$
between the two extreme conditions

Using nine 9.70 kg NaI crystal scintillators located at the deep underground (Gran Sasso), DAMA collaboration conclude:

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



Model independent residual rate in the particular $(2-6$ keV) cumulative energy interval as a function of the time elapsed since January 1-st of the first year of data taking. The expected behaviour of a WIMP signal is a cosine function with a minimum (maximum) roughly at the dashed (dotted) vertical lines

Taking into account uncertainties as e.g. in 170 km/s $\leq v_{\mathrm{W}} \leq$ 270 km/s or possible bulk halo rotation, one obtains a region allowed for the cross section in the range

$$\sigma_{\mathrm{W}-p} \approx 10^{-6} - 10^{-5}\ pb$$

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

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

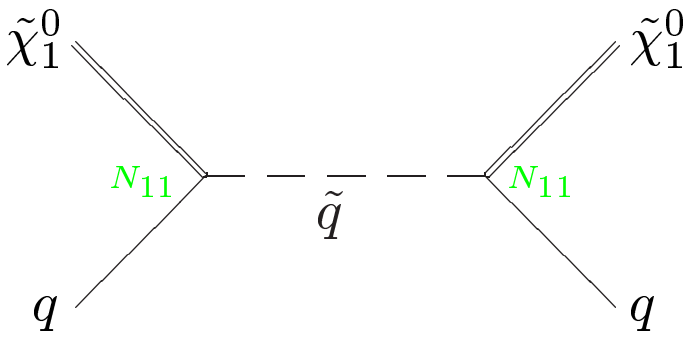
where $\psi^0 = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$

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

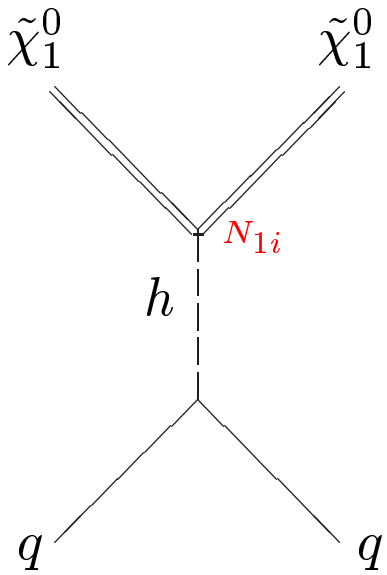
This implies that the lightest mass eigenstate (lightest neutralino) is

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

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



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



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

$$i = 3, 4$$

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

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 $N_{11} \approx 1$

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

RECENT ANALYSES:

Ellis, Ferstl, Olive, 2000

Feng, Matchev, Wilczek, 2000

Bottino, Donato, Fornengo, Scopel, 99

Arnowitt, Nath, 99

Accomando, Arnowitt, Dutta, Santoso, 2000

Arnowitt, Dutta, Santoso, 2000

Regions where $\sigma_{\tilde{\chi}_1^0 - p} \approx 10^{-6}$ pb may be reached in the large $\tan\beta$ regime ($\tan\beta \gtrsim 25$) or with non-universal soft scalar masses m_α

Corsetti, Nath, 2000

Regions where $\sigma_{\tilde{\chi}_1^0 - p} \approx 10^{-6}$ pb may be reached with non-universal gaugino masses M_i

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.

SUPERSTRINGS

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

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

- D-brane configurations where the standard model lives, allow these possibilities in type I strings

  Shiu, Tye, 98; Kakushadze, Tye, 99; Antoniadis, Arkani-Hamed, Dimopoulos, Dvali, 98

  Benakli, 99; Burgess, Ibañez, Quevedo, 99

- Similar results can be obtained in type II strings

  Antoniadis, Pioline, 99

- and strongly and weakly coupled heterotic strings

  Benakli, 99

  Benakli, Oz, 2000; Gregori, 2000

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

$$S_4 = -\int \frac{dx^4}{2\pi}\sqrt{-g}\left(\frac{M_I^8}{\lambda_I^2\ M_c^6}\ R\ +\ \frac{1}{4\lambda_I}\ F_{(3)}^2\ +\ ...\right)$$

and comparing this with

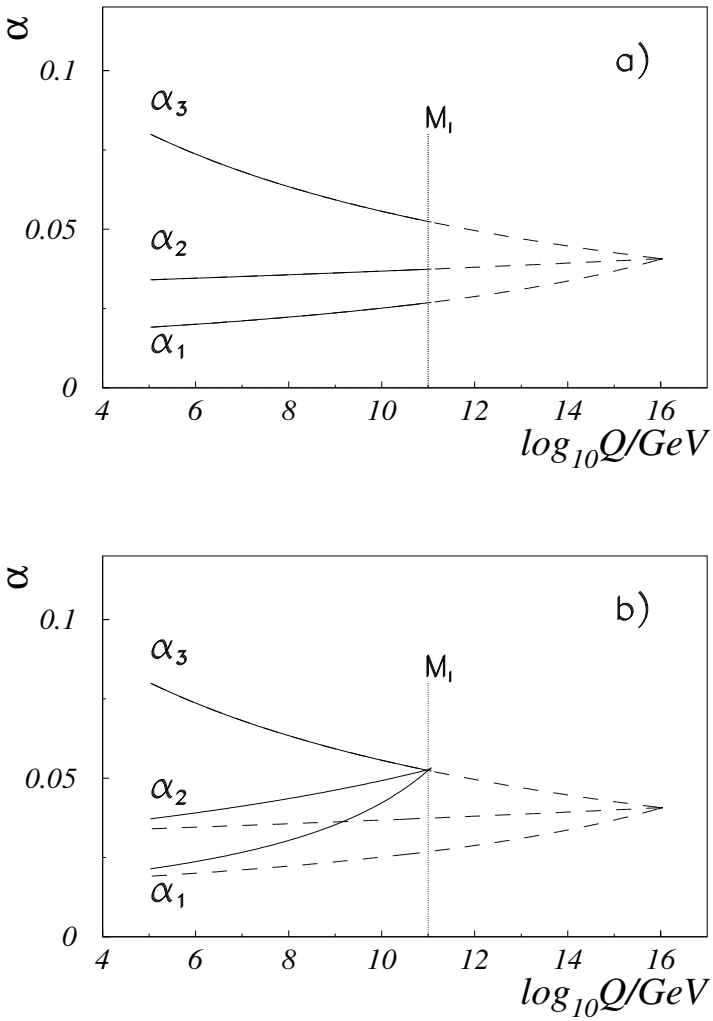
$$S_{\text{SUGRA}} = -\int \frac{dx^4}{2\pi}\sqrt{-g}\left(\frac{M_{\text{Planck}}^2}{16\pi^2}\ R\ +\ \frac{1}{4g^2}\ F^2\ +\ ...\right)$$

the string scale is given by:

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

- α is the gauge coupling
- M_c is the compactification scale

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



Running of the gauge couplings with energy assuming (a) non universality and (b) universality of couplings at the initial scale $M_I = 10^{11}$ GeV. Dashed lines indicate the usual running of the MSSM couplings.

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

  Burgess, Ibañez, Quevedo, 99

  $m_{3/2} \approx \frac{F}{M_{Planck}} \approx M_{Planck}$, since $F \approx M^2_{Planck}$, unless non-perturbative effects produce $F \approx M_W M_{Planck}$.

  However, if the scale of the fundamental theory is $M_I \approx 10^{10-12}$ GeV instead of M_{Planck}, then $F \approx M_I^2$ and one gets $m_{3/2} \approx M_W$

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

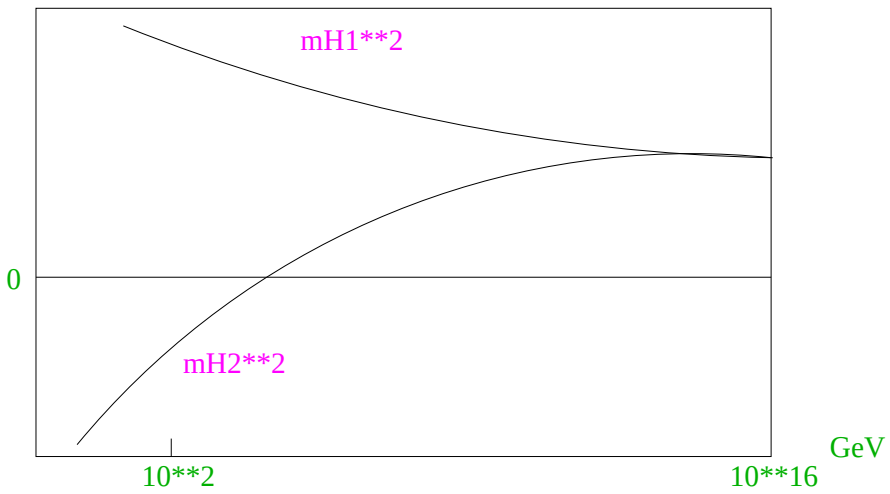
- Several models of chaotic inflation favour also these initial scales

  Kaloper, Linde, 99

INITIAL SCALES AND CROSS SECTIONS

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

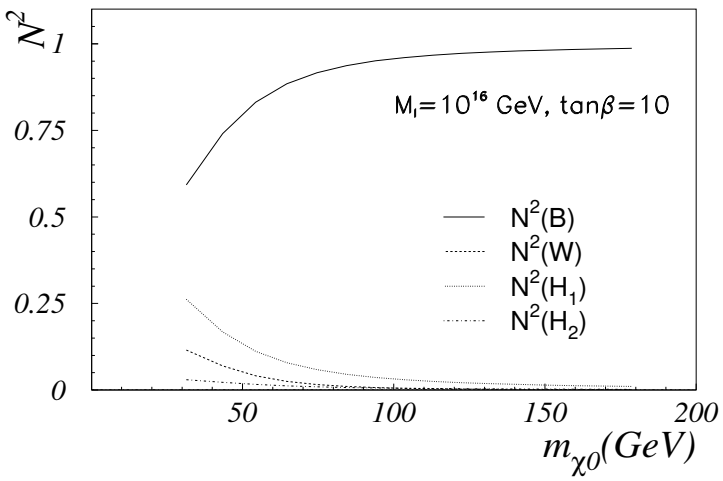
Smaller initial scales, as for example $M_I \approx 10^{11}$ GeV, will imply larger $\sigma_{\tilde{\chi}_1^0-p}$

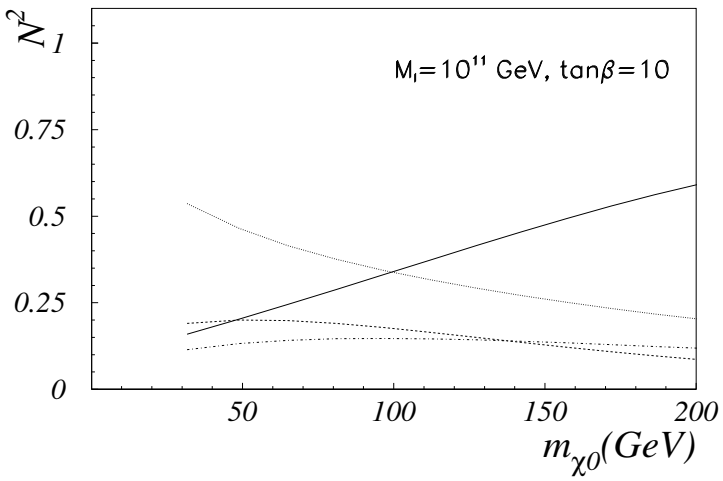


For $\tan\beta$ fixed, the smaller the initial scale for the running is, the smaller the value of μ becomes.

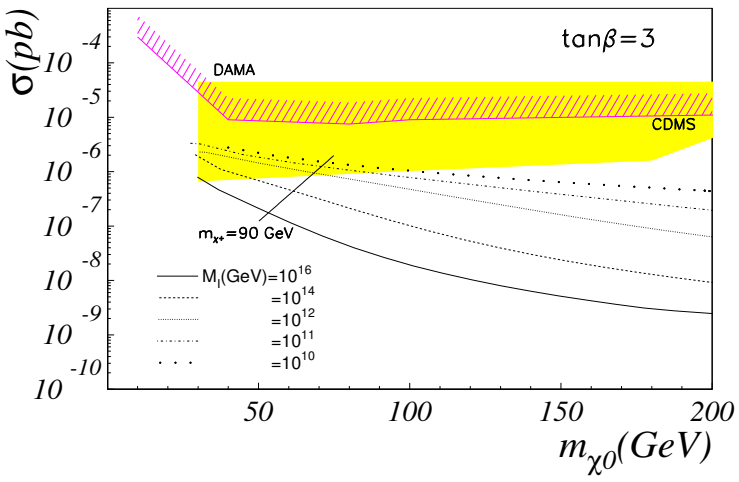
$$\mu^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2$$

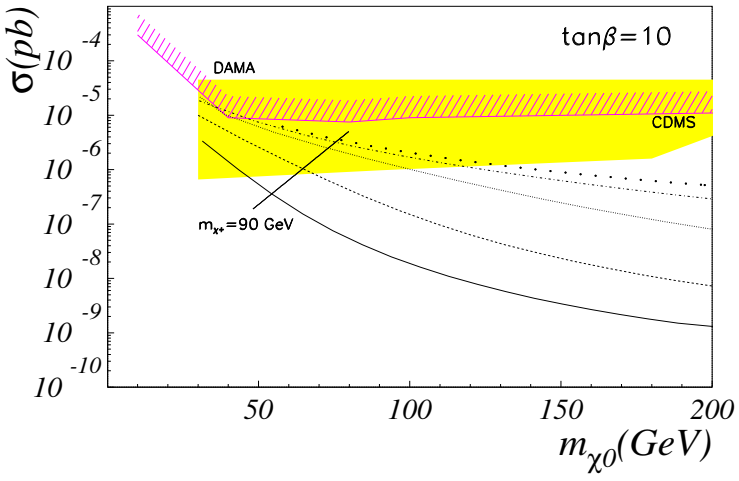
and therefore the larger the Higgsino components of the lightest neutralino become

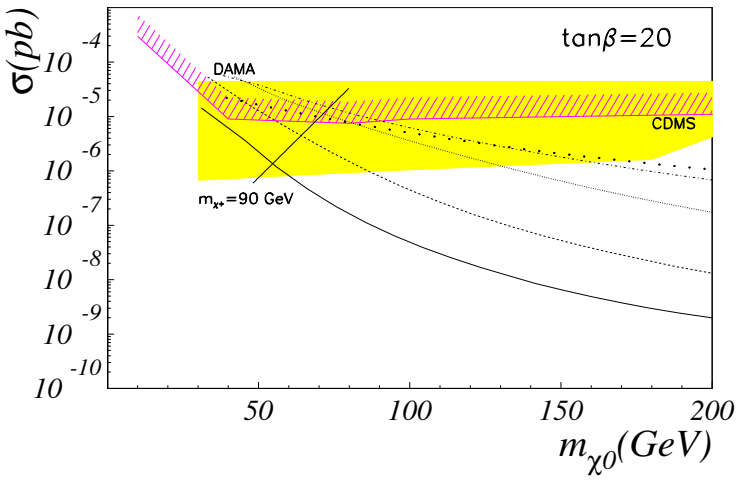




Gaugino-Higgsino components-squared N_{1i}^2 of the lightest neutralino as a function of its mass, for the case $\tan\beta = 10$. Scattering channels through Higgs exchange are now important.







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.

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
- Heidelberg-Genius (projected)
- CDMS Soudan (projected)
- DAMA 250 kg (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

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 $\tan\beta \gtrsim 10$