Dark Matter in Supersymmetry

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Outline

- Introduction

  Motivation for Dark Matter in the Universe
  Supersymmetric dark matter

- Neutralino dark matter in the MSSM

  Theoretical predictions for neutralino direct detection

- Summary

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The motivation for dark matter appears at different scales in astrophysical observations.
Luminous (visible) matter is insufficient to account for the observed gravitational effects

Galactic scale

Rotation curves in spiral galaxies
Elliptic galaxies

Clusters of galaxies

Peculiar velocities
X-ray measurements of the temperature of the gas
Gravitational lensing

Large scale flows

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Alternative... MOdified Newtonian Dynamics?

(Milgrom, Beckenstein)

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The amount of dark matter is usually expressed in terms of the cosmological density parameter:

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

- ρ is the density averaged over the Universe
- ρ_c is the critical density for obtaining a flat Universe.

$$\rho_c = 1.88\, h^2 \times 10^{-29}\,\mathrm{g\,cm}^{-3} = 10^{-5}\, h^2\ \mathrm{GeV\,cm}^{-3}$$

Astrophysical observation seemed to favour

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

Cosmological parameters from CMB

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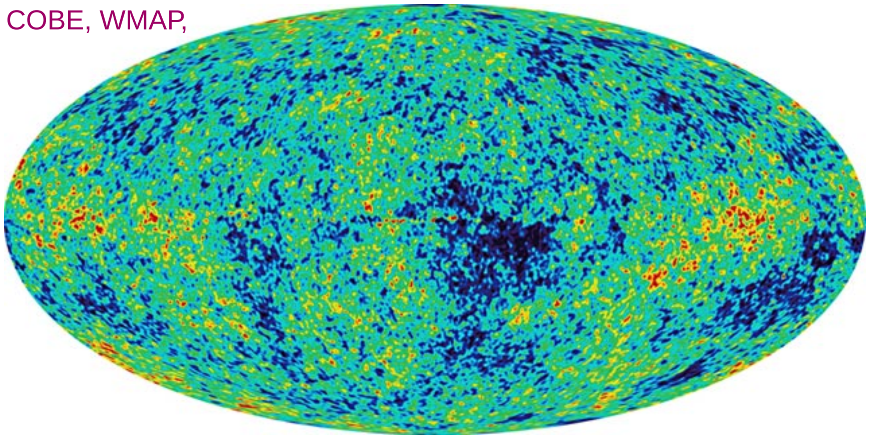
Observations of the Cosmic Microwave Background constitute a primary tool for determining the global properties of our Universe.

DASI, CBI, VSA, MAXIMA, BOOMERanG, COBE, WMAP, PLANCK, ...



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

Combining WMAP with other experiments the best fit is obtained for

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

From where a bound on the abundance of Cold Dark Matter can be extracted

$$0.094 < \Omega_{CDM}\, h^2 < 0.13 \text{ } (2\sigma \text{ c.l.})$$

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- 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.

    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)

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

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

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

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  - Weakly Interacting Massive Particles: They can be present in the right amount to explain the dark matter.

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

$$\Omega_{WIMP} \approx \frac{7\times10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma_{ann}\,v\rangle}$$

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

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  - Lightest Supersymmetric Particle: stable in Supersymmetric theories with R-parity.

The LSP can be the lightest Neutralino, $\tilde{\chi}_1^0$, which is a WIMP.

Other interesting possibilities are axino or gravitino dark matter.

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

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In the MSSM the LSP can be...

Squarks	$\tilde{u}_{R,L}$, $\tilde{d}_{R,L}$ $\tilde{c}_{R,L}$, $\tilde{s}_{R,L}$ $\tilde{t}_{R,L}$, $\tilde{b}_{R,L}$
Sleptons	$\tilde{e}_{R,L}$, $\tilde{\nu}_e$ $\tilde{\mu}_{R,L}$, $\tilde{\nu}_\mu$ $\tilde{\tau}_{R,L}$, $\tilde{\nu}_\tau$
Neutralinos	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
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(Hamaguchi (this afternoon))

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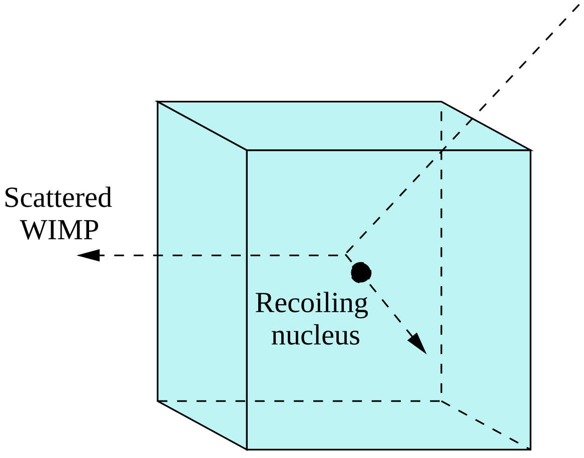
Supergravity models

Summary

If Neutralinos constitute the bulk of dark matter they would cluster with ordinary stars in galactic halos, raising the hope of their direct detection on Earth experiments.

Direct detection of neutralinos would be possible through their elastic scattering with nuclei inside a detector.



Target crystal

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)

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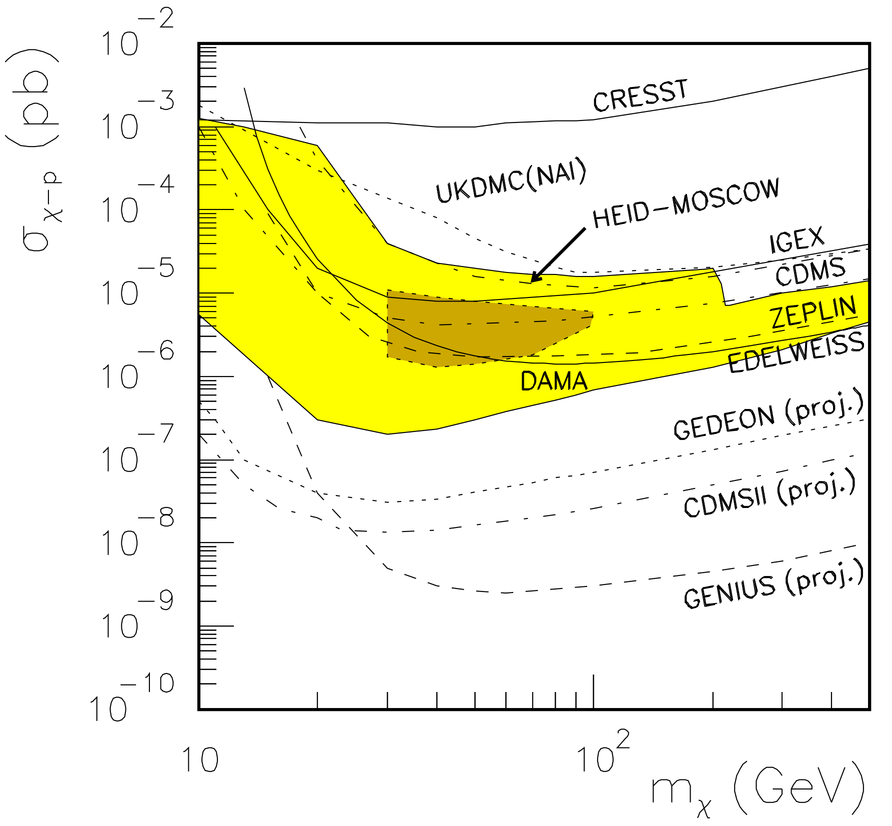
Many experiments around the world

Cresst, Heidelberg-Moscow, IGEX, UKDMC(NAI), DAMA, CDMS, ZEPLIN, EDELWEISS, ...

Sensitivity for WIMP detection (Spin-independent cross section)



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With increasing sensitivities and projected improvements

ZEPLIN II and III, GENIUS, CDMSII, GEDEON, ...

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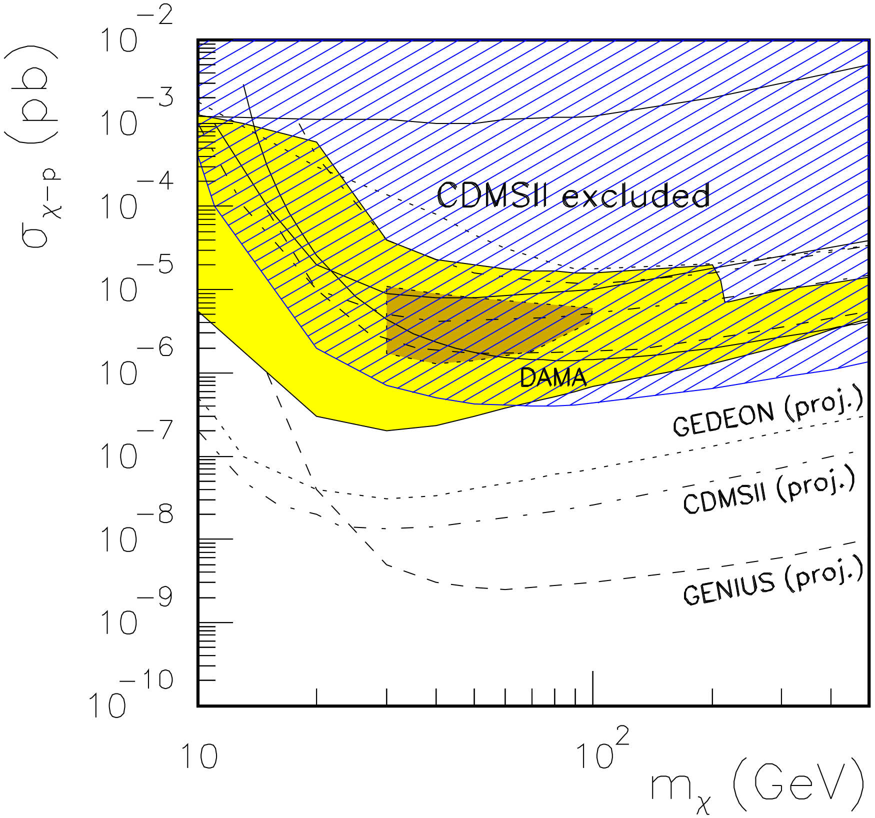

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Summary

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

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

The properties of the lightest neutralino, $\tilde{\chi}_1^0$, are very dependent on its composition.

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

Could neutralinos be detected in the (near) future? How large can their detection cross section be?

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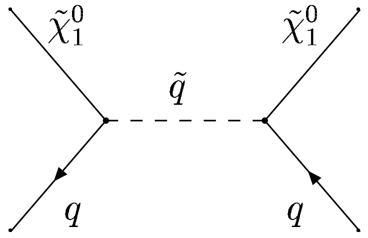
One can evaluate the spin-independent part of the cross-section and analyse the feasibility of their direct detection.



Squark-exchange:

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

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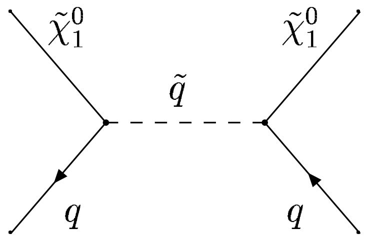

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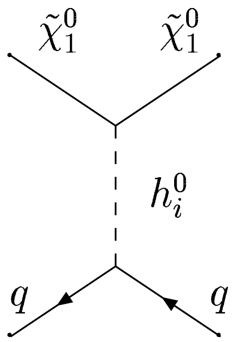

Higgs-exchange:

$$\sigma_{\tilde{\chi}_1^0-p} \propto \frac{m_r^2}{4\pi}\,\frac{\lambda_q^2}{m_h^4}\left|N_{13,\,14}\left(g' N_{11}-g N_{12}\right)\right|^2$$

This diagram is typically dominant and can be enhanced with

- Higgsino-like neutralinos (increase $N_{13,\,14}$)
- Light Higgses (decrease m_h)

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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.

- 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

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

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

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Summary

For consistency with experimental results, several constraints have to be imposed on the SUSY spectrum and low energy observables.

- Supersymmetric spectrum (LEP, Tevatron):

$$m_{\tilde{\chi}_1^\pm} > 103 \text{ GeV},$$
$$m_{\tilde{g}} > 150 \text{ GeV}$$
$$m_{\tilde{\tau}} > 87 \text{ GeV},$$
$$\ldots$$

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  (dependent on $\sin^2(\alpha - \beta)$ in the MSSM)

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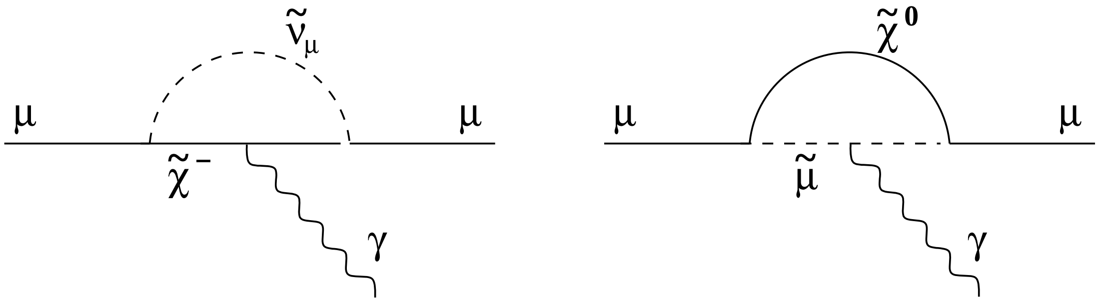

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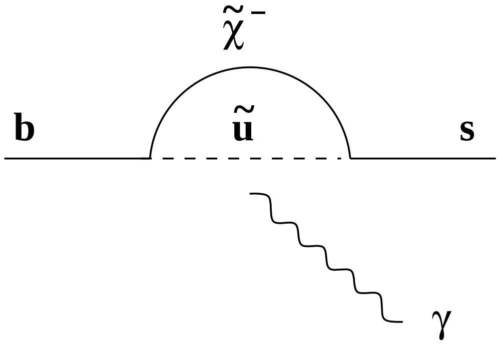

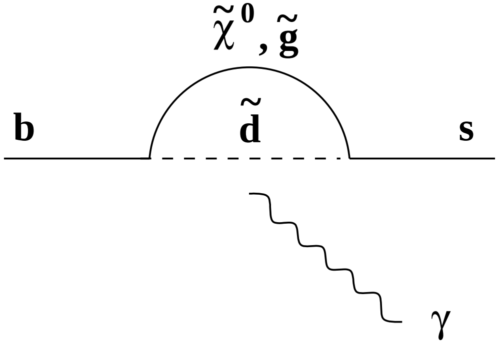

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» Direct detection of neutralinos
» The Lightest Neutralino
» Neutralino-nucleon cross section
» Supergravity scenarios
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Supergravity models

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- B($B_s^0 \to \mu^+\mu^-$) $\lesssim 2.9 \times 10^{-7}$ (CDF, D0)

Astrophysical Constraints

For the neutralino to be a solution to the problem of dark matter, its relic density has to be in agreement with observations

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

Charge and Colour Breaking Constraints

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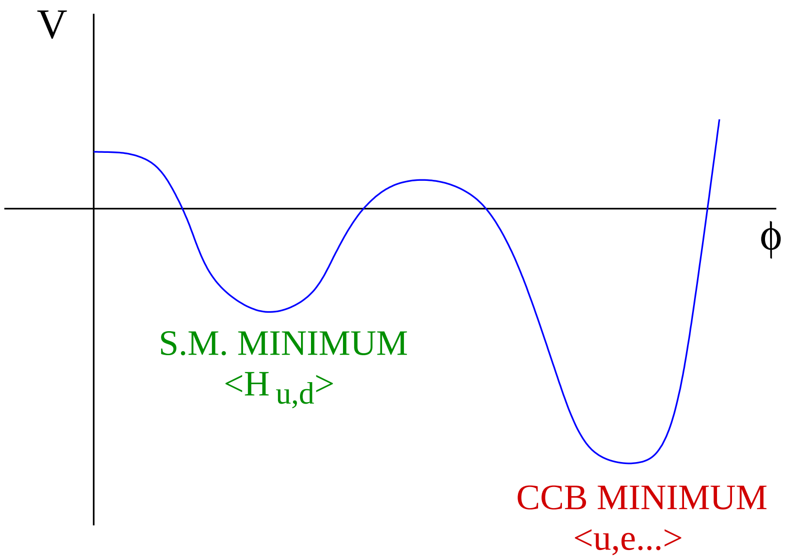
Supergravity models

Summary

- 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.



- Also the (tree level) potential can become Unbounded from Below (UFB) along particular directions in the field space.

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

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Minimal Supergravity (mSUGRA)

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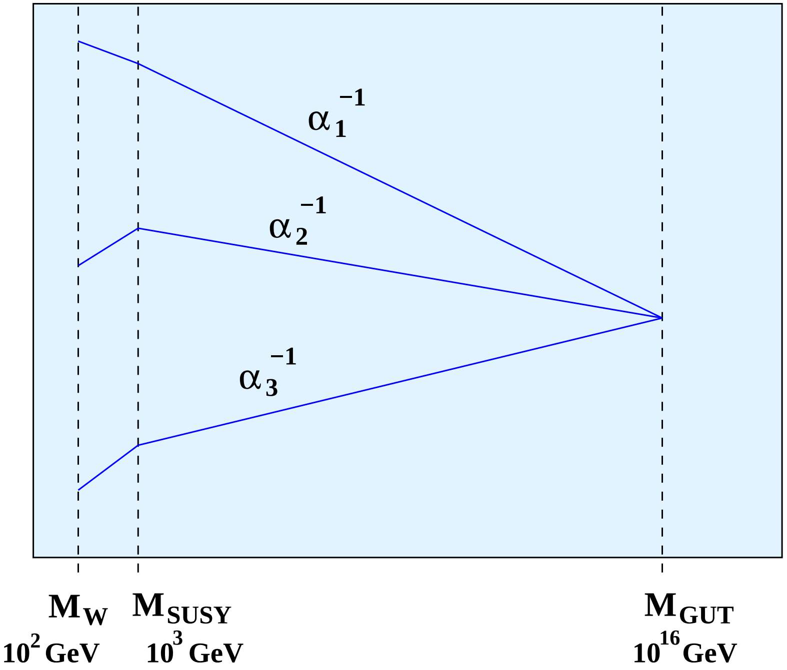
Summary

- 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, $sign(\mu)$, $\tan\beta$

mSUGRA

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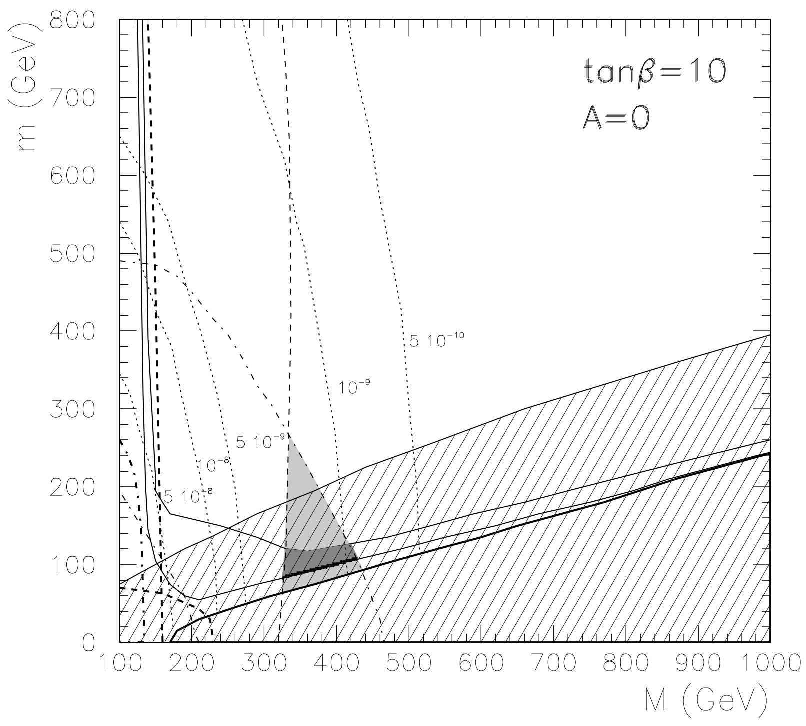

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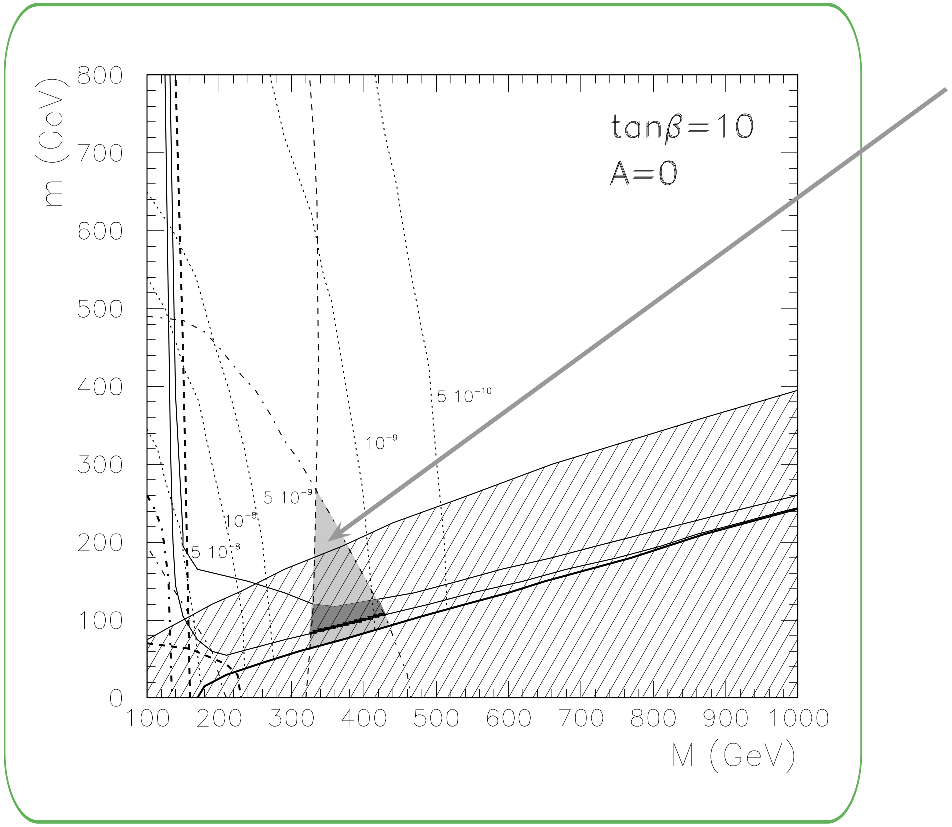

Experimentally accepted

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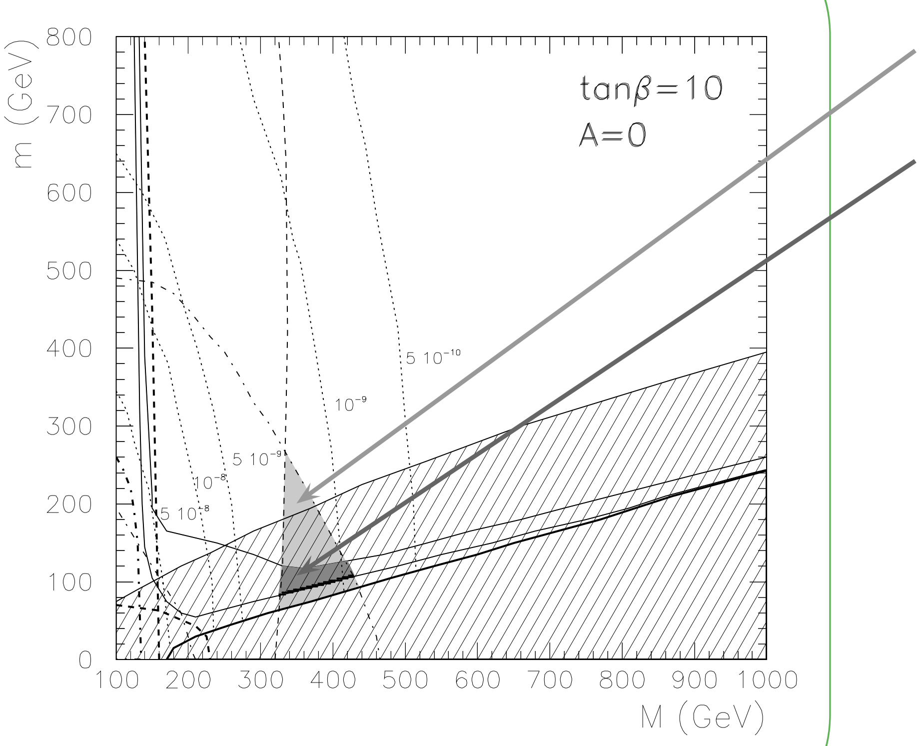

Experimentally accepted

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

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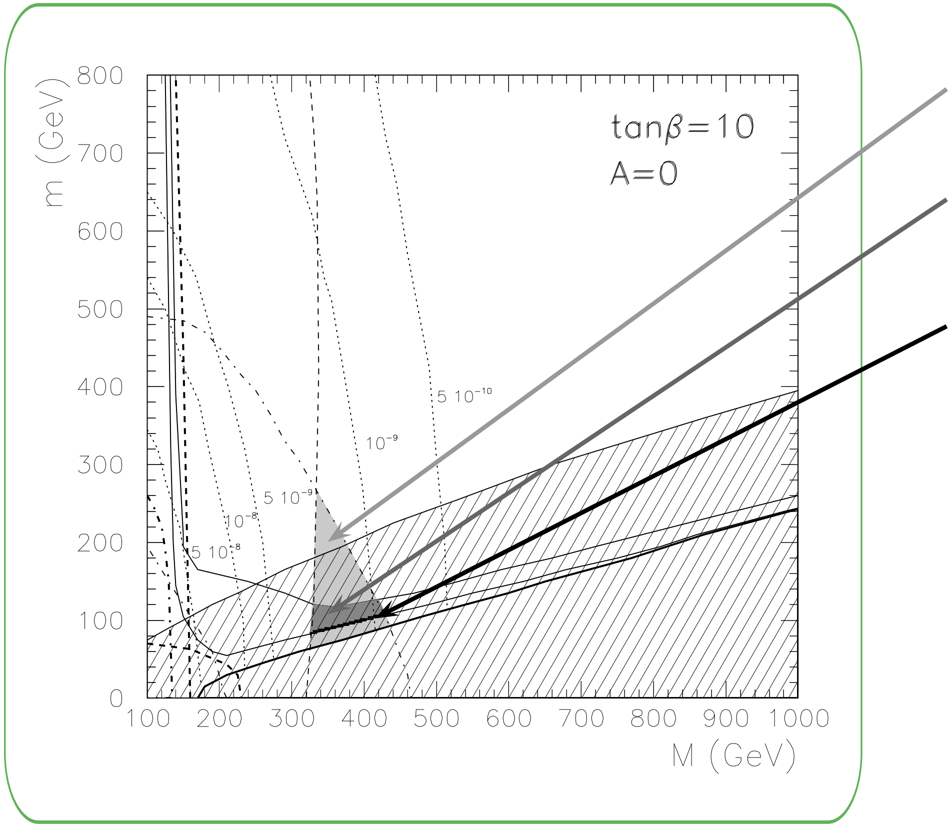

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$0.1 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.3$

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

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

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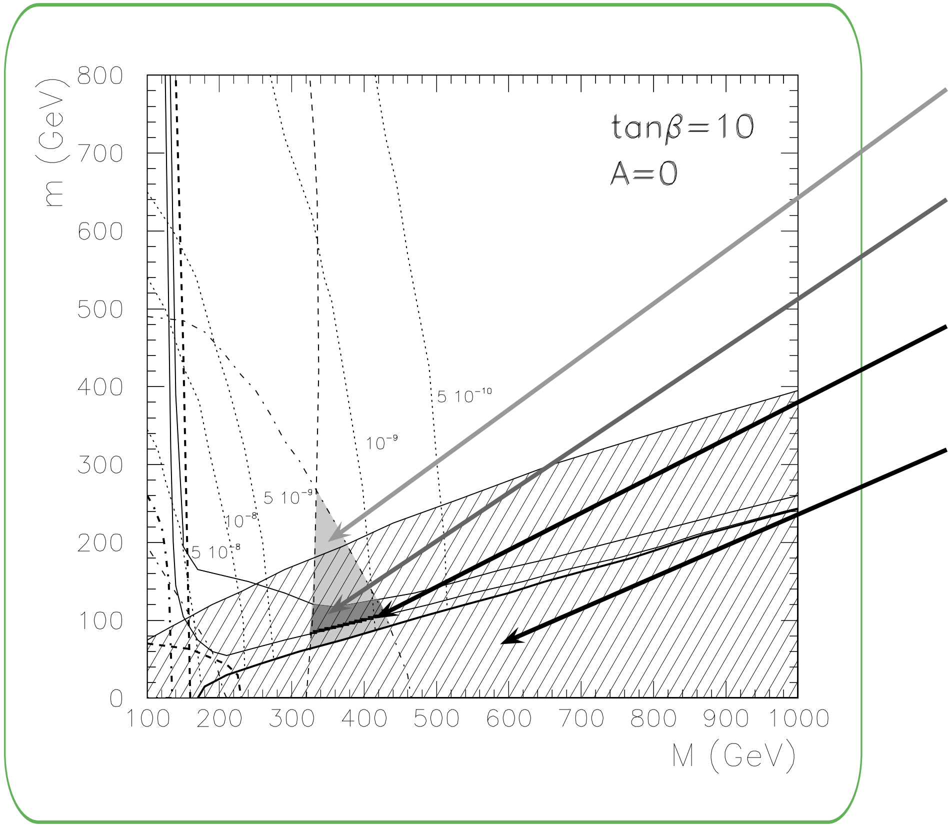

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$0.1 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.3$

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Disfavoured by UFB constraints

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

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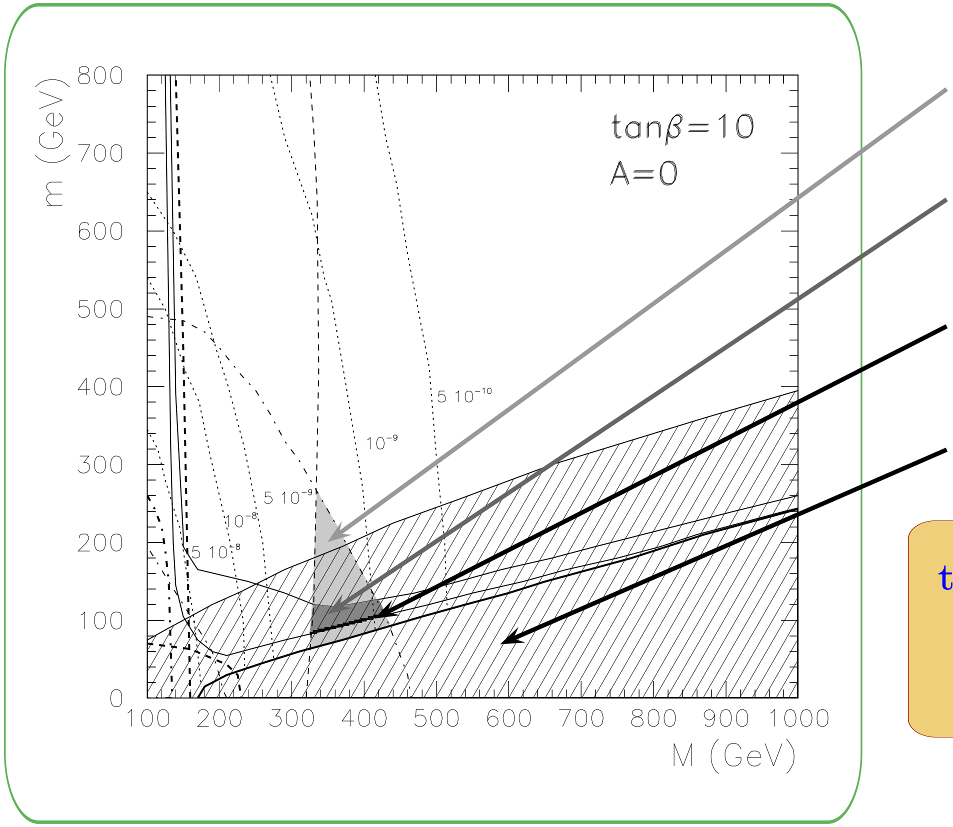

Experimentally accepted

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

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

Disfavoured by UFB constraints

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

Larger values can also be forbidden for certain A

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

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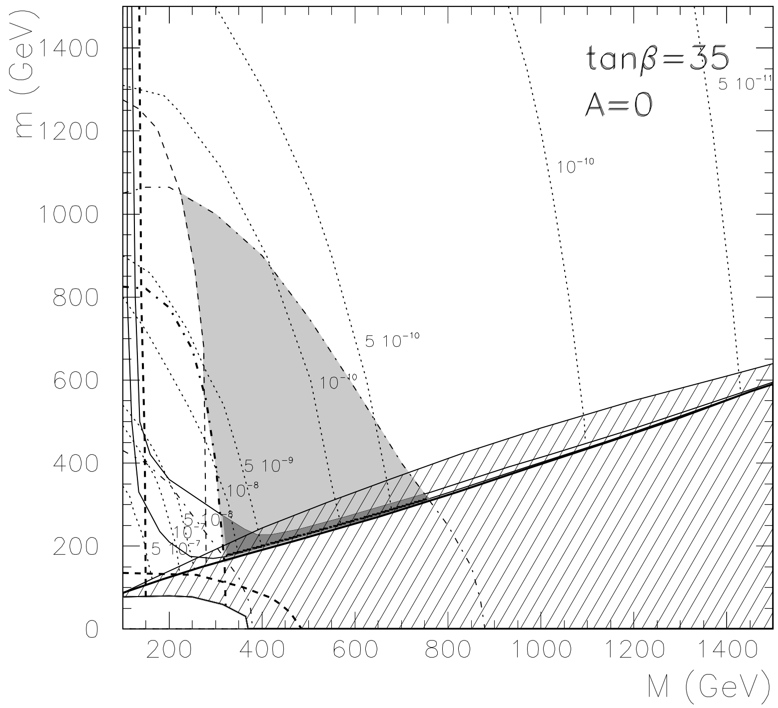
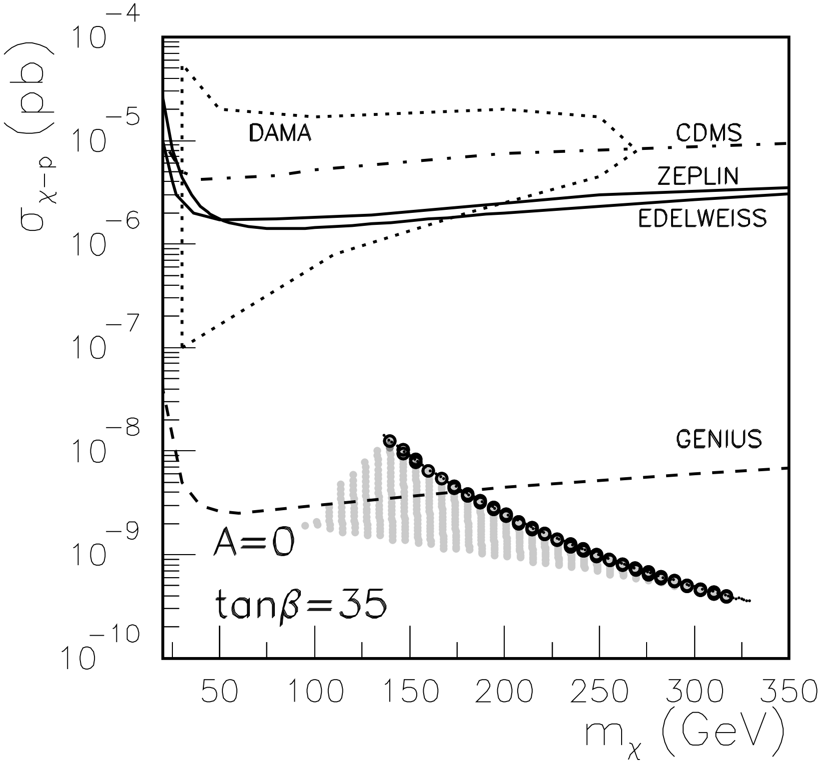
Larger values of $\tan\beta$ lead to an increase of $\sigma_{\tilde{\chi}_1^0-p}$





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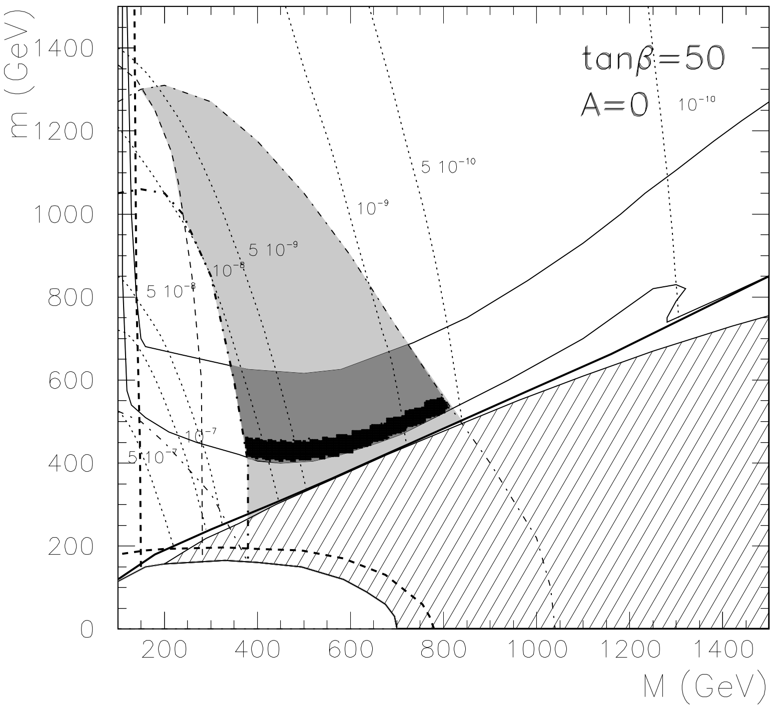

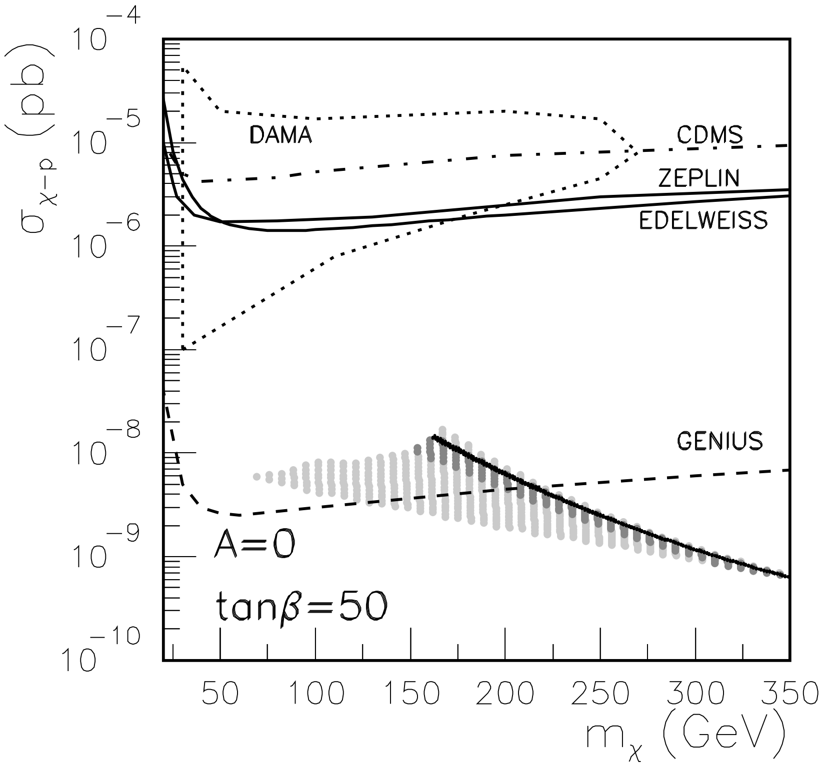

$$\sigma_{\tilde{\chi}_1^0-p} \lesssim 3 \times 10^{-8}\,\mathrm{pb}$$

Increasing the detection cross section

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Summary

Departures from the mSUGRA scenario can 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-universalities in the Higgs sector induce the largest effects.
  - Non-universal gaugino masses M_a

    (Corsetti, Nath '00; D.G.C., Khalil, Muñoz '01)
  - General case, with non-universal scalar and gauginos

    (D.G.C, C. Muñoz '04; Baek, D.G.C., Kim, Ko, Muñoz '05)

Neutralinos within the reach of detectors in the near future can appear with a wide range of masses.

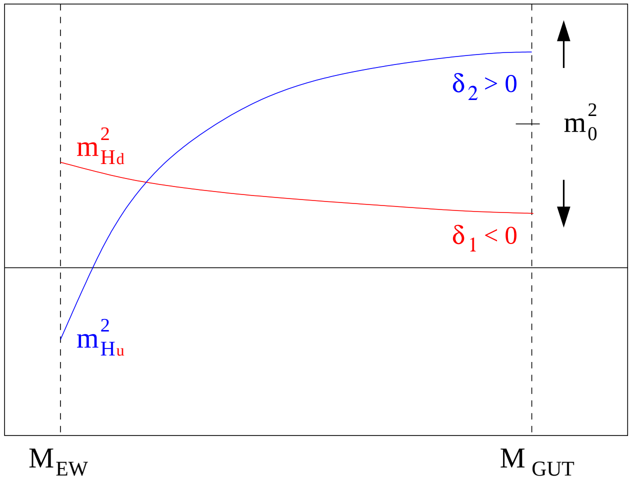
Non-universal scalar masses

Non-universal scalar masses can help increasing $\sigma_{\tilde{\chi}_1^0-p}$.

The most important effect is due to non-universalities in the Higgs masses at the GUT scale, which can be parametrized by δ_1 and δ_2:

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

RGES for the Higgs parameters



$$m_A^2 = m_{H_d}^2 - m_{H_u}^2 - M_Z^2$$

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

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

Non-universal scalar masses

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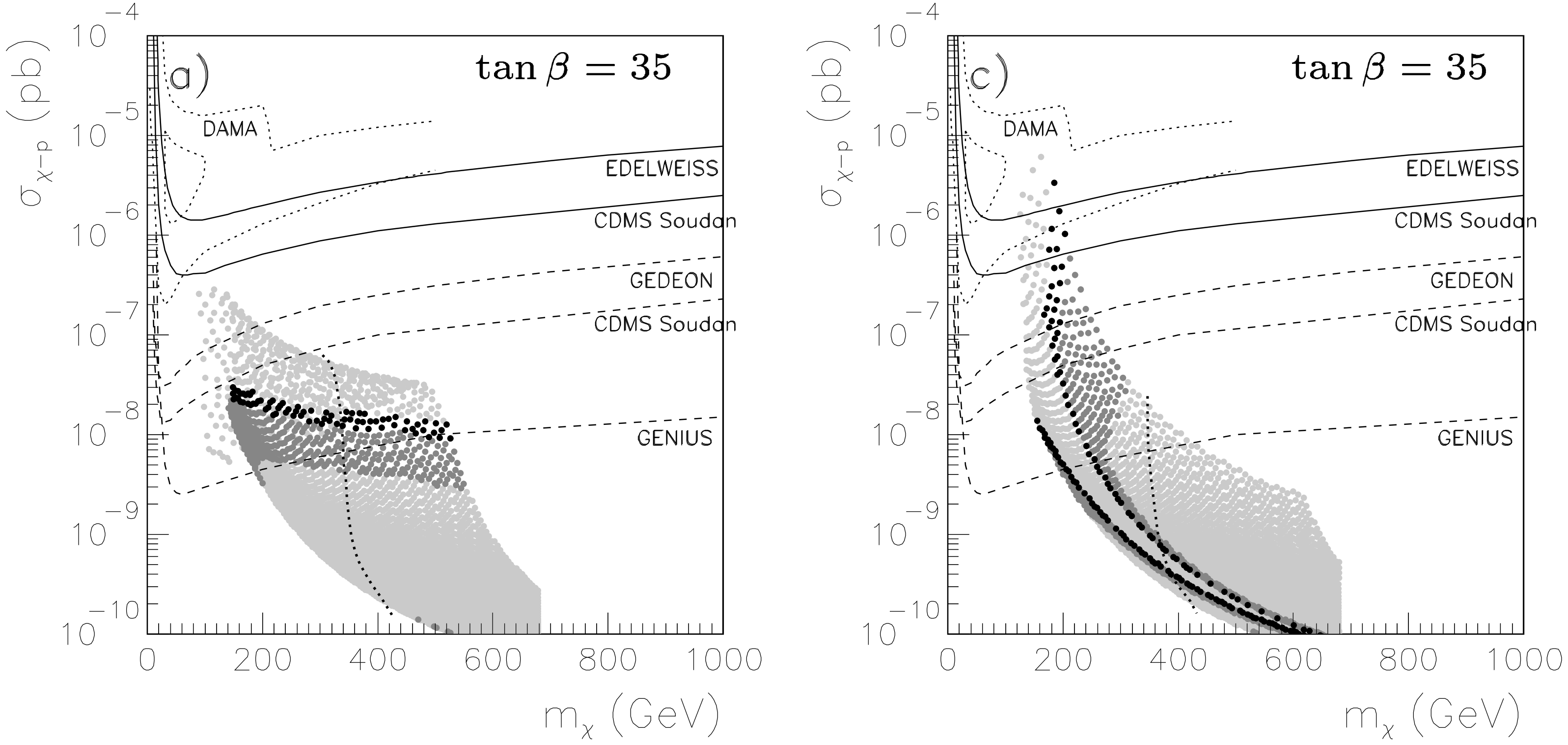
Summary

- $m_{H_d}^2 = m_0^2,\ m_{H_u}^2 = 2m_0^2$
- $m_{H_d}^2 = 0,\ m_{H_u}^2 = 2m_0^2$



Although in principle 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 $\tan\beta$ ...

$$\sigma_{\tilde\chi_1^0-p} \lesssim 3 \times 10^{-6}\,\text{pb}$$

Non-universal scalar masses

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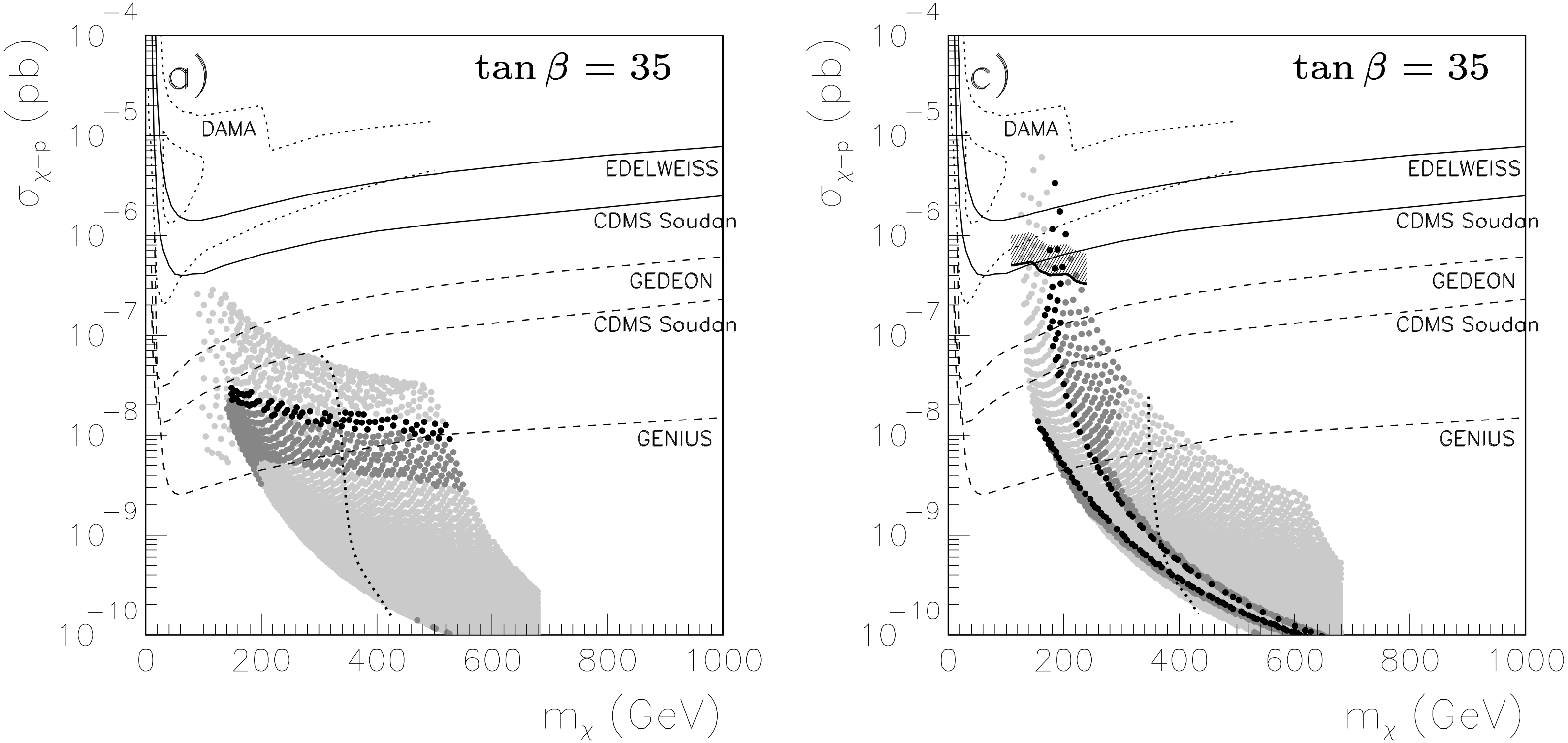

(Baek, D.G.C., Kim, Ko, Muñoz ’05)

. . . the recent experimental constraint on B($B^0_s \to \mu^+\mu^-$) rules out most of those regions.

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Non-universal scalar masses

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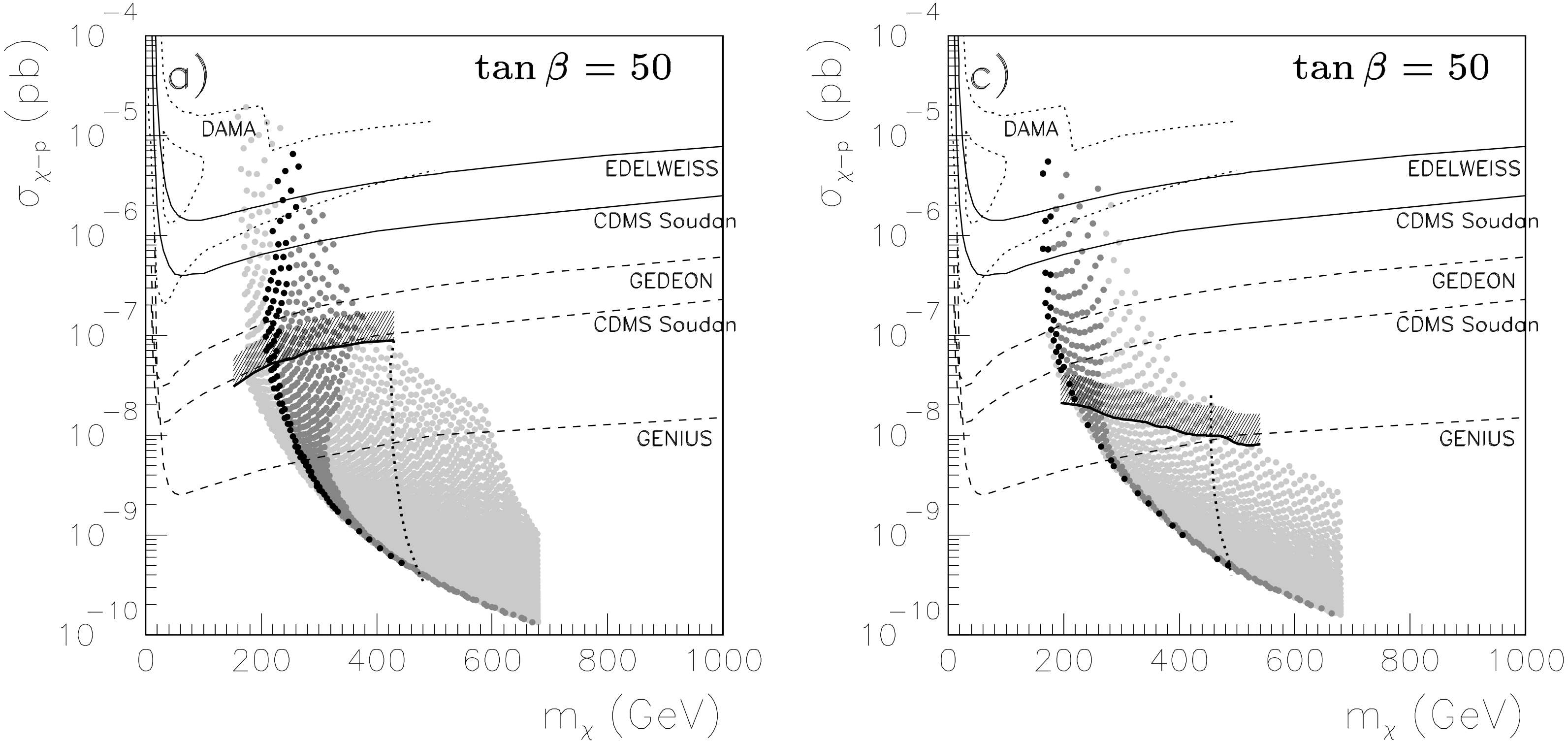

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. . . the recent experimental constraint on B($B_s^0 \to \mu^+\mu^-$) rules out most of those regions.

Especially in the large $\tan\beta$ regime, where neutralinos could escape detection in some of the projected experiments.

Correlation between $\sigma_{\tilde{\chi}_1^0-p}$ and B($B_s^0 \to \mu^+\mu^-$)

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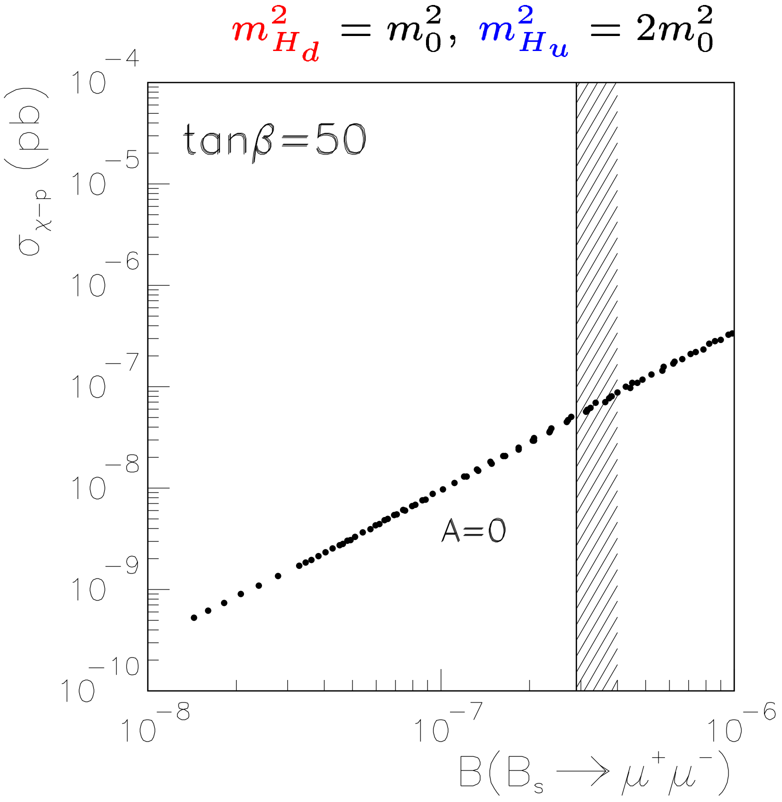
Summary

From the leading contribution to the B($B_s^0 \to \mu^+\mu^-$) process, the chargino mediated $b \to s$ transition one obtains the qualitative expression

$$\mathrm{B}(B_s^0 \to \mu^+\mu^-) \propto \frac{\tan\beta^6}{m_A{}^4} \left(\frac{\mu A_t}{m_{\tilde{t}}^2}\right)^2$$

Both observables, B($B_s^0 \to \mu^+\mu^-$) and $\sigma_{\tilde{\chi}_1^0-p}$, increase for large $\tan\beta$ and small m_A.



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- This implies that those points with larger $\sigma_{\tilde{\chi}_1^0-p}$ are typically excluded.

Correlation between $\sigma_{\tilde{\chi}_1^0-p}$ and B($B_s^0 \to \mu^+\mu^-$)

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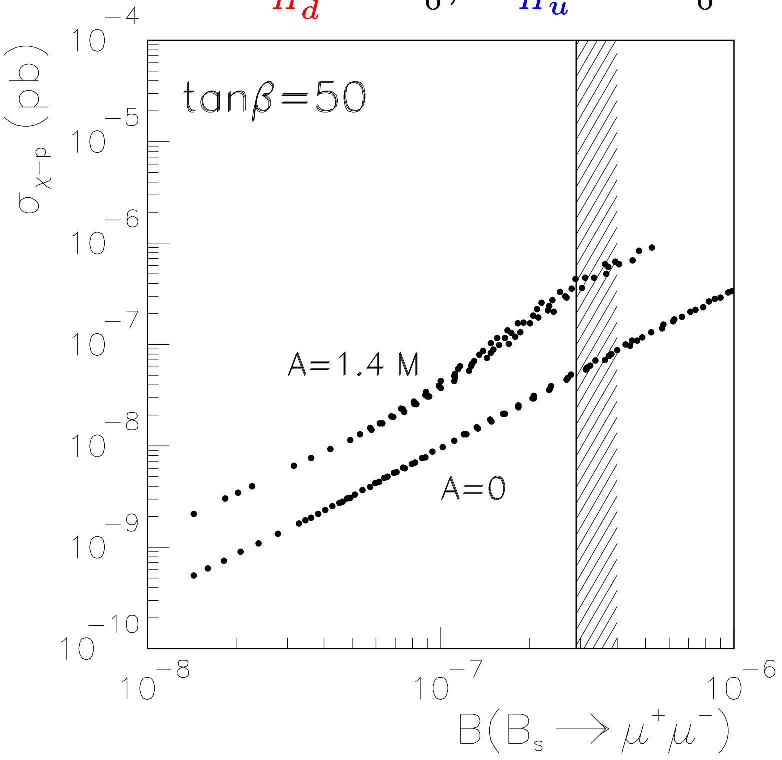

- This implies that those points with larger $\sigma_{\tilde{\chi}_1^0-p}$ are typically excluded.

- The correlation can be diluted if the term in parenthesis is reduced by
  - Decreasing the stop mixing (e.g., with $A > 0$)
  - Decreasing the Higgsino mixing (e.g., with non-universal Higgses)
  - Increasing the stop mass (e.g., with $A > 0$)

Correlation between $\sigma_{\tilde{\chi}_1^0-p}$ and B($B_s^0 \to \mu^+\mu^-$)

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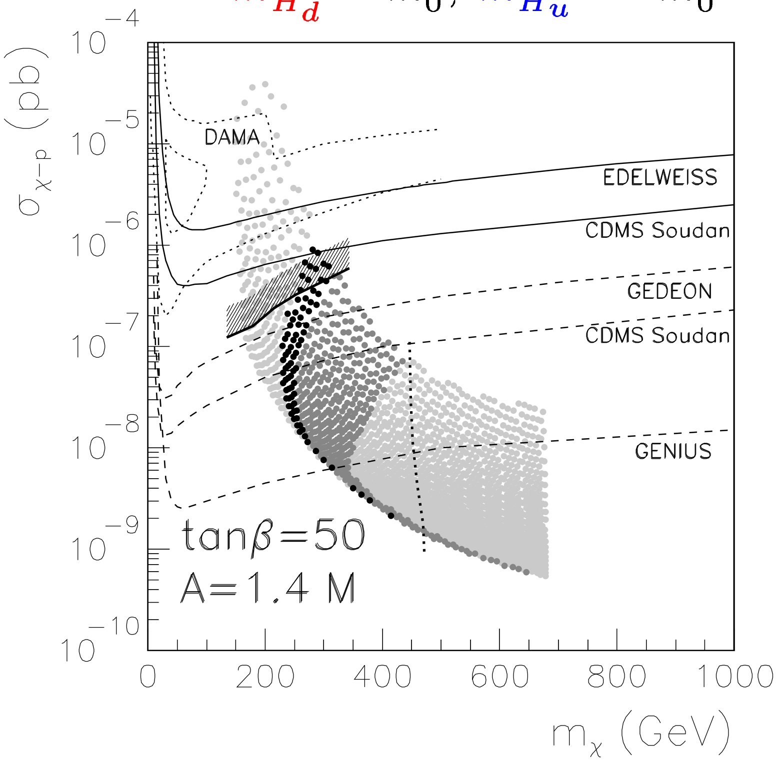

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  - Decreasing the stop mixing (e.g., with $A > 0$)
  - Decreasing the Higgsino mixing (e.g., with non-universal Higgses)
  - Increasing the stop mass (e.g., with $A > 0$)

- As a consequence, points with large $\sigma_{\tilde{\chi}_1^0-p}$ are still attainable.

Non-universal scalar and gaugino masses

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Summary

In the general case, non-universalities in scalars and gauginos provide more flexibility in the neutralino sector. Neutralinos with a wide range of masses can be obtained within the reach of dark matter detectors.

- Decrease $\frac{M_3}{M_1}$

The μ parameter decreases through the influence of M_3 on the RGEs of the Higgs parameters

Heavier neutralinos are found with a larger Higgsino composition.

The Higgs-exchanging interaction becomes more important and there is a slight increase of $\sigma_{\tilde{\chi}_1^0-p}$. There is also a reduction of $\Omega_{\tilde{\chi}_1^0}$.

Also, due to the decrease in μ, and the reduction in the stop mixing, B($B_s^0 \to \mu^+\mu^-$) slightly decreases. As a consequence, larger $\sigma_{\tilde{\chi}_1^0-p}$ are obtained.

Non-universal scalar and gaugino masses

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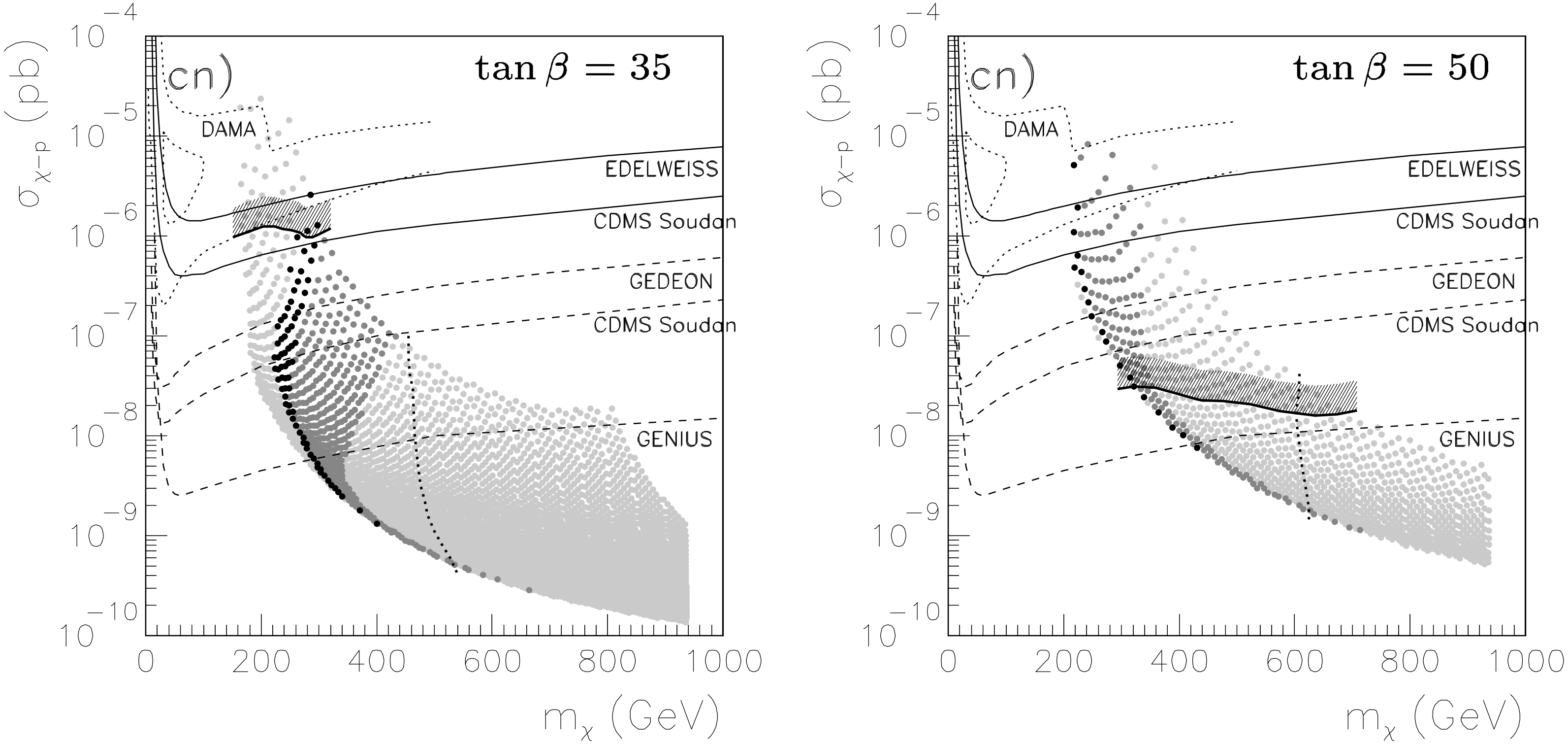
» Non-universal scalar and gaugino masses
» Very light neutralinos

Summary

In the general case, non-universalities in scalars and gauginos provide more flexibility in the neutralino sector. Neutralinos with a wide range of masses can be obtained within the reach of dark matter detectors.

- Decrease $\frac{M_3}{M_1}$

$$M_1 = \tfrac{4}{3} M_{2,3} \qquad m_{H_d}^2 = 0,\ m_{H_u}^2 = 2m_0^2$$



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Summary

In the general case, non-universalities in scalars and gauginos provide more flexibility in the neutralino sector. Neutralinos with a wide range of masses can be obtained within the reach of dark matter detectors.

- Increase $\frac{M_3}{M_1}$

The μ parameter increases

Lighter neutralinos are obtained, which have a larger Bino composition.

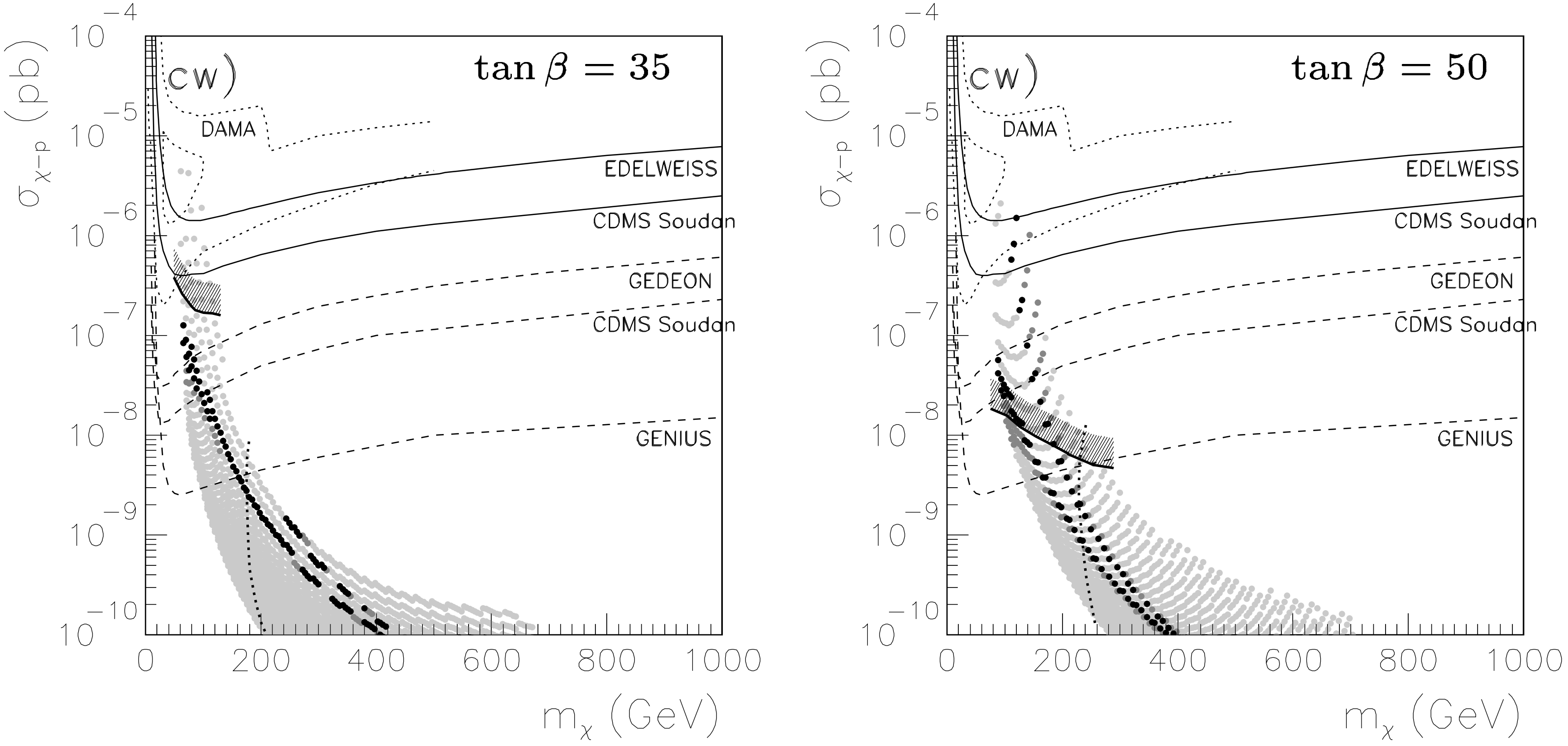
In this case, due to the increase in the μ parameter, and in the the stop mixing, B$(B_s^0 \to \mu^+\mu^-)$ increases, and smaller $\sigma_{\tilde{\chi}_1^0-p}$ are obtained.

Non-universal scalar and gaugino masses

In the general case, non-universalities in scalars and gauginos provide more flexibility in the neutralino sector. Neutralinos with a wide range of masses can be obtained within the reach of dark matter detectors.

- Increase $\frac{M_3}{M_1}$

$$M_1 = \frac{1}{2} M_{2,3} \qquad m_{H_d}^2 = 0,\ m_{H_u}^2 = 2m_0^2$$



Very light neutralinos

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Summary

- With $M_1 \ll M_{2,3},\ \mu$ very light (Bino-like) neutralinos can be obtained, which are compatible with experimental constraints.

(Griest, Roszkowski '92; Gabutti, Olechowski, Cooper, Pokorski, Stodolski '96; Hooper, Plehn '02)

Despite them having typically a too high relic density, a significant reduction in $\Omega_{\tilde{\chi}_1^0}$ can be obtained for large $\tan\beta$ if the mass of the CP-odd Higgs is small ($m_A \lesssim 200$ GeV).

(Bottino, Fornengo, Scopel '02; Bottino, Donato, Fornengo, Scopel '03 '04)

(Bélanger, Boudjema, Cottrant, Pukhov, Rosier-Lees '03)

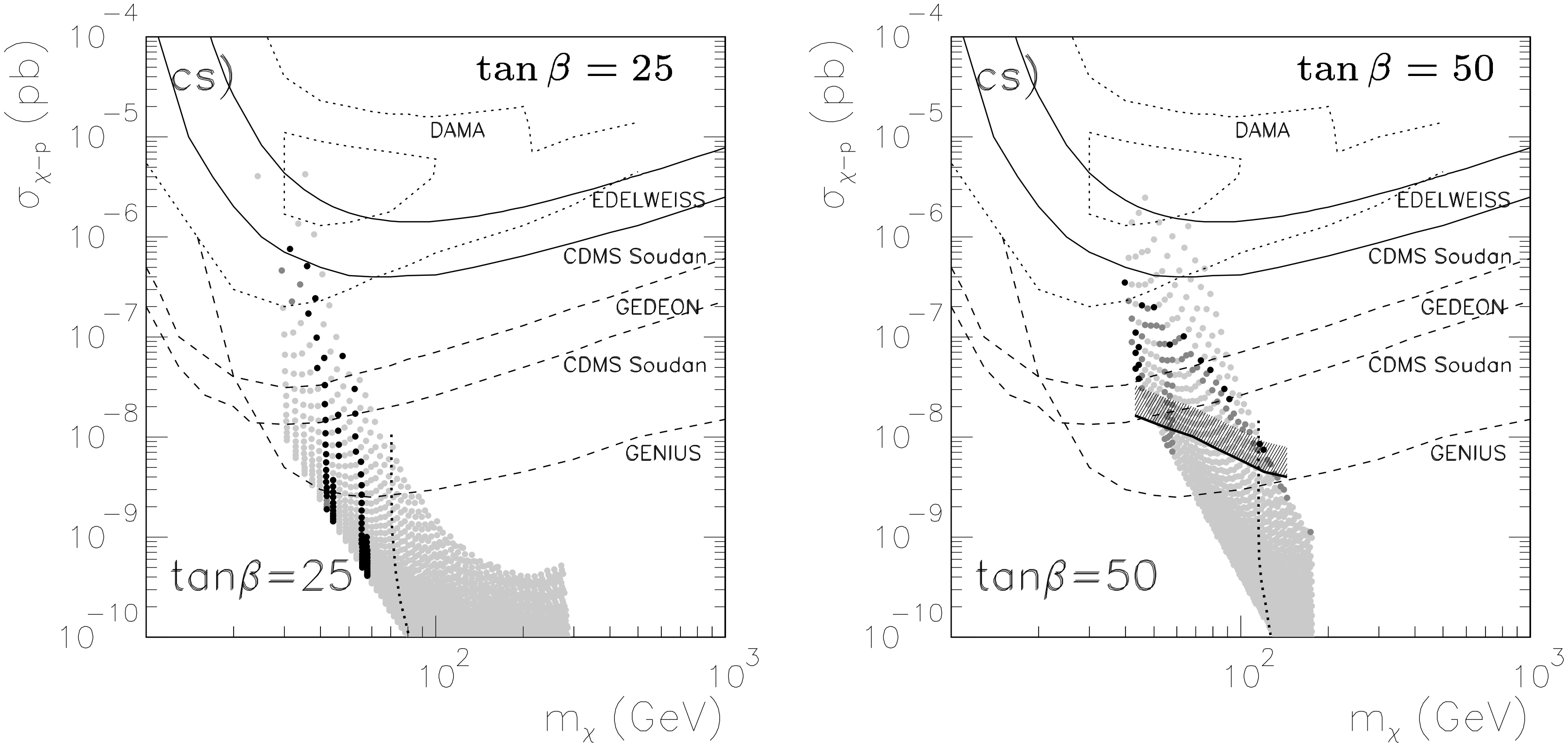
Although this can be achieved precisely with non-universalities in the Higgs masses, this entails a very large increase in B($B_s^0 \to \mu^+\mu^-$) and makes this possibility very constrained.

Very light neutralinos

- With $M_1 \ll M_{2,3},\ \mu$ very light (Bino-like) neutralinos can be obtained, which are compatible with experimental constraints.

Still, for moderate values of $\tan\beta$, neutralinos as light as $m_{\tilde{\chi}_1^0} \gtrsim 30$ GeV can be obtained with very large values for the detection cross section, $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-6}\mathrm{pb}$.

$$M_1 = \frac{1}{4} M_{2,3} \qquad m_{H_d}^2 = 0,\ m_{H_u}^2 = 2m_0^2$$



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- Supersymmetric theories can provide a natural dark matter candidate in terms of the Lightest SUSY particle.

- 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.

- In Supersymmetric models, experimental and astrophysical data play a leading role in constraining the parameter space. The recent B($B_s^0 \to \mu^+\mu^-$) constraint lead to important 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.

- Still, one cannot forget other well motivated Supersymmetric candidates: gravitinos and axinos

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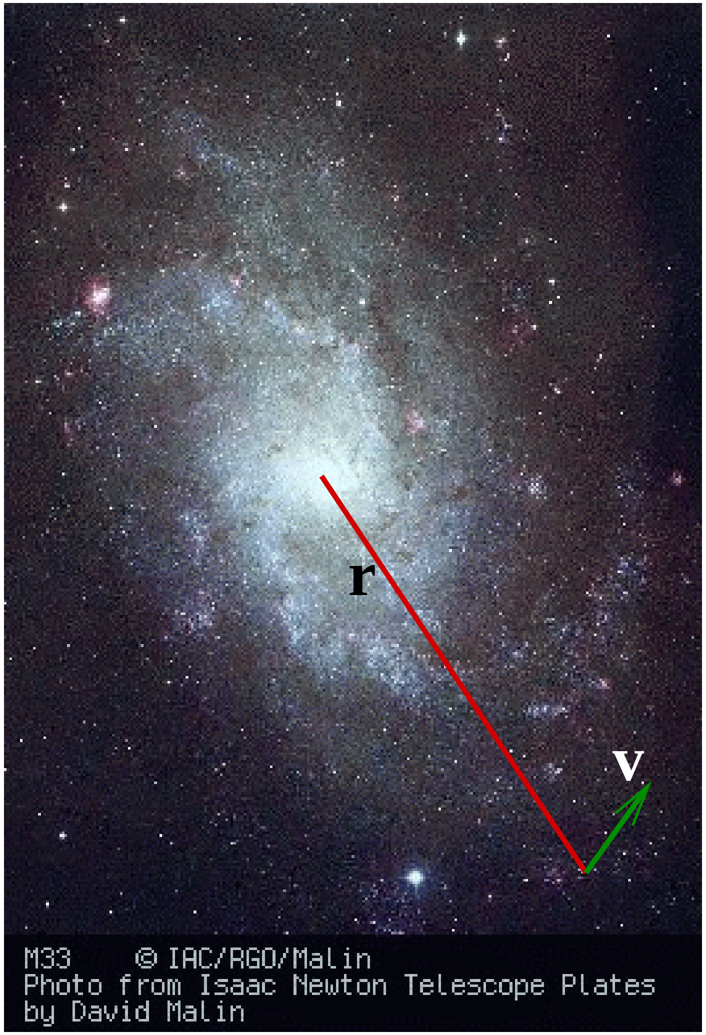

M33 © IAC/RGO/Malin
Photo from Isaac Newton Telescope Plates
by David Malin

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

- 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

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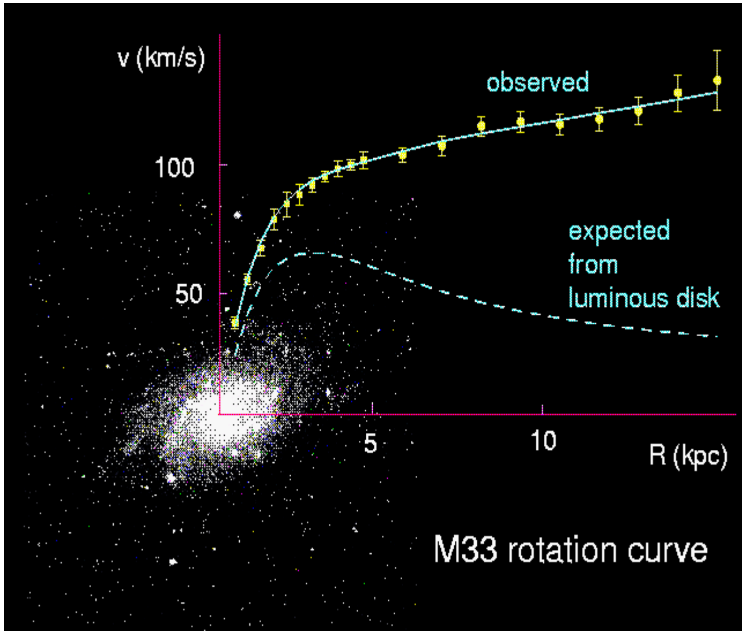

Roy '00, data from Corbelli, Salucci '99

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

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

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 $r \gg r_{disk}$

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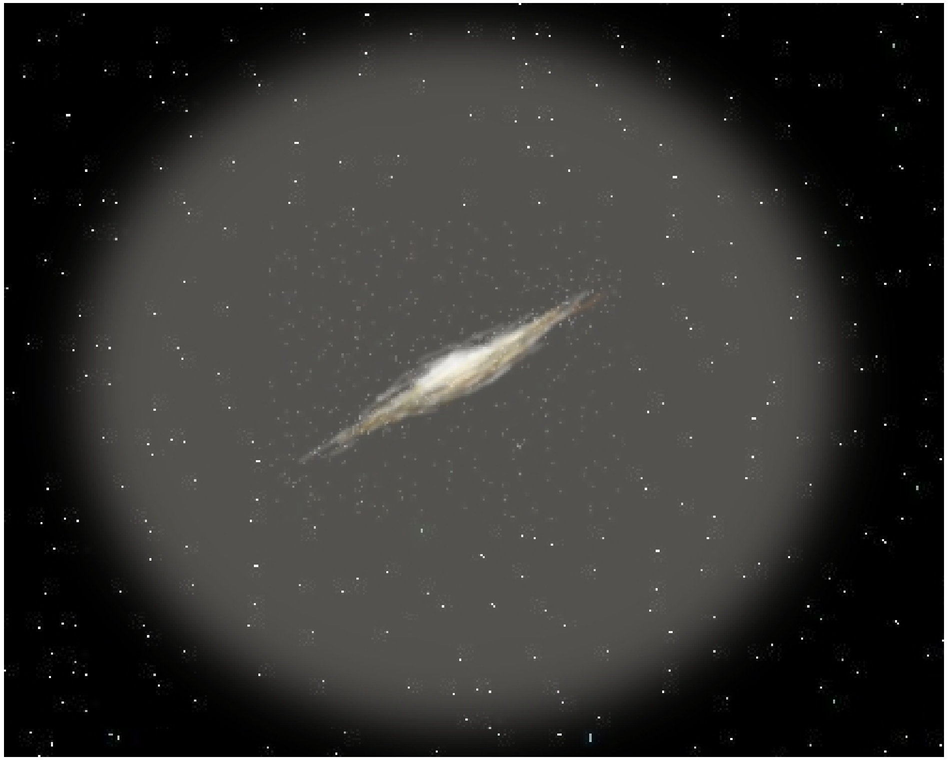
The galaxy is surrounded by a spherical halo of Dark Matter with



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

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

Clusters of galaxies

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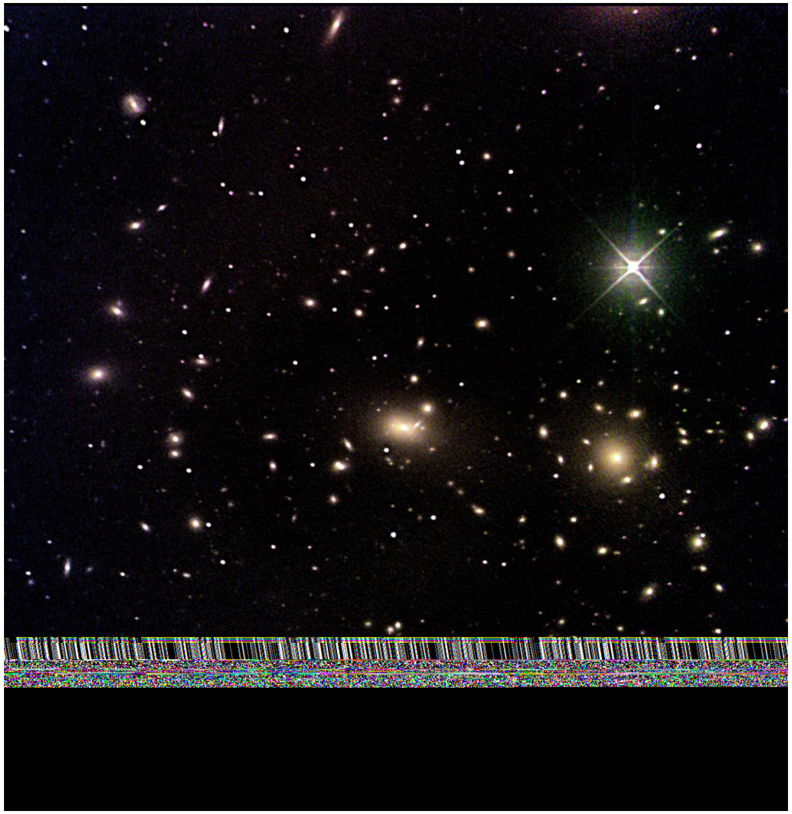

Coma Cluster

- 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)

mSUGRA

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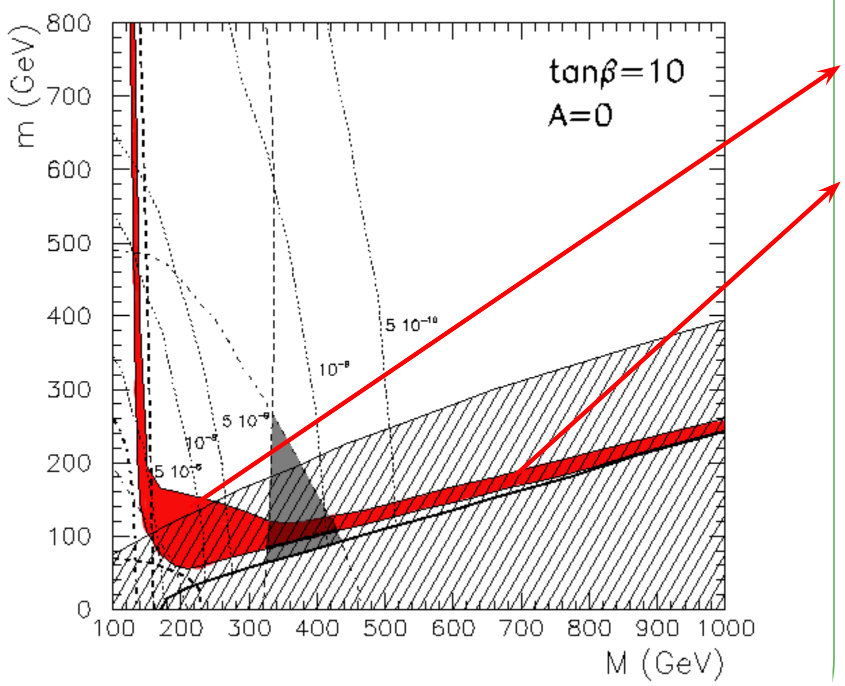
The constraint on the relic density leaves narrow accepted regions.



Bulk region

Coannihilation "tail" with Next-to-LSP (in this case the $\tilde{\tau}$)

mSUGRA

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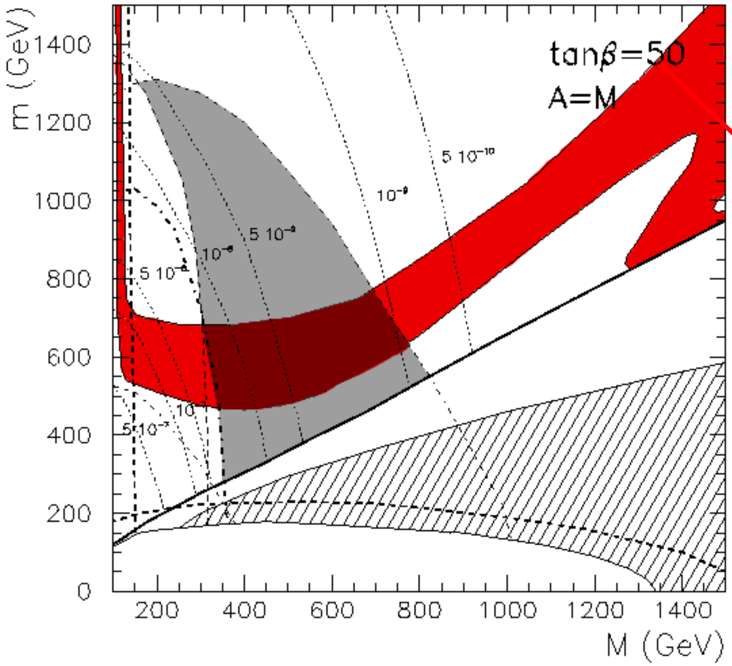

Bulk region

Coannihilation “tail” with Next-to-LSP (in this case the $\tilde{\tau}$)

Rapid annihilation through CP-odd Higgs