Particle Candidates for Dark Matter

(A. BOTTINO)

- Need for (and amount of) dark matter in the Universe

- Particle candidates for dark matter

- Supersymmetric particles as Weakly Interacting Massive Particles (WIMP)

- Probing the supersymmetric parameter space by WIMP direct detection

- Constraints from indirect searches for WIMPs

- Implications of a possible susy Higgs boson at a mass of 115 GeV (a hint from LEP2 ?)

Dark Matter in the Universe

- **Existence of dark matter** required by a host of observational data:
  galactic halos, clusters of galaxies, large scale structures, CMB, high-redshift SNe Ia, ...

  $$\boxed{0.05 \lesssim \Omega_m h^2 \lesssim 0.3} \quad \text{(conservative range)}$$

  $$\Omega_m \equiv \rho_m / \rho_c \,, \qquad \rho_c = 1.88 \times 10^{-29}\, h^2 \; g \cdot cm^{-3}$$

  $$h \equiv H_0 / (100 \; km \cdot s^{-1} \cdot Mpc^{-1}) \,, \quad 0.6 \lesssim h \lesssim 0.8$$

- visible matter

  $$\Omega_v \sim 0.003$$

- baryonic matter

  * from BBN $\quad 0.018 \lesssim \Omega_b h^2 \lesssim 0.020 \quad$ (low D)

    $$0.03 \lesssim \Omega_b \lesssim 0.06$$

  * CMB points to a somewhat higher value: $\Omega_b h^2 \sim 0.03$
  * hard to build a Universe dominated by baryons
    (Griffiths, Melchiorri and Silk: astro-ph/0101413)

  Thus, some dark matter is baryonic, but most of it is non-baryonic

- Particle physics, for its own motivations, provides a number of possible relics

Particle Physics		DM Candidates
Neutrino physics related to ν masses	$\longrightarrow$	light ν's
	$\longrightarrow$	heavy ν's
Supersymmetry	$\longrightarrow$	Lightest Susy Particle (neutralino, ...)
Strong CP-problem	$\longrightarrow$	axion
String theories	$\longrightarrow$	...

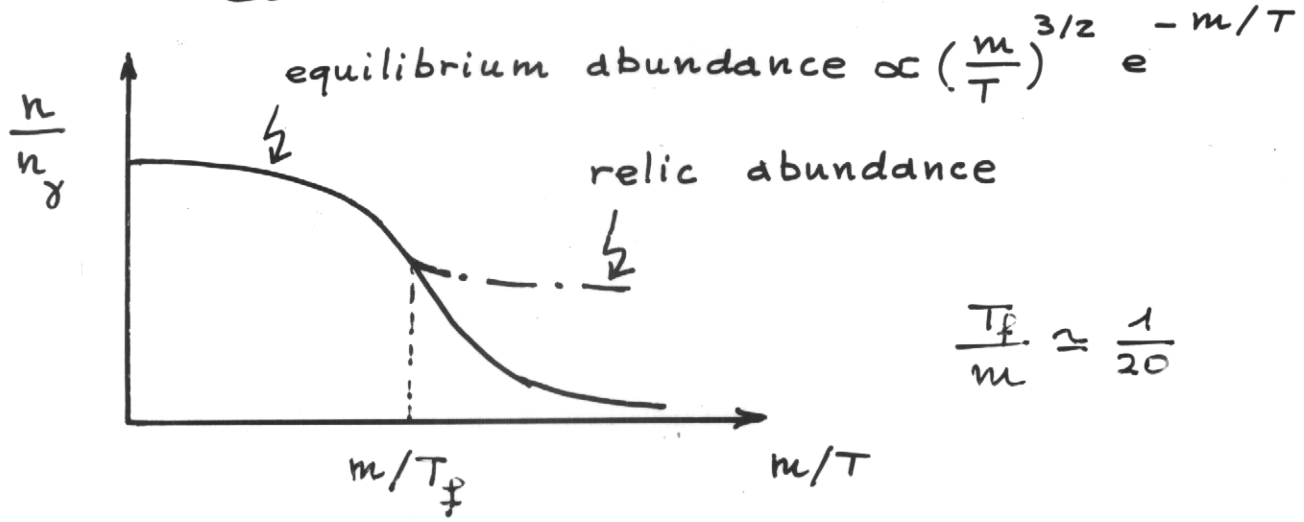
Topological defects associated with spontaneous symmetry breaking : monopoles, ...

Thermal relics

▶ hot relics

relic abundance $\simeq$ abundance at equilibrium
(almost independent of T_f)

▶ cold relics



$$\frac{T_f}{m} \simeq \frac{1}{20}$$

$n \equiv$ density per comoving volume

<u>relic abundance</u> $\quad \Omega h^2 \simeq \dfrac{10^{-37}\, cm^2}{\langle \sigma_{ann} v \rangle}$

then the relic abundance of a weakly interacting particle may be <u>sizeable</u>

<u>Different scenarios</u>

* decoupling of particles which were never in chemical equilibrium
  (see Giudice, Kolb and Riotto : hep-ph/0005123)

* non-thermal production

Relic neutrinos

For light ($m_\nu \lesssim$ MeV) neutrinos

$$\Omega_\nu h^2 = \frac{\sum_\nu m_\nu}{93\ \text{eV}} \qquad \text{relic abundance}$$

For instance, to have $\Omega_\nu \sim 0.1$ $(0.6 \lesssim h \lesssim 0.8)$

$$3.3\ \text{eV} \lesssim \sum_\nu m_\nu \lesssim 6.0\ \text{eV}$$

Experimental indications of ν masses:

a) solar ν's $\quad \Delta m^2 \sim 10^{-5} \div 10^{-4}\ \text{eV}^2$ (if MSW)

b) atmospheric ν's $\quad \Delta m^2 \sim (1 \div 8) \times 10^{-3}\ \text{eV}^2$

c) LSND $\quad 0.2\ \text{eV}^2 \lesssim \Delta m^2 \lesssim 1\ \text{eV}^2$

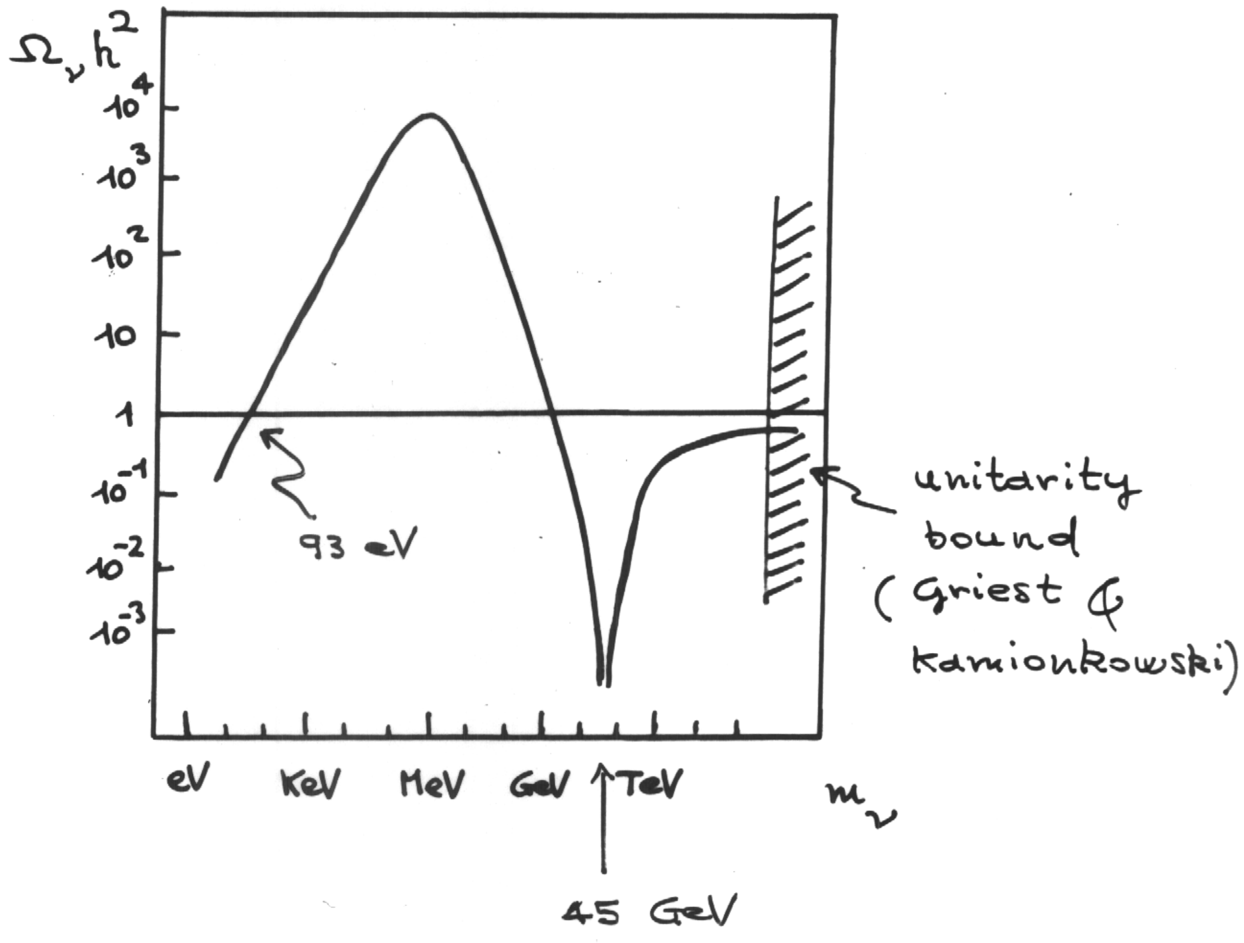
From the atmospheric ν deficit, a very conservative estimate:

$$m_\nu \gtrsim 0.05\ \text{eV}$$

$$\Omega_\nu h^2 \gtrsim 6 \times 10^{-4}$$

$$\Omega_\nu \gtrsim 0.001 \left(\frac{0.7}{h}\right)^2 \qquad \text{not cosmologically interesting}$$

However, Ω_ν could be sizeably larger in case of a substantial degeneracy in ν masses



$\Omega_\nu h^2$
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
93 eV
unitarity bound (Griest & Kamionkowski)
eV
KeV
MeV
GeV
TeV
m_ν
45 GeV

Searches for relic neutralinos

- direct search: elastic scattering of χ off nuclei

$$\chi + \mathcal{N} \rightarrow \chi + \mathcal{N}$$

- indirect searches:

  * signals due to χ-χ annihilations taking place in celestial bodies (where χ's have been accumulated) $\rightarrow$ ν's $\rightarrow$ up-going μ's (Earth, Sun)

  * signals due to χ-χ annihilations taking place in the halo

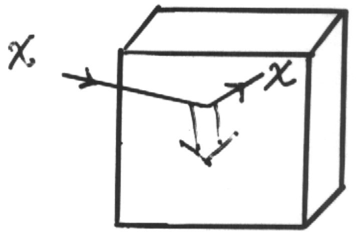
$$\chi + \chi \rightarrow f + \bar{f}, \ldots$$

$$\left.\begin{array}{l} \hookrightarrow \nu, \bar{\nu} \\ \hookrightarrow \gamma \end{array}\right\}$$ keep directionality, detectable if omitted by regions of high χ density

$\hookrightarrow$ gamma line (2γ)

$$\left.\begin{array}{l} \hookrightarrow \bar{p} \\ \hookrightarrow e^+ \\ \hookrightarrow \bar{d} \end{array}\right\}$$ searched for as rare components in cosmic rays

Direct search: χ-nucleus scattering



Ge
NaI
Xe
TeO_2
.....

$E_R = \vec{q}^{\,2}/(2m_N)$

Differential rate

χ-velocity distribution in the Galaxy

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{v_{max}} dv\, f(v)\, v \left\{ \frac{d\sigma^C}{dE_R} + \frac{d\sigma^{SD}}{dE_R} \right\}$$

coherent (dominant)

spin dependent

$$\frac{d\sigma^C}{dE} \propto F^2(q)\, A^2\, \sigma_{scalar}^{(nucleon)}$$

- Discrimination of the signal against the background is based on the expected annual modulation of the signal
  Drukier, Freese and Spergel (1986)
  Freese, Frieman and Gould (1988)

Usually, from the experimental data one extracts

$$\frac{dR}{dE_R} \longrightarrow \rho_\chi \, \sigma^{(nucleon)}_{scalar} \equiv \rho_\ell \underbrace{\frac{\rho_\chi}{\rho_\ell}}_{\xi} \sigma^{(nucleon)}_{scalar}$$

assuming:

1) a Maxwell-Boltzmann speed distribution for $f(v)$

2) dominance of the coherent cross-section over the spin-dependent one.

Caveats! See later on.

Notice that, to get $\sigma^{(nucleon)}_{scalar}$, the uncertainty range for ρ_ℓ

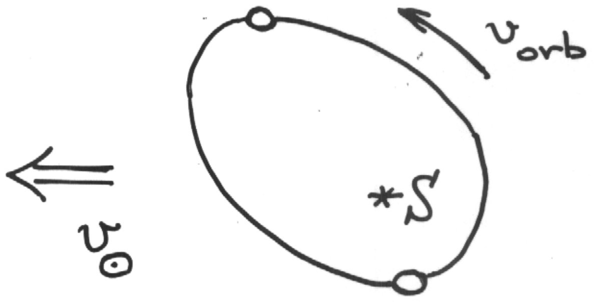
$$(0.1-0.2)\ GeV \cdot cm^{-3} \lesssim \rho_\ell \lesssim 0.7\ GeV \cdot cm^{-3}$$

has to be taken into account.

"Default" value for ρ_ℓ : $\rho_\ell = 0.3\ GeV \cdot cm^{-3}$

definition: $\rho_\ell^{0.3} \equiv \rho_\ell / (0.3\ GeV \cdot cm^{-3})$

Annual modulation



speed of the solar system in the Galactic Rest Frame

$$v_\odot = \underbrace{(220 \pm 30)\ \mathrm{km \cdot s^{-1}}}_{v_0} + 12\ \mathrm{km \cdot s^{-1}}$$

peculiar velocity

speed of the earth in the GRF

$2\pi/1\mathrm{yr}$ June 2nd

$$v_\oplus(t) = v_\odot + v_{orb} \cos\gamma \cos[\omega(t - t_0)]$$

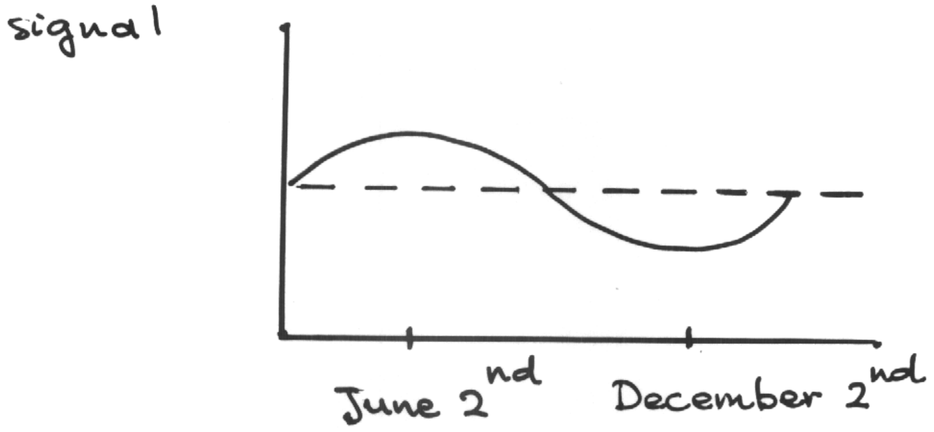
earth orbital speed

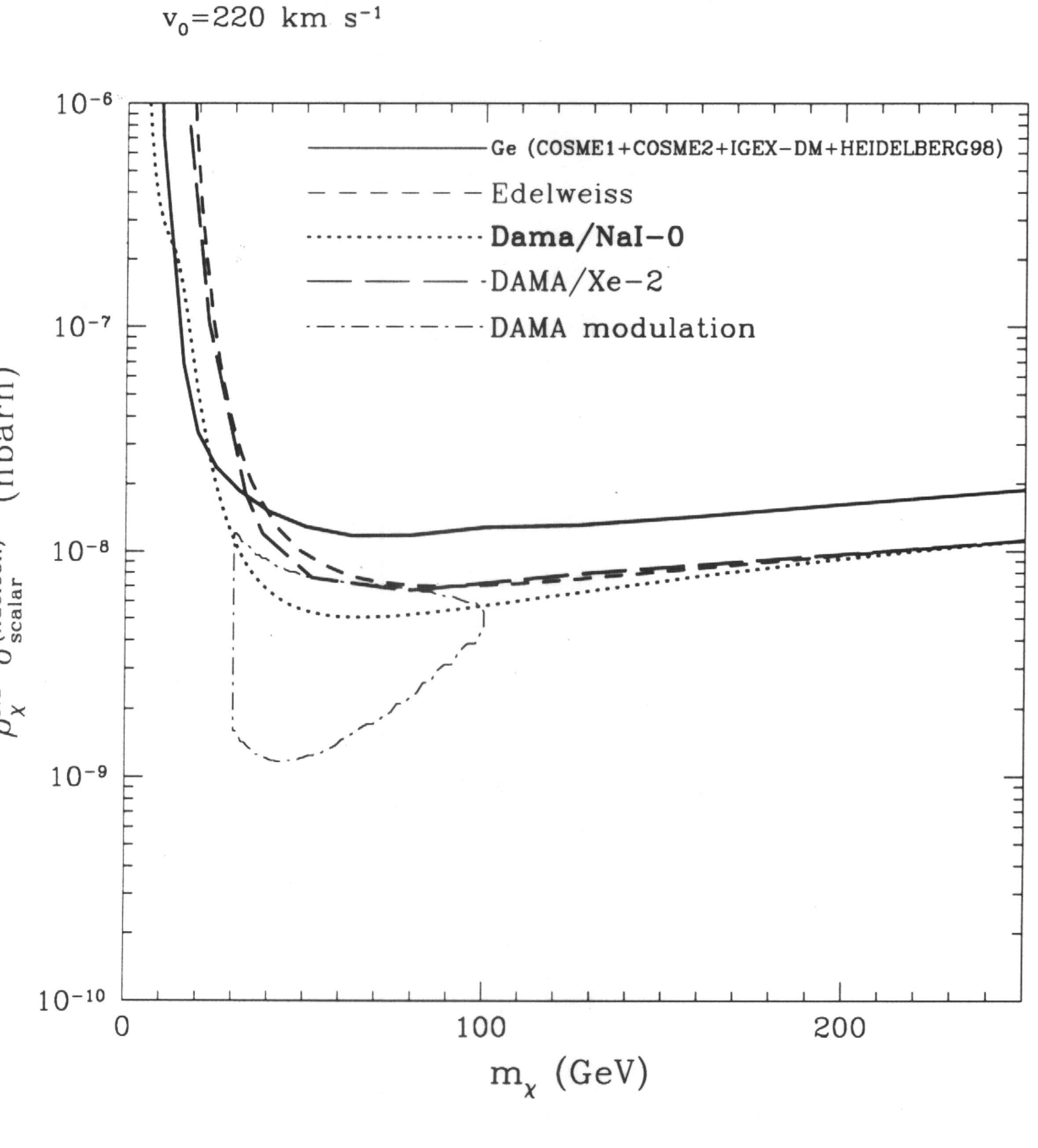
orbit inclination ($\gamma = 60^\circ$)

Defining $\eta(t) \equiv v_\oplus(t)/v_0$, $\eta_{av} \equiv v_\odot/v_0$

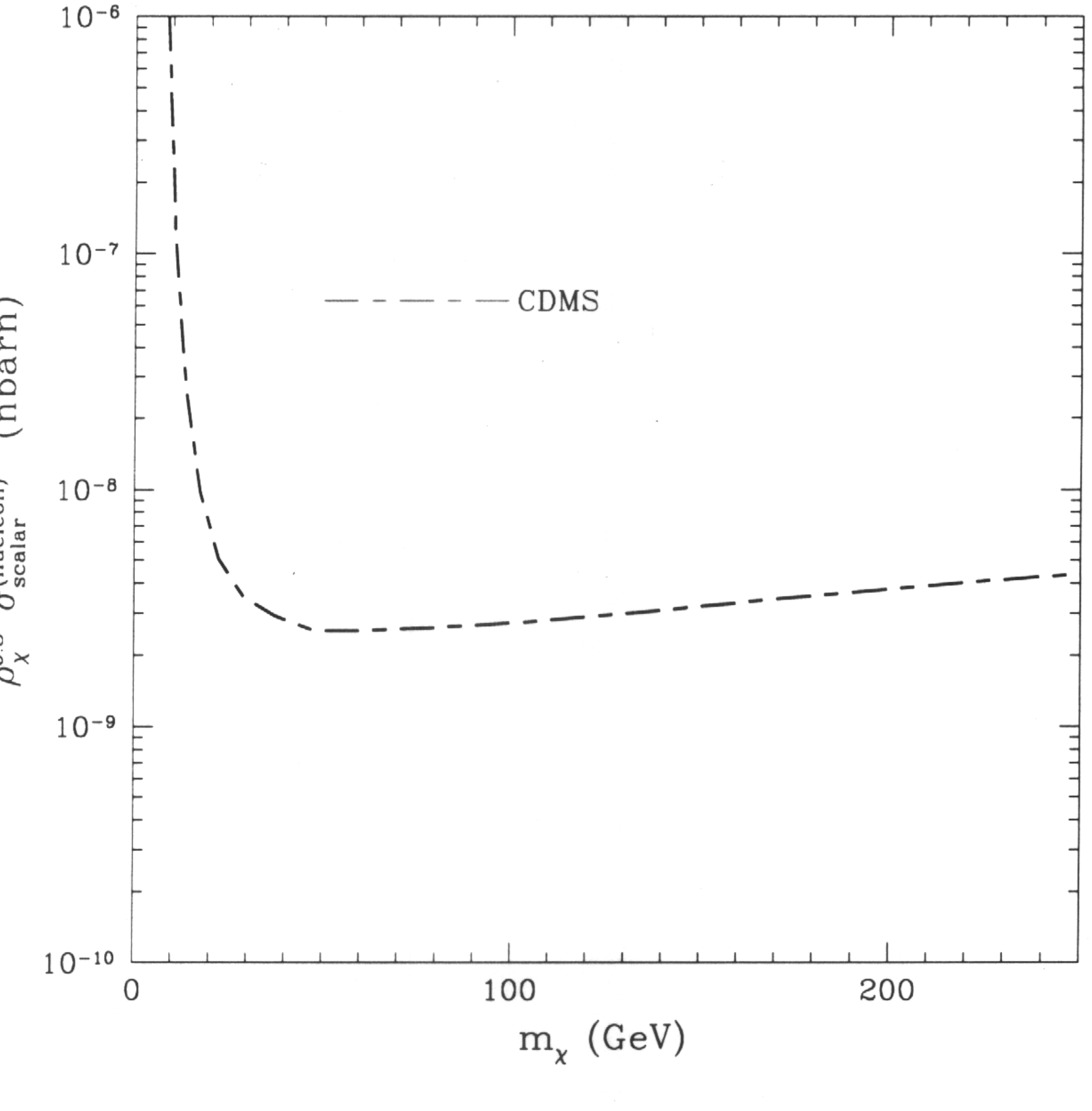
$$\eta(t) = \eta_{av} + \Delta\eta \cos[\omega(t - t_0)]$$

$$\eta_{av} = 1.05 \quad , \quad \Delta\eta = 0.07$$





v0=220 km s-1
Ge (COSME1+COSME2+IGEX-DM+HEIDELBERG98)
Edelweiss
Dama/NaI-0
DAMA/Xe-2
DAMA modulation
10-6
10-7
10-8
10-9
10-10
0
100
200
m_χ (GeV)
ρ_χ^0.3 σ_scalar^(nucleon) (nbarn)



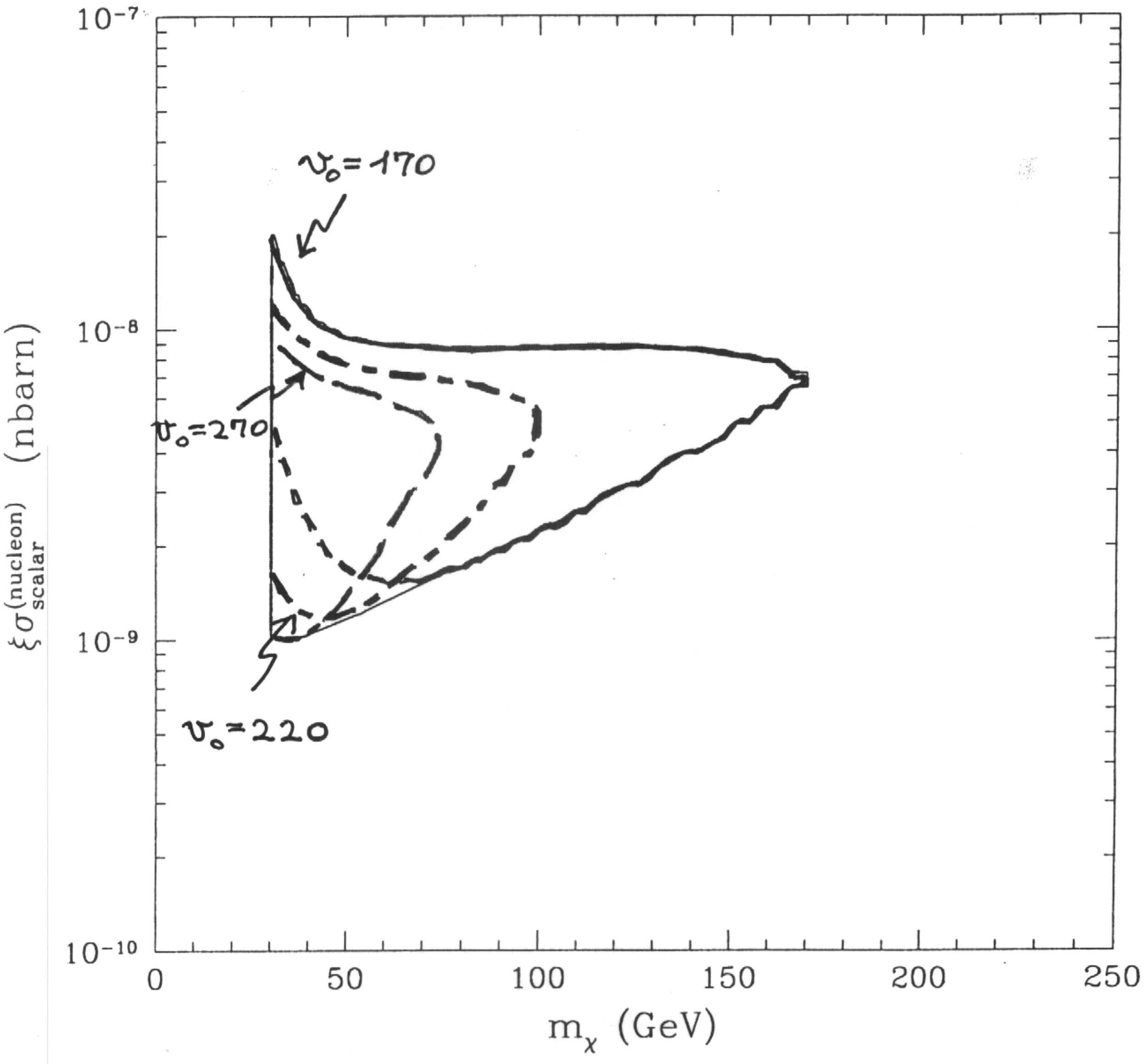
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\rho_\chi^{0.3}\ \sigma_{\rm scalar}^{(\rm nucleon)}$ (nbarn)
CDMS
0
100
200
m_χ (GeV)

DAMA 3σ C.L. annual-modulation region

(exposure: 57986 kg·day)

Bernabei et al., Phys. Lett. B480 (2000) 23
preprint INFN/AE-00/01 (www.lngs.infn.it)

$\rho_\ell = 0.3$ GeV·cm^{-3}, v_0 in km·sec^{-1}



What if we go beyond the standard Maxwell–Boltzmann velocity distribution?

Recent investigations

* Bulk rotation of the dark halo

  Kamionkowski and Kinkhabwala, Phys. Rev. D57 (1998) 3256

  Donato, Fornengo and Scopel, Astrop. Phys. 9 (1998) 247

  Belli et al., Phys. Rev. D61 (2000) 023512

* Anisotropy in WIMP velocities

  Vergados, Phys. Rev. D62 (2000) 023519

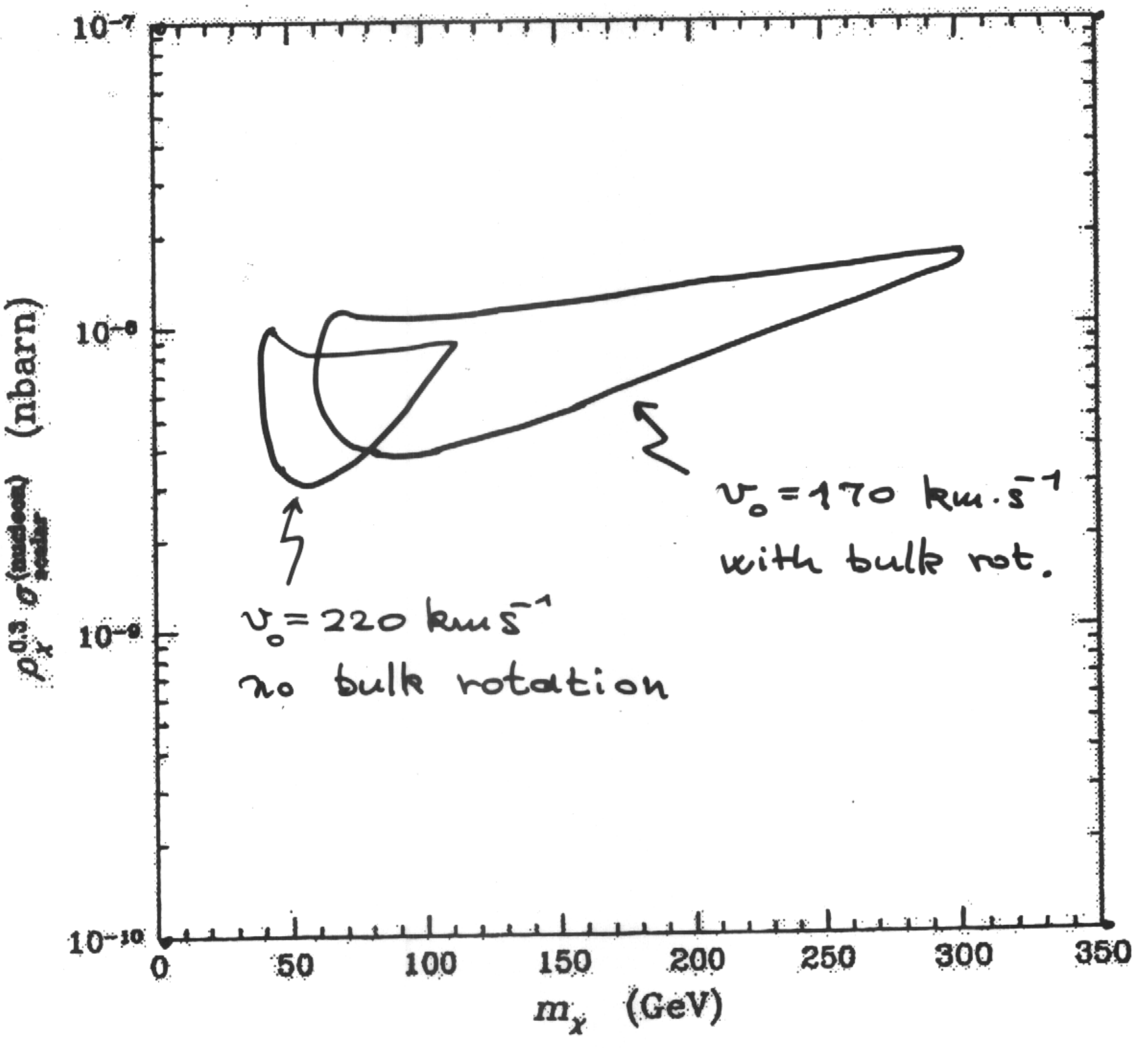
  Ullio and Kamionkowski, hep-ph/0006183

  Evans, Carollo and de Zeeuw, astro-ph/0008156

  A.M. Green, astro-ph/0008318

Effect of a <u>bulk rotation</u> of the dark halo (and of the dispersion velocity v_0).

From Belli et al., Phys. Rev. D 61 (2000) 023512



For the effect of dependence on v_0 (no bulk rotation) see also

Brhlik and Roskzkowski, Phys. Lett. B464 (1999) 303

Effect of an asymmetry in the WIMP velocity distribution from

A.M. Green, astro-ph/0008318

The parameter λ ($0 \le \lambda \le 1$) quantifies the deviation from an isotropic distribution ($\lambda = 0$)

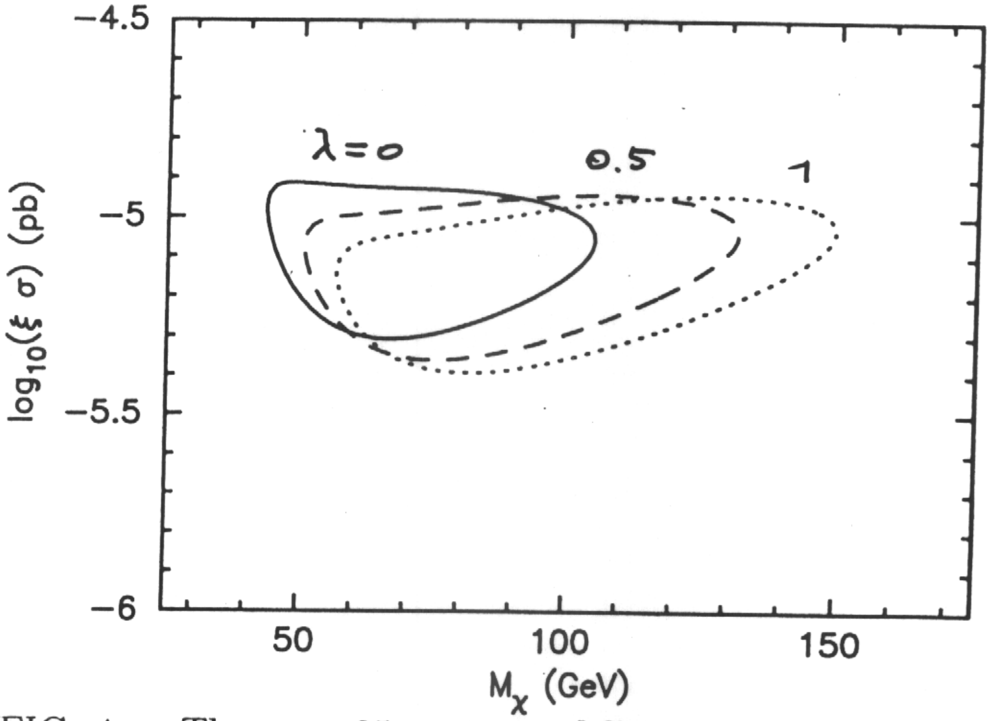


FIG. 4. The $\kappa = 35$ contour, delineating the region of $m_\chi - \xi\sigma$ parameter space compatible with the DAMA annual modulation signal, for asymmetric halo models with $\lambda = 0, 0.5, 1$ (solid, dashed and dotted lines respectively).

- Previous arguments show that for WIMP masses in the range

$$\boxed{40 \text{ GeV} \lesssim m_\chi \lesssim 200 \text{ GeV}}$$

current experiments of direct detection are sensitive to

$$10^{-9} \text{ nbarn} \lesssim \rho_\chi^{0.3} \, \sigma_{\text{scalar}}^{(\text{nucleon})} \lesssim 10^{-8} \text{ nbarn}$$

$$\Rightarrow \boxed{4 \times 10^{-10} \text{ nbarn} \lesssim \xi \sigma_{\text{scalar}}^{(\text{nucleon})} \lesssim 2 \times 10^{-8} \text{ nbarn}}$$

- Questions:

1) Is this range of $\sigma_{\text{scalar}}^{(\text{nucleon})}$ compatible with relic neutralinos ?

2) Does it involve neutralino relic abundances of cosmological interest ?

Answers to both questions are : Yes !

Supersymmetry

▷ strong theoretical motivations

- fermion-boson symmetry
- stability of scalar masses
- unification with gravity in supergravity theories

▷ it would help unification of coupling constants at M_{GUT}

▷ but no experimental confirmation is available yet

- only a number of constraints on Susy parameters are derivable from accelerators

Supersymmetry

- Susy with R-parity conservation entails that the Lightest Susy Particle is stable.

- Depending on the Susy scheme and on the sector of the Susy parameter space the LSP could be:

$$\left.\begin{array}{l}\text{squark}\\ \text{slepton (charged)}\\ \text{sneutrino}\\ \text{neutralino}\\ \text{gravitino}\\ \text{axino}\\ \ldots\end{array}\right\} \text{good candidates for dark matter}$$

- The neutralino is a particularly interesting case of WIMP, since:

  * it may be of cosmological relevance
    $(0.05 \lesssim \Omega_\chi h^2 \lesssim 0.3)$

  * it may be detectable (direct & indirect)

Definition: linear combination

$$\chi = a_1 \tilde{B} + a_2 \tilde{W}^{(3)} + a_3 \tilde{H}_1^{(0)} + a_4 \tilde{H}_2^{(0)}$$

of lowest mass m_χ.

Susy schemes (gravity-mediated)

- ▷ Universal SUGRA: unification conditions for the soft Susy-breaking terms at $M_{GUT} \sim 10^{16}$ GeV

- ▷ However, the unification scale is largely uncertain.

  This implies that at M_{GUT}, significant deviations from universality may occur; typically, for scalar soft masses.

  The resulting Susy phenomenology at the EW scale is largely affected by these deviations. nuSUGRA

- ▷ Effective model: MSSM at the EW scale

  a few mass parameters which set the most relevant scales: effMSSM

- ▷ Extensions:

  * deviations from gaugino unification
  * CP-violating phases

  ...

  ...

(universal) SUGRA

$m_{1/2}$ gaugino mass

m_0 scalar mass

A_0 trilinear coupling

$$\tan\beta = \frac{\langle H_2 \rangle}{\langle H_1 \rangle}$$

sign(μ) (μ = Higgs-mixing coupling)

nu SUGRA

deviations from universality in the Higgs masses at M_{GUT} is allowed

$$m^2_{H_i}(M_{GUT}) = m_0^2 (1+\delta_i)$$

eff MSSM

* Minimal Supersymmetric extension of the Standard Model (MSSM) at the electroweak scale (M_Z), described by

$\tan\beta = \dfrac{\langle H_2 \rangle}{\langle H_1 \rangle}$

M_2 SU(2) gaugino mass ($M_1 = \frac{5}{3}\tan^2\theta_w \cdot M_2$ is assumed)

μ Higgs-mixing parameter

m_A CP-odd neutral Higgs boson (or m_h)

$m_{0\tilde{q}}, m_{0\tilde{\ell}}$ squark, slepton masses

A trilinear coupling

* the supersymmetric parameter space is constrained by

- experimental bounds from accelerators on supersymmetric and Higgs searches
- constraints from $b \to s + \gamma$
- condition that neutralino is the LSP
- cosmological bound $\Omega_\chi h^2 < 0.7$

new muon anomalous magnetic moment ($g-2$) : deviation from SM prediction ?

In Susy we can calculate

* for the <u>neutralino-nucleus interaction</u>

$$\sigma_{\text{coherent}} \, , \quad \sigma_{\text{spin-dependent}}$$

$$\hookrightarrow \sigma^{(\text{nucleon})}_{\text{scalar}}$$

($\sigma_{\text{coherent}} \gg \sigma_{\text{spin-dependent}}$ in the range for σ considered here)

* for <u>neutralino-neutralino annihilation</u>

$$\sigma_{\text{ann}}$$

$$\sigma_{\text{ann}} \longrightarrow \Omega_\chi h^2 \sim \frac{1}{\langle v \, \sigma_{\text{ann}} \rangle}$$

▷ Notice that $\sigma^{(\text{nucleon})}_{\text{scalar}} \sim \sigma_{\text{ann}}$

(i.e. $\sigma^{(\text{nucleon})}_{\text{scalar}}$ & σ_{ann} are both increasing or decreasing functions in terms of typical Susy parameters)

thus

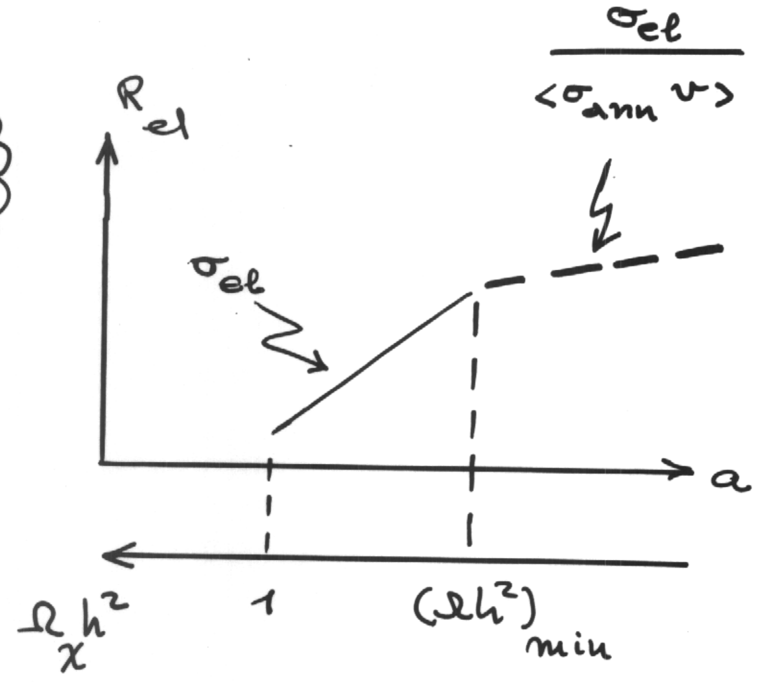
$$\Omega_\chi h^2 \sim \frac{1}{\sigma^{(\text{nucleon})}_{\text{scalar}}}$$

Estimate of neutralino local density (rescaling)

$$\rho_\chi = \xi \rho_\ell = \begin{cases} \rho_\ell & \text{if } \Omega_\chi h^2 \geq (\Omega h^2)_{min} \\ \dfrac{\Omega_\chi h^2}{(\Omega h^2)_{min}} \rho_\ell \propto \dfrac{1}{\langle \sigma_{ann} v \rangle} \rho_\ell & \text{if } \Omega_\chi h^2 < (\Omega h^2)_{min} \end{cases}$$

$$R_{el} \propto \rho_\chi \sigma_{el} \propto \begin{cases} \sigma_{el} & \text{if } \Omega_\chi h^2 \geq (\Omega h^2)_{min} \\ \dfrac{\sigma_{el}}{\langle \sigma_{ann} v \rangle} & \text{if } \Omega_\chi h^2 < (\Omega h^2)_{min} \end{cases}$$

<u>a</u> is a generic parameter (e.g., $\tan\beta$)



Neutralinos of <u>lower densities</u> ($\Omega_\chi h^2$ & ρ_χ) may be <u>more easily detected</u> by WIMP direct detection

A.B., de Alfaro, Fornengo, Mignola and Scopel, Astrop. Phys. 2 (1994) 77

Some recent theoretical papers on evaluation of $\Omega_\chi h^2$ and $\sigma_{\text{scalar}}^{(\text{nucleon})}$ in various susy schemes:

Bottino, Donato, Fornengo and Scopel:
Phys. Lett. B423 (1998) 109; Phys. Rev. D59 (1999) 095003;
Phys. Rev. D59 (1999) 095004; Astrop. Phys. 13 (2000) 215;
Phys. Rev. D62 (2000) 056006

Belli et al.: Phys. Rev. D61 (1999) 023512

Arnowitt and Nath: Phys. Rev. D60 (1999) 044002

Bednyakov and Klapdor-Kleingrothauss: Phys. Rev. D62 (2000) 043524

Ellis, Ferstl and Olive: Phys. Lett. B481 (2000) 304;
Phys. Rev. D63 (2001) 065016

Accomando, Arnowitt, Dutta and Santoso: Nucl. Phys. B585 (2000) 124

Corsetti and Nath: hep-ph/0003186

Gabrielli, Khalil, Muñoz and Torrente-Lujan:
Phys. Rev. D63 (2001) 025008

Feng, Matchev and Wilczek: Phys. Lett. B482 (2000) 388

Mandic, Pierce, Gondolo and Murayama, hep-ph/0008022 v2

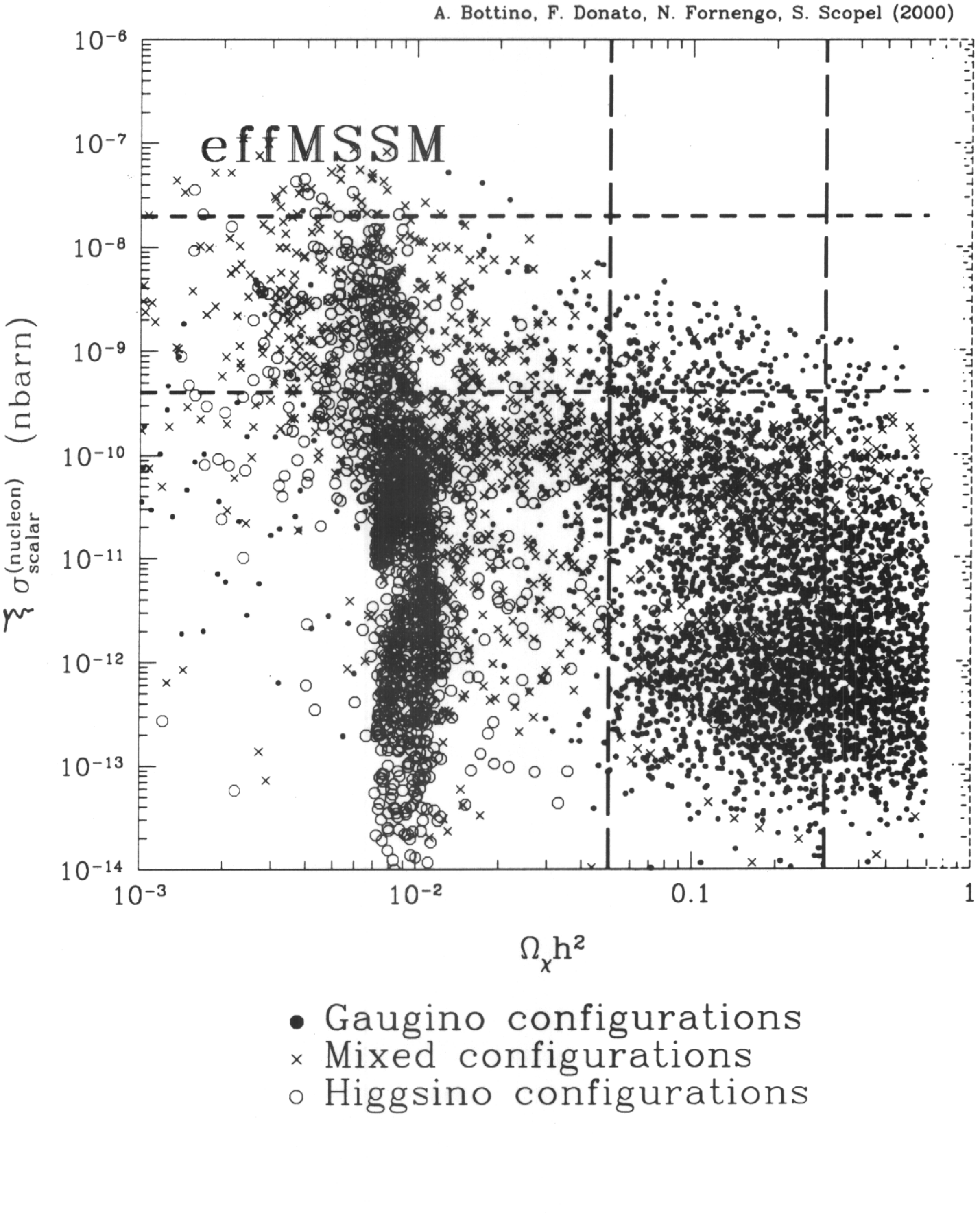
Gómez and Vergados: hep-ph/0012020

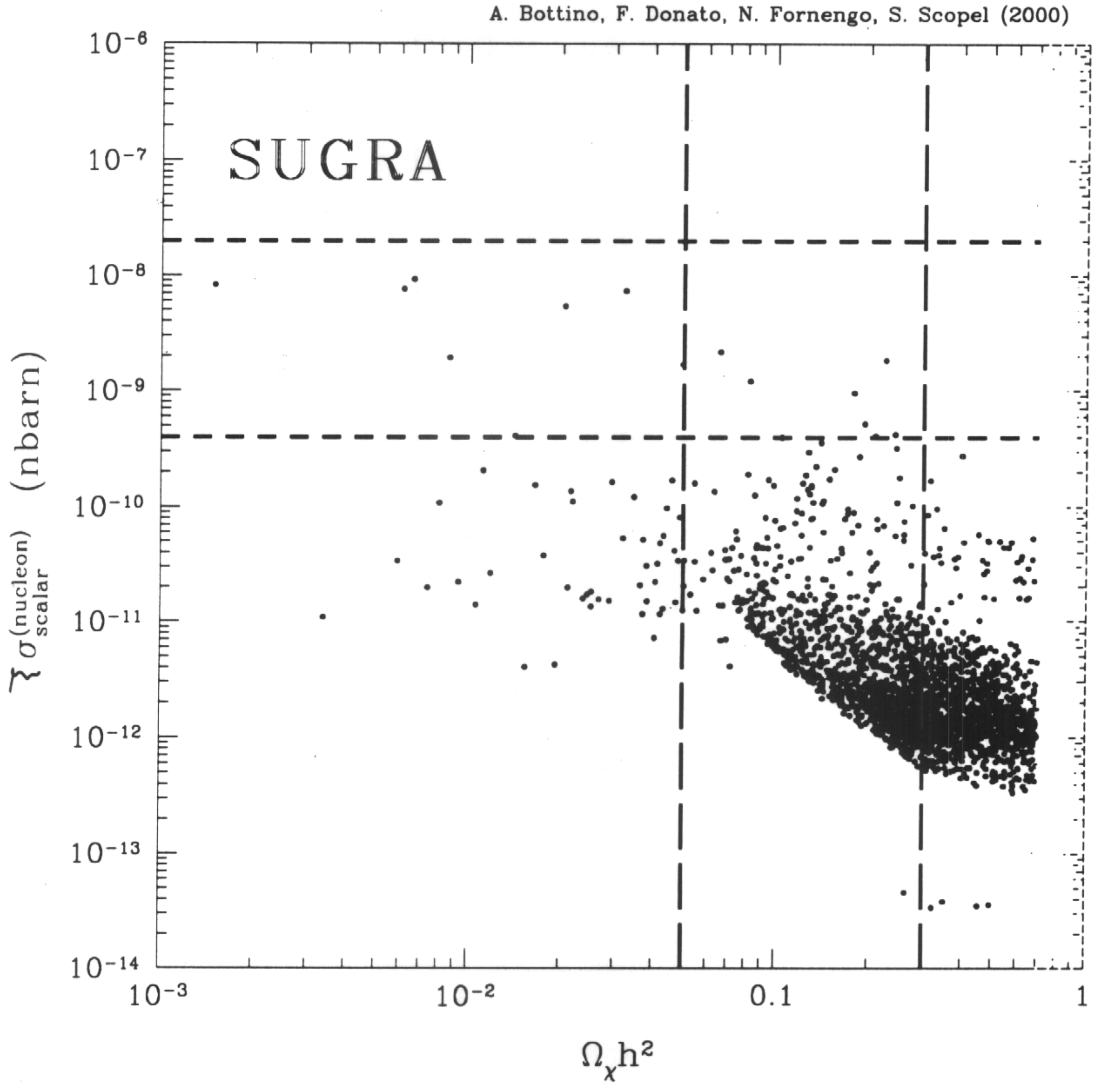
Murakami and Wells: hep-ph/0011082

Lahanas, Nanopoulos and Spanos: hep-ph/000965

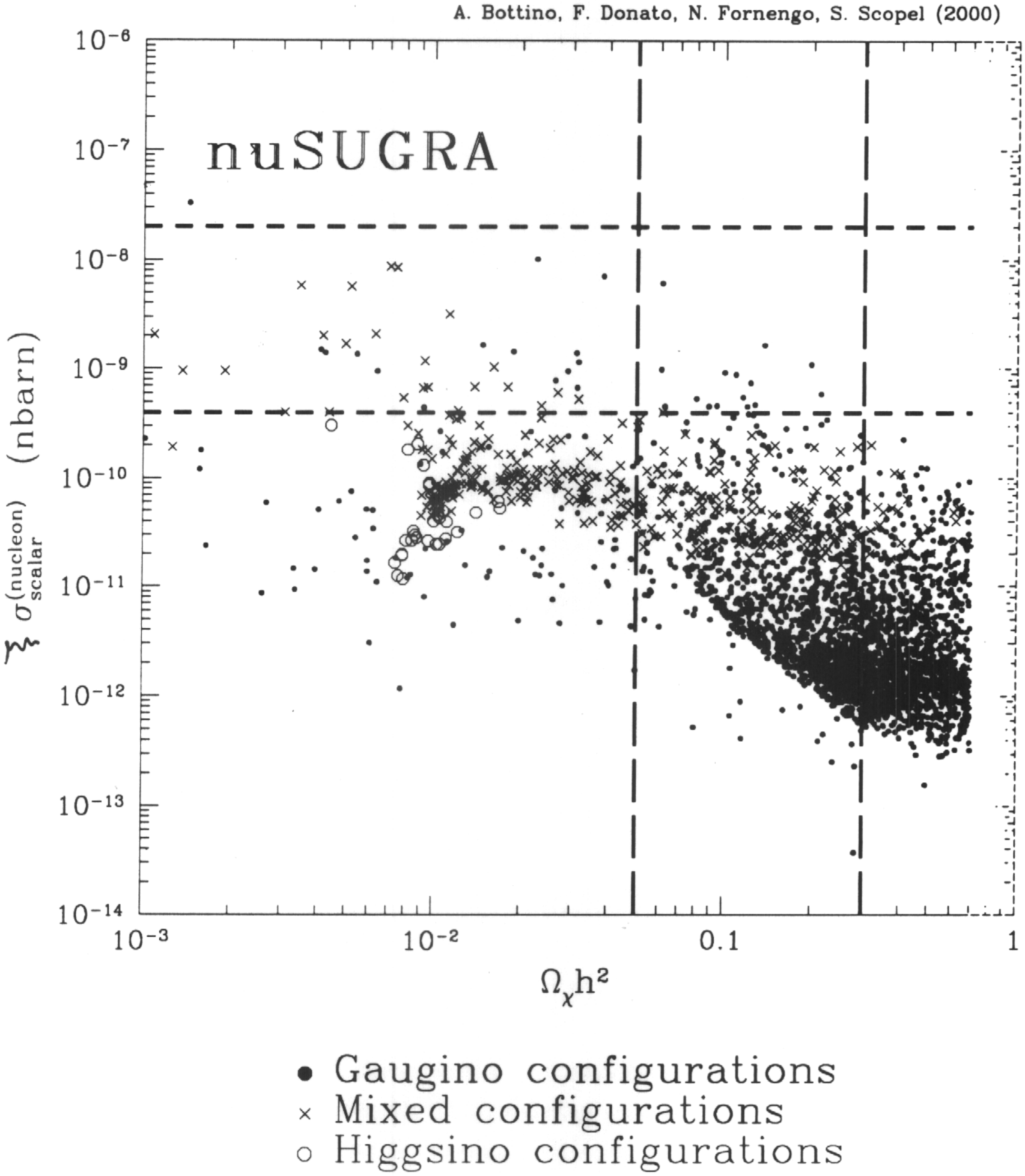
In the following we present the results obtained in

A.B., Donato, Fornengo and Scopel
hep-ph/0010203, to appear in Phys. Rev. D


A. Bottino, F. Donato, N. Fornengo, S. Scopel (2000)
effMSSM
$\xi\,\sigma_{scalar}^{(nucleon)}$ (nbarn)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-3}
10^{-2}
0.1
1
$\Omega_\chi h^2$
• Gaugino configurations
× Mixed configurations
○ Higgsino configurations



• Gaugino configurations


A. Bottino, F. Donato, N. Fornengo, S. Scopel (2000)
nuSUGRA
$\xi\,\sigma^{(nucleon)}_{scalar}$ (nbarn)
$\Omega_\chi h^2$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-3}
10^{-2}
0.1
1
• Gaugino configurations
× Mixed configurations
○ Higgsino configurations

Once $\rho_\chi \sigma^{(nucleon)}_{scalar}$ is measured, we can evaluate

ρ_χ as

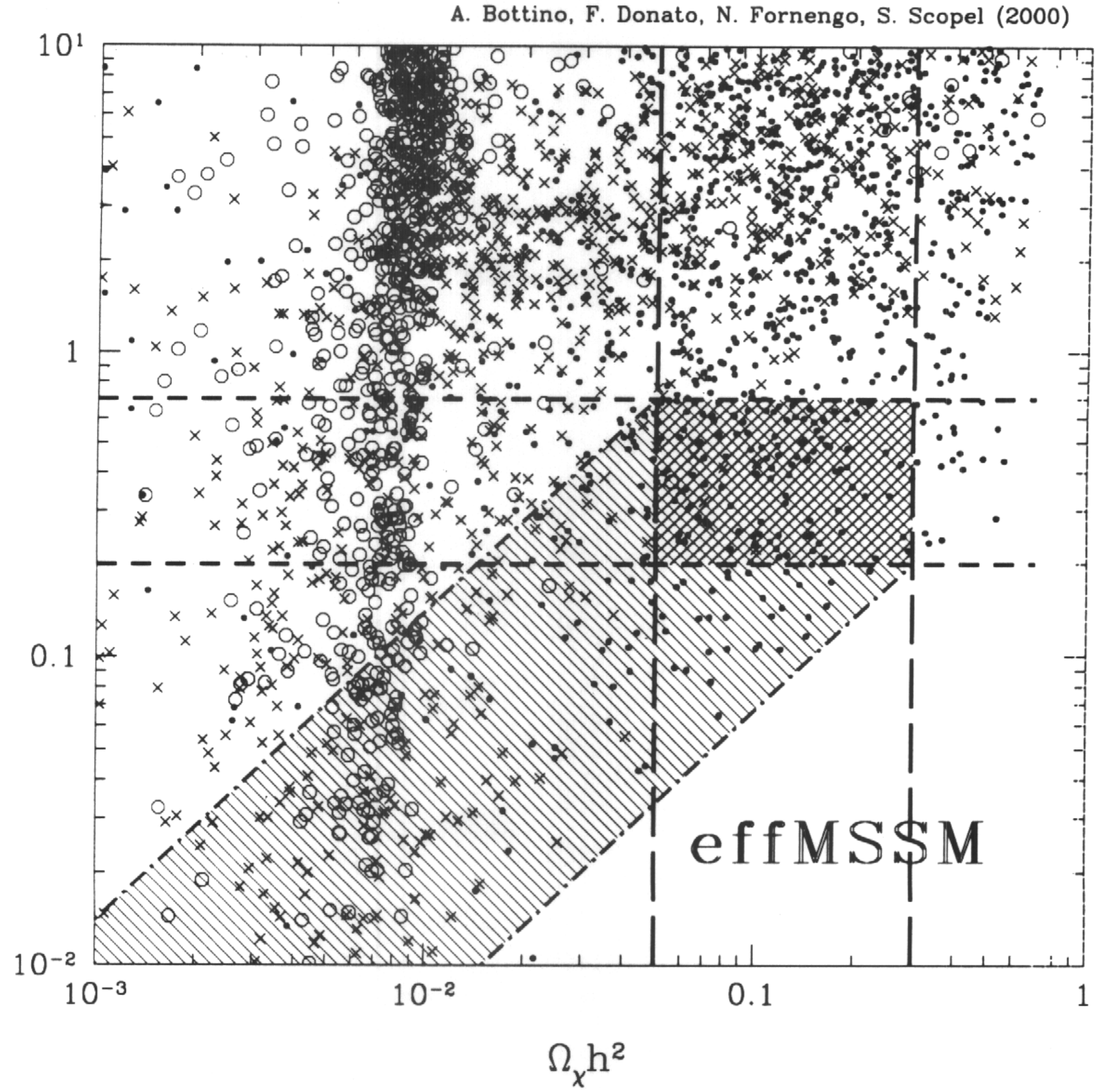
$$\rho_\chi = \frac{\left[\rho_\chi \, \sigma^{(nucleon)}_{scalar}\right]_{expt}}{\sigma^{(nucleon)}_{scalar}}$$

calculated in Susy

and then give a

ρ_χ vs $\Omega_\chi h^2$ scatter plot

where <u>galactic and average</u> cosmological properties for relic neutralinos are displayed.



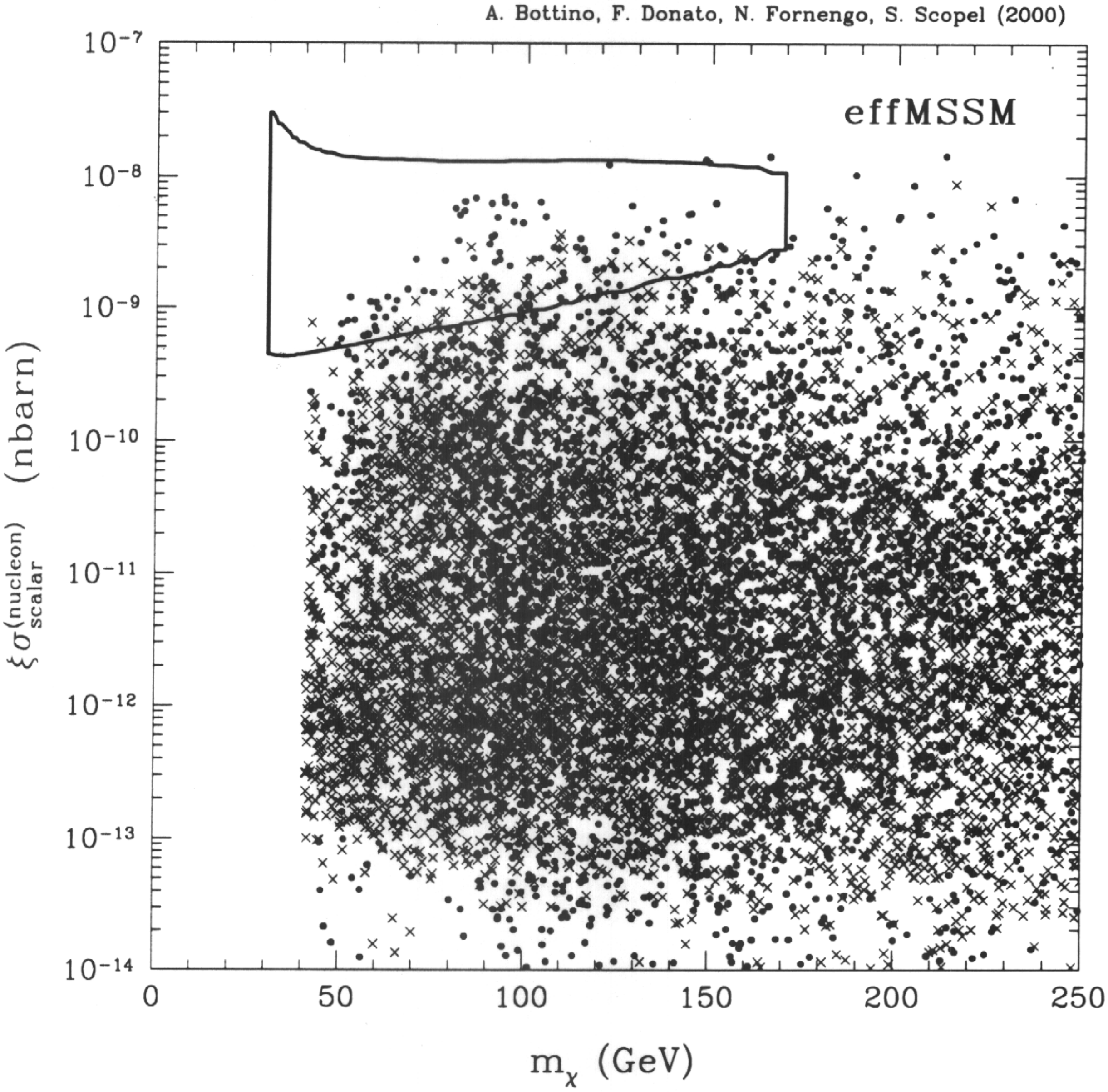
$[\rho_\chi/(0.3\ \mathrm{GeV\ cm^{-3}})\cdot\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}}]_{\mathrm{exp}} = 1\cdot 10^{-9}$ nbarn

40 GeV $\leq m_\chi \leq$ 200 GeV

• Gaugino configurations

× Mixed configurations

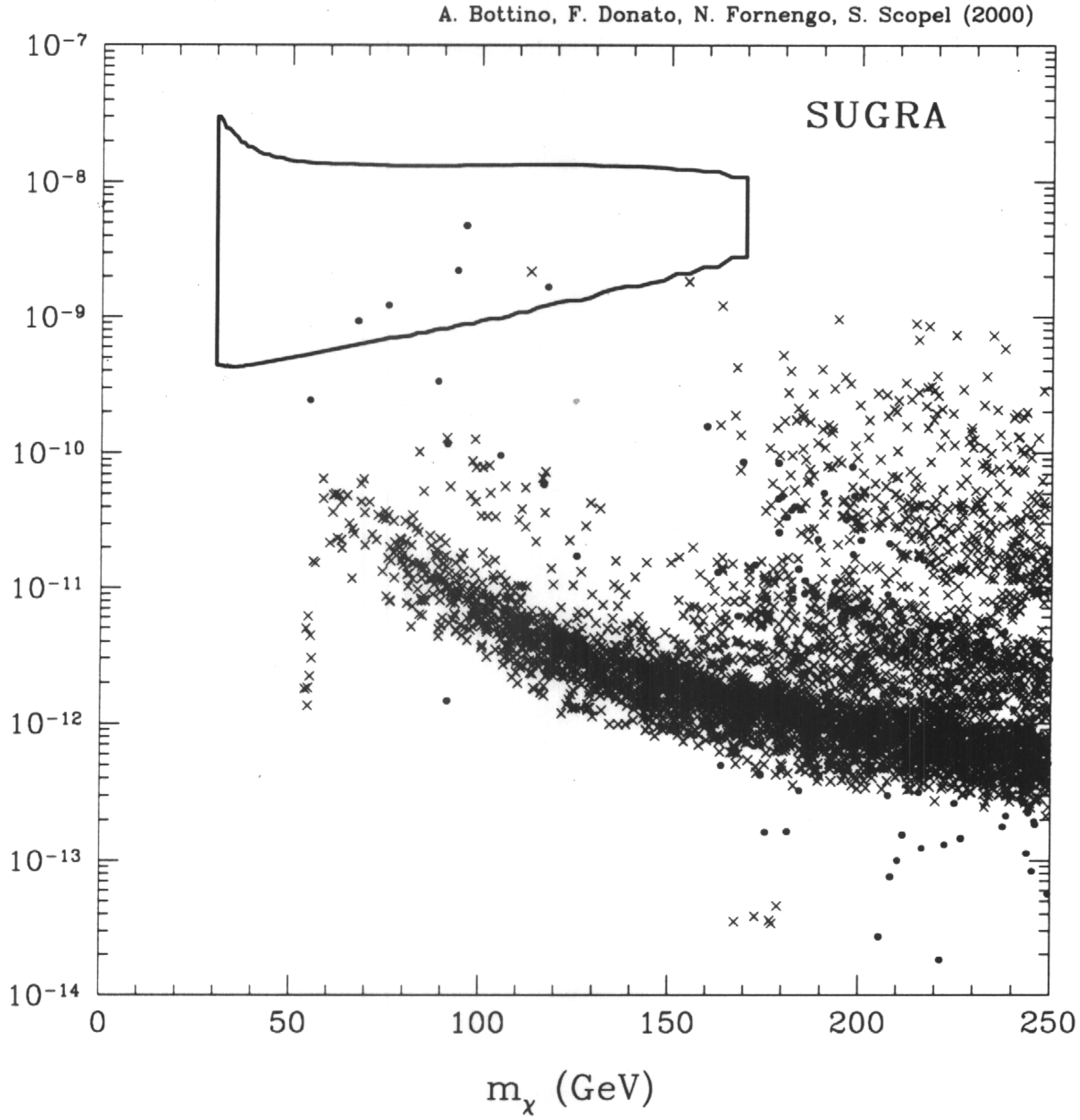
○ Higgsino configurations



× $\Omega_\chi h^2 \geqq 0.05$

• $\Omega_\chi h^2 < 0.05$

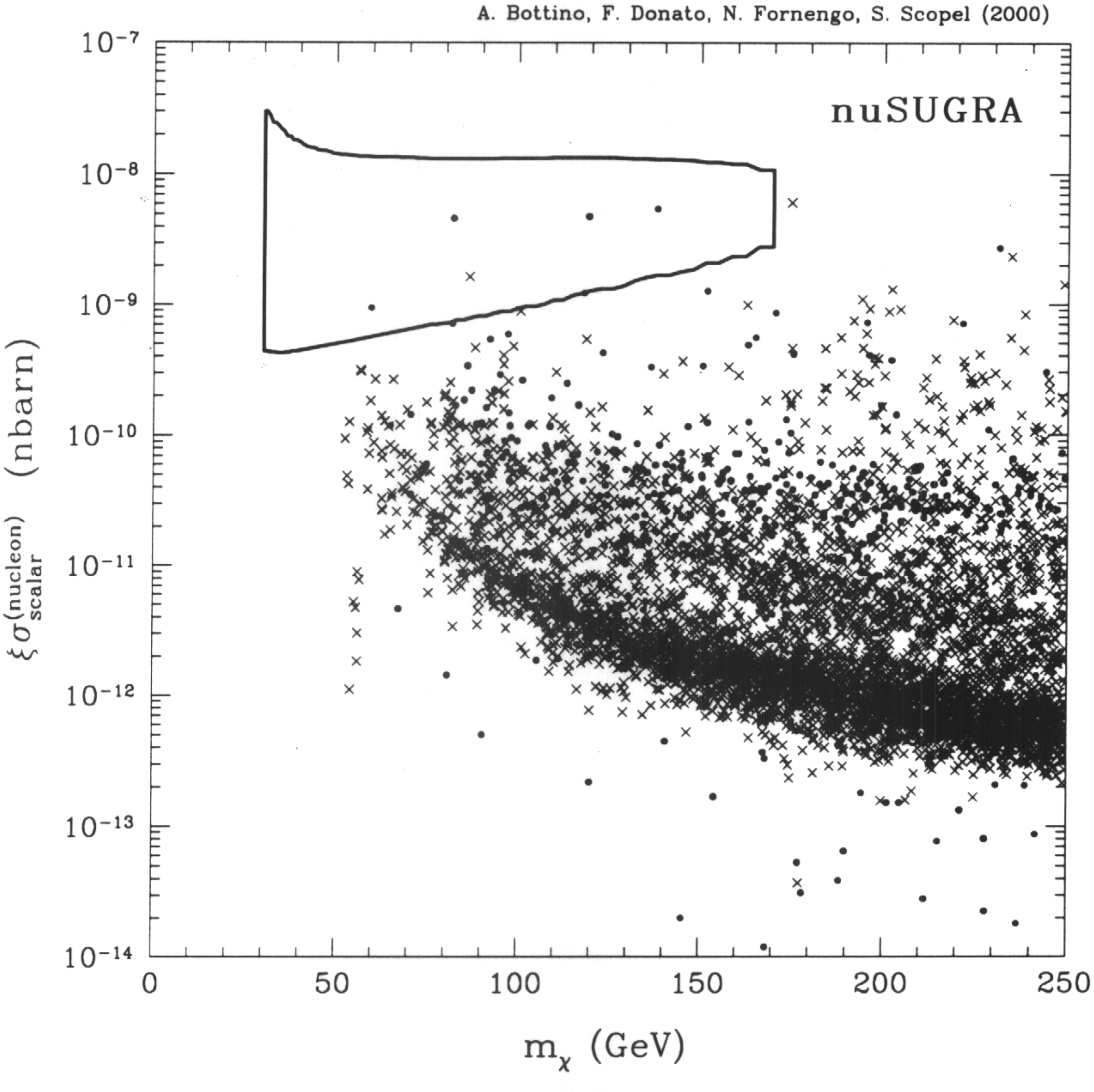
The solid contour denotes the DAMA 3 σ annual modulation region



× $\Omega_\chi\ h^2 \geqq 0.05$

• $\Omega_\chi\ h^2 < 0.05$

The solid contour denotes the DAMA 3 σ annual modulation region



× $\Omega_\chi\ h^2 \geqq 0.05$
• $\Omega_\chi\ h^2 < 0.05$

The solid contour denotes the DAMA 3 σ annual modulation region

Conclusions

- ▷ WIMP direct searches are probing quite significant regions of the supersymmetric parameter space, well beyond those explored by accelerators

- ▷ Part of the relevant susy configurations entail local and average densities of relic neutralinos of cosmological interest

- ▷ A fortiori, present WIMP direct detection experiments are sensitive to relic neutralinos with sub-dominant local and average densities

- ▷ DAMA annual modulation effect is compatible with relic neutralinos as dominant (or sub-dominant) CDM candidates

- ▷ Indirect WIMP searches may add further information on the relevant susy configurations