Supersymmetric candidates for Dark Matter

Nicolás Bernal

Departament d'Estructura i Constituents de la Matèria
& Institut de Ciències del Cosmos
Universitat de Barcelona

Steffen, arXiv:0811.3347 Hooper, arXiv:0901.4090

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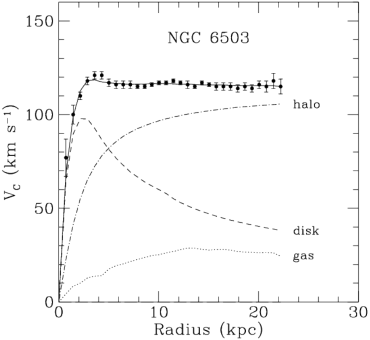
ICC - Journal Club

Dark Matter

The evidence for Dark Matter

- There are many hints at different scales
  - galaxy rotation curves



Galaxy rotation curves

$$v_c(r) \sim \sqrt{\frac{2\,G_N\,M(r)}{r}}$$

$$v_c(r) \sim const \quad \longrightarrow \quad M(r) \propto r$$

Dark Matter

The evidence for Dark Matter

➤ There are many hints at different scales

- galaxy rotation curves
- cluster of galaxies

Clusters of galaxies

- rotation curves
- gravitational lensing
  Light bends differently than predicted from GR, if only luminous matter is taken into account

Dark Matter

The evidence for Dark Matter

➤ There are many hints at different scales

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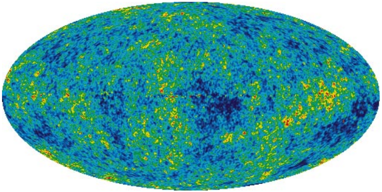
- cluster of galaxies
- CMB



CMB measurements

WMAP $\longrightarrow \quad \Omega_{DM} \sim 23\%$

Blackbody radiation almost homogeneous. Small inhomogeneities due to DM structures during due to DM structures during matter-radiation decoupling in the early universe

Dark Matter

The evidence for Dark Matter

➤ There are many hints at different scales

- galaxy rotation curves
- cluster of galaxies
- CMB

➤ **Dark Matter exists!**

It consists of particles

Permeates galactic haloes

Dark Matter

The evidence for Dark Matter

- ➤ There are many hints at different scales
  - galaxy rotation curves
  - cluster of galaxies
  - CMB

➤ **Dark Matter exists!**
It consists of particles
Permeates galactic haloes

➤ **So, what is the Dark Matter?**

Standard Model

The SM do not provide a good candidate for Dark Matter.

SM neutrinos could be a candidate but they are too light (HDM) implying top-down scenarios not supported by the present observations (the galaxies seems older than clusters).

Standard Model and beyond

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There are other candidates beyond the Standard model?

- Heavy neutrinos Lee & Weinberg, 77; Dolgov, 02; Griest & Kamionkowski, 90
- Sterile neutrinos Dodelson & Widrow, 93; Abazajian, Fuller & Patel, 01
- Axions Peccei & Quinn, 97; Rosenberg & van Bibber, 00
- ➤ SUSY (LSP)
- Extra dimensions (LKP) Cheng, Feng & Matchev, 02; Agashe & Servant, 04
- Scalar Dark Matter Boehm, Fayet & Silk, 04
- Dark Matter form little Higgs model Birkedal & Wacker, 03

MSSM

The MSSM is the minimal supersymmetrical extension of the SM
Additionally to solve

- Hierarchy problem
- Unification of gauge couplings

The MSSM with R-parity could provide a good candidate for DM.

MSSM

R-parity

R-parity introduced to avoid

- baryon number and lepton number violation
- too fast proton decay

$$R = (-1)^{3B+L+2S}$$

$R = +1$ for ordinary particles
$R = -1$ for SUSY particles

Important phenomenological consequences

- SUSY particles always produced in pairs
- a SUSY particle decays in an odd number of SUSY particles
- ➤ the lightest SUSY particle is stable

MSSM bestiary

Quarks	$u_{R,L}$ $d_{R,L}$ $c_{R,L}$ $s_{R,L}$ $t_{R,L}$ $b_{R,L}$
Leptons	$e_{R,L}$ ν_e $\mu_{R,L}$ ν_μ $\tau_{R,L}$ ν_τ
Gauge bosons	Z^0, $W^\pm$, g

Squarks	$\tilde{u}_{R,L}$ $\tilde{d}_{R,L}$ $\tilde{c}_{R,L}$ $\tilde{s}_{R,L}$ $\tilde{t}_{R,L}$ $\tilde{b}_{R,L}$
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Charginos	$\chi_1^\pm, \chi_2^\pm$
Neutralinos	χ_1^0, χ_2^0 χ_3^0, χ_4^0
Gluinos	$\tilde{g}$

Dark matter candidate must be:

- Electrically neutral

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- Two potentially good candidates
  - lightest sneutrino
  - lightest neutralino

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- Two potentially good candidates
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- In SUGRA models
  - gravitino
- MSSM + PQ mechanism
  - axino

Neutralinos in the MSSM

Neutralinos in the MSSM are physical superpositions of
the gauginos (bino $\tilde{B}$ and wino $\tilde{W}$) and the Higgsinos ($\tilde{H}_u$ and $\tilde{H}_d$)

Neutralinos are **WIMPs**, thermally produced.

Mass matrix

$$\mathcal{M}_{\chi^0} = \begin{pmatrix} M_1 & 0 & -M_Z\, s_\theta\, c_\beta & M_Z\, s_\theta\, s_\beta \\ 0 & M_2 & M_Z\, c_\theta\, c_\beta & M_Z\, c_\theta\, s_\beta \\ -M_Z\, s_\theta\, c_\beta & M_Z\, c_\theta\, c_\beta & 0 & -\mu \\ -M_Z\, s_\theta\, s_\beta & M_Z\, c_\theta\, s_\beta & -\mu & 0 \end{pmatrix}$$

M_i: gaugino masses, break SUSY softly
μ: higgsino mass, appear in the superpotential

Lightest neutralino

$$\chi_1^0 = N_{11}\, \tilde{B}^0 + N_{12}\, \tilde{W}^0 + N_{13}\, \tilde{H}_d^0 + N_{14}\, \tilde{H}_u^0$$

➤ The detection properties of the lightest neutralino depend on its composition

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Let us recall that M_1, M_2 and μ are not (usually) free parameters

- μ fixed by the requirement of a proper radiative EW symmetry breaking

$$\mu^2(M_Z) = \frac{m^2_{H_2}\ \sin^2\beta - m^2_{H_1}\ \cos^2\beta}{\cos 2\beta} - \frac{M_Z^2}{2}$$

- M_1 and M_2 fixed at a grand unification scale ($M_{GUT} \sim 2 \cdot 10^{26}$ GeV) and then evolved down to the EW scale by the use of the RGE
$\rightarrow \quad M_1 = \frac{5}{3}\ \tan^2\theta_W \sim M_2/2$ at $Q = M_Z$

cMSSM

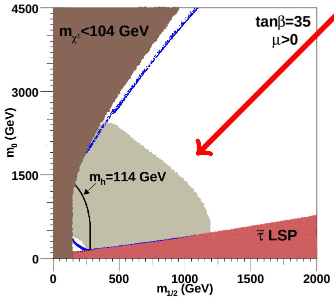
The most general MSSM contains $\sim$ 120 free parameters.
We need a phenomenologically viable model!

Constraining the MSSM

The constraint MSSM contains 5 free parameters

- $\tan\beta$: ratio of the vevs
- sign(μ)
- $m_{1/2}$: Universal gaugino mass
- m_0: Universal scalar (sfermions and Higgs bosons) mass
- A_0: Universal trilinear couplings

cMSSM



Bulk region

* Neutralino is bino-like
* Light sleptons

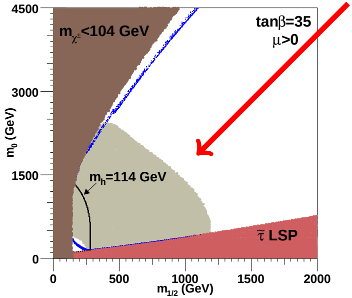
→ annihilation via slepton exchange into a lepton pair:

$$\chi_1^0 \chi_1^0 \to l^+ \, l^-$$

➤ But annihilation cross section small and then Ωh^2 too large

Steffen, 08; Hooper, 09

cMSSM



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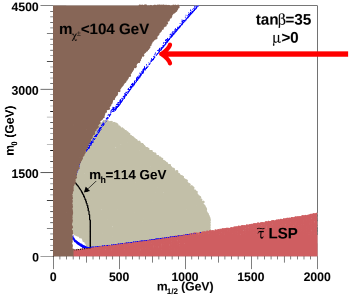
We need to enlarge the annihilation cross section!

cMSSM



Focus point

* Neutralino is a Bino-Higgsino mixture

* Annihilation into vector bosons becomes efficient

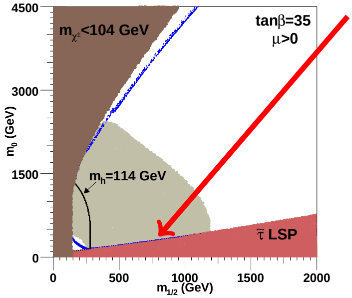
$$\chi_1^0 \chi_1^0 \rightarrow W^+ W^-, Z^0 Z^0$$

Vector bosons only couple to Higgsino-like neutralinos!

➤ Good relic density

Steffen, 08; Hooper, 09

cMSSM



Coannihilation region

* If LSP and NLSP almost degenerate in mass
* Important enhancement for the cross-section

$$\chi_1^0\,\tilde{\tau} \to \tau\, h,\ \tau\, Z,\ \tau\,\gamma \qquad \sigma \propto Exp[-\Delta_m]$$

$$\tilde{\tau}\,\tilde{\tau} \to \tau\,\tau,\ h\,h,\ \gamma\,\gamma \qquad \sigma \propto Exp[-2\,\Delta_m]$$

$$\Delta_m \equiv (m_{NLSP} - m_{LSP})/m_{LSP}$$

Griest & Seckel, 91

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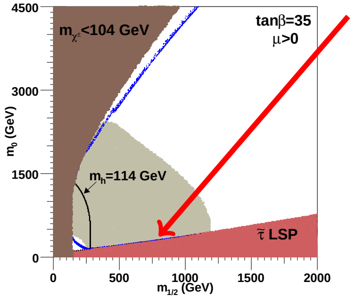

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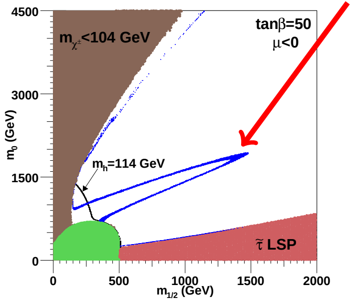
Coannihilation could also take place with any other SUSY particle: $\chi^{\pm}, \chi^0, \tilde{g}\ldots$

cMSSM



Steffen, 08; Hooper, 09

Higgs funnel (for large $\tan\beta$)

$$M_A^2 \propto -\frac{1}{\cos 2\beta} B\,\mu$$

* In the region when $M_A \sim 2\,M_{\chi_1^0}$

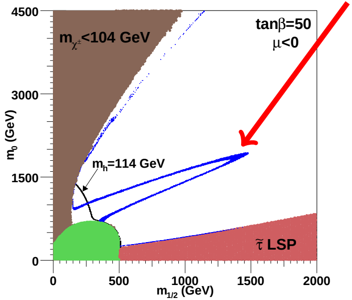
* Resonance in the *s*-channel

$$\chi_1^0 \chi_1^0 \rightarrow A \rightarrow b\,\bar{b}$$

For large $\tan\beta$, $Ab\bar{b}$ coupling enhanced

➤ Good relic density

cMSSM



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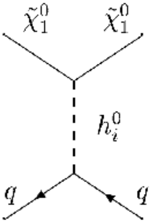
Note that it is also possible to have resonances with h or Z in the general MSSM

Neutralinos: Direct detection

Spin-independent cross section

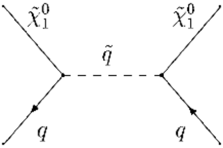


Higgs exchange

$$\sigma_{\chi_1^0-p} \propto \frac{m_r^4}{4\pi}\frac{y_q^2}{m_h^4}\left|N_{13,14}\,(g'\,N_{11} - g\,N_{12})\right|^2$$

It is the leading contribution. Maximum enhancement for:

- Higgsino-líke neutralino $\quad (\mu \ll M_1)$
- low Higgs mass



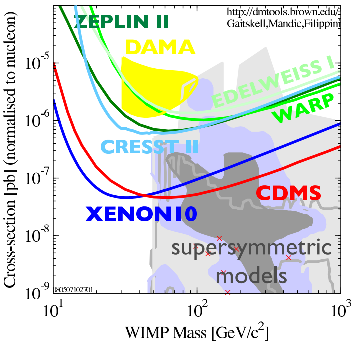
squark exchange

$$\sigma_{\chi_1^0-p} \propto \frac{m_r^2}{4\pi}\left(\frac{g'^2\,\sin\theta_W}{m_{\tilde{q}}^2 - m_\chi^2}\right)^2 |N_{11}|^4$$

- only relevant for a bino-like neutralino $(M_1 \ll \mu)$

Neutralinos: Direct detection

Spin-independent cross section

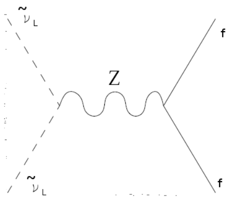


Exclusion regions for different SUSY models

- Baltz & Gondolo, 03
- Baltz & Gondolo, 04
- Ellis, Feng, Ferstl, Matchev & Olive, 02
- Battaglia et al., 04
- Roszkowski, Ruiz de Austri & Trotta, 07

Sneutrinos in the MSSM

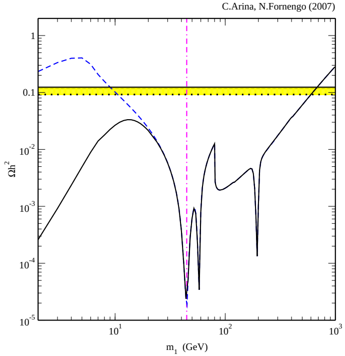
➤ In the MSSM sneutrinos are pure left-handed!
Pure left-handed sneutrinos are **WIMPs** thermally produced.
They faces some problems. . .

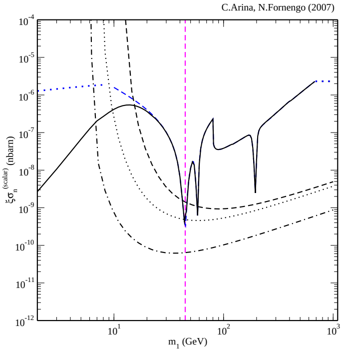


Sneutrino (left-handed) coupling with *Z* boson is rather large, leading to

- ➤ Too large annihilation cross-section
  → implying too small relic density
  Ibáñez, 84; Ellis, Hagelin, Nanopoulos & Olive, 84; Hagelin, Kane & Rabi, 84; Goodmann & Witten, 85; Freese, 86
- ➤ Too large direct detection cross section already disfavoured by current experiments
  Falk, Olive & Srednicki, 94

Sneutrinos in the MSSM





Too large annihilation cross-section

Too large direct detection cross section

Arina & Fornengo, 07; Arina, 08

Sneutrinos in extended SSM

- These problems can be alleviated by reducing the $Z\tilde{\nu}\tilde{\nu}$ coupling

This can be done by including a ‘sterile’ (e.g. right-handed sneutrino) component with which the left-handed sneutrino can mix!!!

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$$\tilde{\nu} = \cos\theta\,\tilde{\nu}_L + \sin\theta\,\tilde{N}$$

- smaller annihilation cross section
- smaller detection cross section

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However in SUGRA sneutrino mixing is proportional to small neutrino Yukawas
→ No enough mixing

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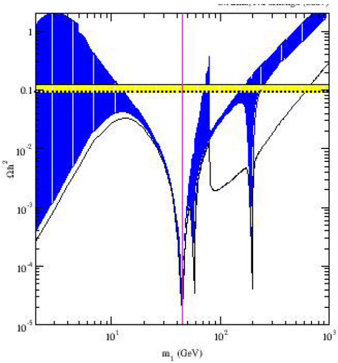


Model independent:

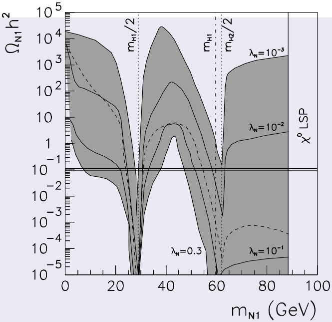
$$\tilde{\nu} = \cos\theta\, \tilde{\nu}_L + \sin\theta\, \tilde{N}$$

letting θ as a free parameter

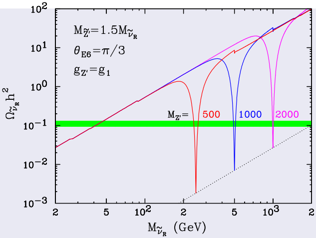
Arina & Fornengo, 07; Arina, 08

Pure right-handed Sneutrinos

Alternatively, a pure right-handed sneutrino could give rise to the good relic density (no coupling with Z boson)



Cerdeño, Muñoz & Seto, 08



Lee, Matchev & Masri, 07

➤ However: in general very small detection cross section (would not account for a WIMP observation)

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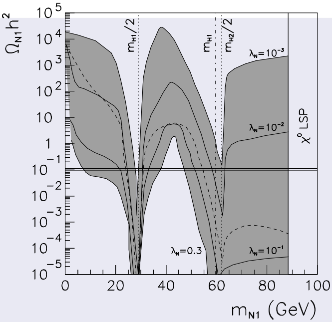
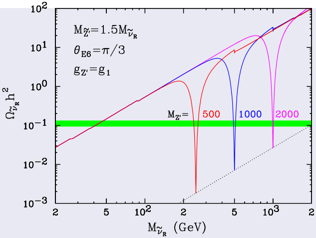


Cerdeño, Muñoz & Seto, 08



Lee, Matchev & Masri, 07

➤ Right-handed sneutrinos could explain **PAMELA** and **ATIC** data!
Allahverdi, Dutta, Richardson-McDaniel & Santoso, 09

Gravitino

* Assuming that SUSY is realized not only as global
but also as a local symmetry: $\tilde{G}$ with spin $3/2$
* Gravitino appears in *gauge-mediated* and *gravity-mediated*
SUSY breaking schemes
* Gravitino is a singlet with respect to the gauge groups of the SM

Gravitino is a very weakly interacting particle
Interactions typically given by dim 5 operators $\rightarrow$ suppressed by $1/M_P$

- Practically undetectable (except for this gravitational effect)
- NLSP could be long-lived! $\tau_{NLSP} \sim 1$ s

Many possibilities for the NLSP ($\tilde{\chi}_1^0$, $\tilde{\nu}$, $\tilde{t}\ldots$) each with its own phenomenology

Gravitino

Gravitino DM relic density

$$\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{T} h^2 + \Omega_{\tilde{G}}^{NT} h^2$$

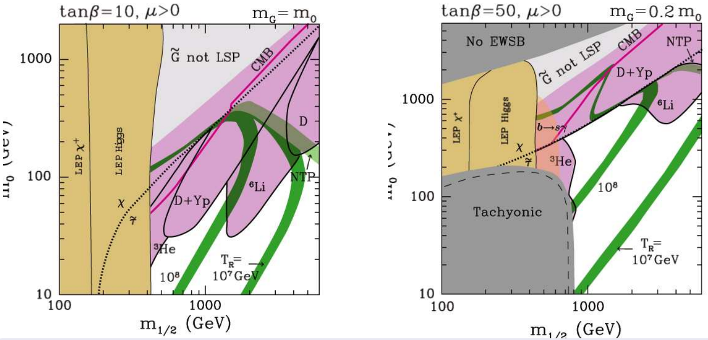
High decoupling temperature because of they extremely weak interactions.

$$\text{Thermal:} \quad \Omega_{\tilde{G}}^{T} h^2 \simeq 0.27 \left(\frac{T_R}{10^{10}\,\text{GeV}} \right) \left(\frac{100\,\text{GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{1/2}}{1\,\text{TeV}} \right)^2$$

Non-thermal production comes from the decay NLSP → LSP + X

$$\text{Non-thermal:} \quad \Omega_{\tilde{G}}^{NT} h^2 = \frac{m_{3/2}}{m_{NLSP}} \Omega_{NLSP} h^2$$

Gravitino in the cMSSM



Cerdeño, Choi, Jedamzik, Roszkowski & Ruiz, 05

Regions with the correct relic density:
* only non-thermal production vs. * thermal and non-thermal production

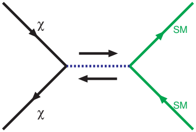
➤ Non-thermal production alone is not sufficient. Large contributions from thermal processes are necessary.

Conclusions

- The existence of dark matter provides strong evidence for physics beyond the Standard Model.
- SUSY could provide many candidates: χ_1^0, $\tilde{\nu}$
  but also $\tilde{G}$ (for local SUSY), axino (if PQ symmetry).
- The lightest neutralino is the most promising.
  Could be tested by direct and indirect detection experiments but also in colliders as pure missing E_T.
- Pure left-handed sneutrino is already excluded, but a mixing with a right-handed sneutrino could give rise to a good DM candidate.
- For gravitinos, Dark matter experiments would not detect anything!
  However, in accelerators (LHC): detection of a (meta)-stable and electrically charged NLSP ($\tilde{\tau}$).

Relic Density

Principle of 'Thermal Relics' (Simplest scenario)



- Begin from a state of thermodynamical equilibrium.
- The universe expands → its temperature falls.
  SM particles no longer energetic enough to produce $\chi\chi$ pairs.

➤ χ's density falls asymptotically.

Evolution described by the Boltzmann equation

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\,(n^2 - n_{eq}^2)$$

A gross estimation of a particle's relic density can be provided by

$$\Omega\,h^2 \sim \frac{3\cdot 10^{-27}\,cm^3\,s^{-1}}{\langle\sigma v\rangle} \sim \frac{1}{\langle\sigma v\rangle} \sim \frac{m_\chi^2}{g_\chi^4}$$

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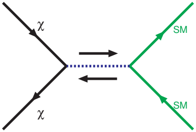

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cMSSM

The most general MSSM contains $\sim$ 120 free parameters.
We need a phenomenologically viable model!

Constraining the MSSM

- All the soft SUSY-breaking parameters are real
- The matrices for the sfermions masses are diagonal
- The matrices for the trilinear couplings are diagonal
- The soft sfermion masses and trilinear couplings are equal for the 1^{st} and 2^{nd} generation
- Universality at M_{GUT}

cMSSM

The most general MSSM contains $\sim$ 120 free parameters.
We need a phenomenologically viable model!

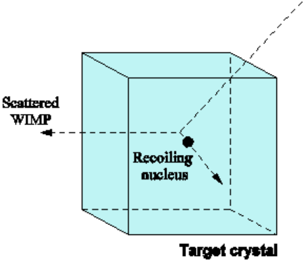
Constraining the MSSM

The constraint MSSM contains 5 free parameters

- $\tan\beta$: ratio of the vevs
- sign(μ)
- $m_{1/2}$: Universal gaugino mass
- m_0: Universal scalar (sfermions and Higgs bosons) mass
- A_0: Universal trilinear couplings

Direct Detection

The direct detection of Dark Matter can take place through their interaction with nuclei inside a detector



The nuclear recoiling energy is measured

- Ionization on solids
- Ionization in scintillators (measured by the emitted photons)
- Temperature increase (measured by the released phonons)

Problems

- Very small interaction rate
- Large backgrounds (experiments must be deep underground)
- Uncertainties in the DM properties in our galaxy

Neutralinos and PAMELA

Two main options:

A 200 GeV wino-like neutralino annihilating into $W^+ W^-$ could explain Pamela data

But: ✘ Wino-like neutralinos usually coannihilates with the lightest chargino generating not enough relic density

✘ A large variation on the rate of energy loss of the positrons is needed

✘ Not possible to explain at the same time Pamela and Atic data

Grajek, Kane, Phalen, Pierce & Watson, 08

A 600 – 1000 GeV wino-like neutralino annihilating into $W^+ W^-$

But: ✘ a large nearby ($\sim 1 - 2$ kiloparsecs of the Solar System) clump of annihilating neutralinos is needed

Hooper, Stebbins & Zurek, 08

Gravitino Dark Matter

- Gravitino production mechanisms