DARK MATTER

David G. Cerdeño

II. Institut für Theoretische Physik

Universität Hamburg

OUTLINE

- Dark Matter in the Universe
  - Experimental motivation
  - Dark Matter candidates
- Detection of WIMP Dark Matter
  - Direct detection & experiments.
- Supersymmetric dark matter
  - Predictions for neutralino dark matter detection in Supersymmetric Scenarios

MOTIVATION FOR DARK MATTER

- Rotation curves in spiral galaxies
- X-ray emitting gas in elliptic galaxies

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Luminous (visible) matter is insufficient to account for the observed gravitational effects.

Most of the matter in the universe is non-luminous (**DARK MATTER**)

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In terms of the cosmological density parameter:

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

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

  - Flat rotation curves indicate that at least 90% of the matter is **DARK** and contained in a spherical galactic halo.

$$\Omega_{LM} \approx 0.01$$
$$\Omega_{DM} \gtrsim 0.1$$

  - Larger scale analysis favour

$$\Omega_{DM} \approx 0.2 - 0.5$$

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"Astrophysical bound"

$$0.1 \lesssim \Omega_{CDM}\, h^2 \lesssim 0.3$$

Cosmological parameters from CMB

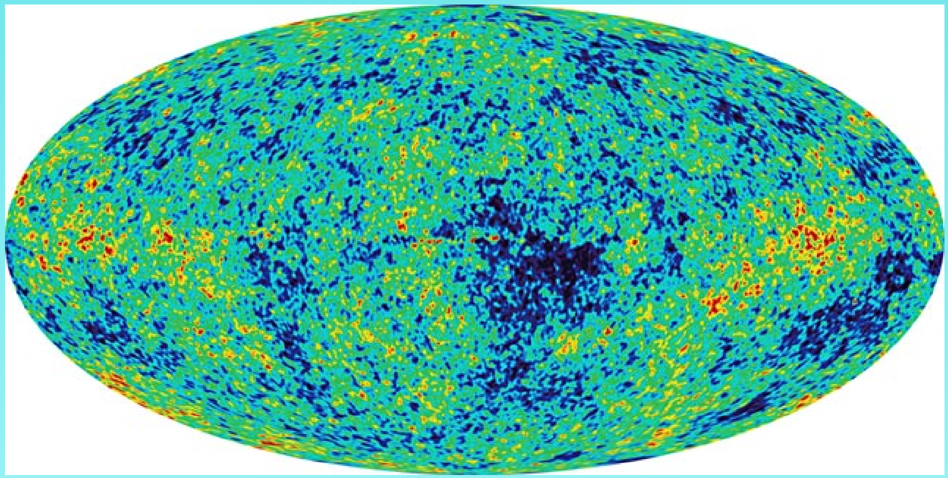
- Observations of the Cosmic Microwave Background constitute a primary tool for determining the global properties of the universe.

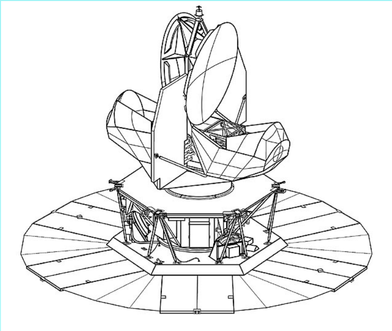
DASI, CBI, VSA,

MAXIMA,

BOOMERanG, COBE,

WMAP, PLANCK, ...





Recently, the WMAP experiment has provided high precision data from which cosmological parameters have been determined.

COSMOLOGICAL PARAMETERS FROM CMB

From the power spectrum, combining WMAP with other experiments the cosmological parameters are extracted.

Ω_{tot}	1.02 ± 0.02
Ω_Λ	0.73 ± 0.04
Ω_m	0.27 ± 0.04
Ω_b	0.044 ± 0.004
h	0.72 ± 0.3
t_0	13.7 ± 0.2 Gyr

Consequences for Dark Matter

- Dark Energy is the major constituent of the Universe.
- Warm dark matter ruled out due to the detection of reionization at early times ($z \sim 20$)
- Cold dark matter contribution within $0.094 < \Omega_{CDM}\, h^2 < 0.113$ (2σ c.l.)

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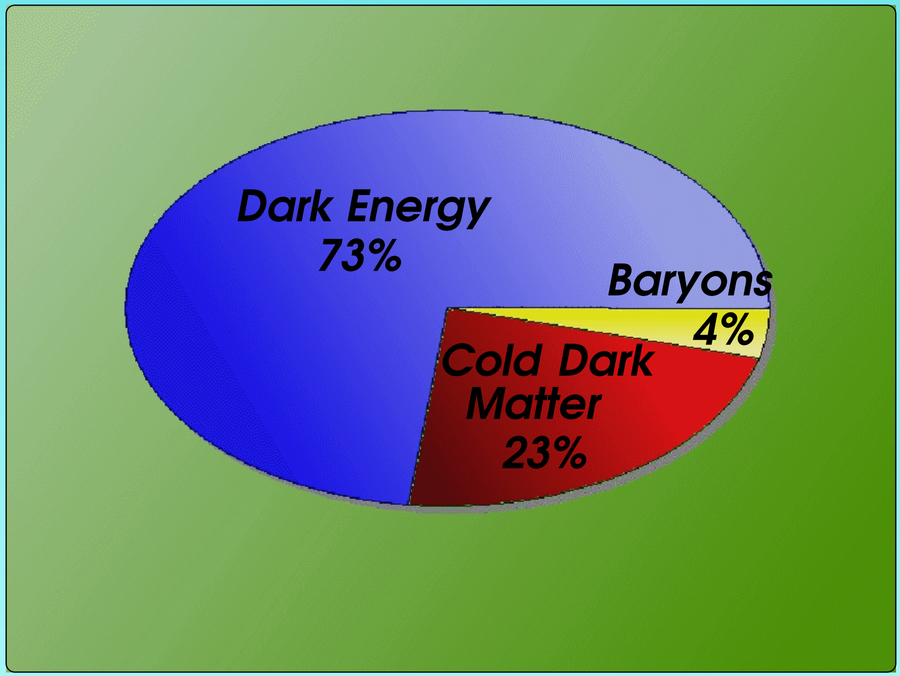

$$0.094 < \Omega_{CDM}\, h^2 < 0.113 \; (2\sigma \text{ c.l.})$$

DARK MATTER CANDIDATES

The nature of dark matter is still to be deciphered

- ♣ Baryonic matter (cold gas, MACHO's, white dwarves...) is not sufficient (inconsistent with BBN)

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- ♣ Non-Baryonic candidates are provided by particle physics:
  - Neutrinos (hot dark matter) constrained by structure formation. $\Omega_\nu \approx \sum_i \frac{m_i/eV}{93\,h^2}$
    Cowsik, McClelland '72; Lee, Weinberg; Dicus, Kolb, Tepliz '77

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  - Axions with a mass of $\sim 10^{-5}$eV.
    Ipser, Sikivie; Stecker, Shafi; Turner, Wilczek, '83

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  - SIMPs, CHAMPs, SIDM, WIMPzillas, Scalar DM, KK...

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EXPERIMENTAL DETECTION OF WIMPS

For already almost $25\mathrm{years}$ the possibility of detecting dark matter has been studied.

- Direct detection (observing the scattering of dark matter in a detector)
    - Detection through elastic scattering
    - Detection through inelastic scattering
- Indirect detection (looking for evidence of dark matter annihilation)

INDIRECT DETECTION

There are promising methods for the indirect detection of a dark halo of WIMPS.

- WIMPs travelling through the Sun or Earth can be slowed down and trapped in their center, where they accumulate. Annihilation of these WIMPs can be detected through the production of energetic neutrinos.

Kamiokande, MACRO, NESTOR, ANTARES, AMANDA(ICECUBE), . . .

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- Annihilation of WIMPs in the galactic halo can give rise to anomalous cosmic rays (positrons, antiprotons, gamma-rays).

PAMELA, AMS, CELESTE, MAGIC, GLAST, . . .

DIRECT DETECTION

If WIMPS are the bulk of dark matter, they would cluster gravitationally with ordinary stars in galactic halos. This raises the hope of their direct detection on Earth experiments.

- From the local properties of our galaxy, the flux of WIMPS is

$$J_{\mathrm{WIMP}} \approx 10^5 \, \frac{\mathrm{particles}}{\mathrm{cm}^2\,\mathrm{s}} \qquad (\text{for } \; m_{WIMP} \approx 100 \text{ GeV})$$

However, the cross-sections are very small and the background (mainly cosmic rays) is large.

DIRECT DETECTION

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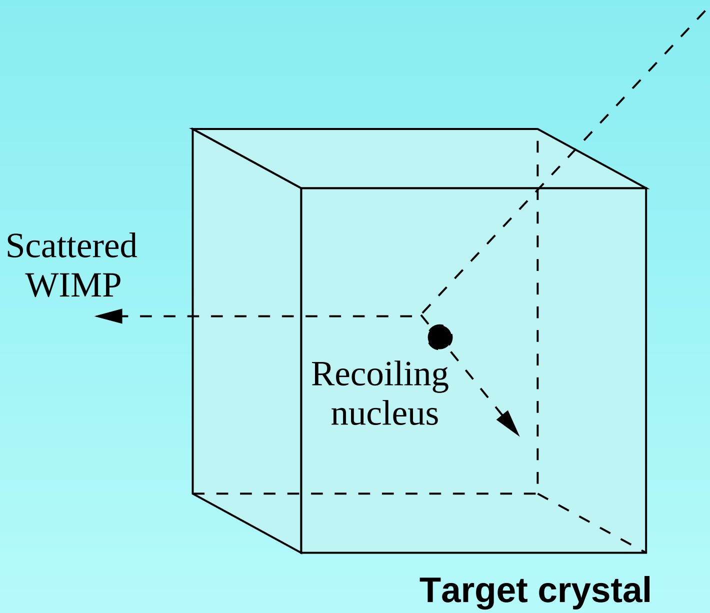
- Detection of WIMPs would be possible through their elastic scattering with nuclei inside a detector.



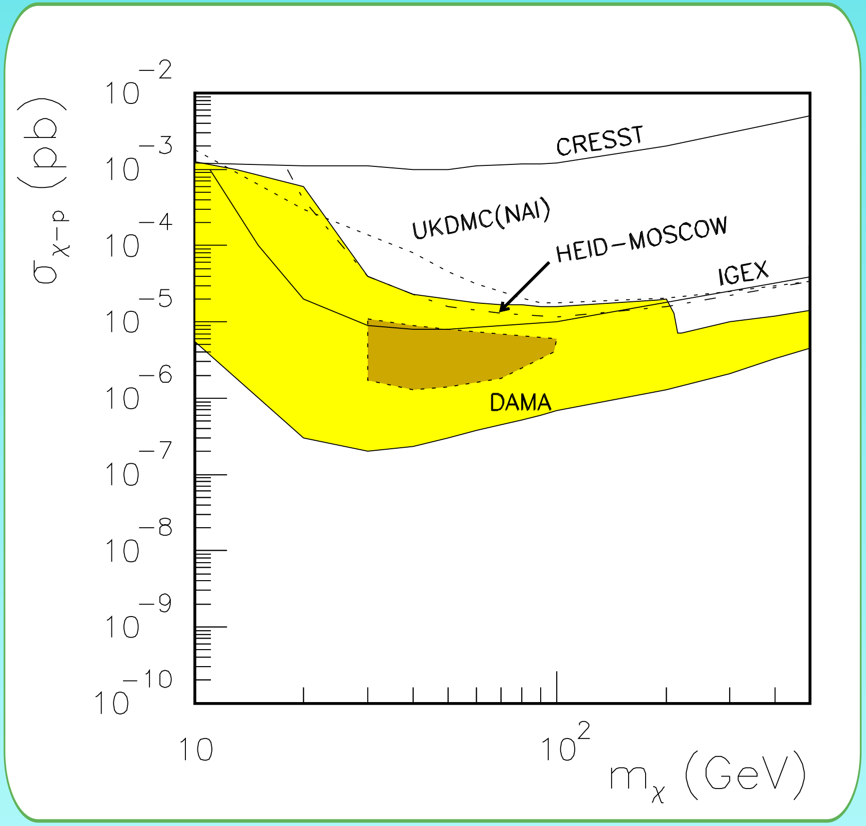
The recoiling energy can be detected by

- Ionization on solids
- Ionization in scintillators (measured by emission of photons)
- Increase in the temperature (measured by the released phonons)

- Ge ionization detectors
  Heidelberg-Moscow, IGEX, ...
- Scintillators
  UKDMC(NAI), DAMA (based on NaI),
- Phonon detection
  CRESST

SENSITIVITY FOR WIMP DETECTION

(spin independent cross-section)



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  CDMS, EDELWEISS, ...

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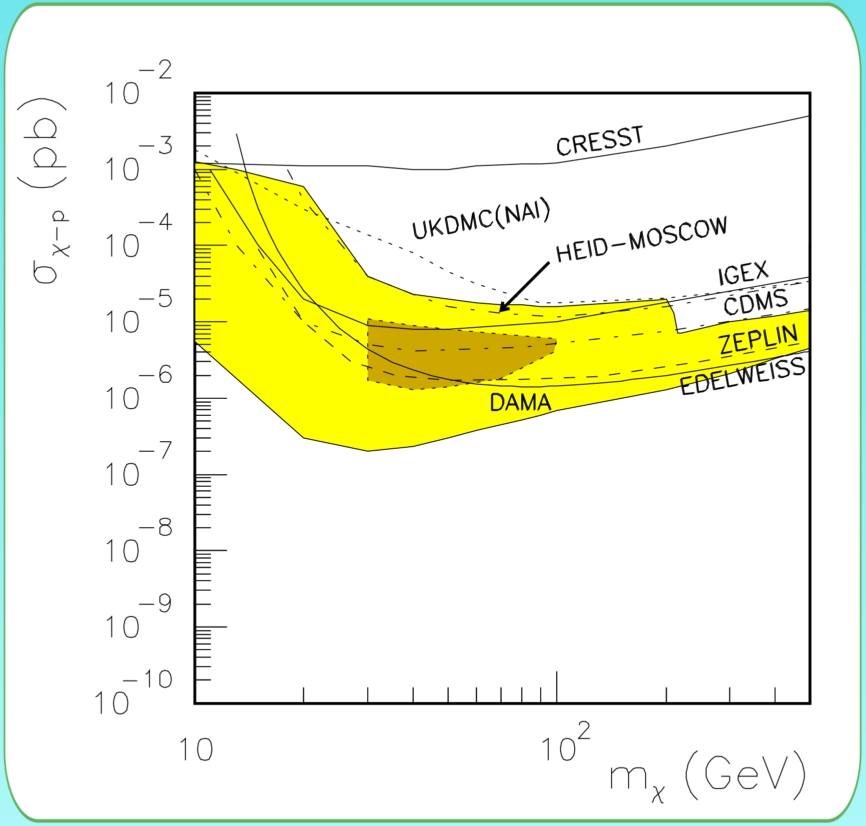

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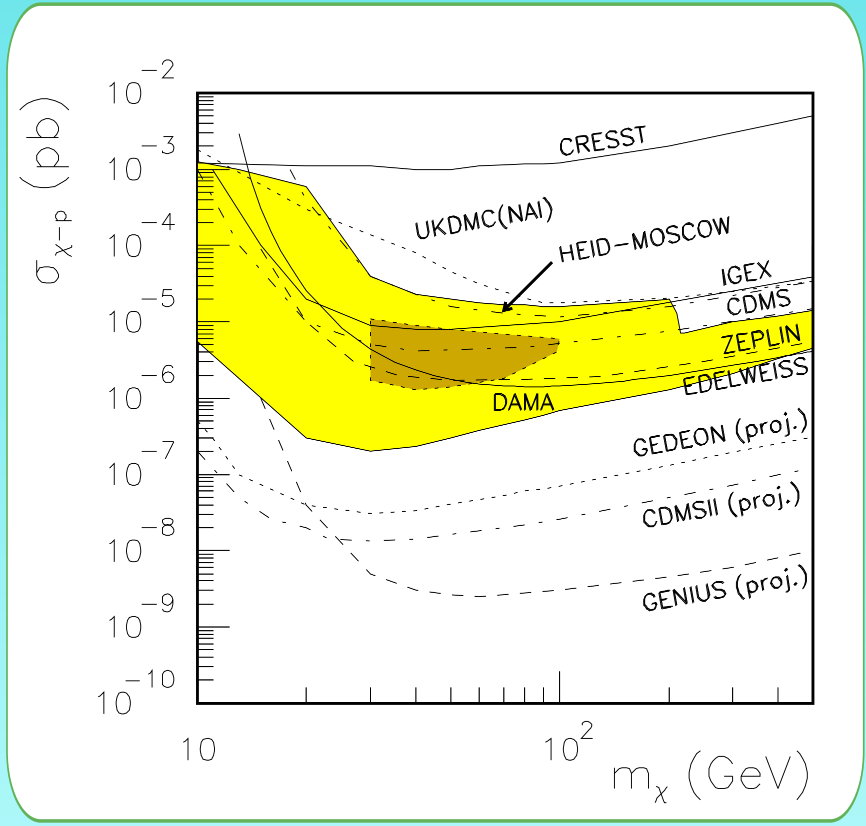

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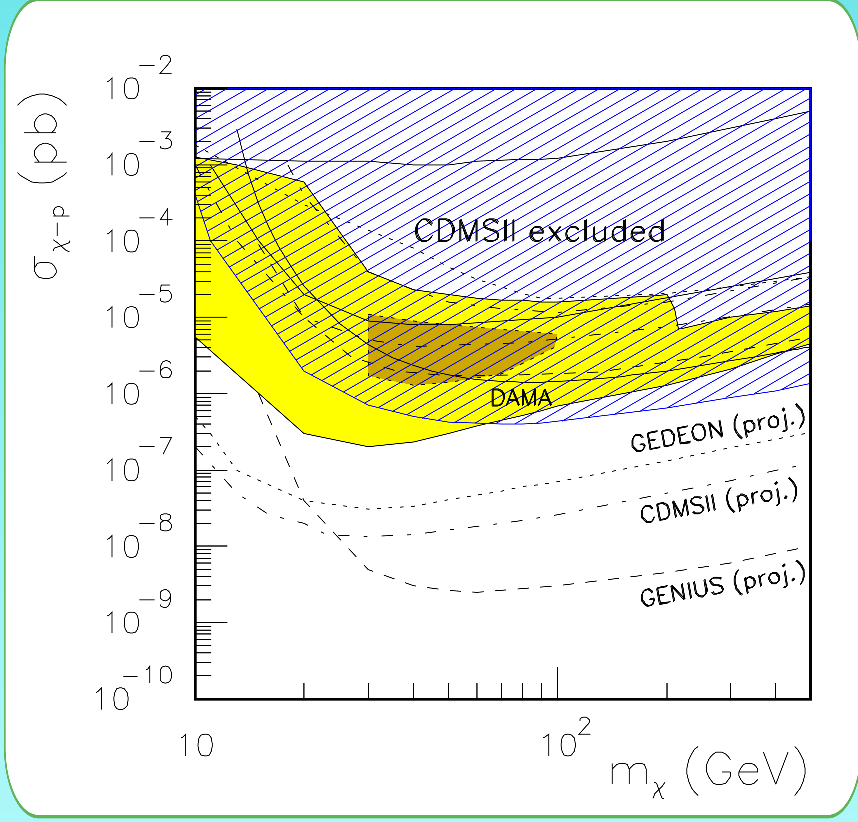

Neutralino Dark Matter

Neutralino dark matter

The neutralinos in the MSSM are physical superpositions of the bino and wino ($\tilde{B}^0$, $\tilde{W}_3^0$) and Higgsinos ($\tilde{H}_d^0$, $\tilde{H}_u^0$).

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

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

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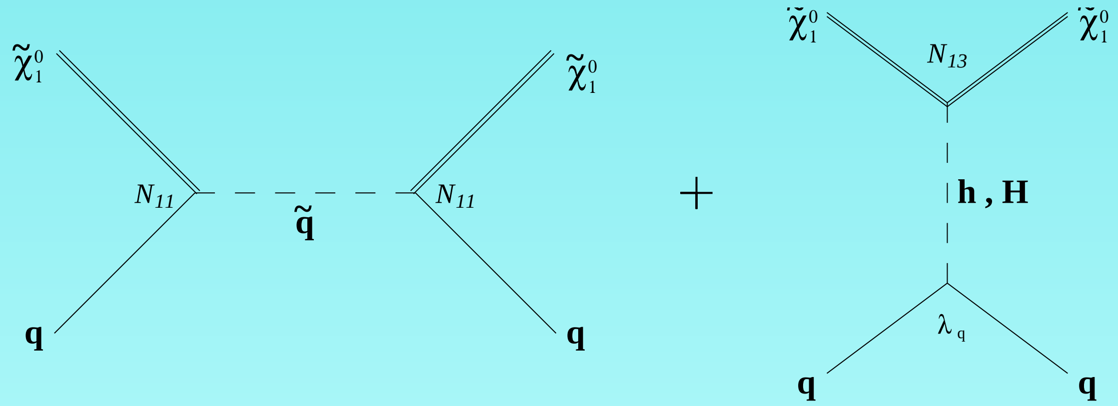
- Evaluate $\sigma_{\tilde{\chi}_1^0 - p}$ (spin-independent part) to determine the feasibility of such a detection



and analyse the compatibility with the sensitivities of detectors.

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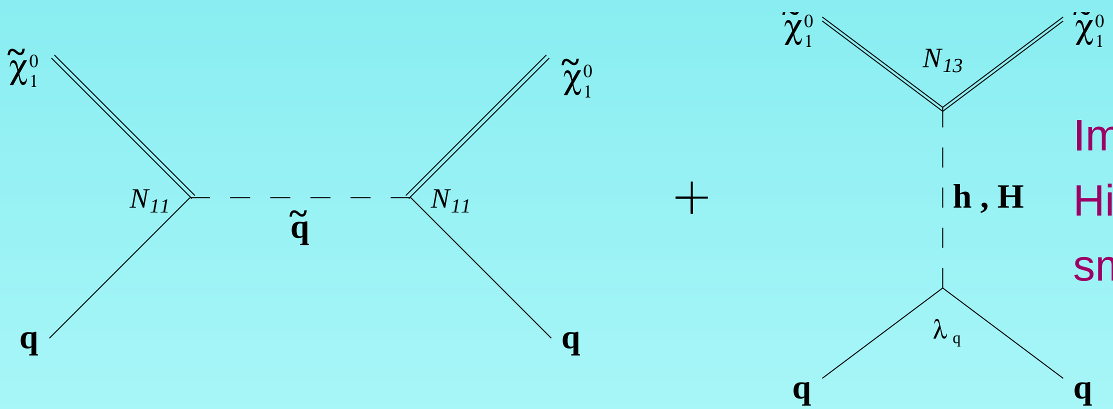
Important for gaugino-like $\tilde{\chi}_1^0$



Important for Higgsino-like $\tilde{\chi}_1^0$ and small Higgs masses

and analyse the compatibility with the sensitivities of detectors.

SPIN VS. SCALAR INTERACTION

The elastic scattering cross section for $\tilde{\chi}_1^0$ with ordinary matter has different components. From the effective lagrangian describing the interaction:

$$\mathcal{L}_{eff} = \alpha_{2i}\, \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\, \bar{q}_i\gamma_{\mu}\gamma^{5}q_i \;+\; \alpha_{3i}\, \bar{\chi}\chi\, \bar{q}_i q_i$$

Spin-dependent interaction

Spin-independent (scalar) interaction

(Goodman, Witten 86)

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Spin-dependent interaction

Spin-independent (scalar) interaction

(Goodman, Witten 86)

$$\frac{\sigma_{spin}}{\sigma_{scalar}} \propto \frac{J(J+1)}{A^2}$$

Typically, the spin-independent contribution is dominant for the scattering with heavy nuclei ($A \gtrsim 20$). Since this is the case in dark matter detectors, we will focus on it.

NEUTRALINO DARK MATTER

Numerous analyses of neutralino-nucleon cross section have been carried out since the mid 80's:

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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
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A.B. Lahanas, D.V. Nanopoulos and V.C. Spanos, 02
E.A. Baltz and P. Gondolo, 02
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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
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H. Baer, C. Balazs, A. Belyaev and J. O'Farril, 03
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Supergravity Scenarios

SUPERGRAVITY SCENARIOS

Working in the framework of SUGRA, several assumptions are made:

- The soft parameters are generated once SUSY is broken through gravitational interactions.

They are given at a high energy scale (e.g., the GUT scale $M_{GUT} \approx 2 \times 10^{16}$ GeV)

$$\begin{aligned} \text{Gaugino masses} &\quad \rightarrow \quad M_a \\ \text{Scalar masses} &\quad \rightarrow \quad m_\alpha \\ \text{Trilinear parameters} &\quad \rightarrow \quad A_{\alpha\beta\gamma} \end{aligned}$$

With these inputs, the RGEs are used to evaluate the low-energy supersymmetric spectrum.

SUPERGRAVITY SCENARIOS

Working in the framework of SUGRA, several assumptions are made:

- The soft parameters are generated once SUSY is broken through gravitational interactions. $M_a,\ m_\alpha,\ A_{\alpha\beta\gamma}$

- Radiative Electroweak Symmetry Breaking is imposed, and as a consequence the Higgsino mass parameter μ is determined by the minimization of the Higgs effective potential. This implies

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

$$\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

EXPERIMENTAL CONSTRAINTS

- Supersymmetric spectrum (LEP, Tevatron): $m_{\tilde{\chi}_1^\pm} > 103$ GeV, $m_{\tilde{g}} > 150$ GeV $m_{\tilde{\tau}} > 87$ GeV, $\ldots$

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Experimental Constraints

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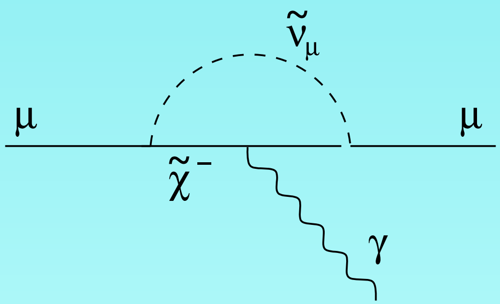
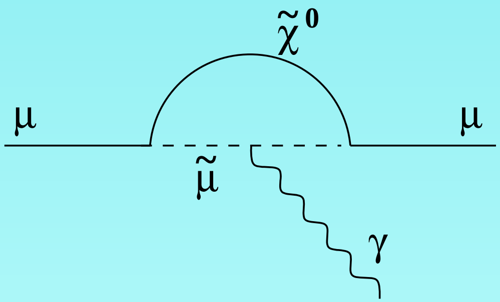
- Muon anomalous magnetic moment (Davier et al.; Hagiwara et al.; Trocóniz, Ynduráin '04):

$7.1 \times 10^{-10} < a_\mu^{\rm SUSY} < 47.1 \times 10^{-10}$ (from e^+e^- data) (Bennett et al. '04)





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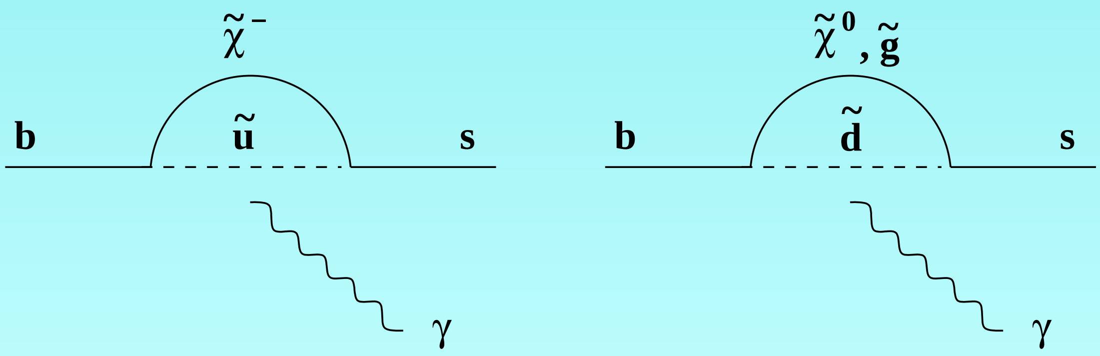

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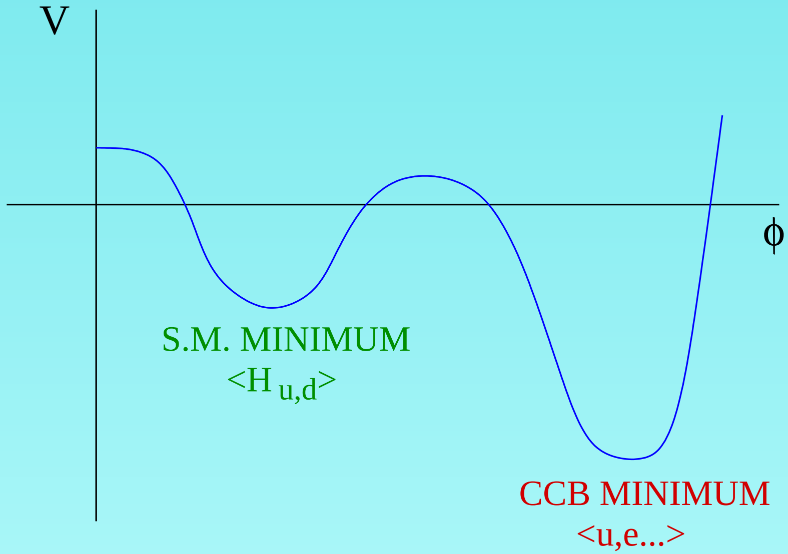
Astrophysical Constraints

- $0.1 \lesssim \Omega_{\tilde{\chi}_1^0} h^2 \lesssim 0.3 \quad (0.094 \lesssim \Omega_{\tilde{\chi}_1^0} h^2 \lesssim 0.129)$

CHARGE AND COLOUR BREAKING CONSTRAINTS

• The presence of scalar fields with Colour and Electric Charge in SUSY theories may induce the appearance of dangerous charge and colour breaking minima (CCB) deeper than the realistic minimum.



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Avoiding these cases leads to constraints on the parameter space, among which the UFB constraints are the most important ones.

The UFB bounds are by far the most restrictive ones. There are three different UFB directions in the field space, labelled as

(Casas, Lleyda, Muñoz ’96)

- UFB-1: involves the scalar fields $\{H_u, H_d\}$
- UFB-2: $\{H_u, H_d, \tilde{\nu}_{L_i}\}$
- UFB-3: $\{H_u, \tilde{\nu}_{L_i}, \tilde{e}_{L_j}, \tilde{e}_{R_j}\}$

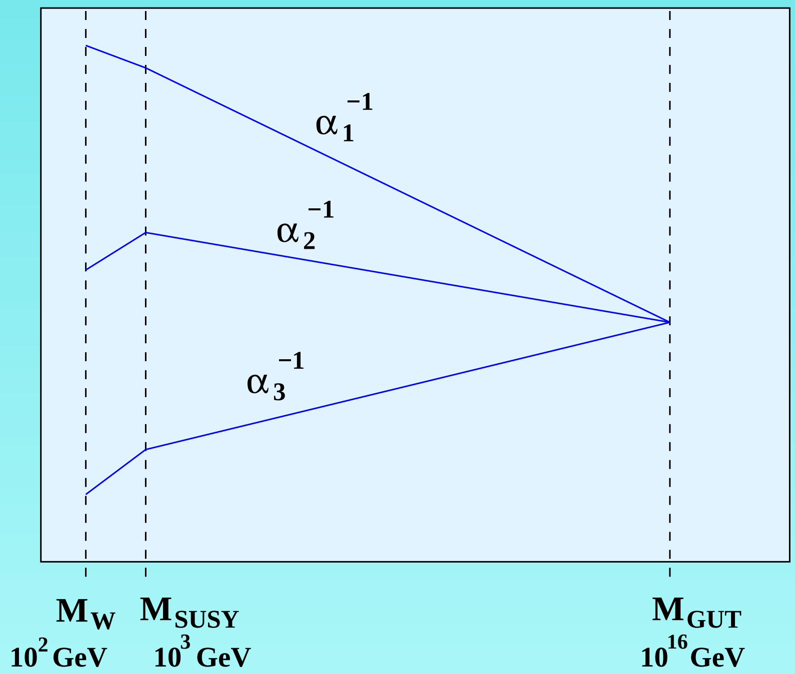
The value of the potential along the UFB-3 direction is given by:

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

Minimal Supergravity

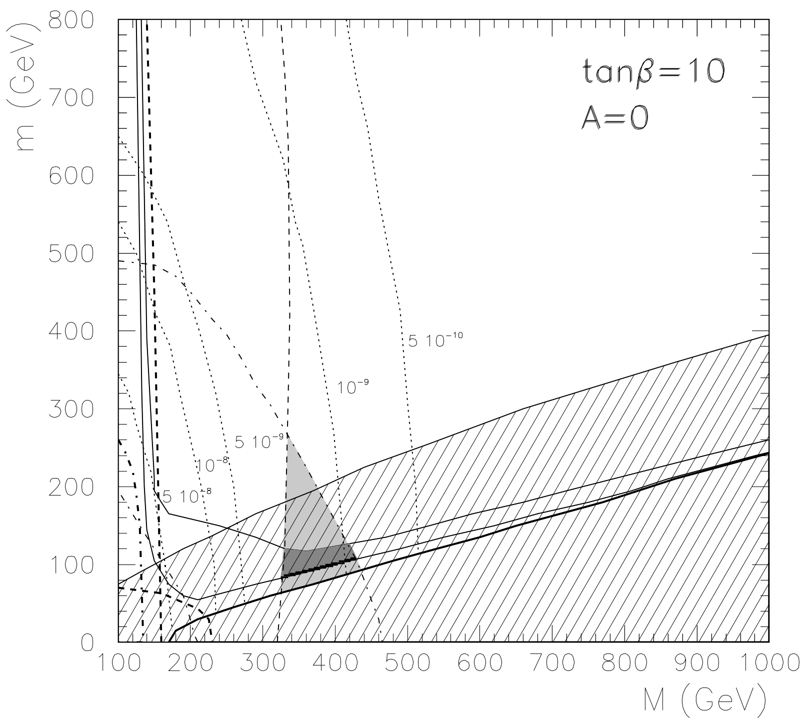
MINIMAL SUPERGRAVITY (MSUGRA)

- Universal soft parameters: M, m, A.
- High energy scale = $M_{GUT} \approx 2 \times 10^{16}$ GeV, with gauge coupling unification



- Five free parameters: M, m, A, $sign(\mu)$, $\tan\beta$

The parameter space is very constrained:



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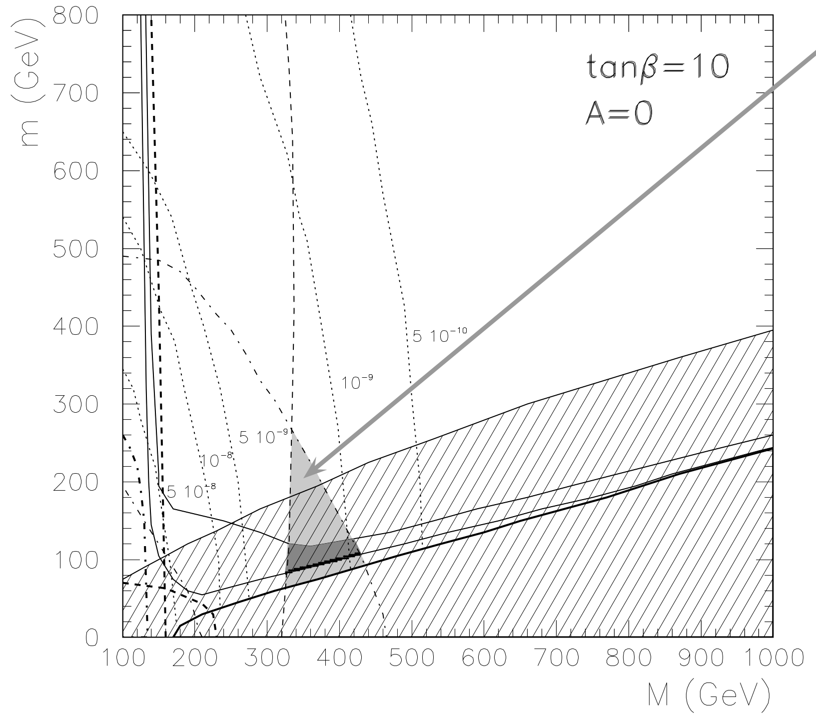
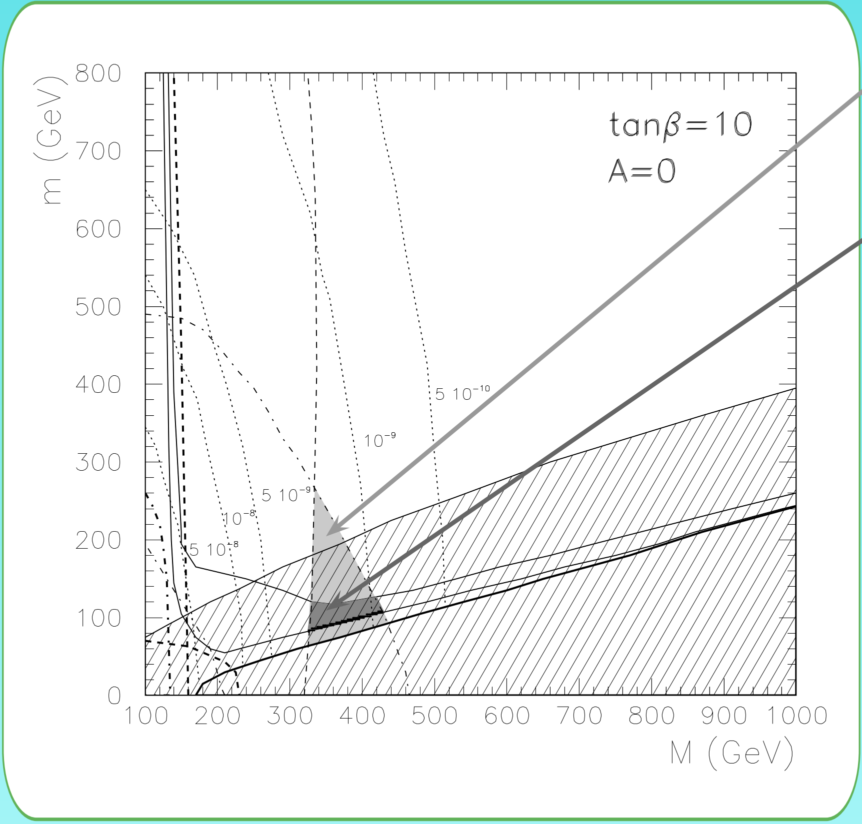


Experimentally accepted

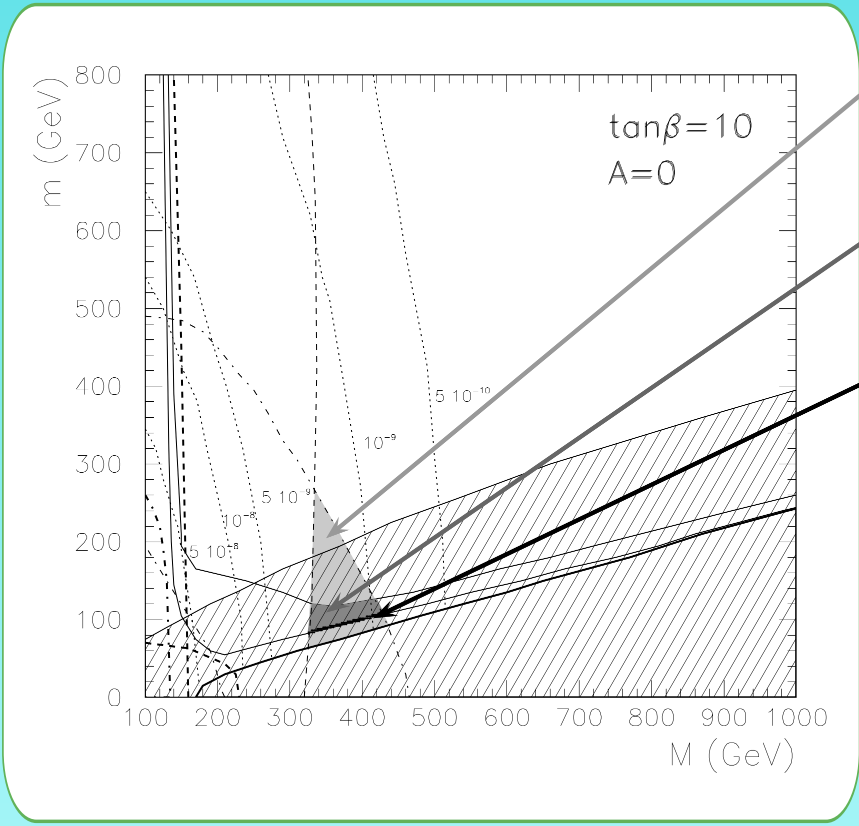
The parameter space is very constrained:



Experimentally accepted

$$0.1 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.3$$

The parameter space is very constrained:



Experimentally accepted

$0.1 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.3$

$0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$

$$\sigma_{\tilde{\chi}_1^0 - p} \approx 10^{-9}\mathrm{pb}$$

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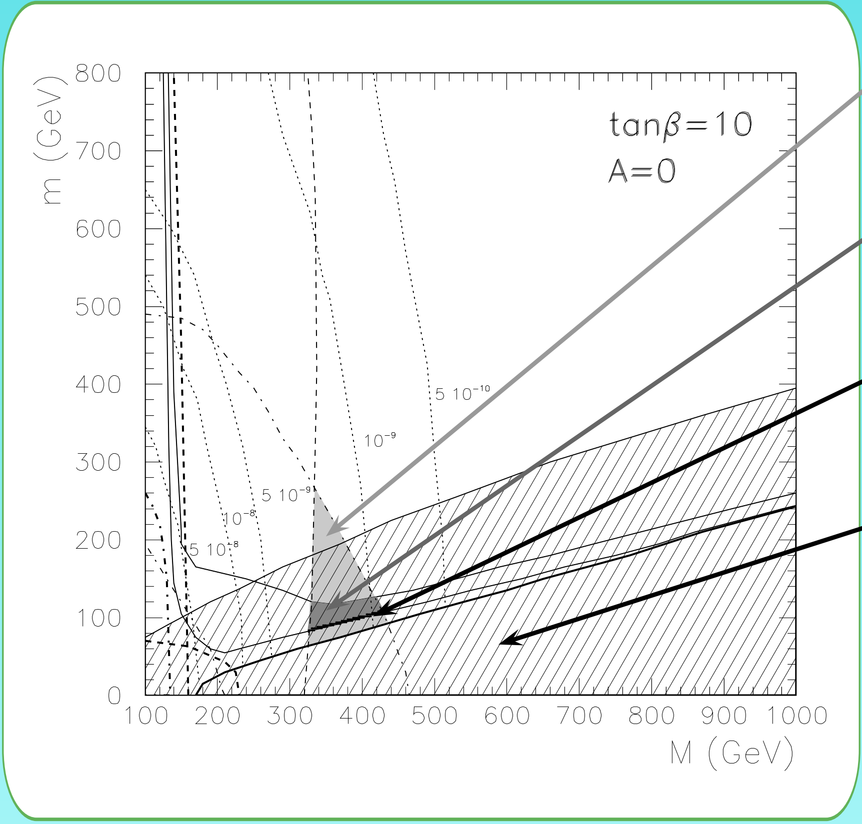

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Excluded by UFB constraints

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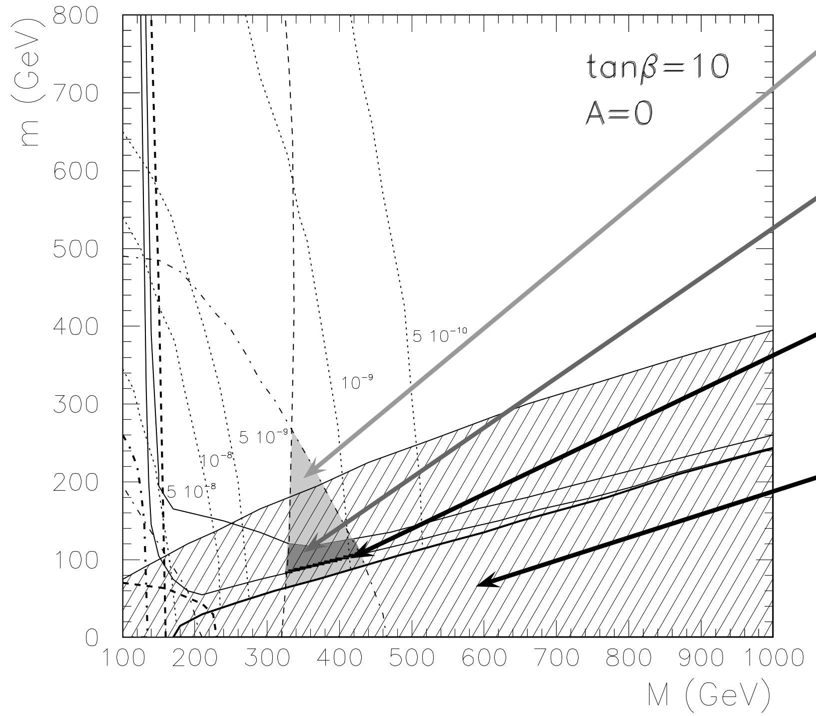

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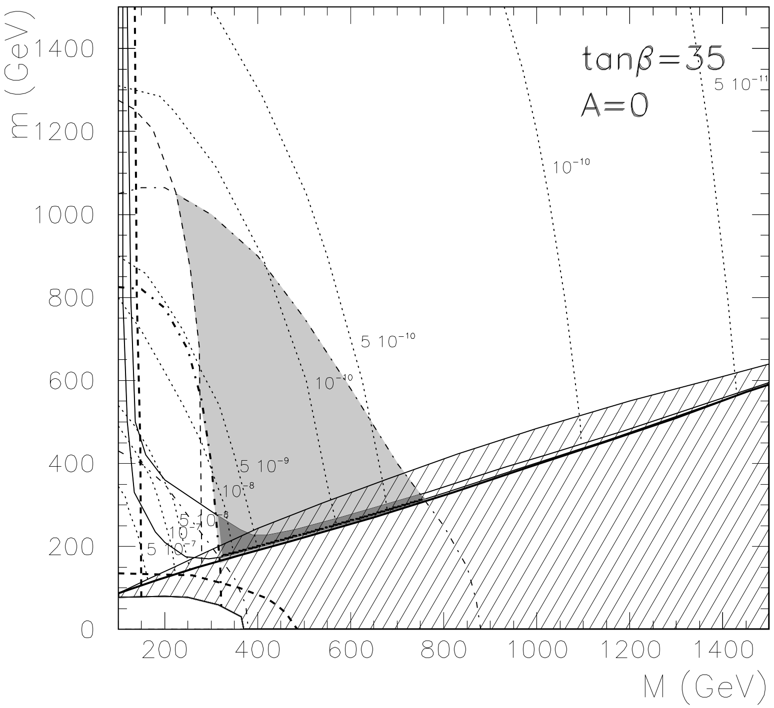
Excluded by UFB constraints

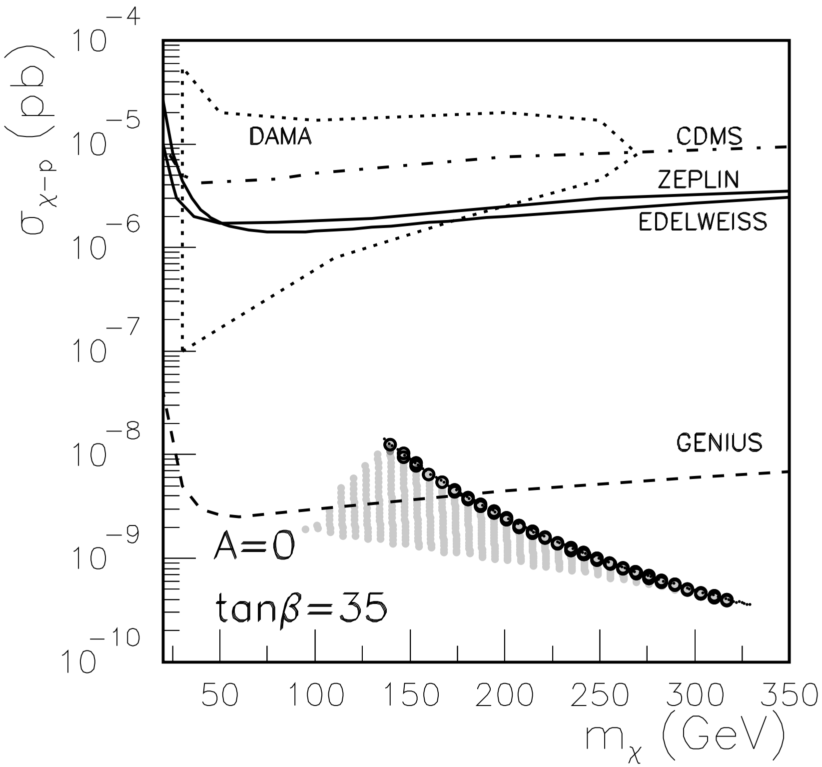
$\tan\beta \lesssim 20$ is excluded for any A

Larger values can also be forbidden for certain A

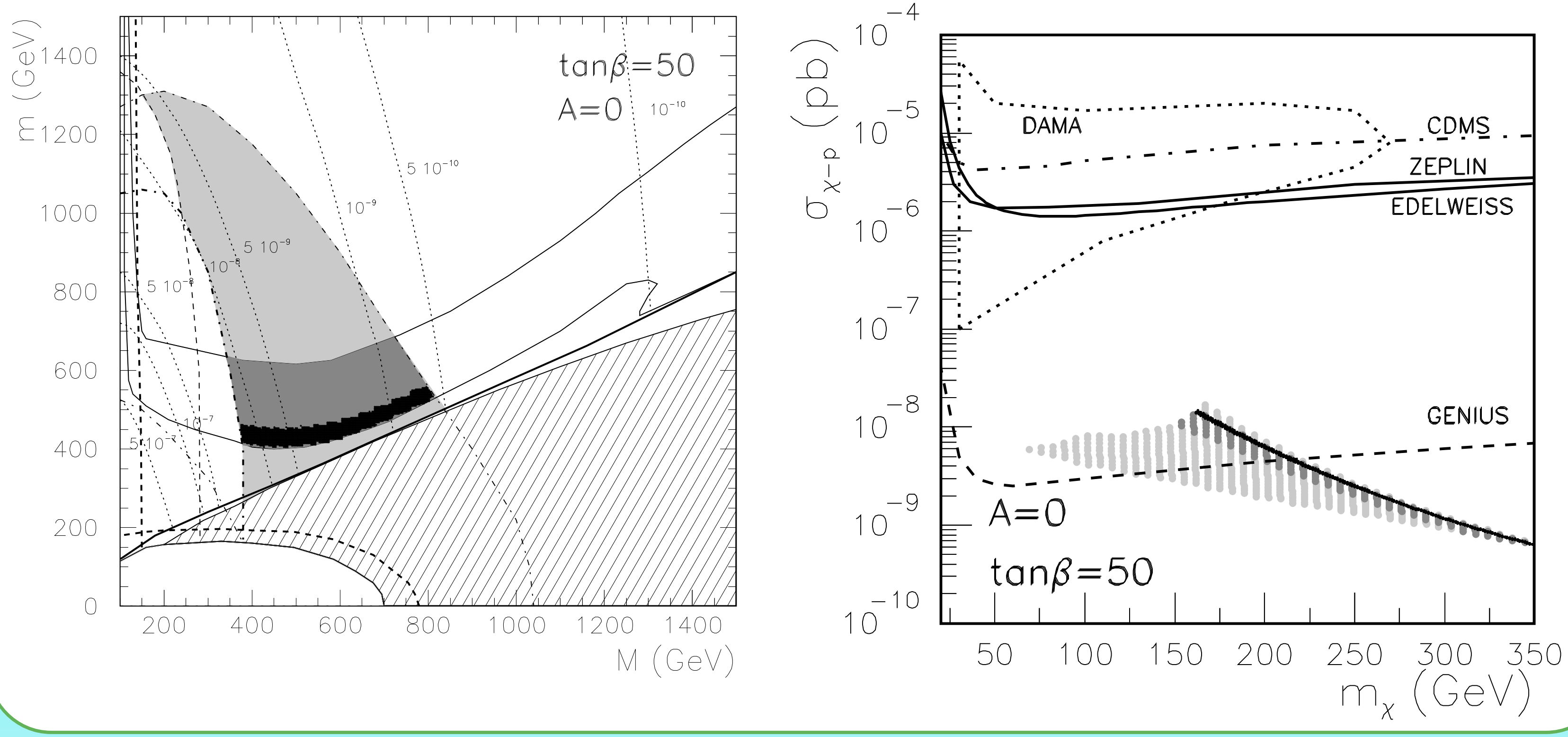
$$\sigma_{\tilde{\chi}_1^0 - p} \approx 10^{-9}\mathrm{pb}$$

Larger values of $\tan\beta$ lead to an increase of $\sigma_{\tilde{\chi}_1^0 - p}$





Larger values of $\tan\beta$ lead to an increase of $\sigma_{\tilde{\chi}_1^0-p}$



$$\sigma_{\tilde{\chi}_1^0-p} \lesssim 3 \times 10^{-8}\mathrm{pb}$$

Departures from the mSUGRA scenario can also lead to an increase in the neutralino-nucleon cross section.

- Intermediate scales

  (Gabrielli, Khalil, Muñoz, Torrente-Lujan '00)

- Non-universal soft parameters

  - Non-universal scalar masses m_α

    (Bottino, Donato, Fornengo, Scopel '99; Arnowitt, Nath '99; Accomando, Arnowitt, Dutta, Santoso '00)

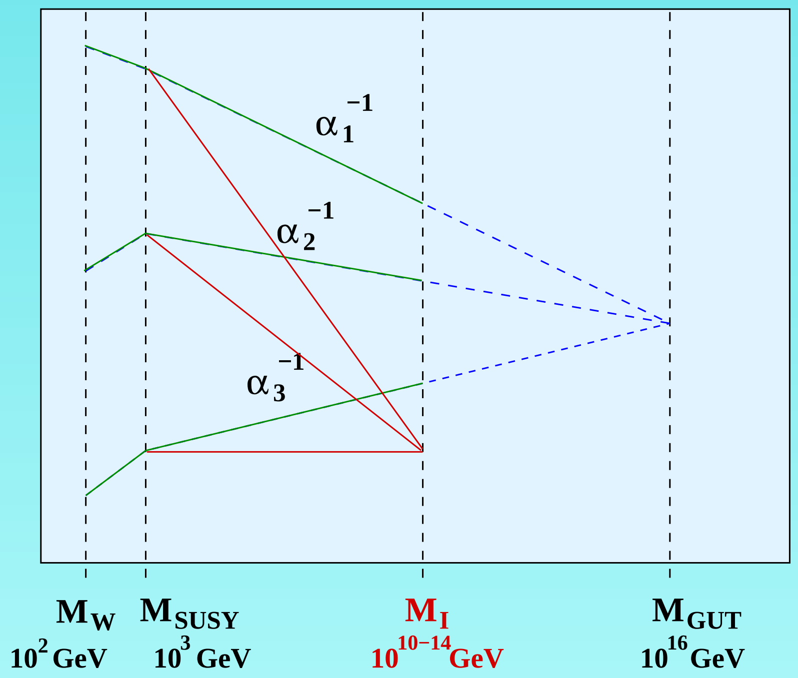
  - Non-universal gaugino masses M_a

    (Corsetti, Nath '00; D.G.C., Khalil, Muñoz '01)

Intermediate Scales

INTERMEDIATE SCALES

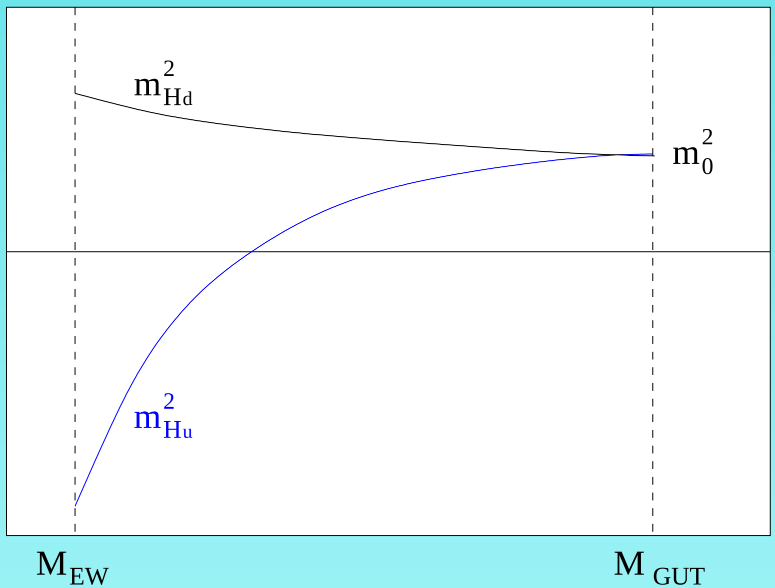
- Universal soft parameters: M, m, A.
- Intermediate high energy scale $M_I = 10^{10-14}$ GeV, with or without gauge coupling unification



- Five free parameters: M, m, A, $sign(\mu)$, $\tan\beta$

Decreasing the initial scale, μ decreases:

RGES for the Higgs parameters



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

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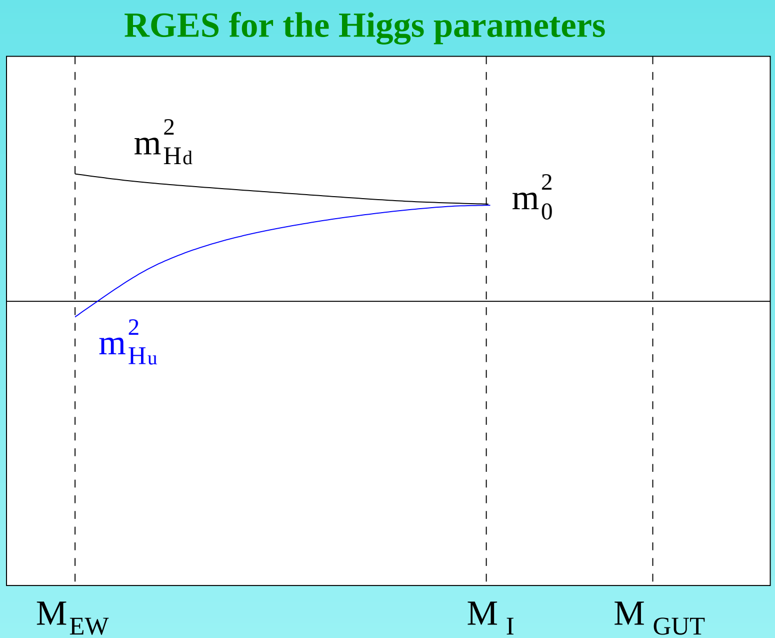


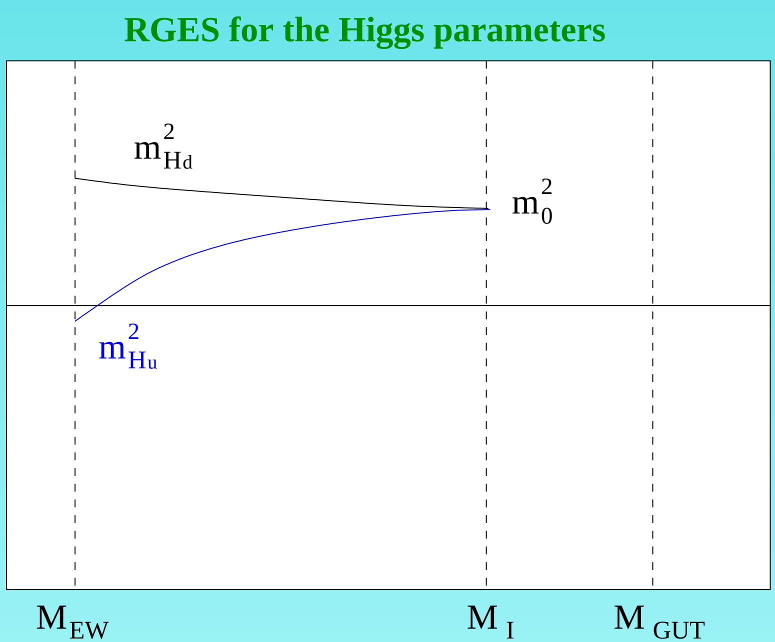
$$m^2_{H_u} \uparrow$$

$$\mu^2 \approx -m^2_{H_u} - \frac{1}{2} M_Z^2 \downarrow$$

In addition m_A^2 (and m_H^2) decreases

$$m_A^2 \approx m^2_{H_d} - m^2_{H_u} - M_Z^2 \downarrow$$

Decreasing the initial scale, μ decreases:



$$m^2_{H_u} \uparrow$$

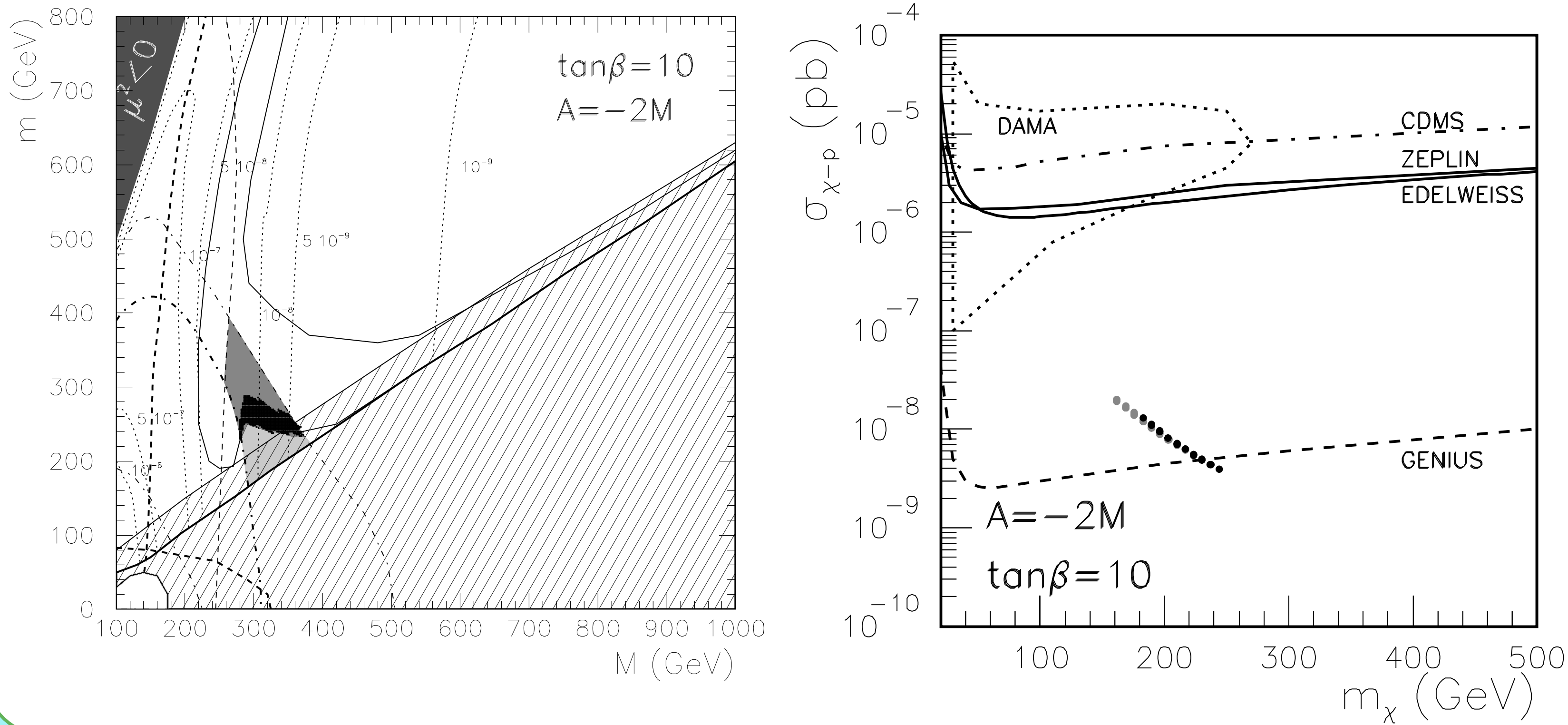
$$\mu^2 \approx -m^2_{H_u} - \frac{1}{2} M_Z^2 \downarrow$$

In addition m^2_A (and m^2_H) decreases

$$m^2_A \approx m^2_{H_d} - m^2_{H_u} - M_Z^2 \downarrow$$

- The Higgsino component of $\tilde{\chi}^0_1$ becomes more important
- $\sigma_{\tilde{\chi}^0_1 - p}$ increases through channels with Higgs exchange

The CCB constraints are less restrictive and low $\tan\beta$ are accepted



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

Non-universal soft terms

NON-UNIVERSAL SCALARS

The most important effect is due to the non-universalities in the Higgs sector, which are parametrized by δ_1 and δ_2:

$$m_{H_d}^2 = m_0^2(1 + \delta_1), \qquad m_{H_u}^2 = m_0^2(1 + \delta_2)$$

The neutralino-nucleon cross section can be increased by

- Decreasing m_A^2 through $\delta_1 < 0$
- Reducing μ via $\delta_2 > 0$

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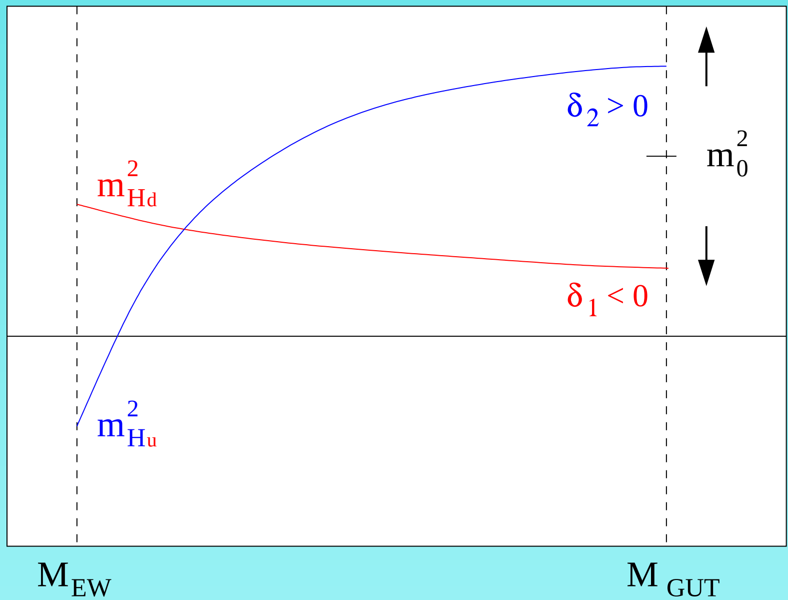
- Decreasing m_A^2 through $\delta_1 < 0$
- Reducing μ via $\delta_2 > 0$

Representative cases

$$\delta_1 = 0,\ \delta_2 = 1$$
$$\delta_1 = -1,\ \delta_2 = 0$$
$$\delta_1 = -1,\ \delta_2 = 1$$

A decrease in $m^2_{H_d}$ and a increase in $m^2_{H_u}$ imply smaller m^2_A.

RGES for the Higgs parameters



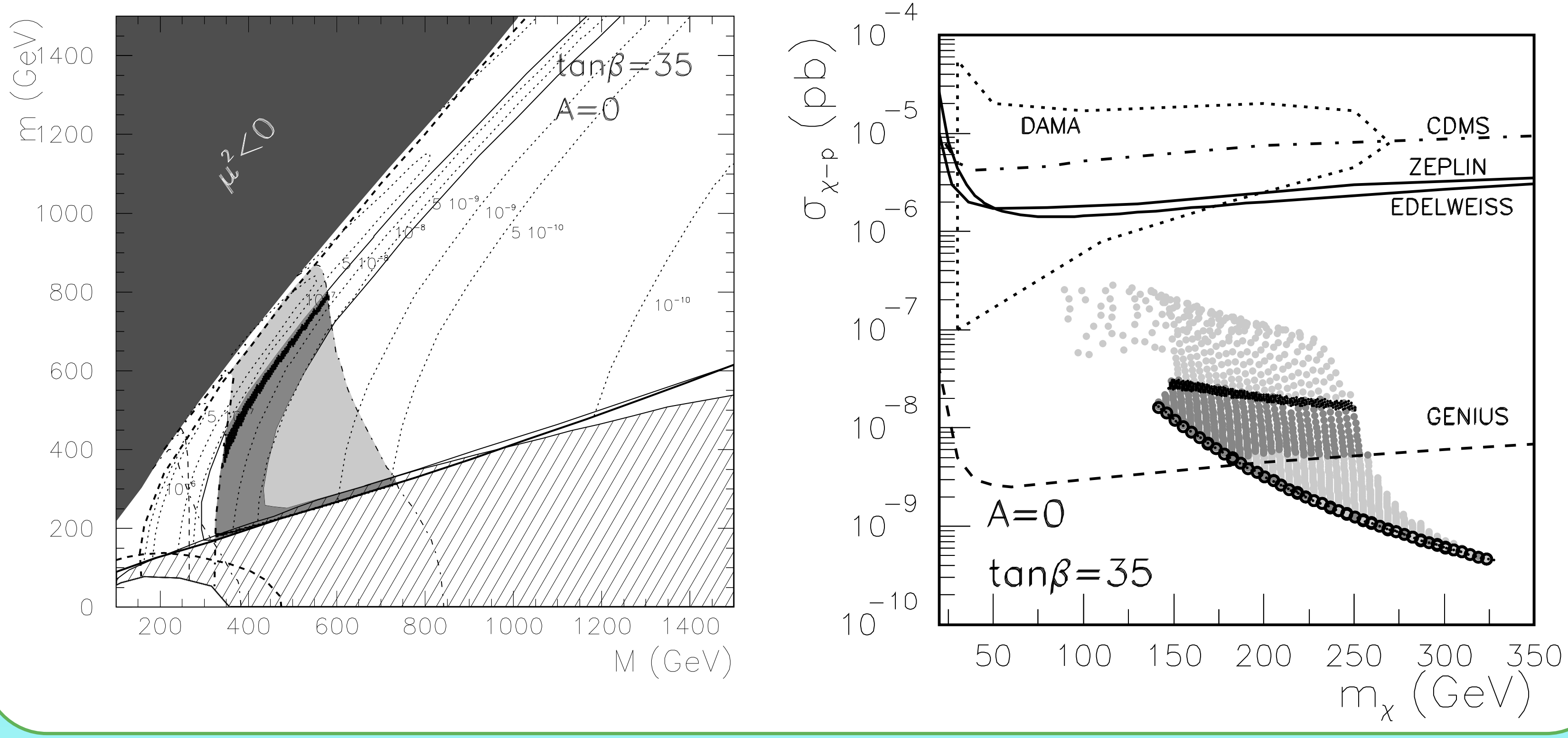
$$m^2_A = m^2_{H_d} - m^2_{H_u} - M^2_Z$$

The μ parameter decreases

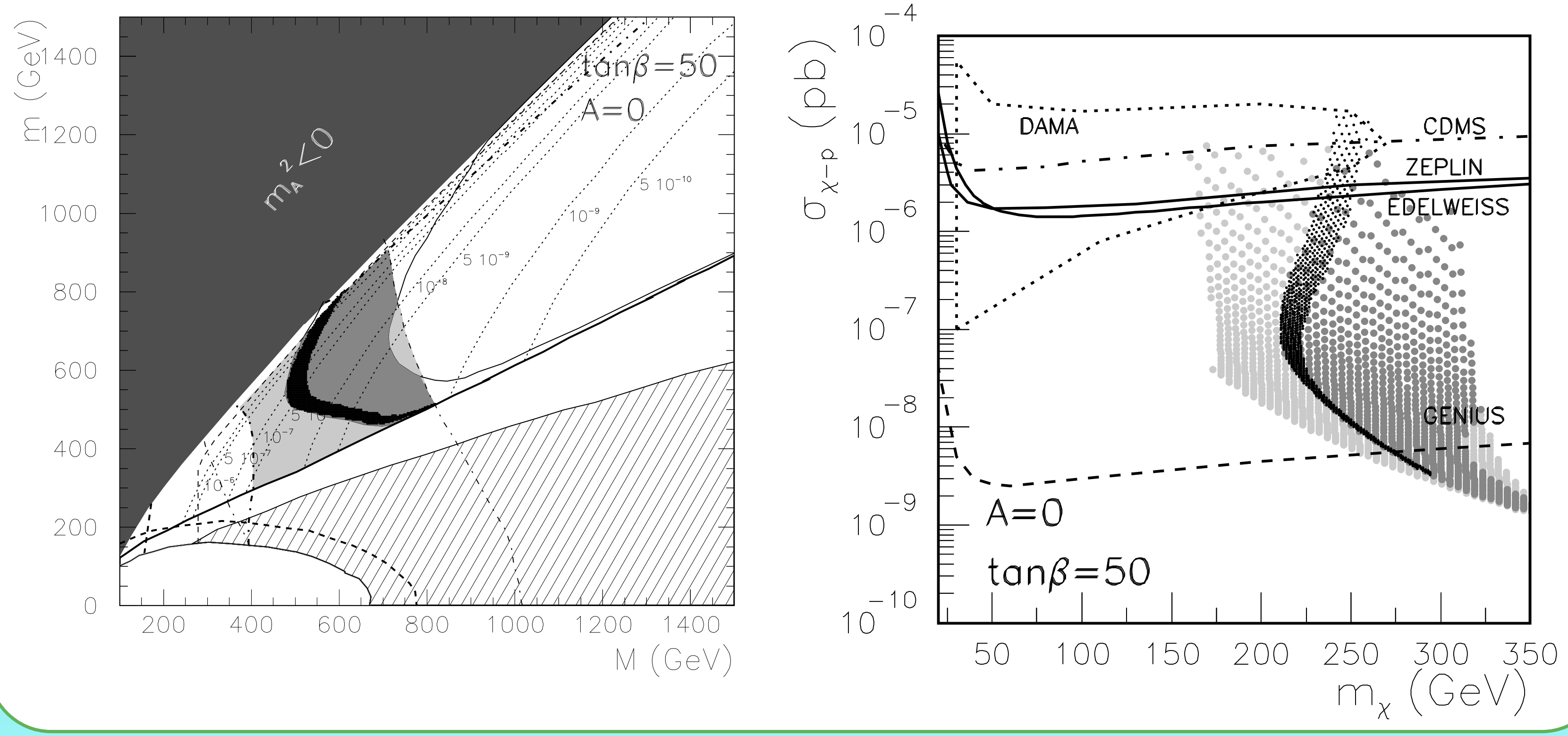
$$\mu^2 = \frac{m^2_{H_d} - m^2_{H_u} \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2} M^2_Z$$

The Higgsino components of the lightest neutralino increase and new annihilation channels appear (with e.g., WW, hW, ZZ in the final products). There is also an increase in $\sigma_{\tilde{\chi}^0_1 - p}$.

• $\delta_1 = 0,\ \delta_2 = 1$

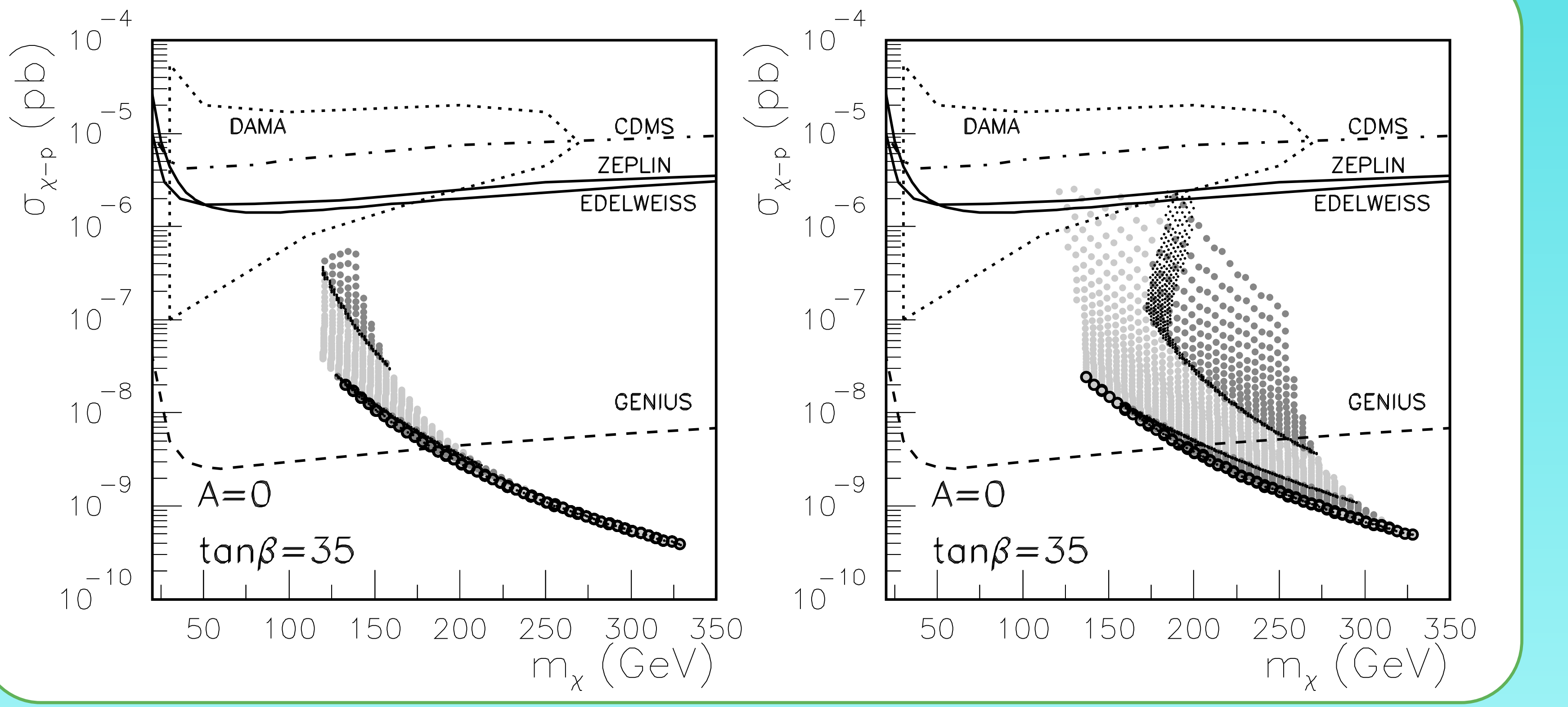


• $\delta_1 = 0, \ \delta_2 = 1$



Charge and Colour Breaking constraints are less restrictive

- $\delta_1 = -1,\ \delta_2 = 0$
- $\delta_1 = -1,\ \delta_2 = 1$



Points fulfilling all the experimental constraints and with a consistent value for the relic density can be found within the reach of dark matter detectors, even for moderate $\tan\beta$

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

Non-universal gauginos

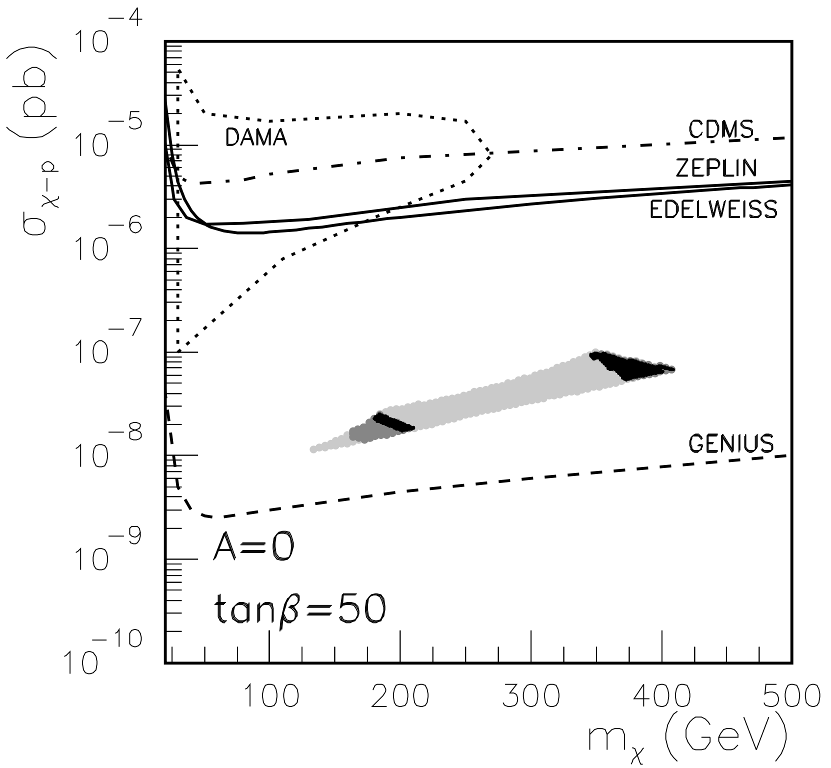
Non-universal soft gaugino masses might also induce an increase of $\sigma_{\tilde{\chi}_1^0 - p}$.

$$\begin{aligned} M_1 &= M(1+\delta'_1) \\ M_2 &= M(1+\delta'_2) \\ M_3 &= M(1+\delta'_3) \end{aligned}$$

- Decreasing M_3 ($\delta'_3 < 0$) leads to an increase in the value of $m^2_{H_u}$ through the corresponding RGEs. Thus, the cross section increases.

However, the Higgs mass is also very reduced and the experimental bound is more constraining.

- $\delta'_{1,2} = 0,\ \delta'_3 = -0.5$



After including all the constraints, regions left in the parameter space are small and with

$$\sigma_{\tilde{\chi}_1^0-p} \lesssim 10^{-7}\mathrm{pb}$$

Non-universal scalar & gauginos

Combining non-universalities in the scalar and gaugino sectors allows more flexibility in the neutralino sector.

- Neutralinos close to the present detection limits are possible with a wide range of masses.

- Heavy (more Higgsino like) neutralinos $m_{\tilde{\chi}_1^0} \gtrsim 400\mathrm{GeV}$ can be obtained close to the sensitivity of dark matter detectors.
- Very light neutralinos $m_{\tilde{\chi}_1^0} \lesssim 50\mathrm{GeV}$ can be obtained fulfilling all the constraints.

• Very light neutralinos $10\mathrm{GeV} \lesssim m_{\tilde{\chi}_1^0}$ can be obtained fulfilling all the constraints.

$M_1 \ll M_2, M_3$ at the GUT scale $\rightarrow$ very light (bino) $\tilde{\chi}_1^0$.

However, the relic density of very light neutralinos is typically too large, $\Omega_{\tilde{\chi}_1^0}\, h^2 > 1$

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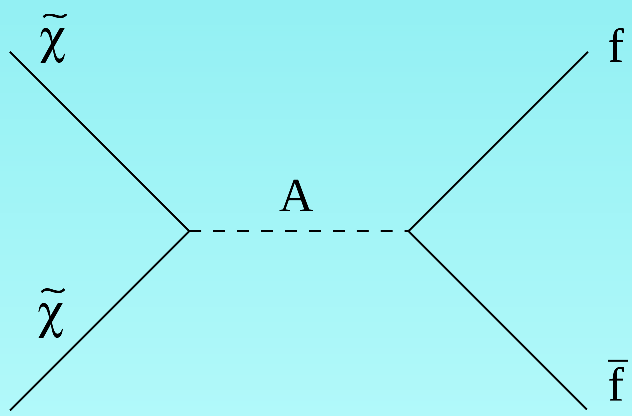
For light CP-odd Higgses ($m_A^2 \lesssim 200\mathrm{GeV}$) s-channel annihilation can be enhanced and $\Omega_{\tilde{\chi}_1^0} h^2$ very effectively decreased.



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For light CP-odd Higgses ($m_A^2 \lesssim 200\mathrm{GeV}$) s-channel annihilation can be enhanced and $\Omega_{\tilde{\chi}_1^0} h^2$ very effectively decreased.

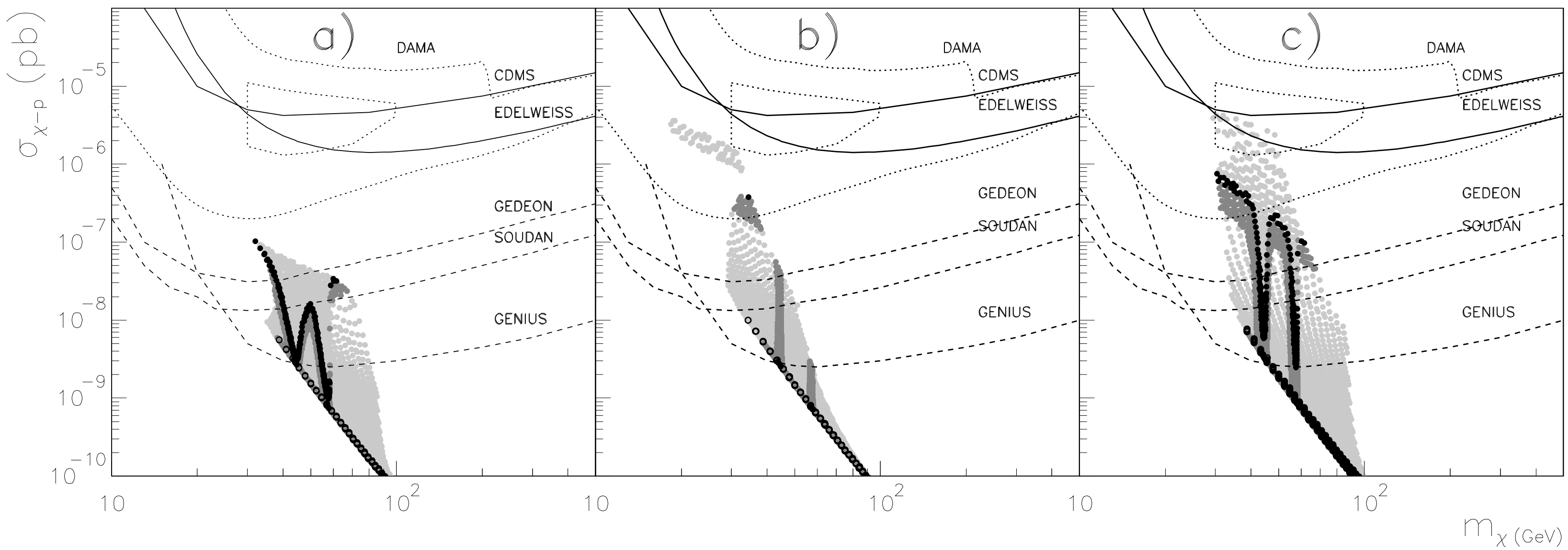
This can be done with non-universalities in the Higgs sector:

$$\begin{aligned} m_{H_d}^2 &= m_0^2(1+\delta_1) \\ m_{H_u}^2 &= m_0^2(1+\delta_2) \end{aligned}$$

Representative cases

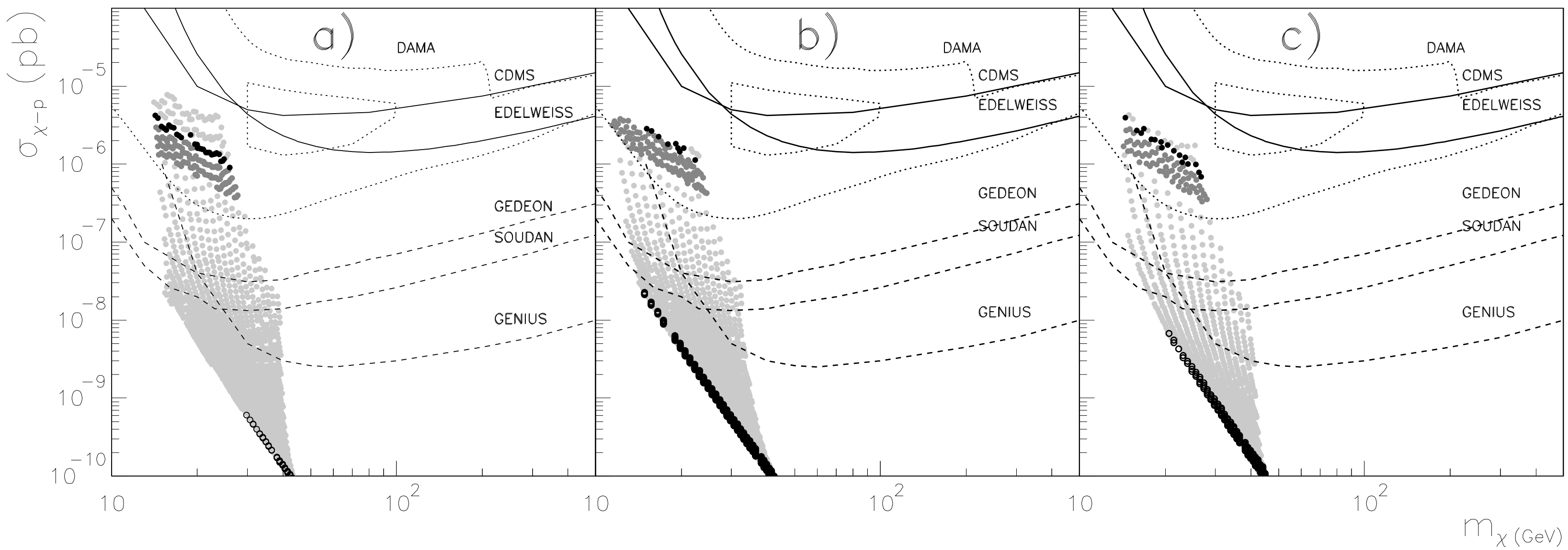
$$\delta_1 = 0,\ \delta_2 = 1$$
$$\delta_1 = -1,\ \delta_2 = 0$$
$$\delta_1 = -1,\ \delta_2 = 1$$

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



$\delta_1 = 0,\ \delta_2 = 1$ $\delta_1 = -1,\ \delta_2 = 0$ $\delta_1 = -1,\ \delta_2 = 1$

- $M_1 = \frac{1}{11} M_{2,3}$



$\delta_1 = 0,\ \delta_2 = 1$ $\delta_1 = -1,\ \delta_2 = 0$ $\delta_1 = -1,\ \delta_2 = 1$

Very light neutralinos $m_{\tilde{\chi}_1^0} \gtrsim 10\mathrm{GeV}$ are obtained within the sensitivity of future detectors.

String Scenarios

STRING-INSPIRED SCENARIOS

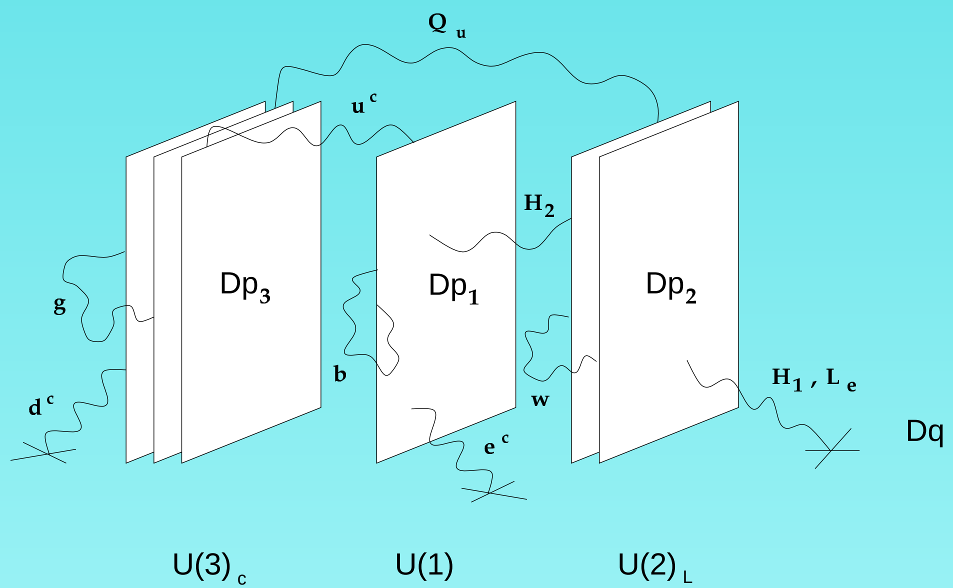
We can consider the case when Supergravity corresponds to the low enery limit of string theory, thus having concrete realizations of the former scenarios.

The soft breaking terms are predictions of these constructions, as functions of the moduli fields. The scale at which they are given is also computed.

• Non-universal soft terms and intermediate scales are characteristic of some phenomenologically interesting string constructions. E.g., D-brane scenarios in Type I string theory.

D-BRANE SCENARIOS IN TYPE I

The MSSM could be built using D-brane configurations in the Type I string.



The SM gauge group can be embedded within

- the same set of D-branes
- different sets of branes

$U(1)_Y$ is in general a linear combination of the remaining $U(1)$ that reproduces the correct hypercharges for the matter fields.

The soft terms are generically non-universal in these constructions.

★ Example: $Dp_3 \neq Dp_2 \neq Dp_1 \neq Dp_3$

A correct expression of the hypercharge is:

$$Y = c_3\sqrt{6}Q_3 + c_2\sqrt{4}Q_2 + \sqrt{2}Q_1$$

(Antoniadis, Kiritsis, Tomaras '00)

The soft terms were evaluated under the assumption of dilaton-moduli supersymmetry-breaking and are non-universal (both scalar and gauginos).

(Ibáñez, Muñoz, Rigolin '99)

The string scale can be calculated from low-energy data ($\alpha_i(M_Z)$) and is found to be within the range $M_I = 10^{10-15}$ GeV

(D.G.C., Gabrielli, Khalil, Muñoz, Torrente-Lujan '01)

Gaugino masses:

$$
\begin{aligned}
M_3 &= \sqrt{3}\, m_{3/2} \sin\theta \\
M_2 &= \sqrt{3}\, m_{3/2}\, \Theta_1 \cos\theta\,, \\
M_Y &= \sqrt{3}\, m_{3/2}\, \alpha_Y(M_I) \left(\frac{2}{\alpha_1(M_I)} \Theta_3 \cos\theta + \frac{1}{\alpha_2(M_I)} \Theta_1 \cos\theta + \frac{6c_3^2}{\alpha_3(M_I)} \sin\theta \right)
\end{aligned}
$$

Scalar masses:

$$
\begin{aligned}
m_{Q_u}^2 &= m_{3/2}^2 \left[1 - \frac{3}{2} \left(1 - {\Theta_1}^2\right) \cos^2\theta \right]\,, \\
m_{d^c}^2 &= m_{3/2}^2 \left[1 - \frac{3}{2} \left(1 - {\Theta_2}^2\right) \cos^2\theta \right]\,, \\
m_{u^c}^2 &= m_{3/2}^2 \left[1 - \frac{3}{2} \left(1 - {\Theta_3}^2\right) \cos^2\theta \right]\,, \\
m_{e^c}^2 &= m_{3/2}^2 \left[1 - \frac{3}{2} \left(\sin^2\theta + {\Theta_1}^2 \cos^2\theta\right) \right]\,, \\
m_{L_e}^2 &= m_{3/2}^2 \left[1 - \frac{3}{2} \left(\sin^2\theta + {\Theta_3}^2 \cos^2\theta\right) \right]\,.
\end{aligned}
$$

❋ Higgs mass parameters:

$$\begin{aligned} m_{H_2}^2 &= m_{3/2}^2\left[1-\frac{3}{2}\left(\sin^2\theta+{\Theta_3}^2\cos^2\theta\right)\right] \\ m_{H_1}^2 &= m_{3/2}^2\left[1-\frac{3}{2}\left(\sin^2\theta+{\Theta_2}^2\cos^2\theta\right)\right] \end{aligned}$$

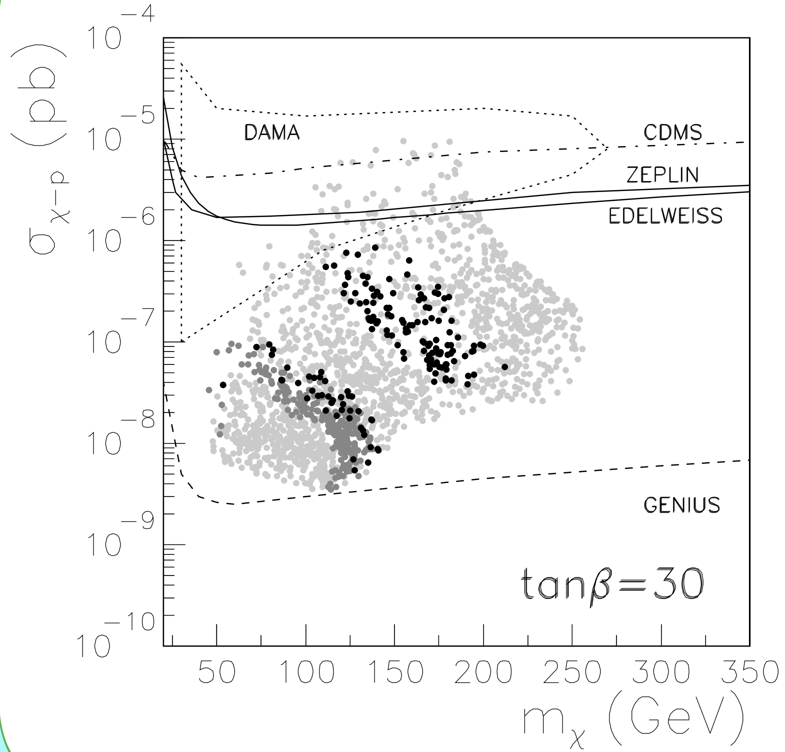
New Goldstino angles Θ_i parameterize SUSY breaking in the enlarged moduli space. ($\sum_i \Theta_i^2 = 1$)

* Parameters: $m_{3/2}^2$, θ, Θ_i, $\tan\beta$, sign$|\mu|$

✔ Diminishing the value of $m_{H_1}^2$ is possible.

✔ $M < m_{L,E}$ is also attainable

• Regions in the parameter space fulfilling all the experimental and astrophysical constraints are found for a wide range of values of $\tan\beta$. Theoretical predictions for the cross-section are typically beyond present detection ranges ($\sigma_{\tilde{\chi}_1^0-p} \lesssim 10^{-7}\,\mathrm{pb}$).



• In some cases, a reduction of the CP-odd Higgs mass makes it possible to fulfil the WMAP requirement for the relic density and have a large cross section ($\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-7}\,\mathrm{pb}$).

SUMMARY

- Although most of the matter in the Universe is dark we still do not know its nature.

- The impressive experimental efforts in dark matter detection, in particular of WIMPS (Heidelberg-Moscow, IGEX, UKDMC, DAMA, HDMS, EDELWEISS, CRESST, CUORE, GENIUS, ...) motivate the theoretical analysis of Supergravity scenarios, where the lightest neutralino is a natural candidate. (Do not forget indirect searches...)

- In Supersymmetric models, experimental and astrophysical data play a leading role in constraining the parameter space. UFB constraints lead to important further reductions.

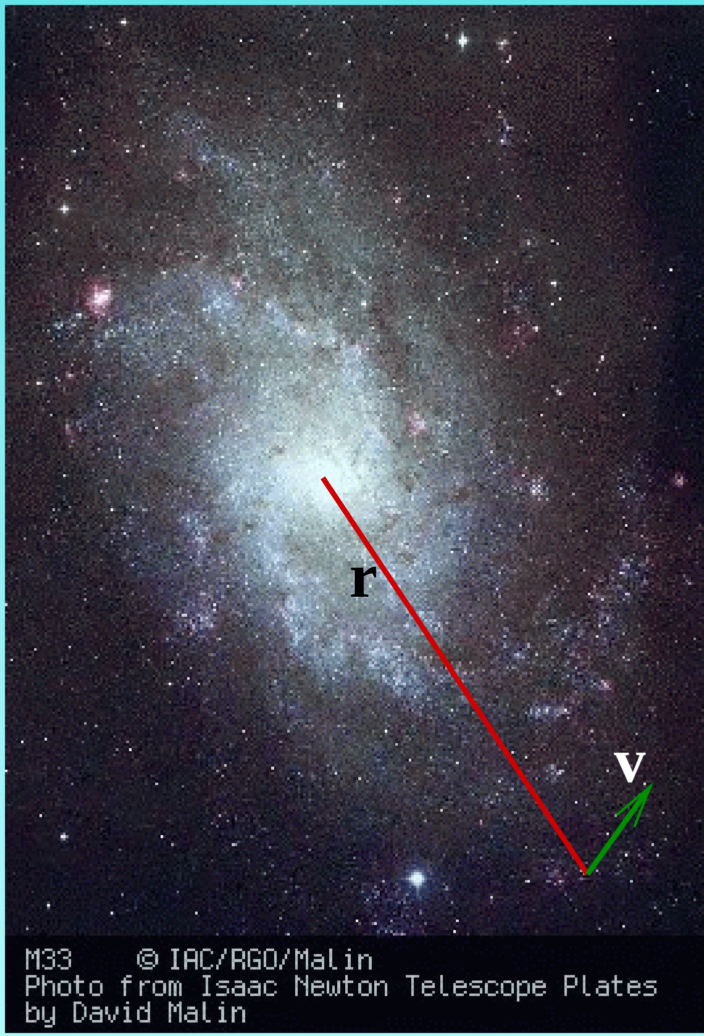
SUMMARY

- Experimental and astrophysical data play a leading role in constraining the parameter space. UFB constraints lead to further reductions.
  - The minimal Supergravity scenario is very constrained and $\sigma_{\tilde{\chi}_1^0-p}$ beyond the sensitivity of detectors.
  - Departures from this case, allowing intermediate initial scales and/or non-universal soft parameters can lead to neutralino dark matter accessible for future experiments.

SUMMARY

- String theory scenarios provide explicit realizations of Supergravity which exhibit these properties.
  - In D-brane constructions of Type I string theory intermediate scales and non-universal soft terms arise naturally. Neutralinos compatible with current experiments can be found with large predictions for the detection rate.

Rotation curves in spiral galaxies



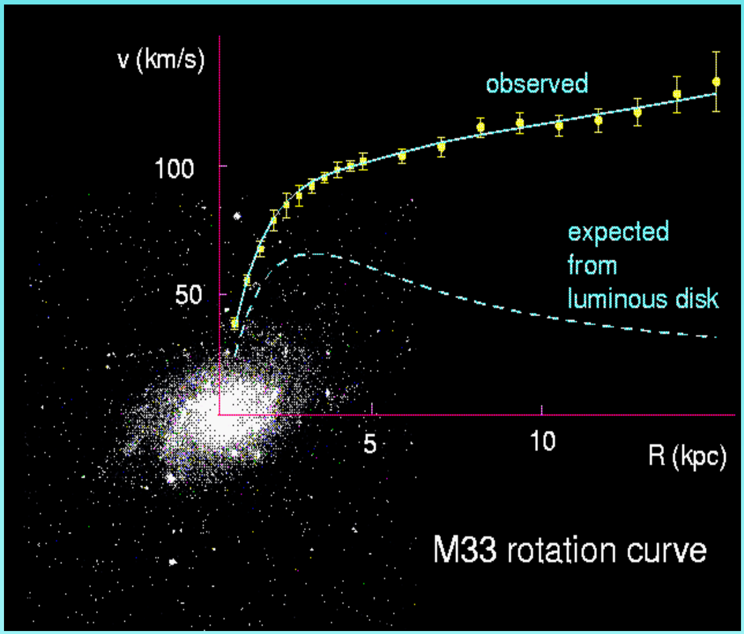
$$\boxed{\frac{v_{\text{rot}}^2}{r} = \frac{G\ M(r)}{r^2}} \rightarrow \boxed{v_{\text{rot}} = \sqrt{\frac{G\ M(r)}{r}}}$$

- r = distance to the center of the galaxy
- $M(r)$ = mass contained within that radius

Beyond the luminous disk

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

ROTATION CURVES IN SPIRAL GALAXIES



Roy '00, data from Corbelli, Salucci, '99

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

- r = distance to the center of the galaxy
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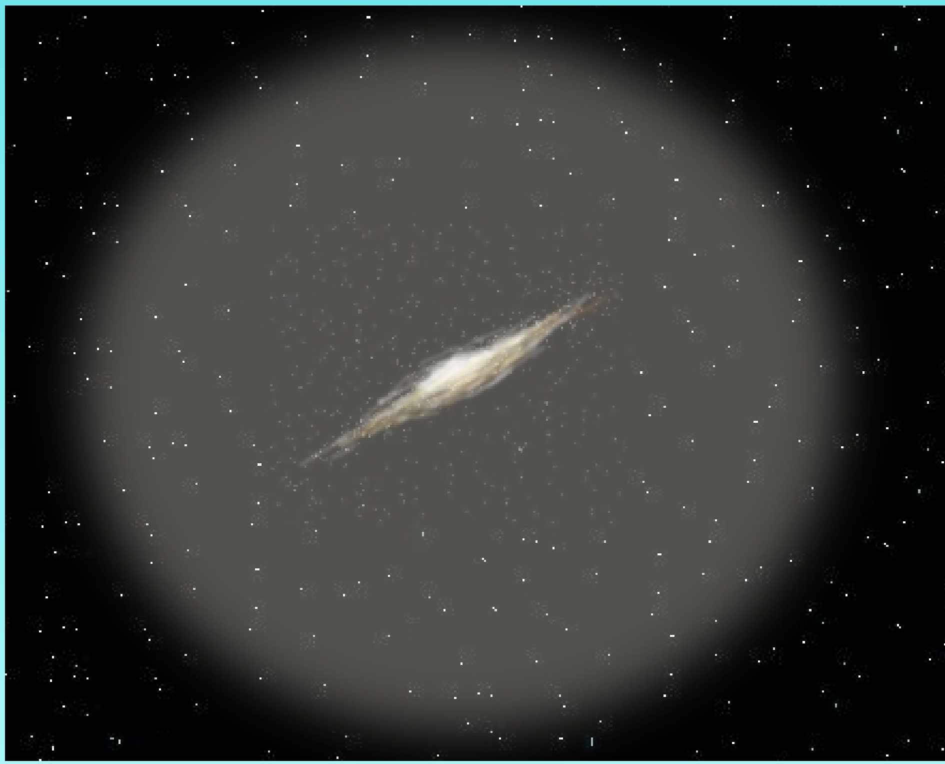
Beyond the luminous disk

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

However, observations show $v_{\text{rot}} \sim cte$ for $r \gg r_{disk}$

ROTATION CURVES IN SPIRAL GALAXIES

The galaxy is surrounded by a spherical halo of Dark Matter with



$$M(r) \propto r \rightarrow v_{\text{rot}} \propto cte$$

(i.e., self gravitational ball of ideal gas)

Measurements suggest

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

CLUSTERS OF GALAXIES

Coma Cluster

- Measurement of peculiar velocities

(Zwicky '33)

- X-ray measurements of the temperature of the gas

(Briel, Henry, Bohringer '92; White '93)

- Gravitational lensing

(Tyson '94)

CLUSTERS OF GALAXIES

Coma Cluster

- Measurement of peculiar velocities

(Zwicky '33)

- X-ray measurements of the temperature of the gas

(Briel, Henry, Bohringer '92; White '93)

- Gravitational lensing

(Tyson '94)

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

Axions

Axions are spin 0 particles associated to the spontaneous breaking of the global $U(1)$ Peccei Quinn symmetry (postulated to solve the strong CP-Problem)

$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \sim 10^{-5}\mathrm{eV} \times \left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

Axions can be produced in the Big Bang (out of equilibrium) and are always non-relativistic. They are excellent candidates for cold dark matter.

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- Axion emission does not over-cool stars (e.g., SN1987)

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The axion decay constant (f_a) is constrained:

- Axion emission does not over-cool stars (e.g., SN1987)
- Axions do not overclose the universe ($\Omega \lesssim 1$)

$$10^9\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\mathrm{GeV}$$

WIMPs

A generic Weakly Interacting Massive Particle constitutes a natural dark matter candidate, if stable or long-lived.

✻ The relic density of WIMPs fulfils naturally $\Omega_{WIMP} \approx 1$

$$\Omega_{WIMP} \approx \frac{7\times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma_{ann}\, v\rangle}$$

Particles with weak-scale interactions have the appropriate value of the annihilation cross-section, $\sigma_{ann} \approx \alpha^2/m_{weak}^2$

LIGHTEST SUPERSYMMETRIC PARTICLE (LSP)

The Lightest Supersymmetric Particle is be stable if R-parity is invoked and thus constitutes a candidate for dark matter.

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

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- Lightest Neutralino, $\tilde{\chi}_1^0$
  It is a WIMP with $m \sim 10^{2-3}$ GeV
- Axino, $\tilde{a}$
- Gravitino, $\tilde{G}$
- Sneutrino, $\tilde{\nu}$

AXINO

Axinos (fermionic superpartners of axions) can easily be the LSP (their mass is not directly related to the SUSY breaking scale).

(Rajagopal, Turner, Wilczek 91)

Relic cold axinos can be produced through thermal scattering and decays in the plasma or in out-of-equilibrium decays of the NLSP. Their interactions with ordinary matter are very weak and detection very involved.

GRAVITINO

The Gravitino, $\tilde{G}$, (fermionic superpartner of the graviton) can also be the LSP in Supergravity theories.

The Gravitino relic density can be sizeable but is constrained from BBN.

This is due to the decays of NLSP into $\tilde{G}$, which can spoil BBN predictions.

Sneutrino

Dark matter searches exclude sneutrinos with relic density larger than $\Omega_{\tilde{\nu}}\, h^2 \gtrsim \mathcal{O}(10^{-4})$.

It cannot therefore be the main constituent of dark matter.

At the position of the Sun in our Galaxy ($\sim 8.5 kpc$ distance from the center) the estimated **dark matter density** is

$$\rho_{\rm WIMP} \sim 5 \times 10^{-24}\,{\rm gr\,cm^{-3}} \approx 0.3\,{\rm GeV\,cm^{-3}}$$

For a **WIMP** with $m_{\rm WIMP} \approx 100\,{\rm GeV}$ this implies a number density of

$$n_{\rm WIMP} \approx 3 \times 10^{-3}\,{\rm cm^{-3}}$$

The velocity of **WIMPs** in the galactic halo is

$$v \approx 300\,{\rm km\,s^{-1}}$$

Thus, the flux of **WIMPs** through the Earth is

$$J_{\rm WIMP} = n_{\rm WIMP} \cdot v \approx 10^5\,{\rm cm^{-2}\,s^{-1}}$$

CDMS

- Cryogenic Dark Matter Search
- located at Stanford
- Measure of ionization and temperature rise on Germanium and Silicon detectors
- Event by event discrimination allows to identify electron background from possible WIMP or neutron ionization.
- 2001-2002 Data run in Stanford in 4 Ge and 2 Si detectors

CRESST

- Cryogenic Rare Event Search with Superconducting Thermometers
- located in Gran Sasso (Max Planck Institute of Physics, Technical University of Munich, University of Oxford, and Gran Sasso National Laboratory collaboration)
- Phase I (sapphire cryogenic detectors) finished in March 2001 proved the detector to be compelling enough for WIMP searches.
- The second phase will allow for simultaneous measurement of the phonon and scintillation light to reduce background.

IGEX

- International Germanium EXperiment
- Designed for the search for the neutrinoless double beta decay of ^{76}Ge
- The sophisticated shielding techniques, along with the extreme radiopurity of the detectors and their components, allow them to reach a low energy background as well as a low enough threshold, leading to very stringent countour limits for cross sections and masses of dark matter particles.

ZEPLIN

- Zoned Electroluminiscence Proportional scintillation in LIquid Noble gases
- UK Dark Matter Collaboration
- Located at the Boulby Mine
- Single phase liquid Xe detector. Xe is an excellent high A target (better matched to high mass WIMPs) with various isotopes, complementing NaI; It gives larger recoil energy and a improved sensitivity to the spin-independent cross-sections, proportional to A^2.
- ZEPLIN II, II based on double phase xenon.

NAI

-
- Located at the Boulby Mine
- Started in 1997 and had some anomalous events in 1998. Although some possible sources have been ruled out, a WIMP origin of these nuclear recoils is still uncertain.

UKDMC

- (ZonEd Proportional scintillation in LIquid Noble gases) UK Dark Matter Collaboration
- Located at the Boulby Mine
- Comprises ZEPLIN and NAI experiments.

EDELWEISS

- Expérience pour DÉtecter Les Wimps En SIte Souterrain
- Located in Modena (since 1994) began to take data in 2000
- Cryogenic Ge crystal with bolometer. Temperature and ionization are measured, permitting a good discrimination of the background.
- Combined data 2000-2002 provide the stringest constraint on WIMP dark matter, ruling out most of the DAMA solution.

Heidelberg-Moscow

- Installed at Gran Sasso.
- Operates five enriched ^{76}Ge ionization detectors, optimized for neutrinoless double beta decay.
- Was able to exclude, with their data on 1998, part of the DAMA region.

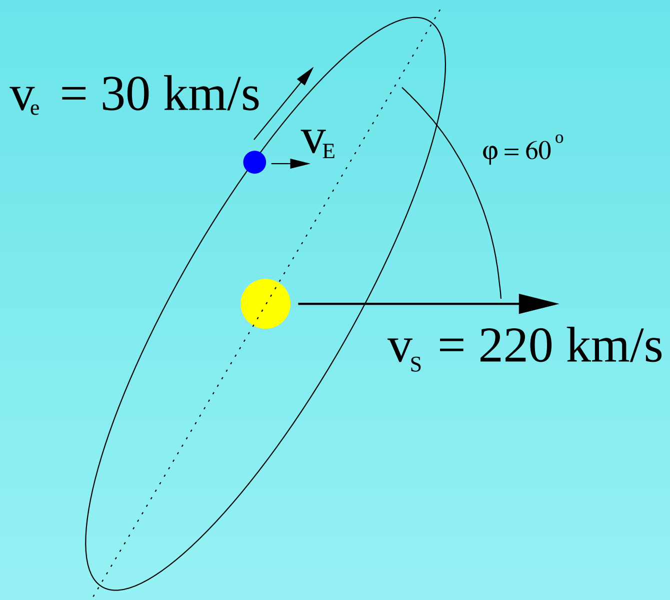
HDMS

- Heidelberg Dark Matter Search
- Installed at Gran Sasso in August 2000, will be able to test the DAMA region.
- Based on two Ge ionization detectors.
- Already started data-taking and reaching sensitivities close to the Heidelberg-Moscow experiment.
- The expectation for HDMS after 2 years of measurement and a background index of 0.07 events per kg, day and keV in the 2-30 keV energy region should test the entire DAMA ‘evidence region’ with raw data and using a completely different detection technique, namely ionization in a HPGe-detector.

- particle DArk MAtter searches with highly radiopure scintillators at Gran Sasso
- Experimental results since 1992
- Various results with the 100 kg NaI(Tl) set-up published since 1996; set-up devoted mainly to the investigation of the WIMP annual modulation signature.
- New NaI tanks available. The new 250 kg NaI(Tl) set-up named LIBRA running.
- The galactic halo is usually described with an isothermal spherical model. Possible departures from this description lead to an enlargement of the allowed DAMA region.

Annual modulation effect

(Drukier, Freese, Spergel 86; Freese, Fierman, Gould 88; Griest 88)



The Earth's velocity through the halo has a seasonal dependence.

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

$$t_m = \text{June } 2 \pm 1.3 \text{ days}$$

$\approx 7\%$ summer-winter variation in the detection rate.

(DAMA coll. 03)