Supersymmetric Dark Matter

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Outline of the talk

- Susy DM candidates and main susy scenarios
- The neutralino:
  - gaugino non universality & neutralino mass
  - cosmological lower bound on $m_\chi$ from WMAP
  - direct searches
  - indirect searches
- Conclusions

LIGHT NEUTRALINOS
($m_\chi \leq 50$ GeV)
“Indirect signals from light neutralinos in supersymmetric models without gaugino mass unification”, A. Bottino, F. Donato, N. Fornengo, S. Scopel, hep-ph/0401186

“Light neutralinos and WIMP direct searches”, A. Bottino, F. Donato, N. Fornengo, S. Scopel, hep-ph/0307303


Dark Matter Candidates

- light neutrino
- heavy neutrino
- axion
- Kaluza-Klein partners
- sneutrino
- GMSB messengers
- axino
- gravitino
- neutralino
- ...

\{ SUSY \}
Supersymmetry and Dark Matter

Supersymmetry:
fermions ↔ bosons

<table>
<thead>
<tr>
<th>R=1</th>
<th>R=-1</th>
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<tbody>
<tr>
<td>leptons,quarks</td>
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<td>gauge fields</td>
<td>gauginos</td>
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<td>Higgs fields</td>
<td>higgsinos</td>
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R-parity conservation forbids barion number violation at the tree level

...and prevents the decay of the Lightest Susy Particle (LSP)
THE LSP CAN BE THE DARK MATTER

Supersymmetry must be broken
Different Susy mechanisms imply different DM candidates:

- Gravity Mediated
  → neutralino (Bino,Higgsino)
- Anomaly Mediated
  → neutralino(Wino), stau sneutrino
- Gauge Mediated
  → gravitino,
  GMSB messangers
SUSY schemes (Gravity Mediated Susy breaking)

- **Universal SUGRA**: unification of soft breaking terms at $M_{GUT} \approx 10^{16}$ GeV + Radiative Electro–Weak Symmetry Breaking (REWSB)

- **Non–universal SUGRA**: deviation from universality of soft breaking terms at $M_{GUT}$ (Higgs sector, sfermions, gauginos)

- **Effective MSSM**: effective model at the EW scale with a few MSSM parameters which set the most relevant scales
Supergravity-inspired models (SUGRA)

GUT-scale ($M_{GUT} \approx 10^{16}$ GeV) relations:

- Unification of gaugino masses: $M_i(M_{GUT}) \equiv m_{1/2}$

- Unification of scalar masses: $m_i(M_{GUT}) \equiv m_0$

- Universality of trilinear couplings: $A_u(M_{GUT}) = A_d(M_{GUT}) = A_l(M_{GUT}) \equiv A_0 m_0$

Other parameters: $\text{sign}(\mu), \tan \beta$

Typical predictions:
- $\chi \rightarrow \text{gaugino}$ (except "focus point region", $m_0 \gg m_{1/2}$)
- $m_A \gg O(m_Z)$ unless $\tan \beta \gtrsim 50$
- $\mu - M_2$ correlation
- $m_{\text{quark}} > m_{\text{slepton}}$

Deviations from universality at $M_{GUT}$ or a different unification scale imply significant modifications of these properties.
SUGRA


For tan $\beta = 10$, $\mu > 0$:
- $m_\chi = 114$ GeV
- $m_{1/2} = 104$ GeV

For tan $\beta = 50$, $\mu > 0$:
- $m_\chi = 114$ GeV

Allowed by Cosmology
The neutralino

The neutralino is defined as the lowest-mass linear superposition of bino $\tilde{B}$, wino $\tilde{W}^{(3)}$ and the two higgsino states $\tilde{H}_1^0$, $\tilde{H}_2^0$:

$$\chi = a_1 \tilde{B} + a_2 \tilde{W}^{(3)} + a_1 \tilde{H}_1^0 + a_1 \tilde{H}_2^0$$

- neutral, colourless, only weak-type interactions
- stable if R-parity is conserved, thermal relic
- non relativistic at decoupling $\rightarrow$ Cold Dark Matter (required by CMB data + structure formation models)

- relic density can be compatible with cosmological observations: $0.095 \leq \Omega_\chi h^2 \leq 0.131$
  $\rightarrow$ IDEAL CANDIDATE FOR COLD DARK MATTER
Most analysis on the SUSY model assume that **gaugino soft masses unify at the GUT scale**. Gaugino mass unification implies a lower bound on the neutralino mass:

\[ m_\chi \gtrsim 50 \text{ GeV} \]

However the assumption of gaugino mass unification at the GUT scale might not be justified (for instance, the gaugino unification scale may be much lower than the standard GUT scale).
Previous papers with $M_1 \neq M_2$ include...

Effective MSSM scheme (effMSSM) - Independent parameters

- $M_1$ U(1) gaugino soft breaking term
- $M_2$ SU(2) gaugino soft breaking term
- $\mu$ Higgs mixing mass parameter
- $\tan \beta$ ratio of two Higgs v.e.v.’s
- $m_A$ mass of CP odd neutral Higgs boson (the extended Higgs sector of MSSM includes also the neutral scalars $h, H$, and the charged scalars $H^\pm$)
- $m_{\tilde{q}}$ soft mass common to all squarks
- $m_{\tilde{\ell}}$ soft mass common to all sleptons
- $A$ common dimensionless trilinear parameter for the third family \((A_\tilde{b} = A_\tilde{t} \equiv Am_{\tilde{q}}; A_\tilde{\tau} \equiv Am_{\tilde{\ell}})\)
- $R \equiv M_1 / M_2$

SUGRA $\rightarrow R = 0.5$
Lower limit on the neutralino mass from $m_\chi \geq 31\text{GeV}$

Warning: this limit is model dependent!
Lower limits on the neutralino mass from accelerators

- **Indirect limits from chargino production** ($e^+e^- \rightarrow \chi^+\chi^-$):

  $$m_{\chi^\pm} \gtrsim 100 \text{ GeV} \Rightarrow m_\chi \gtrsim 50 \text{ GeV} \quad \text{if} \quad R \equiv \frac{M_1}{M_2} = \frac{5}{3} \tan^2 \theta_w$$

- **Direct limits from** $e^+e^- \rightarrow \chi_0^i\chi_0^j$ ($\chi_0^1 \equiv \chi$, $m_{\chi_0^1} < m_{\chi_0^2} < m_{\chi_0^3} < m_{\chi_0^4}$):
  - Invisible width of the Z boson (upper limit on number $N_\nu$ of neutrino families)
  - Missing energy + photon(s) or $f\bar{f}$ from $\chi_0^{i>1} \rightarrow \chi_0^1$ decay

- **Direct limits from** $\tilde{t} \rightarrow c\chi$ and $\tilde{b} \rightarrow b\chi$ at Tevatron
  - $\dagger$ small production cross sections
  - $\ddagger$ light squark masses ($\lesssim 100 \text{ GeV}$) required

- **No absolute direct lower bounds on** $m_\chi$
Mass matrices: Neutralino vs. chargino

**Neutralino**

\[
\begin{pmatrix}
M_1 & 0 & -m_Z \sin \theta_W \cos \beta & -m_Z \sin \theta_W \sin \beta \\
0 & M_2 & m_Z \cos \theta_W \cos \beta & -m_Z \cos \theta_W \sin \beta \\
-m_Z \sin \theta_W \cos \beta & m_Z \cos \theta_W \cos \beta & 0 & -\mu \\
-m_Z \sin \theta_W \sin \beta & -m_Z \cos \theta_W \sin \beta & -\mu & 0
\end{pmatrix}
\]

\(M_1\) appears only in neutralino mass. Limits on chargino mass affect \(M_2\)

**Chargino**

\[
\begin{pmatrix}
M_2 \\
\frac{m_W \sqrt{2} \sin \theta_W}{\mu}
\end{pmatrix}
\]

- If \(\mu \gg M_1, M_2 \Rightarrow m_\chi \sim \text{min}(M_1, M_2), \ m_{\chi^\pm} \sim M_2\)
- If \(\mu \ll M_1, M_2 \Rightarrow m_\chi \sim m_{\chi^\pm} \sim \mu\)
Properties of light neutralinos (R<0.5)

By diagonalizing the neutralino mass matrix for $M_1 << M_2, \mu$:

- $\chi \approx \tilde{B}$
- small $\tilde{H}_1^0$ component:
  \[ a_3/a_1 \approx \sin \theta_W \sin \beta \times \frac{M_Z}{\mu} \]
  \[ |a_3/a_1| \leq 0.42 \sin \beta \]
  (taking into account the experimental lower bound $|\mu|>100$ GeV)

\[ (a_1)^2 + (a_3)^2 = 1 \]
Experimental constraints

- accelerators data on supersymmetric and Higgs boson searches (CERN $e^+e^-$ collider LEP2 and Collider Detector CDF at Fermilab)

- measurements of the $b \to s \gamma$ decay

- measurement of the muon anomalous magnetic moment $a_\mu \equiv (g_\mu - 2)/2$
  
  (we use $-142 \leq \Delta a_\mu \cdot 10^{11} \leq 474$, M. Davier et al., Eur. Phys. J. C31 (2003) 503; K. Hagiwara et al., hep-ph/0312250)

- $B_S \to \mu^+ \mu^-$ decay, D. Acosta et al. (CDF Collaboration), hep-ex/0403032 (we use $\text{BR}(B_S \to \mu^+ \mu^-) \leq 9.5 \times 10^{-7}$)
$B_S \rightarrow \mu^+\mu^-$ decay

- SUSY contribution strongly enhanced at high $\tan \beta$ and low $m_A (\propto (\tan \beta)^6 / m_A^4)$

(C. Bobeth, T. Ewerth, F. Kruger and J. Urban, PRD64(2001) 074014)

- $\tan \beta$ - enhanced SUSY QCD corrections to $b$ Yukawa coupling included
$B_S \rightarrow \mu^+\mu^- \text{ decay}$

Excluded configurations

✓ Strong correlation with direct detection signals (S. Baek, Y. G. Kim, P. Ko, hep-ph/0406033)
Dark matter density from WMAP

- CMB data, used in combination with other cosmological observations, are narrowing down the range of the matter abundance $\Omega_m h^2$ and some of its constituents, $\Omega_\nu h^2$ and $\Omega_b h^2$:

$$0.095 < \Omega_{CDM} h^2 < 0.131$$

(2 $\sigma$ range)

- The upper bound $(\Omega_{CDM} h^2)_{\text{max}}$ establishes a strict upper limit for any specific cold species

- The lower bound $(\Omega_{CDM} h^2)_{\text{max}}$ fixes the value of the average abundance below which the halo density of a specific cold constituent has to be rescaled as compared to the total CDM halo density

Rescaling factor: $\xi \equiv \rho_\chi / \rho_0 \equiv \min(1, \Omega_\chi h^2 / (\Omega_{CDM} h^2)_{\text{min}})$

$\rho_\chi =$ local neutralino density; $\rho_0 =$ total local dark matter density
Neutralino relic abundance

\[ \Omega \chi h^2 = \frac{x_f}{g_*(x_f)^{1/2}} \frac{3.3 \cdot 10^{-38} \text{ cm}^2}{\langle \sigma_{\text{ann}} v \rangle} \]

\[ \langle \sigma_{\text{ann}} v \rangle \equiv x_f \langle \sigma_{\text{ann}} v \rangle_{\text{int}}, \]

\[ \langle \sigma_{\text{ann}} v \rangle_{\text{int}} \equiv \int_{x_f}^{x_0} \langle \sigma_{\text{ann}} v \rangle \, dx \]

\[ \langle \sigma_{\text{ann}} v \rangle = \text{thermally averaged product of the annihilation cross-section times the relative velocity of a pair of neutralinos} \]

\[ x_{f,0} = \frac{m_\chi}{T_{f,0}}, \quad T_f = \text{freeze-out temperature}; \ T_0 = \text{today's temperature} \]

Standard expansion in S and P waves for \( \langle \sigma_{\text{ann}} v \rangle \):

\[ \langle \sigma_{\text{ann}} v \rangle \simeq \tilde{a} + \frac{1}{2x_f} \tilde{b} \]
\( \chi - \chi \rightarrow f \bar{f} \) annihilation cross section - Diagrams (low \( m_\chi \))
Approximate analytic expressions at small $m_\chi$

- The dominant terms in $\langle \sigma_{\text{ann}} v \rangle_{\text{int}}$ are the contributions due to Higgs-exchange in the $s$ channel and sfermion-exchange in the $t, u$ channels of the annihilation process $\chi + \chi \rightarrow \bar{f} + f$.

- For $m_A \lesssim 200$ GeV Higgs-exchange contribution due to S-wave annihilation into down-type fermions dominates:

$$\langle \sigma_{\text{ann}} v \rangle_f^{\text{Higgs}} \approx \tilde{a}_f^{\text{Higgs}} \approx \frac{2\pi a_{e.m.}^2 c_f}{\sin^2 \theta_W \cos^2 \theta_W} a^2_1 a^2_3 \tan^2 \beta (1 + \epsilon_f)^2 \frac{m^2_f}{m^2_W} \frac{m^2_\chi}{[(2m_\chi)^2 - m^2_A]^2} \left[1 - \frac{m^2_f}{m^2_\chi}\right]^{1/2}$$

- $c_f = 3$ for quarks, $c_f = 1$ for leptons
- $\bar{m}_f$ = fermion running mass evaluated at the energy scale $2m_\chi$
- $m_f$ = fermion pole mass
- $\epsilon_f$ = one-loop correction to the relationship between a down-type fermion running mass and the corresponding Yukawa coupling ($m = h \times v \times (1 + \epsilon)$)
Cosmological lower bound on $m_\chi$ (low $m_A$ mass)

- $\Omega_\chi h^2 < 0.131$

- $\langle \sigma_{ann} v \rangle$ is an increasing function of $m_\chi$

- The maximal value $\langle \sigma_{ann} v \rangle_{\text{max}}$ at fixed $m_\chi$ is obtained by inserting into $\langle \sigma_{ann} v \rangle$ the product $a_1^2 a_3^2 \tan^2 \beta$ for maximal bino–higgsino mixing:

  - $\frac{|a_3|}{|a_1|} \sim 0.42 \sin \beta$
  - for $m_A \sim 90$ GeV, $\tan \beta < 45$ (CDF)

  - $(a_1^2 a_3^2 \tan^2 \beta)_{\text{max}} \sim 260$

- Keeping only the dominant contribution to $b\bar{b}$ final state:

  $$m_\chi \left[1 - m_b^2/m_\chi^2 \right]^{1/4} \gtrsim 5.3 \text{ GeV} \left(\frac{m_A}{90 \text{ GeV}}\right)^2$$
Sfermion-exchange contribution

- Important if $m_A \gtrsim 200$ GeV

- Both S-wave and P-wave contributions have to be taken into account in the expression:

  $$\langle \sigma_{\text{ann}} v \rangle_{\widetilde{\text{sfermion}}} \approx \tilde{a}_f^\text{sf} + \frac{1}{2x_f} \tilde{b}_f^\text{sf}$$

- Lowest $\Omega_X h^2$ obtained for $\tilde{\tau}$ exchange. Lightest $\tilde{\tau}$ ($m_{\tilde{\tau}} \approx 87$ GeV) if mixing is maximal

- $\langle \sigma_{\text{ann}} v \rangle_{\widetilde{\text{sfermion}}} \approx \langle \sigma_{\text{ann}} v \rangle_{\tau}$ maximized by:

  $$\left( \langle \sigma_{\text{ann}} v \rangle_{\widetilde{\text{sfermion}}} \right)_{\text{max}} \approx \frac{\pi a_{\text{em}}^2}{8 \cos^4 \theta_W} \frac{m_X^2 [1 - m_{\tilde{\tau}}^2 / m_X^2]^{1/2}}{m_{\tilde{\tau}}^4} \left[ \left( 2 + \frac{5}{2} \frac{m_{\tilde{\tau}}}{m_X} \right)^2 + \frac{23}{2x_f} \right]$$
Cosmological lower bound on $m_\chi$ (low $m_A$)

upper bound on $\Omega_{CDM} h^2$

curve: analytical approximation for minimal $\Omega_{CDM} h^2$

scatter plot: full calculation

$m_\chi \left[ 1 - m_b^2/m_\chi^2 \right]^{1/4} \gtrsim 5.3 \, \text{GeV} \left( \frac{m_A}{90 \, \text{GeV}} \right)^2$
Cosmological lower bound on $m_\chi (m_A > 200 \text{ GeV})$

upper bound on $\Omega_{CDM}h^2$

curve: analytical approximation for minimal $\Omega_{CDM}h^2$

scatter plot: full calculation

\[ m_\chi \left[ 1 - \frac{m_\tau^2}{m_\chi^2} \right]^{1/4} \gtrsim 22 \text{ GeV} \left( \frac{m_\tau}{90 \text{ GeV}} \right)^2 \]
The bottom line: the cosmological lower bound on $m_\chi$ depends on the value of $m_A$:

- $m_\chi > 6$ GeV for light $m_A$
- $m_\chi > 22$ GeV for heavy $m_A$

$$(\Omega_{CDM} h^2)_{\text{max}} = 0.3$$

$$(\Omega_{CDM} h^2)_{\text{max}} = 0.131$$
SEARCHES
**Searches for relic WIMPs**

- **Direct searches.** Elastic scattering of $\chi$ off nuclei ($\propto$ WIMP local density)

$$\chi + N \rightarrow \chi + N$$

- **Indirect searches.** Signals due to $\chi - \chi$ annihilations

$$g \bar{g}, f \bar{f}, W^+W^-, ZZ$$

$$\chi + \chi \rightarrow HH, hh, AA, hH, hA, HA, H^+H^- \rightarrow \nu, \bar{\nu}, \gamma, \bar{p}, e^+, d$$

- Annihilations taking place in celestial bodies where $\chi$’s have been accumulated: $\nu$’s $\rightarrow$ up-going $\mu$’s from Earth and Sun

- Annihilations taking place in the Halo: enhanced in high density regions ($\propto (\text{WIMP density})^2$) $\Rightarrow$ Galactic center, clumpiness
Annihilations taking place in the Halo
\( (\propto \text{WIMP (local density)}^2) \)

\[ \chi + \chi \rightarrow \nu, \bar{\nu} \]

\[ \gamma \ (\text{continuum}) \]

\[ \gamma \text{ line (Z\gamma)} \]

\[ \bar{p}, \bar{D}, e^+ \]

\{ \text{keep directionality} \}

\{ \text{searches for rare components in cosmic rays} \}

\{ \text{((diffusion))} \}
Neutralino direct detection

- Elastic recoil of non relativistic halo neutralinos off the nuclei of an underground detector
- Recoil energy of the nucleus in the keV range
- Yearly modulation effect due to the rotation of the Earth around the Sun (the relative velocity between the halo, usually assumed at rest in the Galactic system, and the detector changes during the year)

\[ v_0 = 232 \text{ km/sec} \]
\[ v_\odot = 30 \text{ km/sec} \]
Differential detection rate

\[
\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{\text{min}}}^{v_{\text{max}}} d\bar{v} f(\bar{v}) |\bar{v}| \frac{d\sigma(\bar{v}, E_R)}{dE_R}
\]

\(E_R=\) nuclear recoil energy
\(N_T=\) number of nuclear targets
\(\bar{v}=\) WIMP velocity in the Earth’s rest frame

Astrophysics:
* \(\rho_\chi=\) neutralino local density
* \(f(\bar{v})=\) neutralino velocity distribution function

Particle and nuclear physics:
* \(\frac{d\sigma(\bar{v}, E_R)}{dE_R}=\) neutralino–nucleus elastic cross section

\[
\frac{d\sigma(\bar{v}, E_R)}{dE_R} = \left(\frac{d\sigma(\bar{v}, E_R)}{dE_R}\right)_{\text{coherent}} + \left(\frac{d\sigma(\bar{v}, E_R)}{dE_R}\right)_{\text{spin-dependent}}
\]

usually dominates, \(\propto (\text{atomic number})^2\)
Neutralino–quark cross section - Diagrams

\[
\begin{array}{cc}
\chi & \chi \\
| & | \\
q & q \\
\end{array} & \begin{array}{cc}
\chi & \chi \\
| & | \\
q & q \\
\end{array}
\]

\[
\begin{array}{cc}
\chi & q \\
| & | \\
q & \tilde{q} \\
\end{array} & \begin{array}{cc}
\chi & \chi \\
| & | \\
q & q \\
\end{array}
\]

\[
\begin{array}{cc}
\chi & q \\
| & | \\
\tilde{q} & \tilde{q} \\
\end{array} & \begin{array}{cc}
\chi & \chi \\
| & | \\
q & q \\
\end{array}
\]
DAMA: 7 years of annual modulation (108000 kg day)

Residuals:

Power spectrum of residuals in the (2-6) keV energy range:

Frequency = 1/365.36 d⁻¹
The DAMA annual modulation result

- The DAMA/NaI experiment shows an annual-modulation effect at the 6.3 $\sigma$ C.L. after a 7-years running with a total exposure of $\approx 108,000$ kg · day.

- DAMA analysis extended to a large class of possible phase-space distribution functions (DF) for WIMPs in the galactic halo.

- The full set of experimental data analyzed in terms of a spin-independent effect over an unconstrained range for the mass of a generic WIMP.
Detectability of light $\chi$'s by WIMP direct measurements


Very light $m_\chi, m_A \lesssim 200$ GeV $\rightarrow$

1. $\chi$-nucleon elastic cross section $\sigma^{(\text{nucleon})}_{\text{scalar}}$ dominated by $h$-exchange in the $t$-channel

2. Annihilation cross section $\sigma_{\text{ann}}$ dominated by $A$-exchange in the $s$-channel

\[
(\Omega_{\chi} h^2) \sigma^{(\text{nucleon})}_{\text{scalar}} \approx 1.4 \times 10^{-40} \text{cm}^2 T \left( \frac{m_\chi \langle N|\bar{s}s|N \rangle}{200 \text{ MeV}} \right)^2 \frac{\text{GeV}^2}{m_\chi^2 [1-m_b^2/m_\chi^2]^{1/2}} \left( \frac{m_A}{m_h} \right)^4
\]

\[
T = \frac{a_3 \sin \alpha + a_4 \cos \alpha}{(a_4 \cos \beta - a_3 \sin \beta)^2} \frac{(\sin \alpha + \epsilon_s \cos(\alpha - \beta) \sin \beta)^2}{\sin^2 \beta (1 + \epsilon_b)^2} = O(1)
\]

- $\langle N|\bar{s}s|N \rangle = s$-quark density matrix element over the nucleonic state
- $\alpha = \text{Higgs fields mass-eigenstates rotation angle}$
Neutralino - nucleon cross section

\[ \Omega \chi^2 \leq (\Omega_CDM h^2)_{max} \]

\[ \sigma^{(\text{nucleon})} \gtrsim \frac{10^{-40} 	ext{cm}^2}{\Omega_CDM h^2_{\text{max}}} \frac{\text{GeV}^2}{m_N^2 \left| 1 - m_\chi^2/m_N^2 \right|^{1/2}} \text{ for } m_\chi \lesssim 20 \text{ GeV} \]

The elastic cross section is bounded from below:

→ “funnel” at low mass
Neutralino – nucleon cross section

\[ \Omega \chi h^2 \leq (\Omega_{CDM} h^2)_{max} \]

\[ \sigma_{\text{scalar}} \gtrsim 10^{-40} \text{cm}^2 (\Omega_{CDM} h^2)_{max} \frac{\text{GeV}^2}{m^2_{\chi} |1-m_y^2/m_{\chi}^2|^{1/2}} \] for \( m_{\chi} \lesssim 20 \text{ GeV} \)

The elastic cross section is bounded from below:

→ “funnel” at low mass

DAMA modulation region, likelyhood function values distant more than 4 \( \sigma \) from the null result (absence on modulation) hypothesis, Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403
Neutralino - nucleon cross section

Upper limits from direct searches

assumptions:
iso thermal sphere,
$\nu_0=220$ km/sec,
$\rho_0=0.3$ GeV/cm$^3$

---
CDMS, D. S. Akerib et al., astro-ph/0405033

---
Uncertainty due to velocity distribution

- Many possible departures from the isothermal sphere model, which is the parameterization usually adopted to describe the halo.

- Different density profiles, effects due to anisotropies of the velocity dispersion tensor, rotation of the galactic halo.

- Non-thermal components:
Compatibility DAMA-CDMS?

No combined analysis of the 2 experiments available

However, some trivial considerations:
for \( m_\chi \geq 25 \text{ GeV} \) capture on DAMA is dominated by the I target \( \rightarrow \) WIMPS above threshold in DAMA are also above threshold in the CDMS Ge

for \( m_\chi \leq 25 \text{ GeV} \) capture on DAMA is dominated by the Na target \( \rightarrow \) WIMPS above threshold in DAMA can be below threshold in the CDMS Ge

\( \rightarrow \) Gelmini and Gondolo, hep-ph/0405278, “qualitative” compatibility both for a thermalized maxwellian and for high velocity (extragalactic?) streams
Compatibility between CDMS and low mass neutralinos?
Uncertainty due to velocity distribution

Sodium Iodide

\[ m_{\text{WIMP}} = 50 \text{ GeV} \]
\[ \sigma_{\text{scalar}} = 10^{-8} \text{ nbarn} \]
\[ v_0 = 220 \text{ km/sec} \]

Each curve corresponds to a different halo model:

Time-independent component

Modulation amplitude
Uncertainty due to velocity distribution

**Germanium**

\[ m_{WIMP} = 50 \text{ GeV} \]
\[ \sigma_{\text{nucleon, scalar}} = 10^{-8} \text{ nbarn} \]
\[ v_0 = 220 \text{ km/sec} \]

Each curve corresponds to a different halo model:

- **Time-independent component**
- **Modulation amplitude**
Neutralino - nucleon cross section

Upper limit from CDMS using a different velocity distribution

assumptions:
NFW, anisotropic velocity dispersion
\( \rho_0 = 0.2 \text{ GeV/cm}^3 \)

- \( v_0 = 220 \text{ km/sec} \)
- \( v_0 = 270 \text{ km/sec} \)
- \( v_0 = 170 \text{ km/sec} \)

NO POINTS EXCLUDED AT LOW MASS
Uncertainty due to velocity distribution


<table>
<thead>
<tr>
<th>Class A: Spherical $\rho_{DM}$, isotropic velocity dispersion</th>
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<tbody>
<tr>
<td>A0 Isothermal sphere</td>
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<td>A1 Evans' logarithmic [15]</td>
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<td>A2 Evans' power-law [16]</td>
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<td>A3 Evans' power-law [16]</td>
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<td>A4 Jaffe [14]</td>
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<td>A5 NFW [18]</td>
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<tr>
<td>A6 Moore at al. [19]</td>
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<td>A7 Kravtsov et al. [20]</td>
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<tr>
<th>Class B: Spherical $\rho_{DM}$, non-isotropic velocity dispersion (Osipkov–Merrit, $R_0 = 0.4$)</th>
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<tbody>
<tr>
<td>B1 Evans' logarithmic</td>
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<tr>
<td>B2 Evans' power-law</td>
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<tr>
<td>C1 Evans' logarithmic</td>
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<td>C3 Evans' power-law</td>
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<tr>
<td>C4 Evans' power-law</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class D: Triaxial $\rho_{DM}$ [17] ($q = 0.8$, $p = 0.9$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 Earth on major axis, radial anisotropy</td>
</tr>
<tr>
<td>D2 Earth on major axis, tangential anisotropy</td>
</tr>
<tr>
<td>D3 Earth on intermediate axis, radial anisotropy</td>
</tr>
<tr>
<td>D4 Earth on intermediate axis, tangential anisotropy</td>
</tr>
</tbody>
</table>
Uncertainty on $\rho_0$ due to velocity distribution


<table>
<thead>
<tr>
<th>Model</th>
<th>$G=170$ km sec$^{-1}$</th>
<th>$G=220$ km sec$^{-1}$</th>
<th>$G=270$ km sec$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho_0^{\text{min}}$</td>
<td>$\rho_0^{\text{max}}$</td>
<td>$\rho_0^{\text{min}}$</td>
</tr>
<tr>
<td>A0</td>
<td>0.18</td>
<td>0.28</td>
<td>0.30</td>
</tr>
<tr>
<td>A1 , B1</td>
<td>0.20</td>
<td>0.42</td>
<td>0.34</td>
</tr>
<tr>
<td>A2 , B2</td>
<td>0.24</td>
<td>0.53</td>
<td>0.41</td>
</tr>
<tr>
<td>A3 , B3</td>
<td>0.17</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>A4 , B4</td>
<td>0.26</td>
<td>0.27</td>
<td>0.44</td>
</tr>
<tr>
<td>A5 , B5</td>
<td>0.20</td>
<td>0.44</td>
<td>0.33</td>
</tr>
<tr>
<td>A6 , B6</td>
<td>0.22</td>
<td>0.39</td>
<td>0.37</td>
</tr>
<tr>
<td>A7 , B7</td>
<td>0.32</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>C1</td>
<td>0.36</td>
<td>0.56</td>
<td>0.60</td>
</tr>
<tr>
<td>C2</td>
<td>0.34</td>
<td>0.67</td>
<td>0.56</td>
</tr>
<tr>
<td>C3</td>
<td>0.30</td>
<td>0.66</td>
<td>0.50</td>
</tr>
<tr>
<td>C4</td>
<td>0.32</td>
<td>0.65</td>
<td>0.54</td>
</tr>
<tr>
<td>D1 , D2</td>
<td>0.32</td>
<td>0.50</td>
<td>0.54</td>
</tr>
<tr>
<td>D3 , D4</td>
<td>0.19</td>
<td>0.30</td>
<td>0.32</td>
</tr>
</tbody>
</table>

($0.17 \leq \rho_0 \leq 1.68$)

($v_0 = \text{galactic rotational velocity at the Earth's position}$)
Distortion of the signal time dependence

N. Fornengo, S. Scopel, PLB 576 (2003) 189

Triaxial system described by a multivariate gaussian:
(Galaxy rest frame)
\[ f(\vec{v}) = N \exp \left( -\frac{v_x^2}{2\sigma_x^2} - \frac{v_y^2}{2\sigma_y^2} - \frac{v_z^2}{2\sigma_z^2} \right) \]

\[ \text{Rate} = F(v_{\text{min}}) \]

\[ v_{\text{min}} \equiv \text{minimal WIMP incoming velocity at fixed recoil energy} \]
(Earth rest frame)

Each curve corresponds to a different value of \( v_{\text{min}} \):
- \( \sigma_x/\sigma_y = 0.2 \)
- \( \sigma_z/\sigma_y = 0.8 \)

Departure from sinusoidal behavior at low \( v_{\text{min}} \)
(\( \rightarrow \) low recoil energies)
To set a solid constraint on theoretical predictions it is necessary to derive from the experimental data the upper bounds on $\xi_{\text{nucleon}}^{(nucleon)}$ for a large variety of DFs and of the corresponding astrophysical parameters (with their own uncertainties).

Only the intersection of these bounds would provide an absolute limit to be used to possibly exclude a subset of supersymmetric population.

A combined investigation of all experiments along these lines is not available at the moment.
WIMP indirect detection: annihilations in the halo

\[ \chi_\text{ann} \propto \sigma \]

example:

\[ \chi \rightarrow \gamma, e^+, \bar{p}, \bar{d} \]

\[ \chi \rightarrow \text{Higgs} \]

\[ \sigma_{\text{ann}} \propto \frac{1}{m_A^4} \]
Neutralino self annihilations and dark matter density distribution

Signals depend quadratically on the dark matter density $\rho$.

Common parametrization:

$$\rho(r) = \rho_l \left( \frac{R_\odot}{r} \right)^\gamma \left[ 1 + \left( \frac{R_\odot}{a} \right)^\alpha \right]^{(\beta - \gamma)/\alpha}$$

$\rho_l =$ dark matter local density

$\rho_0 = \frac{\rho(r)}{\rho_0} = 8 \text{ kpc}$

$a =$ scale length

$(\alpha, \beta, \gamma) = (2, 2, 0)$ Isothermal

$(\alpha, \beta, \gamma) = (1, 3, 1)$ NFW, $\propto r^{-1}$ in GC

$(\alpha, \beta, \gamma) = (1.5, 3, 1.5)$ Moore et al., $\propto r^{-1.5}$ in GC

Recent numerical simulation suggest the non-singular form:

(J. F. Navarro et al., astro-ph/0311231)

$$d(\ln(\rho))/d(\ln(r)) \bigg|_{\rho = \rho_0} = -2$$

$$\rho_2 \approx \rho(r_2)$$

$\alpha \approx 0.17$

Large differences in the behaviour towards GC

N.B. Anyway, current simulations not reliable for radii smaller than 0.1 - 1 kpc
Gamma rays from neutralino pair annihilations

\[ \Phi_{\gamma}(E_{\gamma}, \psi) = \frac{1}{4\pi} \langle \sigma_{\text{ann}} v \rangle \frac{dN_{\gamma}}{dE_{\gamma}} \frac{1}{2} I(\psi) \]

\[ \langle \sigma_{\text{ann}} v \rangle \equiv \text{annihilation cross section time relative velocity} \]

mediated over the galactic velocity distribution

Integration along the line of sight:

\[ I(\psi) = \int_{1.0.s} \rho^2(r(\lambda, \psi)) \ d\lambda(\psi) \]

\[ I_{\Delta\psi} \equiv \frac{1}{\Delta\psi} \int_{\Delta\psi} I(\psi) \ d\psi \]

\[ \Delta\psi \equiv \text{telescope aperture} \]

\[ |\Delta l| \leq 5^\circ, |\Delta b| \leq 2^\circ \]

<table>
<thead>
<tr>
<th>Isothermal</th>
<th>Isothermal</th>
<th>NFW</th>
<th>Moore et al.</th>
<th>( r )-dependent log-slope Eq.(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a = 3.5 \ \text{kpc} )</td>
<td>( a = 2.5 \ \text{kpc} )</td>
<td>( a = 25 \ \text{kpc} )</td>
<td>( a = 30 \ \text{kpc} )</td>
<td>( \alpha = 0.142 )</td>
</tr>
<tr>
<td>( r_c = 0.01 \ \text{pc} )</td>
<td>( r_c = 0.01 \ \text{pc} )</td>
<td>( r_c = 0.01 \ \text{pc} )</td>
<td>( r_{-2} = 26.4 \ \text{kpc} )</td>
<td>( \rho_{-2} = 0.035 \ \text{GeV cm}^{-3} )</td>
</tr>
<tr>
<td>18.5</td>
<td>42.5</td>
<td>184.2</td>
<td>10866</td>
<td>600</td>
</tr>
</tbody>
</table>

Toward GC

strong dependence on profile, less relevant in other directions
Below $m_\chi \equiv m_W$, dominated by production and decay of $\pi^0$'s from $q\bar{q}$ hadronization:

- scale invariance broken by gluon showering
- for $E<100$ MeV, sizeable contribution from electromagnetic showering of leptons and from production and decay of $\eta, \eta'$, charm and bottom mesons (peak from $B^*\rightarrow B + \gamma$ for $m_\chi<10$ GeV?)

At higher masses, annihilation channels into Higgs bosons, gauge bosons and $t\bar{t}$ pairs become kinematically accessible. We compute analytically the full decay chain down to the production of a quark, gluon or a lepton.

calculated using Pythia
EGRET excess toward GC?

$1 = 0^\circ$

---

Gamma flux due to neutralino annihilation from Galactic Center

A. Bottino, F. Donato, N. Fornengo, S. Scopel (2004)

EGRET

$E_\gamma = 0.12 \text{ GeV}$

NFW profile

$|\Delta l| < 5^\circ, |\Delta b| < 2^\circ$

low mass "funnel"

no bounds
Gamma flux due to neutralino annihilation from Galactic Center

A. Bottino, F. Donato, N. Fornengo, S. Scopel (2004)

EGRET $E_\gamma = 1.5$ GeV

low mass “funnel”

NFW profile galactic center $|\Delta l|<5^\circ, |\Delta b|<2^\circ$

NFW not enough to explain excess
Gamma flux due to neutralino annihilation from Galactic Center

NFW not enough to explain excess
It has already been shown that neutralinos with $m_\chi > 50$ GeV could explain the EGRET excess (A. Cesarini, F. Fucito, A. Lionetto, A. Morselli and P. Ullio, astro-ph/0305075).

Could the EGRET excess be explained also by light neutralinos?

YES!

$m_\chi = 30$ GeV

Enhancement required compared to NFW
It has already been shown that neutralinos with \( m_\chi > 50 \) GeV could explain the EGRET excess (A. Cesarini, F. Fucito, A. Lionetto, A. Morselli and P. Ullio, astro-ph/0305075)

Could the EGRET excess be explained also by light neutralinos?

YES!

\( m_\chi = 40 \) GeV

Enhancement required compared to NFW
EGRET residual flux at high latitudes after subtraction of known components (identified sources, spectrum due to cosmic rays interaction with the galactic disk)


extragalactic origin?

...or exotic production?
Gamma flux due to neutralino annihilation from high latitudes

Region A: $|b| > 10^0$, $|l| > 40^0$, $10^0 < |b| < 30^0$

low mass “funnel”

Gamma flux due to neutralino annihilation from high latitudes

Gamma flux due to neutralino annihilation from high latitudes

- γ signals from high altitudes turn out to be one order of magnitude below present sensitivities.
- Contrary to GC, in this case $I_{\Delta \psi}$ is practically independent on the halo profile.

Clumpiness?

Effect discussed by several authors, sometimes with signal improvements at the level of a few orders of magnitude.

However, recent analytical investigation on the production of small-scale dark matter clumps suggest that the clumpiness effect would not be large. Enhancement effect on the annihilation signals limited to a factor of a few. Similar conclusions also reached with high-resolution numerical simulations. (V. Berezinsky, et al., Phys. Rev. D68, 103003 (2003); F. Stoher et al., Mon. Not. Roy. Astron. Soc. 345, 1313 (2003)).
Antiprotons in cosmic rays due to neutralino annihilation

- $p$ from hadronization of quarks and gluons created by the annihilation of neutralinos
- Antiproton data can be used to constrain the susy parameter space
A SIMPLE VIEW OF THE GALAXY

- Thin disc: $2h = 200 \text{ pc}$
- Acceleration $\sim R^{-\alpha}$
- Diffusion $\sim R^\delta$
- Convection $V_c$
- Spallations & Energy losses
- Solar System
- Reacceleration $V_A$
- Energy losses
- $\beta$-disintegration
- $R = 20 \text{ kpc}$
Antiprotons in cosmic rays

small room left to exotic $p$'s:

secondary flux

primaries due to neutralino annihilations
Antiprotons in cosmic rays due to neutralino annihilation

Amount of primary p compatible with BESS (PRL 84, 1078 (2000); Astrop. Phys. 16, 121 (2001))

Best fit values for propagation parameters (using data from B/C ratio)
Antiprotons in cosmic rays due to neutralino annihilation

Amount of primary p compatible with BESS (PRL 84, 1078 (2000); Astrop. Phys. 16, 121 (2001))

Conservative choice for propagation parameters
Up-going muons from neutralino annihilation in the center of the Earth

resonant capture on $O$, $Si$, $Mg$
Up-going muons from neutralino annihilation in the center of the Sun

ττ annihilation channel drops, b b required in $\Omega_\chi h^2$

--- SuperKamiokande  --- Baksan
--- MACRO ---
--- AMANDA ---
Conclusions - 1

- Relic neutralinos with masses $m_\chi < 45$ GeV are allowed in MSSM models without gaugino-mass unification at the GUT scale.

- The cosmological lower bound on the neutralino mass from WMAP CMB data combined with other measurements is $m_\chi \geq 6$ GeV.

- For $m_\chi < 20$ GeV various direct and indirect neutralino signals are bounded from below (low-mass \text{``funnel''}).

- These neutralinos, mainly a $\tilde{B} - \tilde{H}_1$ mixture, are compatible with the final modulation result presented by the DAMA Collaboration (108000 kg day exposure).
Conclusions - 2

- WIMP direct experiments with cryogenic detectors with improved sensitivities may potentially provide useful constraints on low-mass neutralinos - CDMS is underground now.
- Astrophysical uncertainties must be taken into account when comparing different experimental results.
- Current data from experiments of WIMP indirect searches (p's, γ's, up-going μ's), if interpreted conservatively, do not yet set constraints.
- In case of steep distributions of dark matter in the galactic center, neutralinos of masses around 30-40 GeV could explain the EGRET excess.