A. BOTTINO

Where do we stand with Dark Matter Supersymmetric candidates?

- ▷ Some generalities about Susy candidates (neutralino)
- ▷ Indication of an annual modulation effect in WIMP direct search by the DAMA/NaI experiment
- ▷ Implications of these new results when interpreted in terms of relic neutralinos:
  - * relevance for Ω_m
  - * explorability at accelerators
  - * explorability by indirect searches for WIMPs
  - * compatibility with SUGRA schemes

Dark Matter & Susy

▷ A host of observational data and calculations of cosmological structures imply that most of the matter in the Universe is dark

▷ The dominant role is played by Cold Dark Matter
(a generic name : WIMP ≡
≡ Weakly Interacting Massive Particle)

▷ The most favorite candidate for a WIMP is the neutralino, as the Lightest Supersymmetric Particle in a Susy theory with R-parity conservation

Supersymmetry

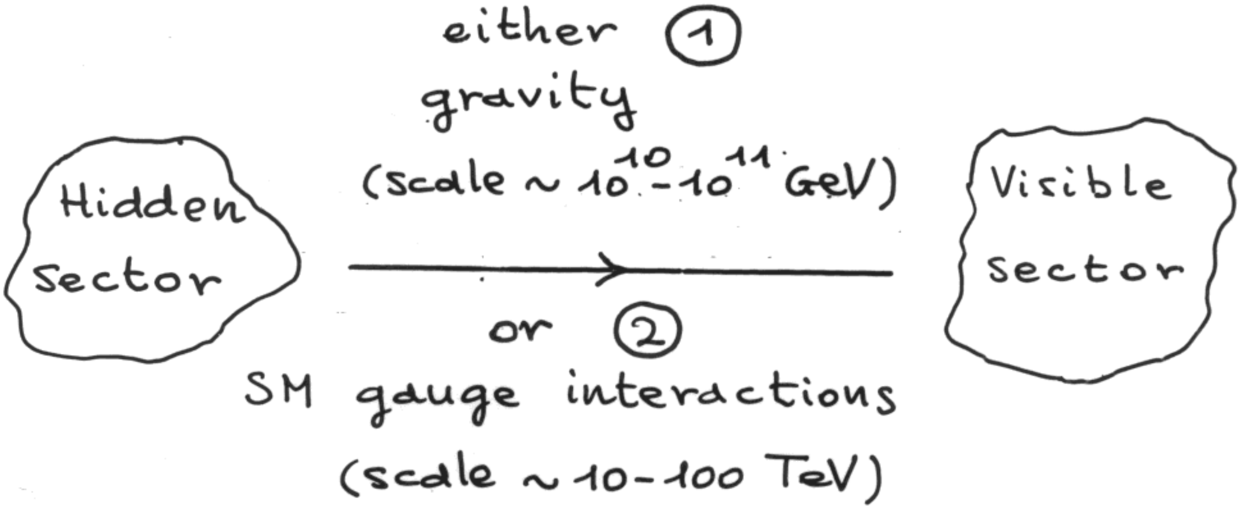
- ▷ strong theoretical motivations
  - * fermion – boson symmetry
  - * stability of scalar masses
  - * unification with gravity in supergravity theories

- ▷ 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 breaking

2 schemes



case ①: **neutralino** is LSP

case ②: gravitino is LSP, neutralino NLSP

LSP ≡ Lightest Supersymmetric Particle

NLSP ≡ Next-to-Lightest SuSy Particle

In this talk only low-energy phenomenology connected to case ① is discussed.

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for case ②, see for instance:

E. Pierpaoli, S. Borgani, A. Masiero, M. Yamaguchi for a light gravitino-dominated universe

S. Dimopoulos, G.F. Giudice, A. Pomarol for DM candidates in the hidden and messenger sectors

▶ Neutralino is a good candidate as a Weakly Interacting Massive Particle

* would have decoupled from primeval plasma at a temperature $T \sim \frac{1}{20} m_\chi$ (cold relic)

⇒ could contribute sizeably to Ω_m

⇒ could be detectable either directly or indirectly in searches for relic particles

——— o ———

Definition: linear combination

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

of lowest mass m_χ.

gaugino fractional weight: $P = a_1^2 + a_2^2$

Susy scheme adopted here:

<u>Minimal Supersymmetric extension of Standard Model</u>

at the electroweak scale, implemented by some assumptions to reduce drastically the number of Susy parameters (to six).

Δ The ranges of Susy parameters are very <u>loosely constrained</u>
(by experimental bounds & theoretical arguments)

⇒ this implies <u>large dispersions</u> in the values for $\Omega_\chi h^2$

and

for detection rates

⊕ Some considerations about SUGRA schemes

Supersymmetric model

* 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 scalar soft-mass ($\tilde{q}$ & $\tilde{\ell}$)

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 $\Omega_\chi h^2 < 0.7$

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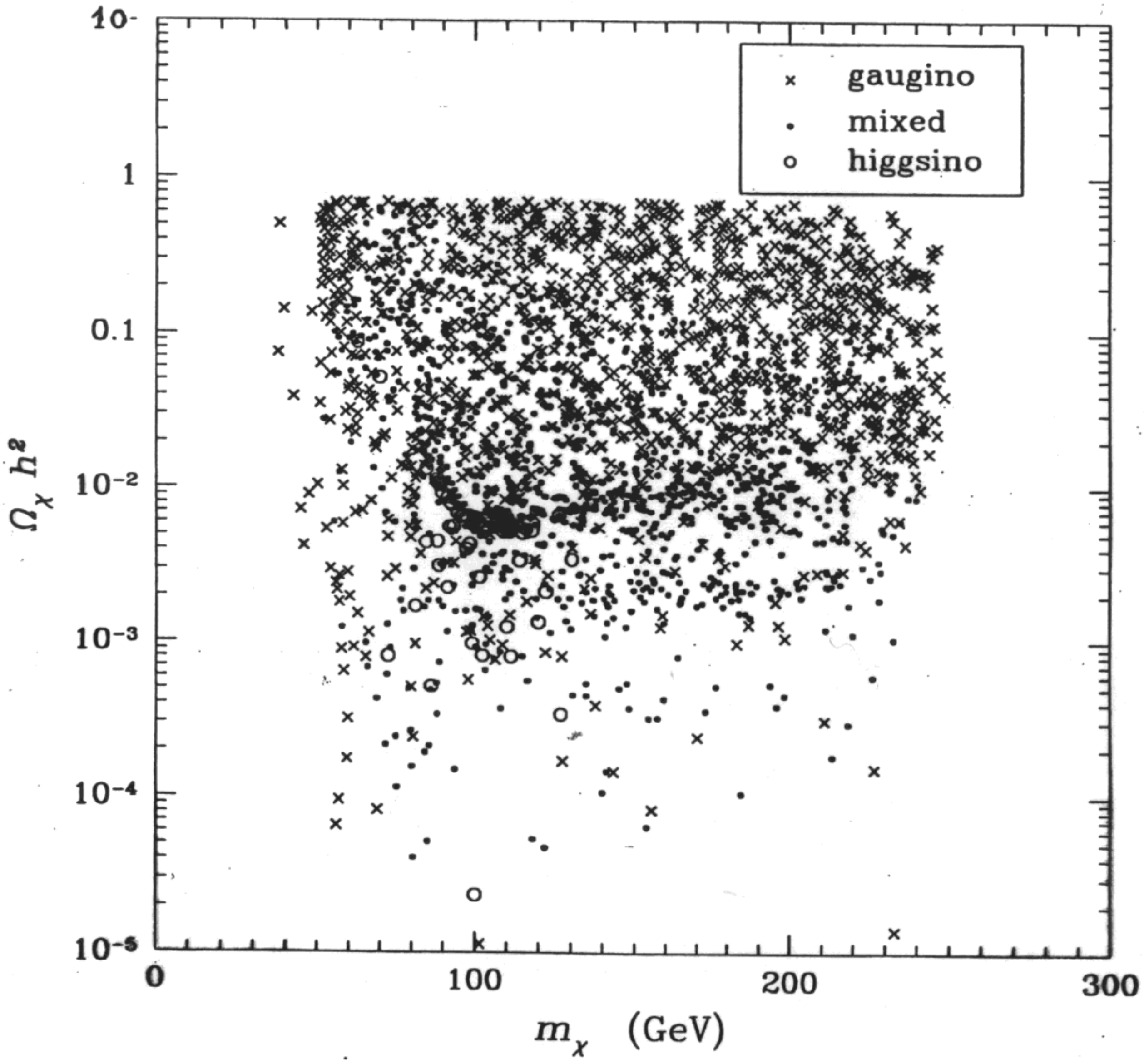
cosmologically interesting range:

$$0.01 \leq \Omega_\chi h^2 \leq 0.7$$

most appealing interval:

$$0.02 \leq \Omega_\chi h^2 \leq 0.2$$



gaugino
mixed
higgsino
10
1
0.1
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0
100
200
300
$\Omega_\chi h^2$
m_χ (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) $\longrightarrow$ ν's $\rightarrow$ up-going μ's
    (Earth, Sun)
  * signals due to χ-χ annihilations taking place in the halo

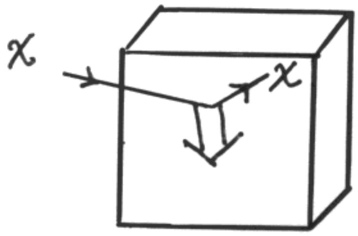
$$\chi + \chi \rightarrow f + \bar{f}, \ldots$$

↳ $\nu, \bar{\nu}$
↳ γ
} keep directionality, detectable if emitted by regions of high χ density

↳ gamma line
(2γ)

↳ $\bar{p}$
↳ e^+
} 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

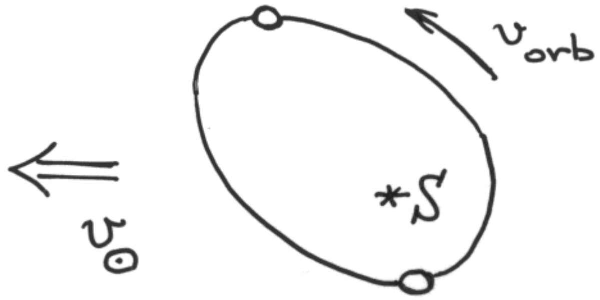
$$\frac{d\sigma^C}{dE} \propto F^2(q)\, A^2\, \sigma^{(nucleon)}_{scalar}$$

Assuming a specific expression for f(v) (usually, a Maxwell-Boltzmann speed distribution) and a set of values for the astrophysical velocities: $v_\odot$, v_{escape}

$$\frac{dR}{dE_R} \Longrightarrow \rho_\chi\, \sigma^{(nucleon)}_{scalar}$$

Discrimination of the signal against the background is based on the expected annual modulation of the signal

Annual modulation



speed of the solar system in the Galactic Rest Frame

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

(12 km·s⁻¹: peculiar velocity)

speed of the earth in the GRF

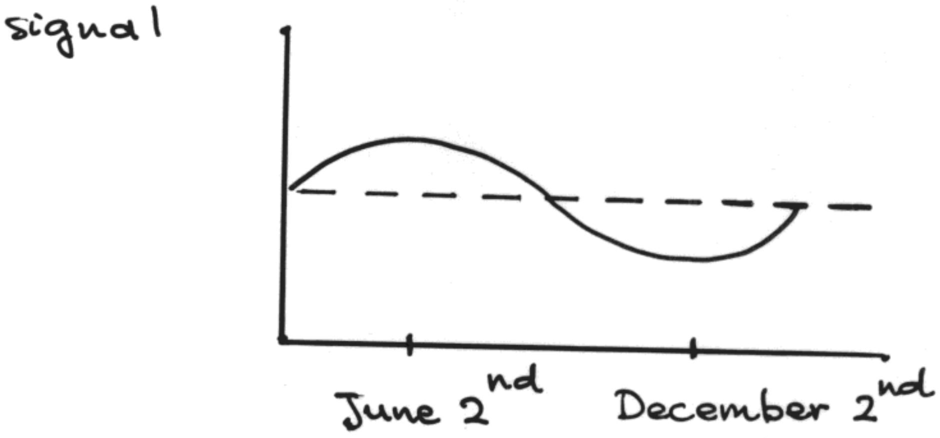
$$v_\oplus(t) = v_\odot + v_{orb} \cos\gamma \cos[\omega(t - t_0)]$$

- v_{orb}: earth orbital speed
- γ: orbit inclination ($\gamma = 60°$)
- ω: $2\pi / 1yr$
- t_0: June 2nd

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

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

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



DAMA data on annual modulation (NaI detector)

- 1^{st} set of data collected with an exposure of 4,549 kg·day
- 2^{nd} set of data collected with an exposure of 14,962 kg·day

both provide indication of an annual modulation effect.

Combination of the 2 samples (total exposure of 19,511 kg·day) singles out a well delimited region in the plane $\rho_\chi \sigma_{sc}^{(n)} - m_\chi$, centered at

$$\frac{\rho_\chi}{0.3\ \mathrm{GeV\cdot cm^{-3}}}\ \sigma_{sc}^{(n)} = 7.0^{+0.4}_{-1.2} \times 10^{-9}\ \mathrm{nb}$$

$$m_\chi = 59^{+17}_{-14}\ \mathrm{GeV}$$

(taking $v_0 = 220\ \mathrm{km\cdot s^{-1}}$, $v_{esc} = 650\ \mathrm{km\cdot s^{-1}}$)

Hypothesis of presence of modulation vs hypothesis of absence favoured at 99.6 % C.L.

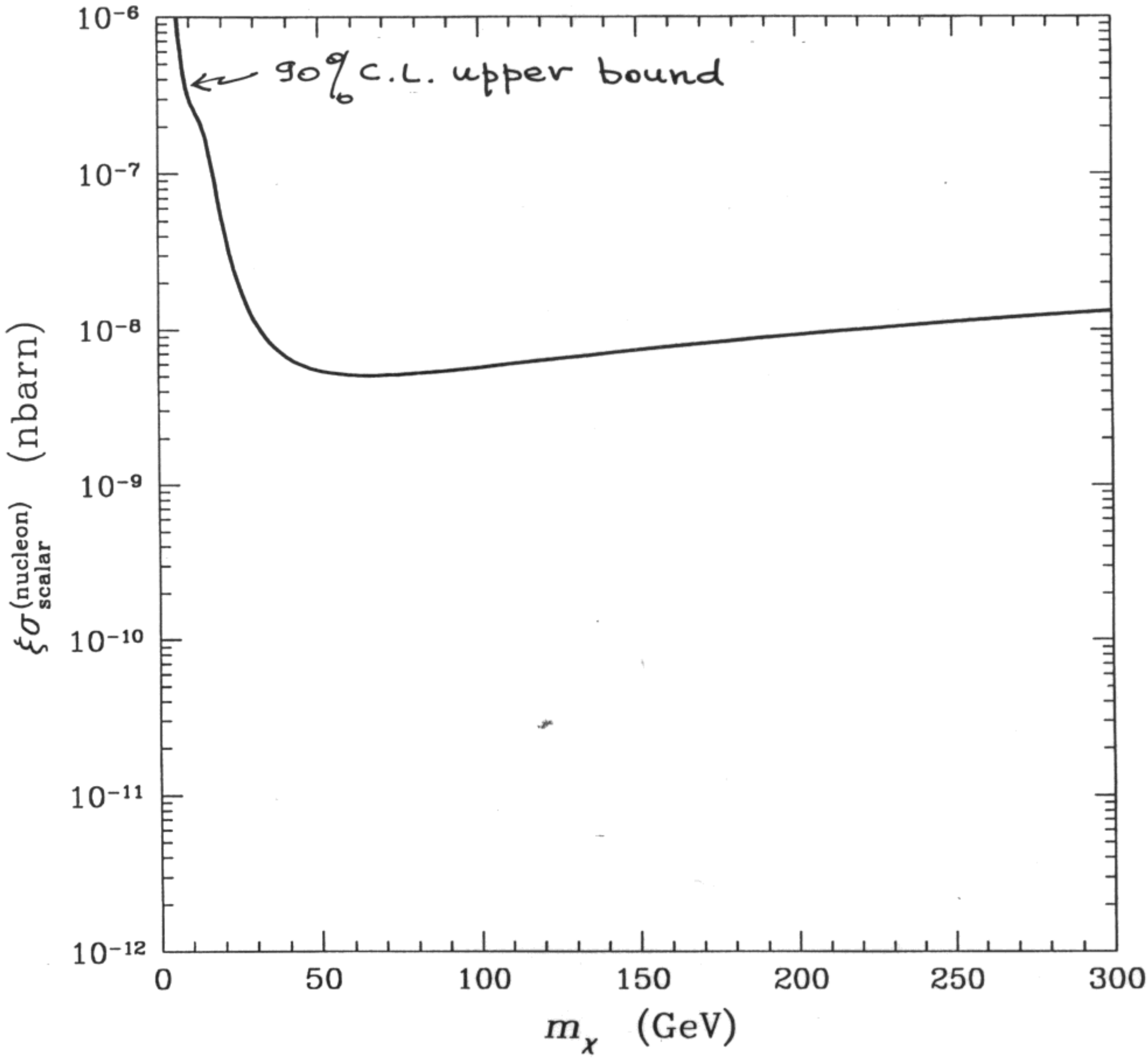
DAMA Collaboration (R. Bernabei et al.):

Phys. Lett. B 424 (1998) 195

ROMA2F/98/27

{ ROMA2F/98/34 (to appear in Phys. Lett. B)
INFN/AE-98/20 }

$$\left(\frac{\rho_\chi}{0.3\ \mathrm{GeV\cdot cm^{-3}}}\right)\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}} \quad \mathrm{vs} \quad m_\chi$$



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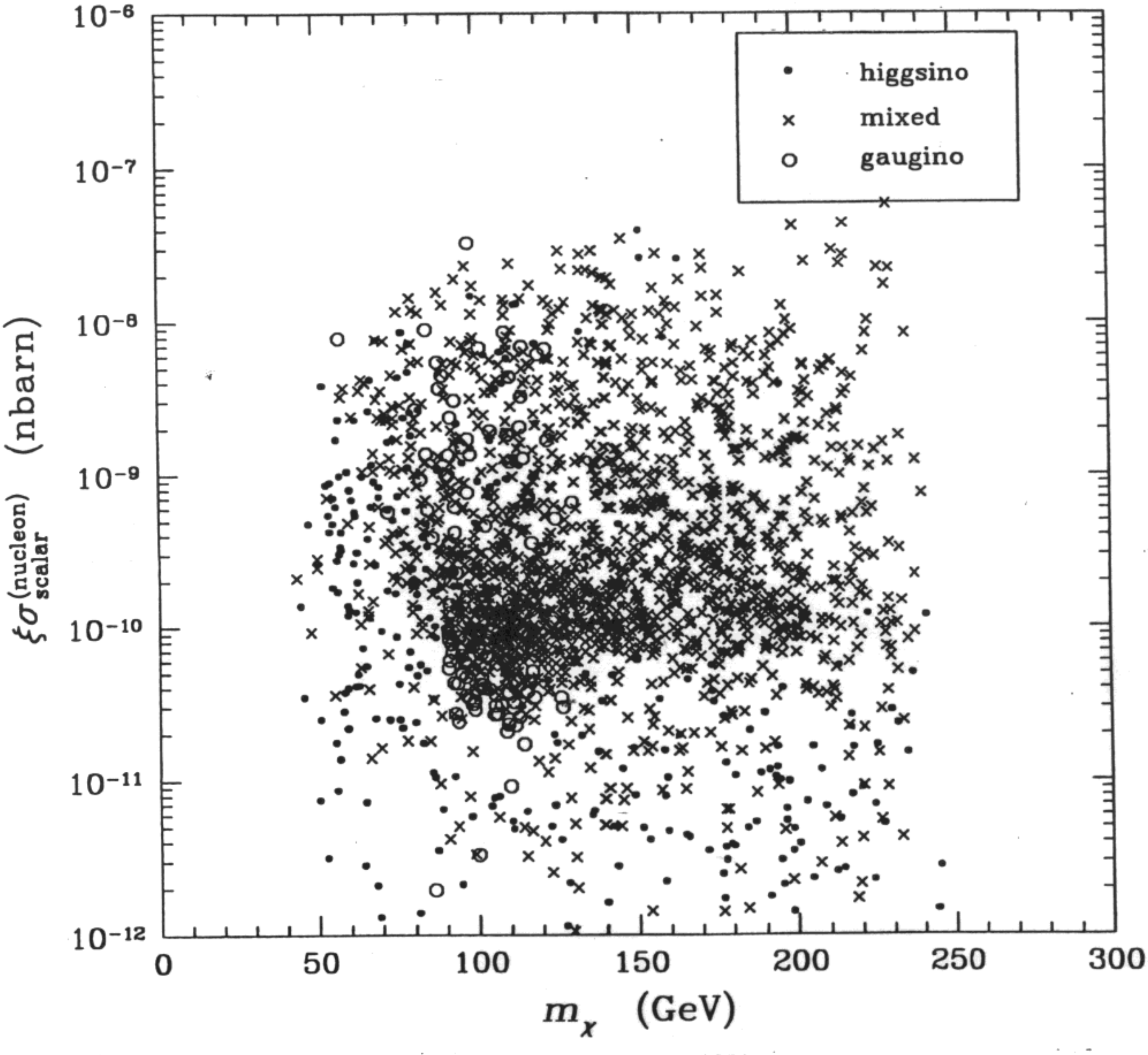
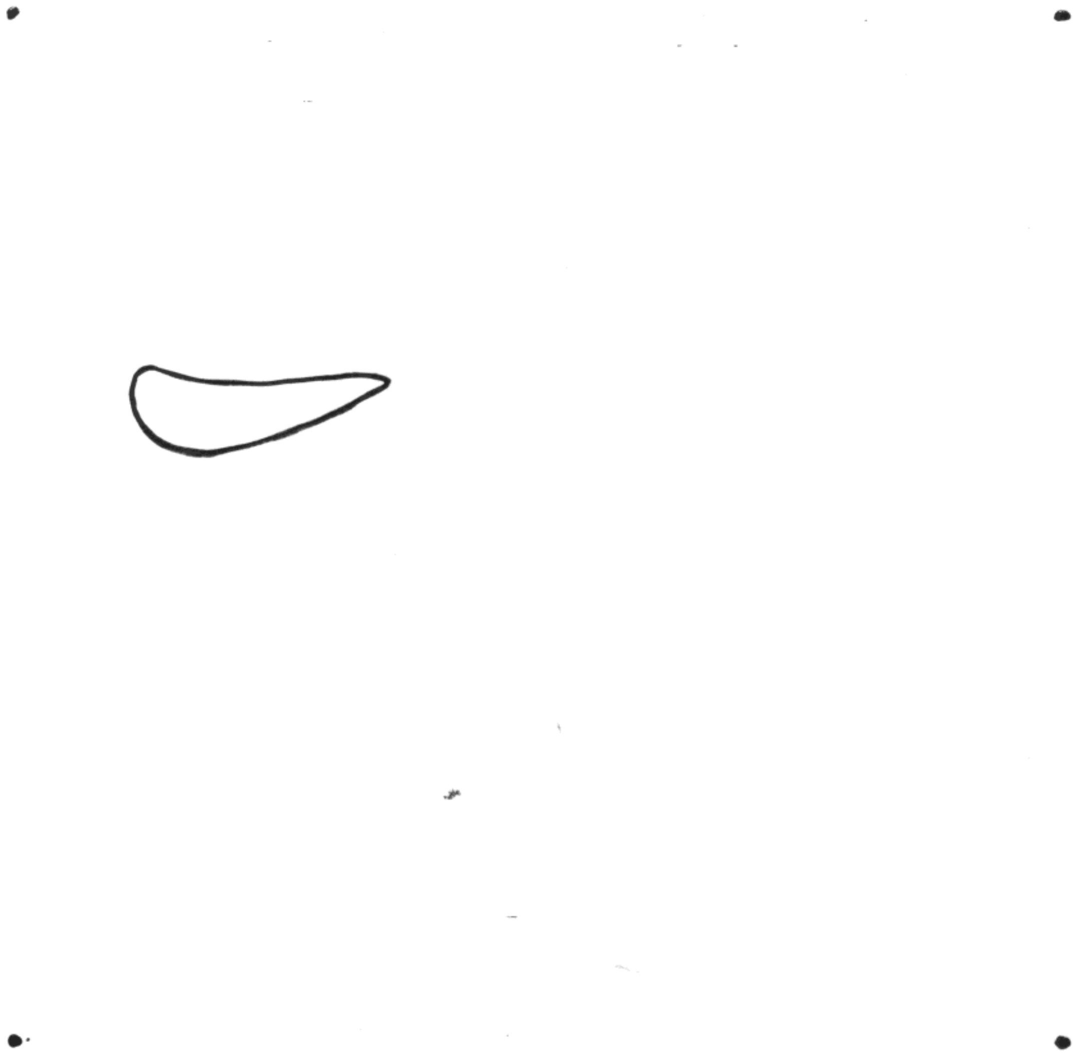




Region singled out by DAMA data on annual modulation (2-σ C.L.)

$v_0 = 220\ \mathrm{km \cdot s^{-1}}$, $v_{escape} = 650\ \mathrm{km \cdot s^{-1}}$

▷ The indication of a possible modulation effect singled out by the DAMA data needs confirmation by further experimental investigation in direc search (already under way)

▷ <u>If confirmed</u>, this effect would be a <u>major breakthrough</u> in establishing the existence of particle DM in the Universe

▷ We have analysed DAMA data in terms of <u>relic neutralinos</u> and investigated the relevant Susy configurations to establish:

* contribution to $\underline{\Omega_{CDM}}$
* explorability <u>at accelerators</u>
* investigation by <u>indirect searches</u> for WIMPs (upgoing μ's at ν-telescopes, $\bar{p}$'s in CR)
* compatibility with <u>SUGRA</u> schemes

A.B., F. Donato, N. Fornengo and S. Scopel:

Phys. Lett. B 423 (1998) 109

hep-ph/9710295

hep-ph/9808456 to appear in Phys. Rev. D

hep-ph/9808459 " " " " " "

hep-ph/9809239 to appear in Astrop. Phys.

We select Susy configurations whose representative points fall inside the DAMA region

$$\xi \sigma_{sc}^{(n)} - m_\chi \qquad \left(\xi \equiv \frac{\rho_\chi}{\rho_{loc}} \right)$$

by provisionally setting

$$v_0 = 220 \text{ km} \cdot s^{-1}, \quad v_{esc} = 650 \text{ km} \cdot s^{-1}$$

(for an extension, see later on)

We take into account the uncertainty in ρ_{loc}

$$0.1 \text{ GeV} \cdot cm^{-3} \leq \rho_{loc} \leq 0.7 \text{ GeV} \cdot cm^{-3}$$

and use

$$\xi = \min \left\{ 1, \frac{\Omega_\chi h^2}{(\Omega h^2)_{min}} \right\}$$

$(\Omega h^2)_{min}$ is set here to $(\Omega h^2)_{min} = 0.01$

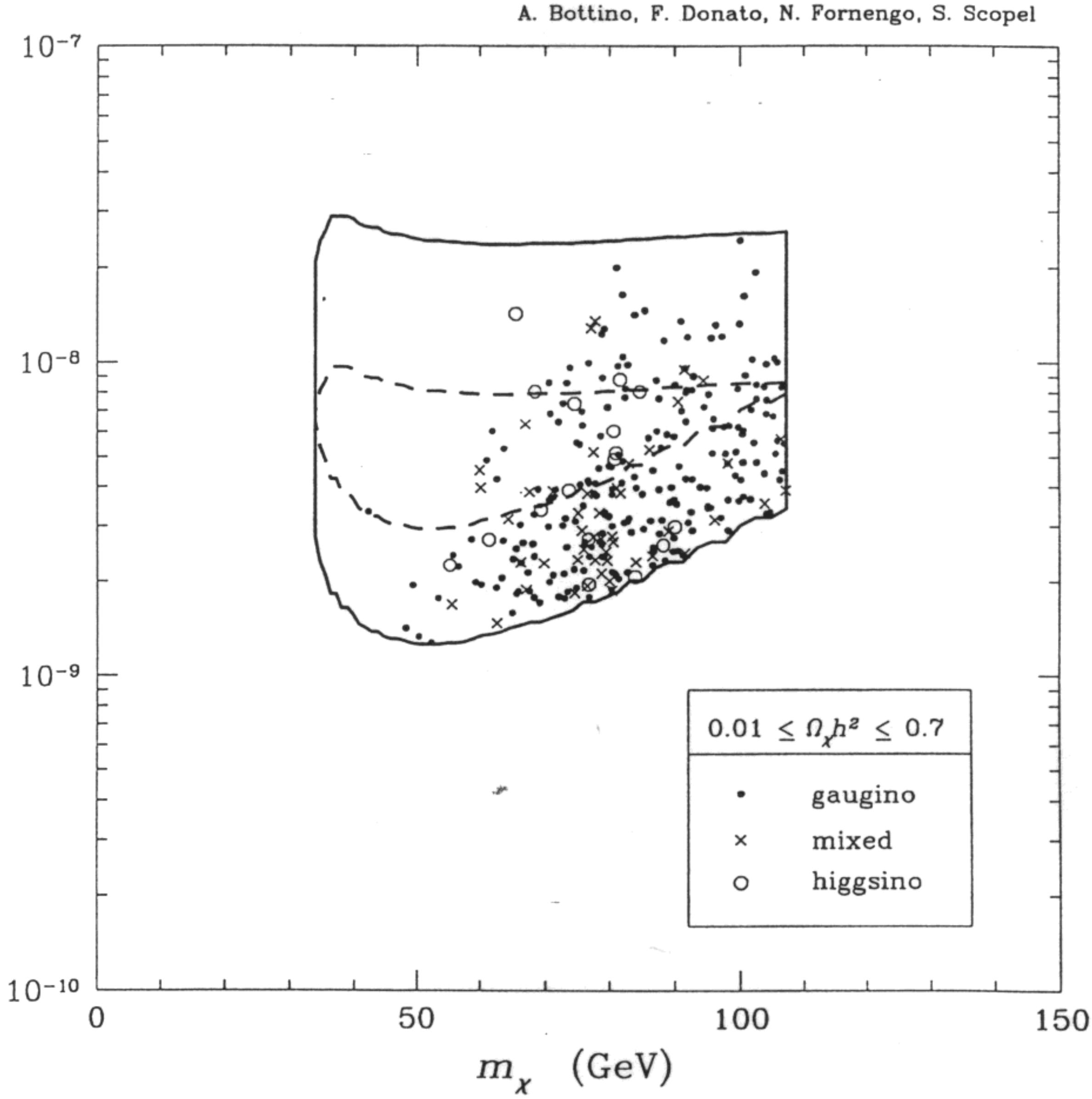

A. Bottino, F. Donato, N. Fornengo, S. Scopel
$\xi\sigma^{(nucleon)}_{scalar}$ (nbarn)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
50
100
150
m_χ (GeV)
$0.01 \leq \Omega_\chi h^2 \leq 0.7$
gaugino
mixed
higgsino

Figure 2 (a)

A. Bottino, F. Donato, N. Fornengo, S. Scopel

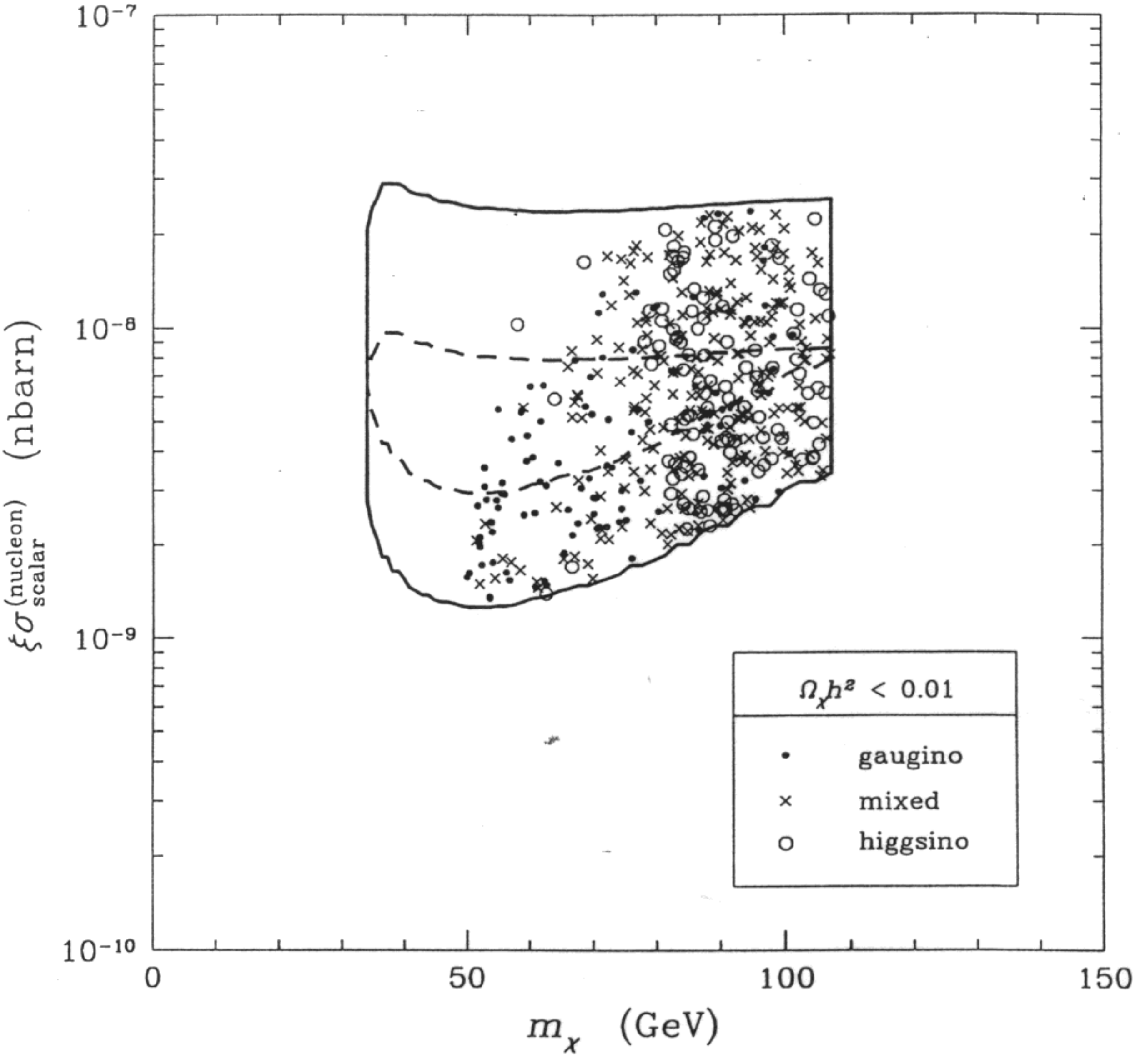


Figure 2 (b)

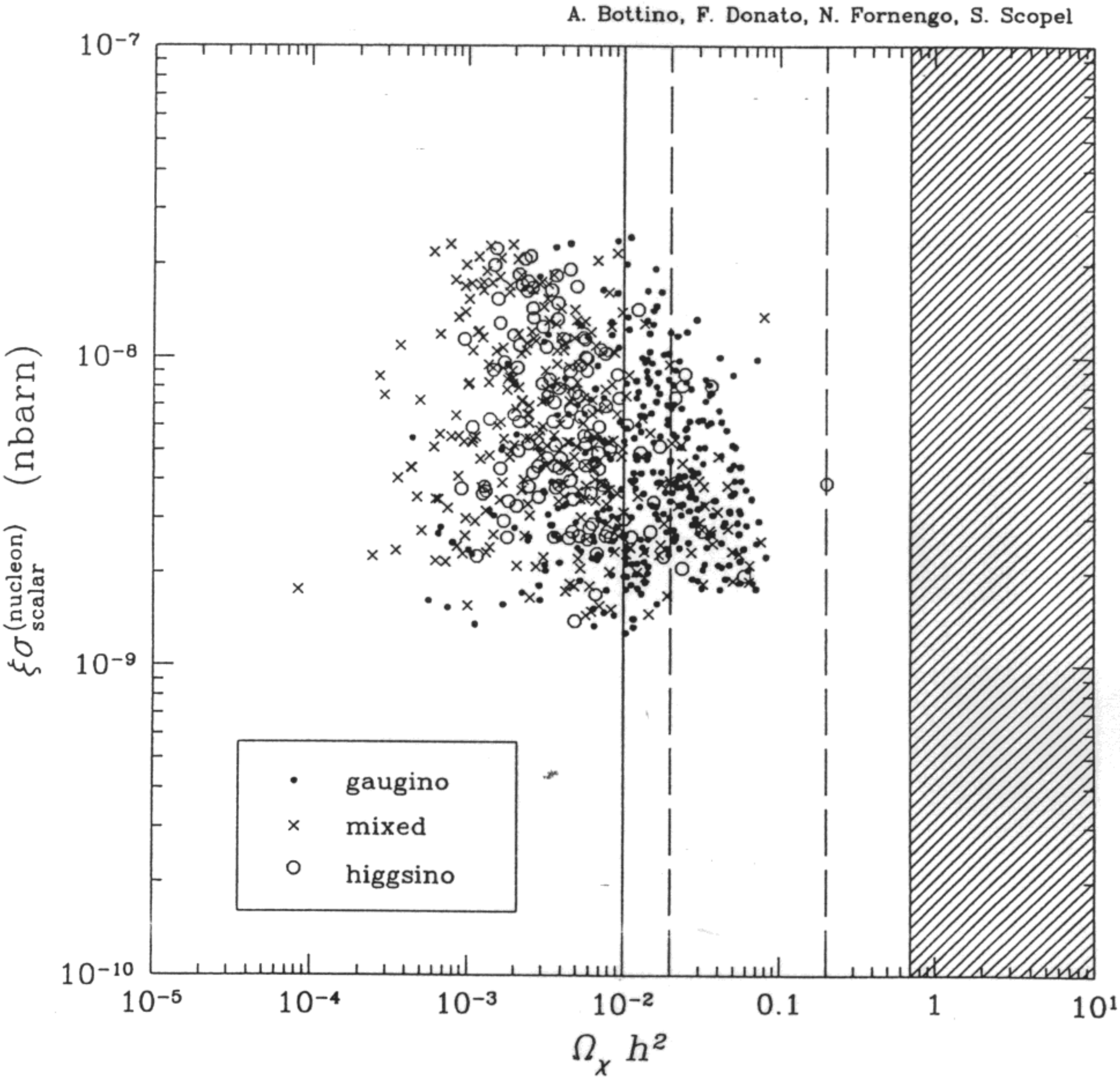
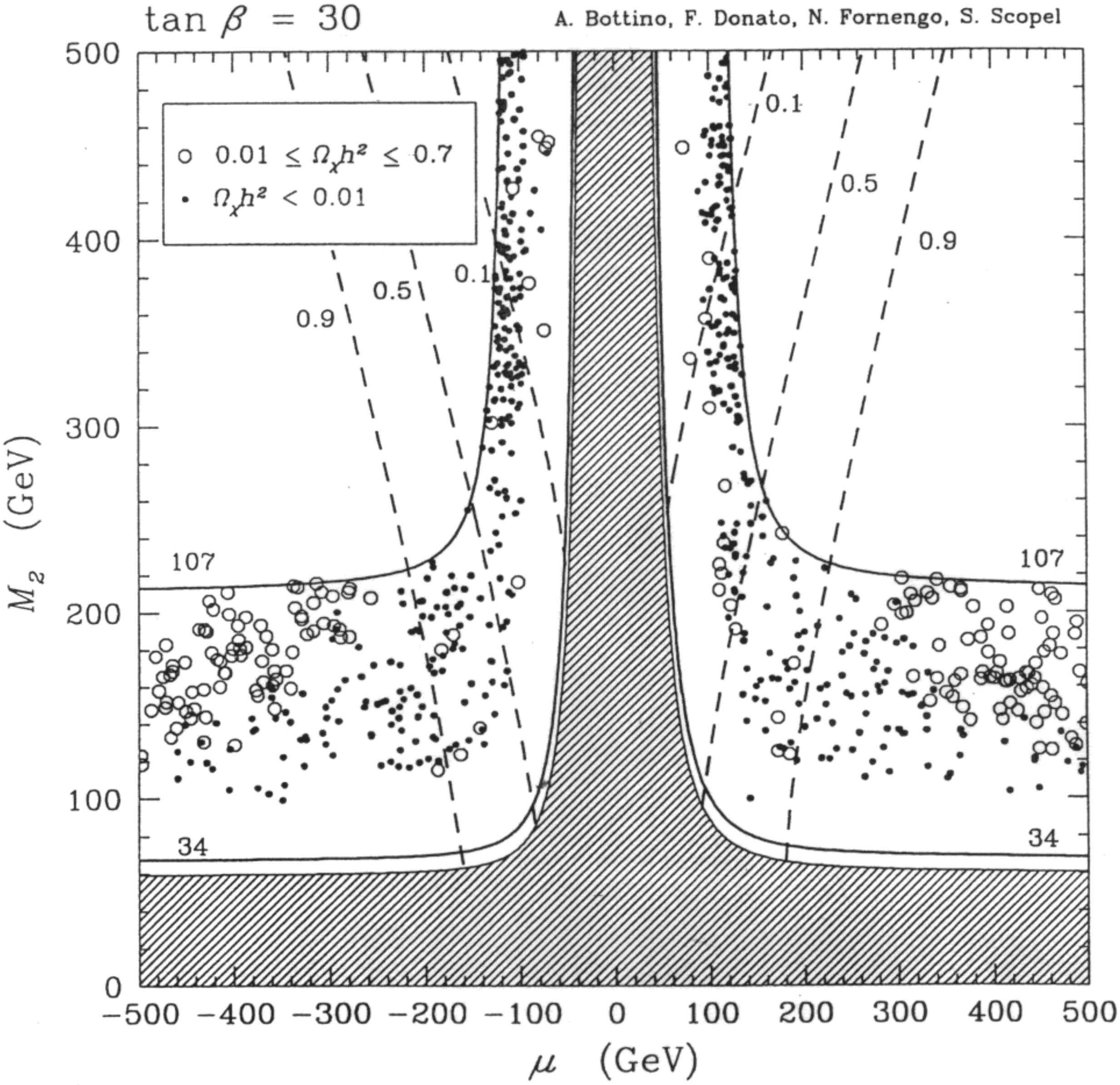

A. Bottino, F. Donato, N. Fornengo, S. Scopel
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\xi\sigma^{(nucleon)}_{scalar}$ (nbarn)
gaugino
mixed
higgsino
10^{-5}
10^{-4}
10^{-3}
10^{-2}
0.1
1
10^{1}
$\Omega_\chi h^2$

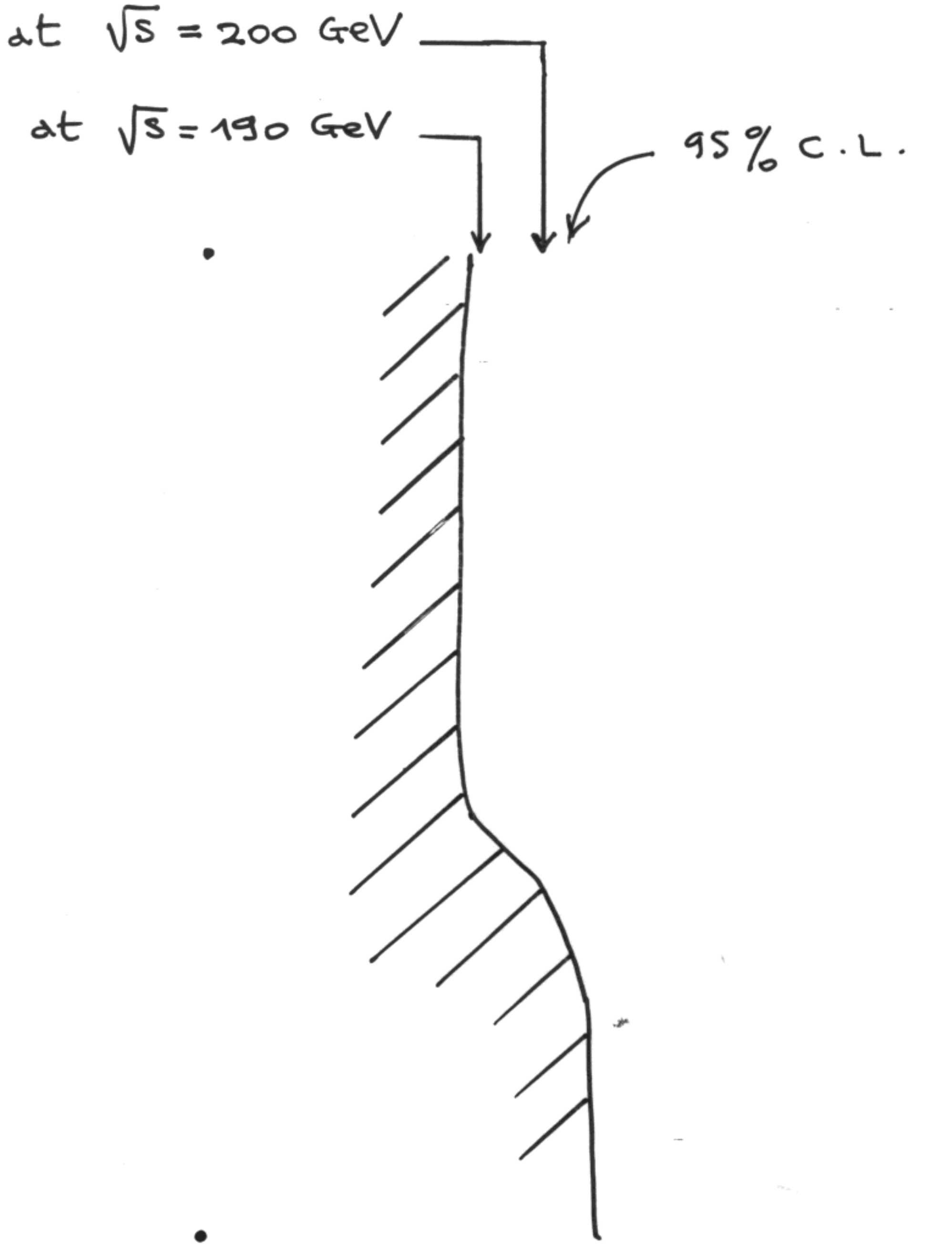
Figure 3



tan β = 30
A. Bottino, F. Donato, N. Fornengo, S. Scopel
0.01 ≤ Ω_χh² ≤ 0.7
Ω_χh² < 0.01
0.1
0.5
0.9
107
34
M₂ (GeV)
μ (GeV)
500
400
300
200
100
0
−500 −400 −300 −200 −100 0 100 200 300 400 500

Figure 4 (b)

Reach at LEP2



A. Bottino, F. Donato, N. Fornengo, S. Scopel

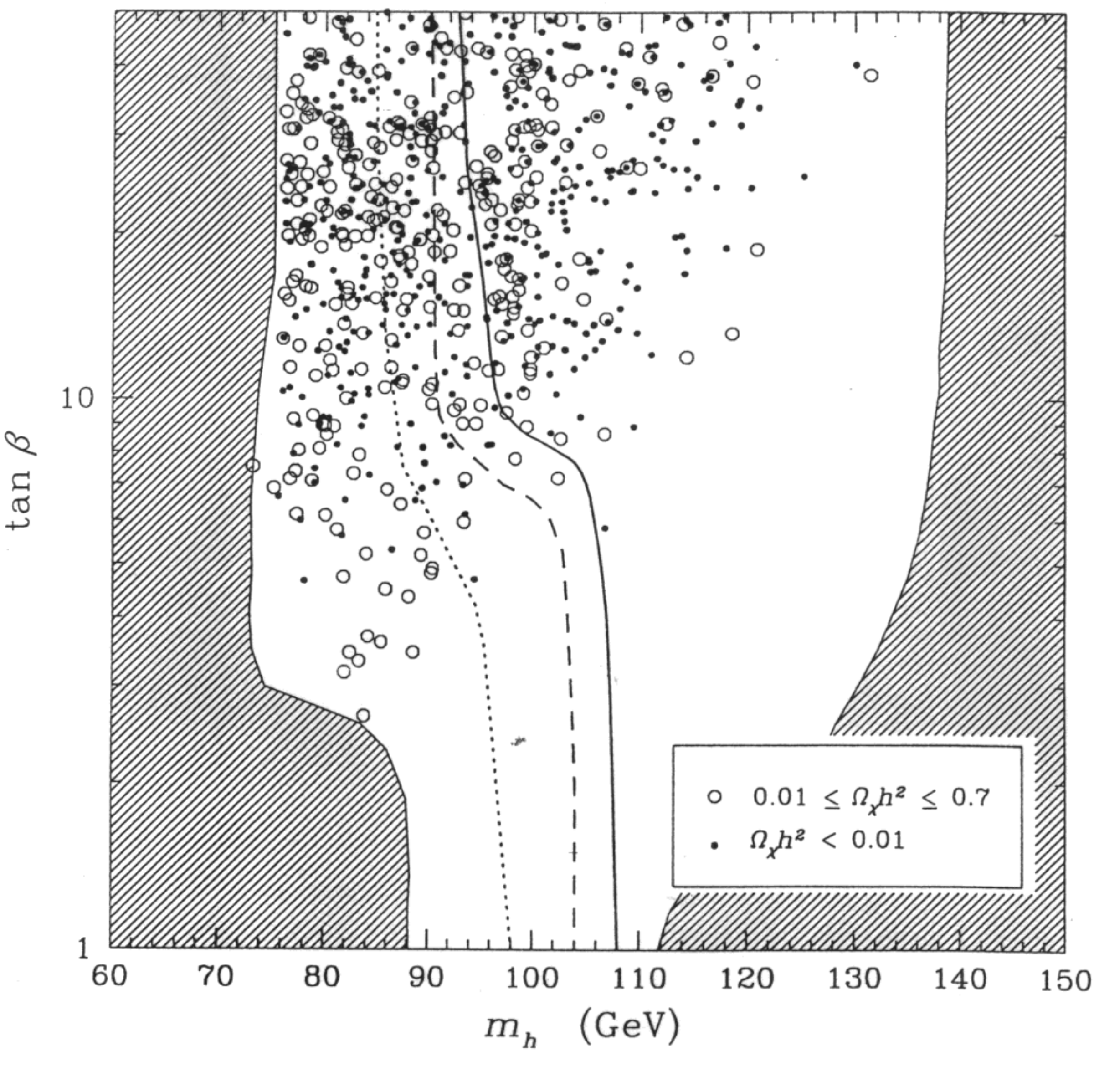


Figure 5 (a)

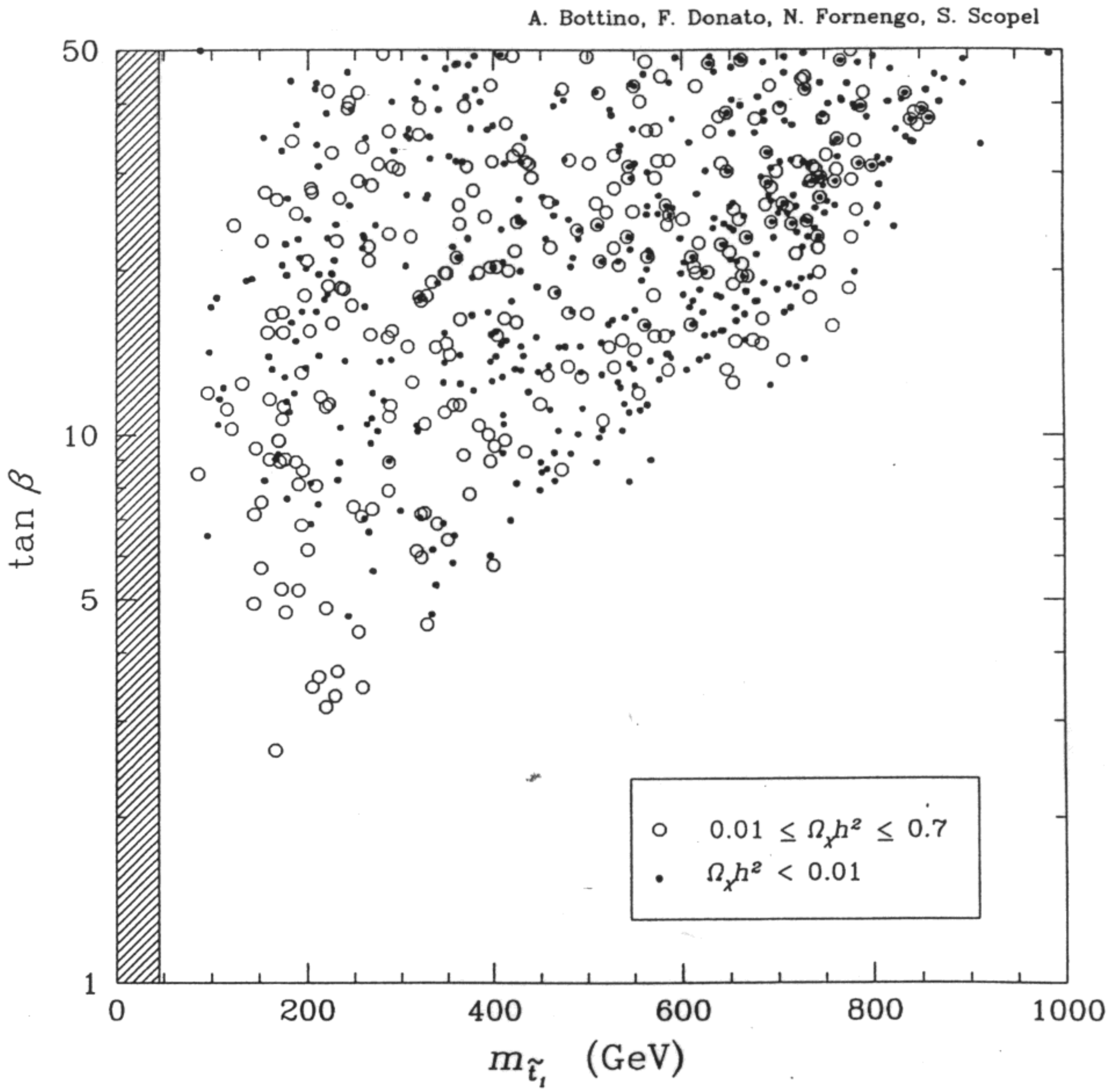

A. Bottino, F. Donato, N. Fornengo, S. Scopel
50
10
5
1
tan β
0
200
400
600
800
1000
$m_{\tilde{t}_1}$ (GeV)
$0.01 \leq \Omega_\chi h^2 \leq 0.7$
$\Omega_\chi h^2 < 0.01$

Figure 6

reach of LEP2

reach of TeV33

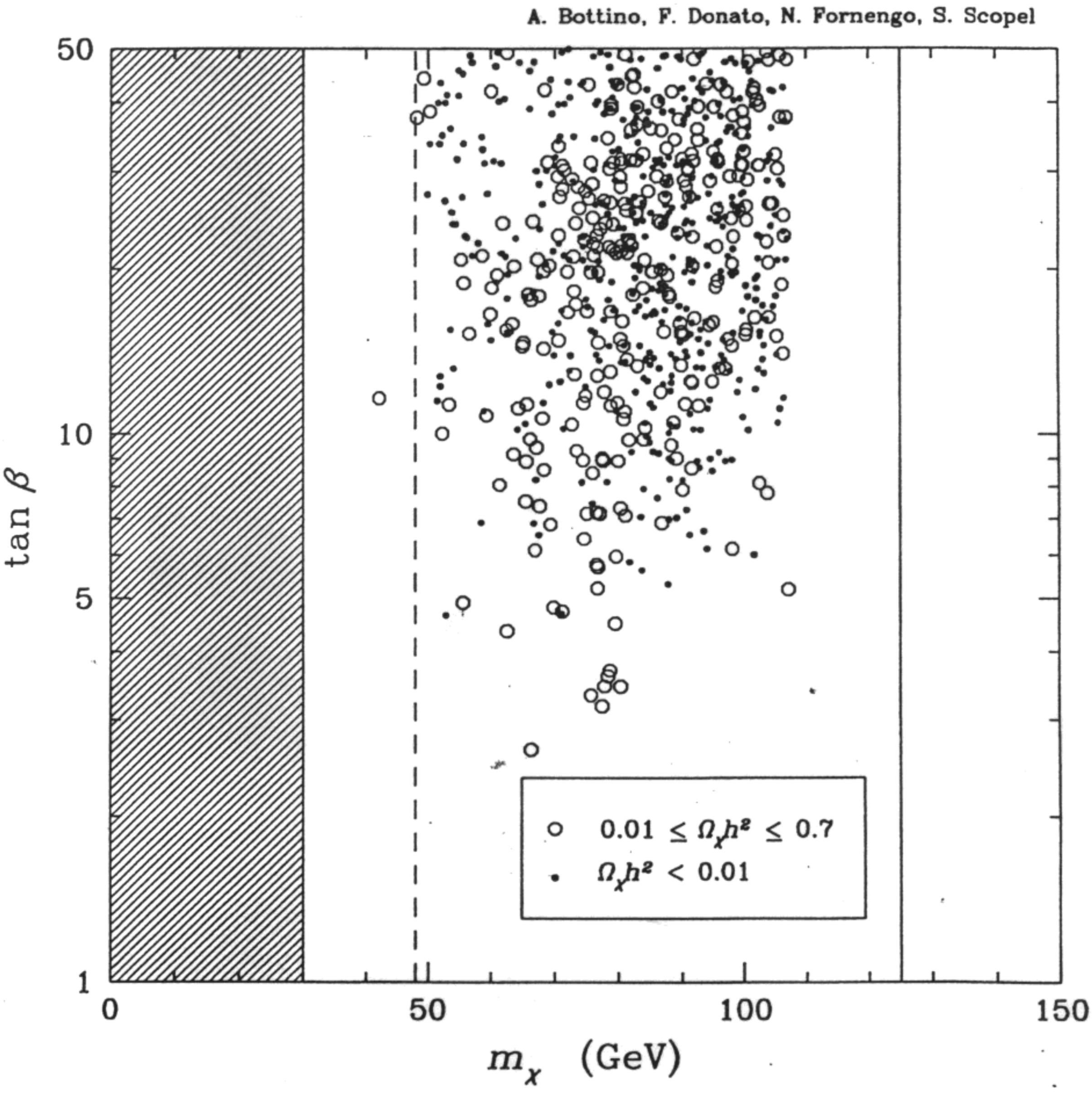

A. Bottino, F. Donato, N. Fornengo, S. Scopel
50
10
5
1
tan β
0
50
100
150
m_χ (GeV)
0.01 ≤ $\Omega_\chi h^2$ ≤ 0.7
$\Omega_\chi h^2$ < 0.01

Figure 7

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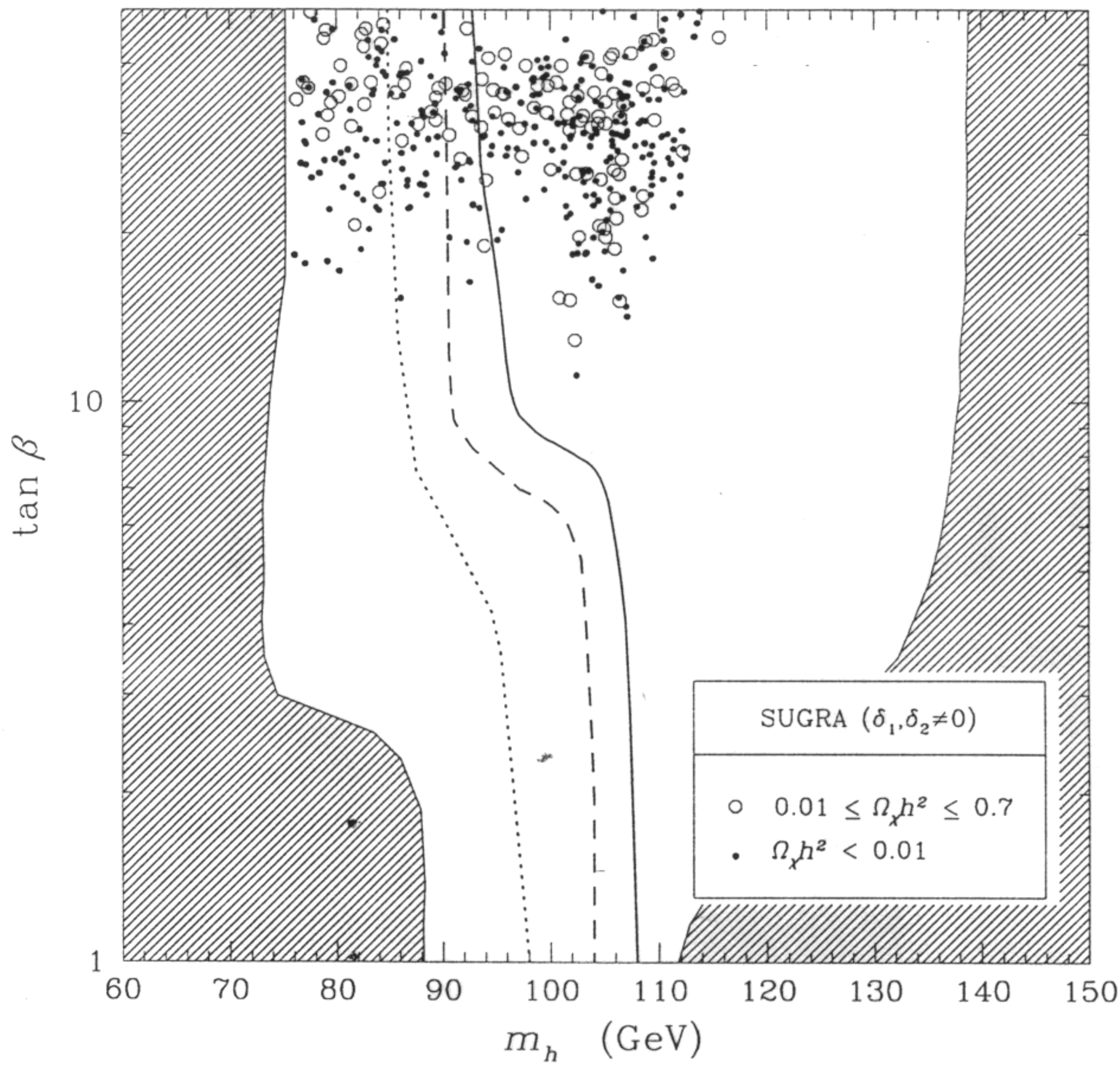
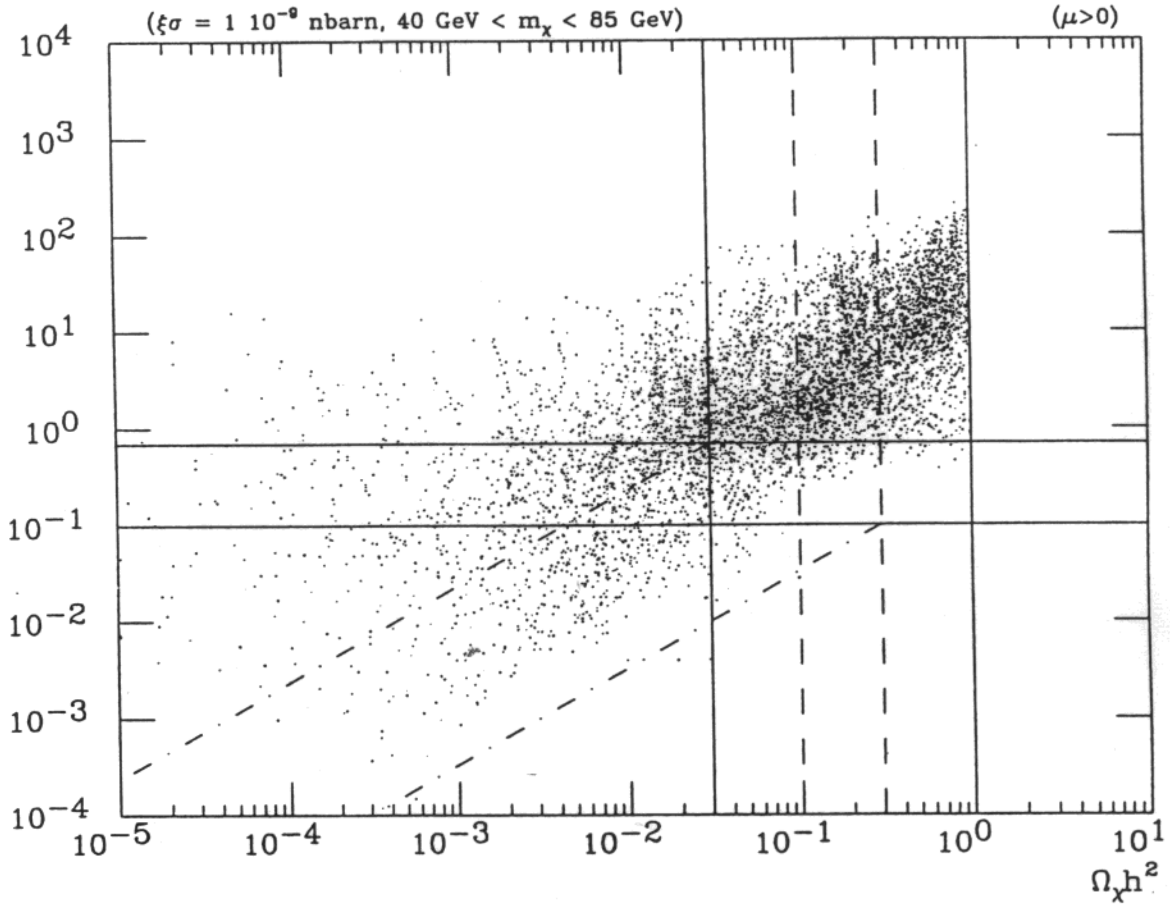


Figure 9



($\xi\sigma$ = 1 10^{-9} nbarn, 40 GeV < m_χ < 85 GeV)
(μ>0)
ρ_χ (GeV cm^{-3})
$\Omega_\chi h^2$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1

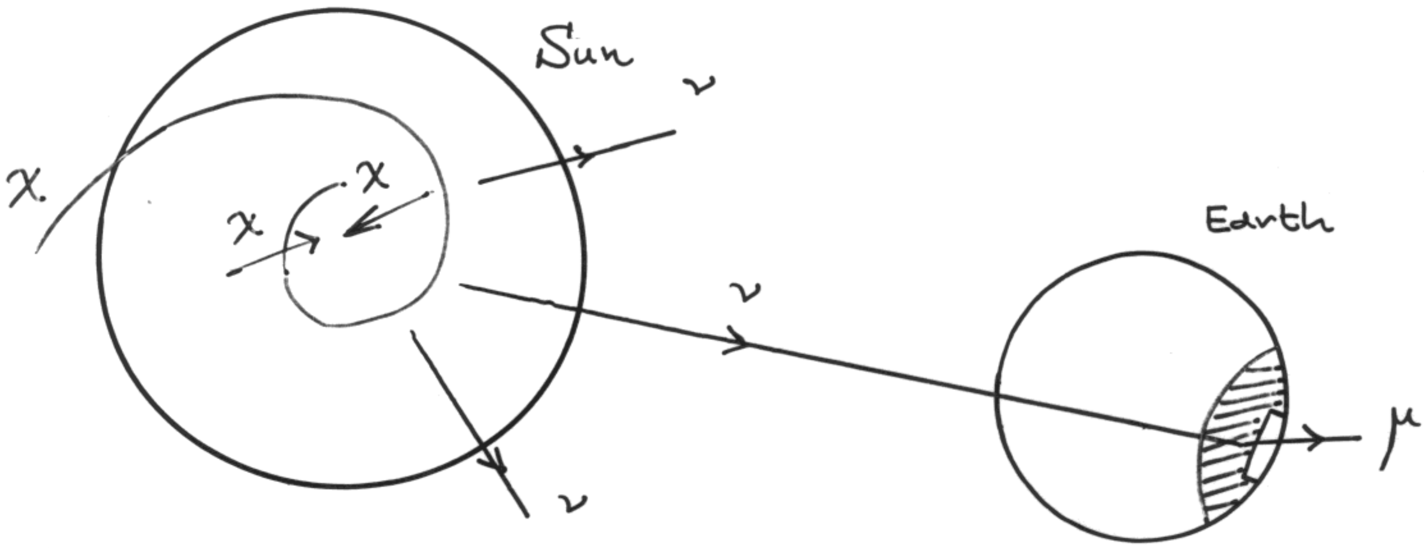
Figure 4

χ-χ annihilation in celestial bodies

(Sun, Earth)

emission of ν's $\longrightarrow$

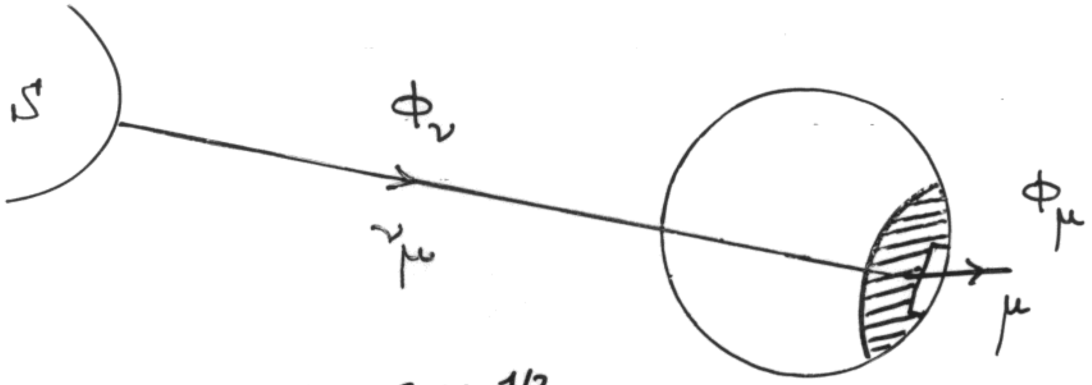
$\longrightarrow$ up-going μ's in neutrino telescopes



Φ_μ vs m_χ

▶ detection of <u>upgoing muons</u> due to conversion of ν_μ's in Earth

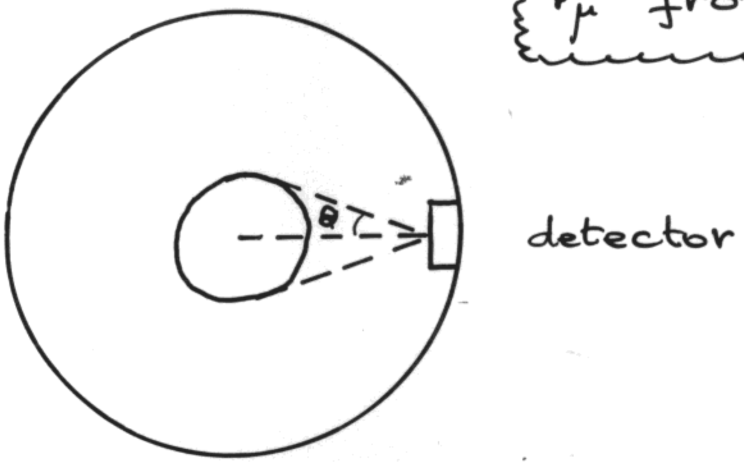
ν_μ from the Sun



$$\psi_{\nu\mu} \simeq 2.5^\circ \left(\frac{100\ \text{GeV}}{E_\nu}\right)^{1/2}$$

plus extra angular spread to μ-straggling

ν_μ from the Earth



$$\theta \simeq 5^\circ \left(\frac{100\ \text{GeV}}{m_\chi}\right)^{1/2}$$

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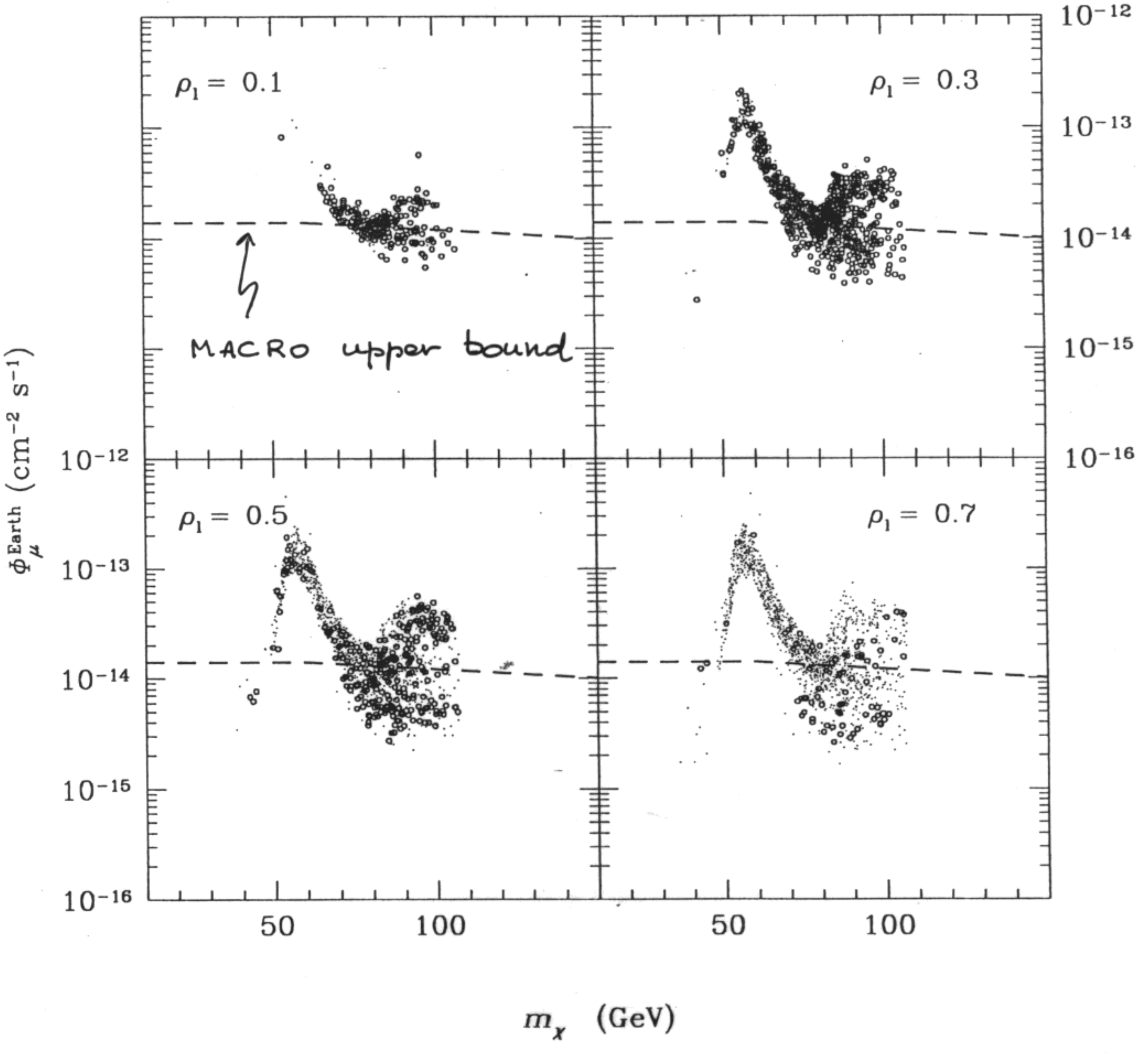


Figure 6

Scatter plots for DAMA configurations

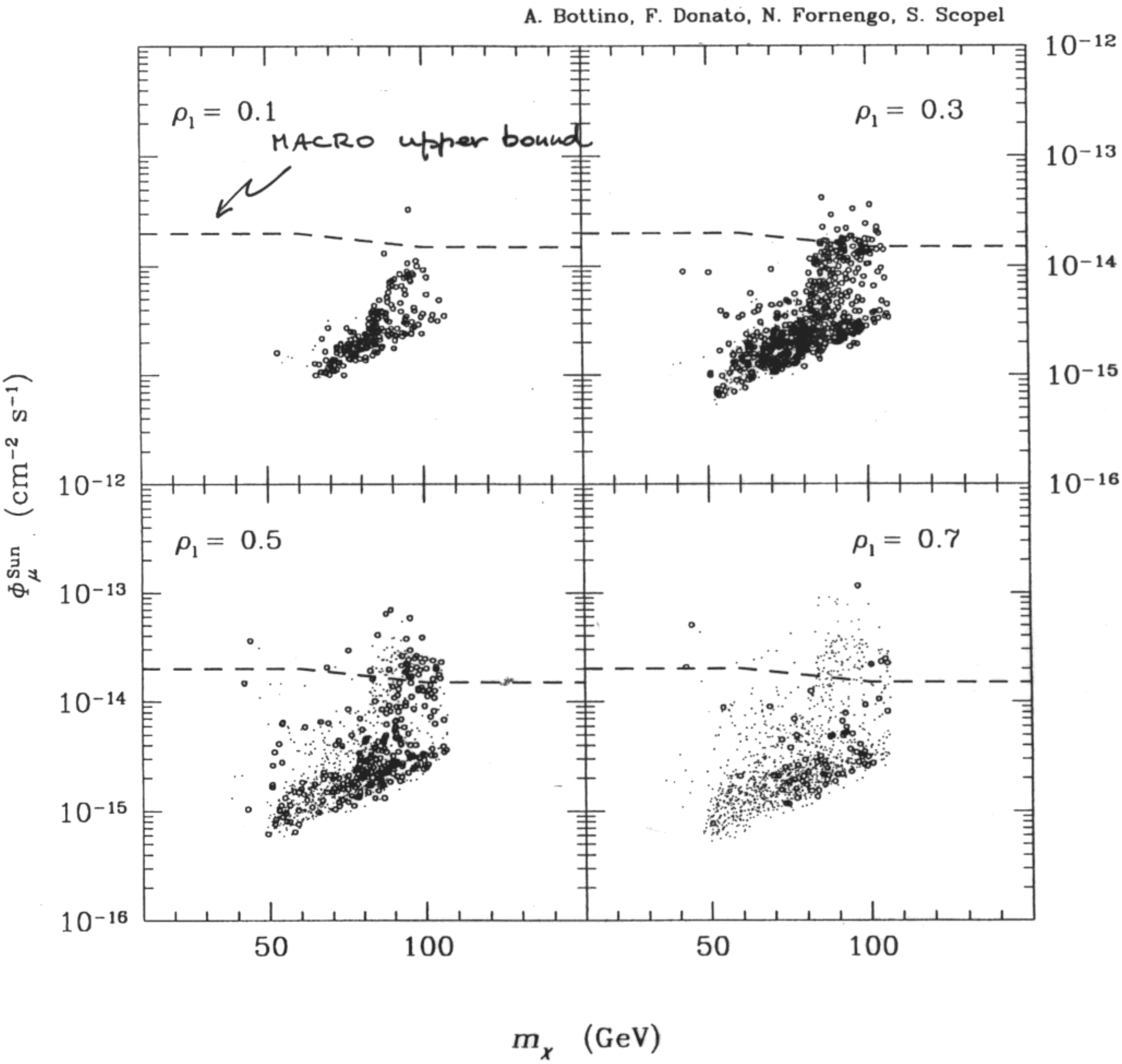


Figure 8

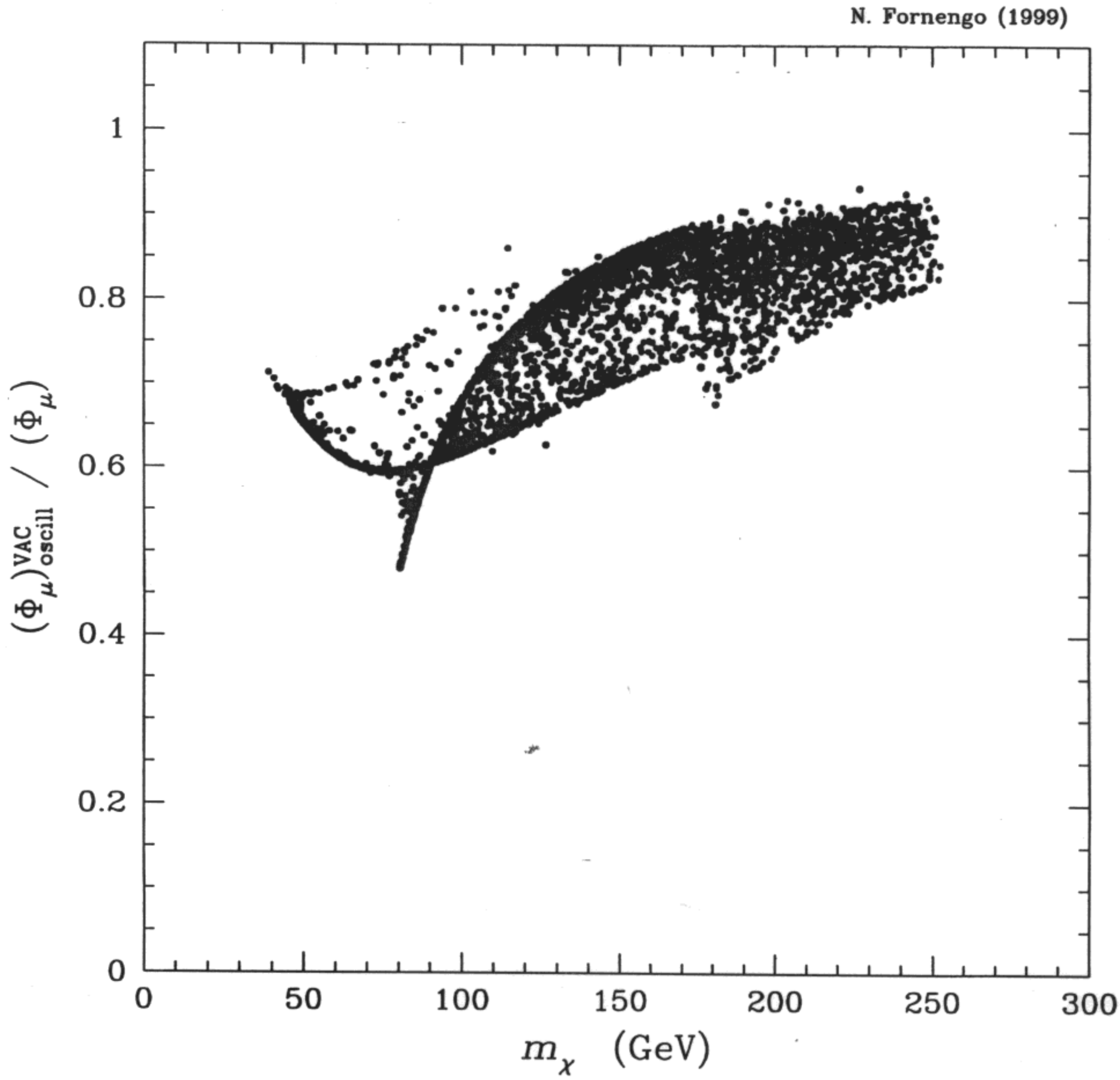
Scatter plots for DAMA configurations

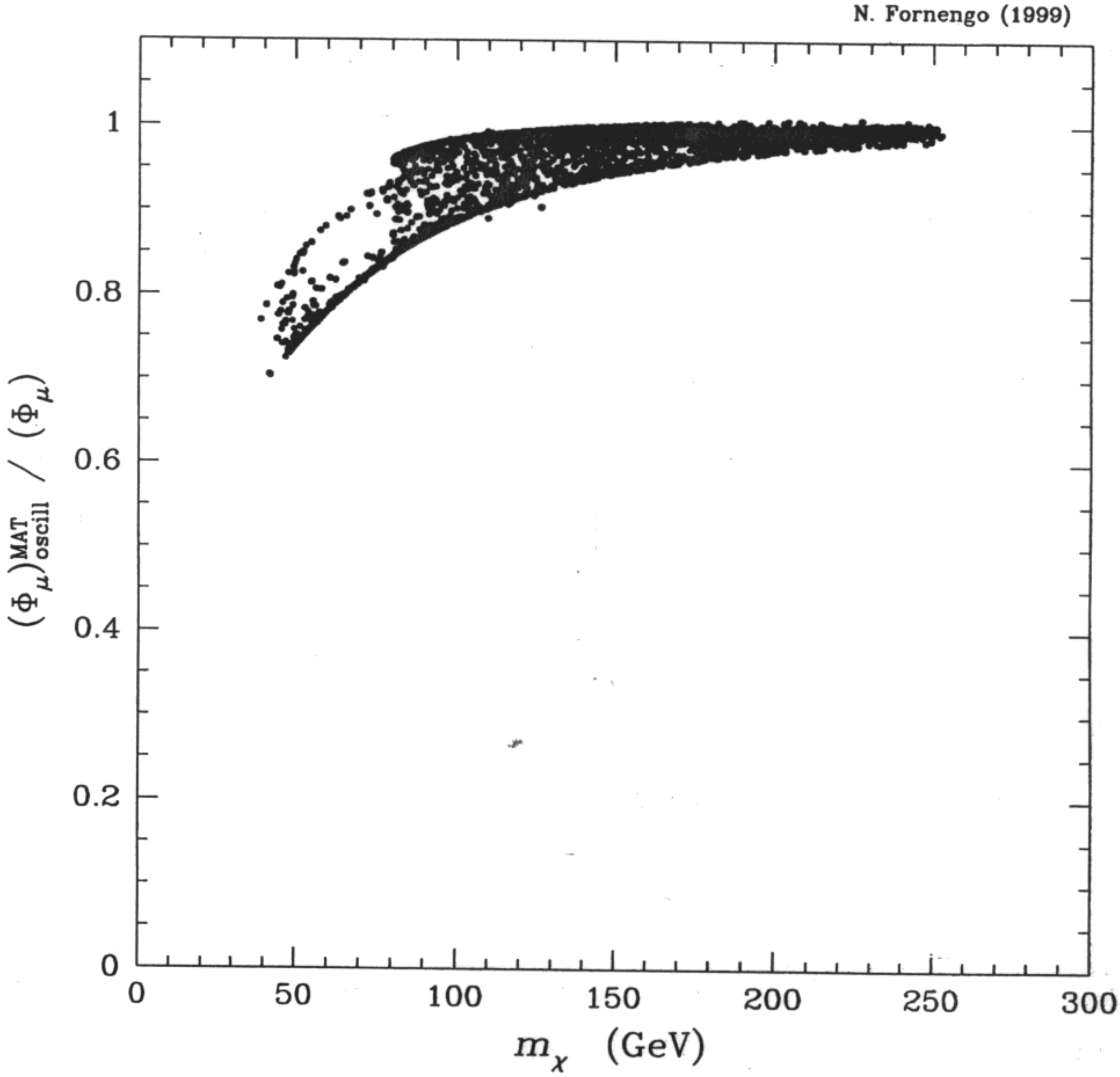
generic scatter plot
(not limited to DAMA configurations)

$\Phi_\mu \equiv$ flux of upgoing muons generated by χ-χ annihilation in the center of the Earth

$(\Phi_\mu)^{VAC}_{oscill} / \Phi_\mu \equiv$ its fractional depletion in case of

$\nu_\mu \to \nu_\tau$ oscillation ($\Delta m^2 = 5\times10^{-3}\,eV^2$, $\sin^2(2\theta) = 0.8$)


N. Fornengo (1999)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
$(\Phi_\mu)^{VAC}_{oscill}$ / (Φ_μ)
m_χ (GeV)



$(\Phi_\mu)^{MAT}_{oscill} / \Phi_\mu \equiv$ flux depletion in case of $\nu_\mu \to \nu_s$ oscillation ($\Delta m^2 = 5 \times 10^{-3}\,eV^2$, $\sin^2(2\theta) = 0.8$)

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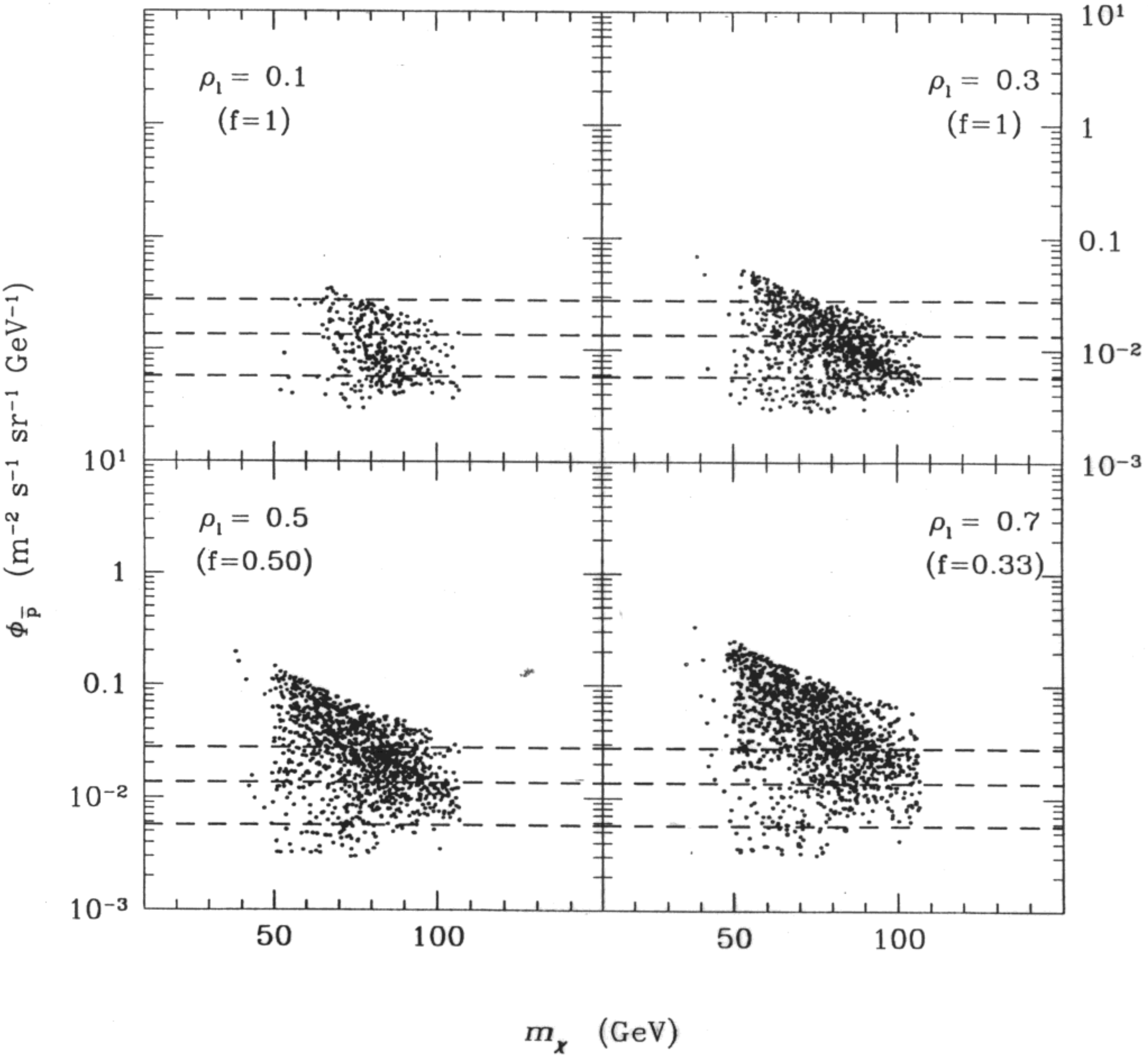

Figure 2

Comparison with BESS 95 data (1st bin)

Scatter plots for DAMA configurations

total fluxes (include contributions due to neutralinos of the indicated masses)

62 GeV

81 GeV

95 GeV

secondary flux

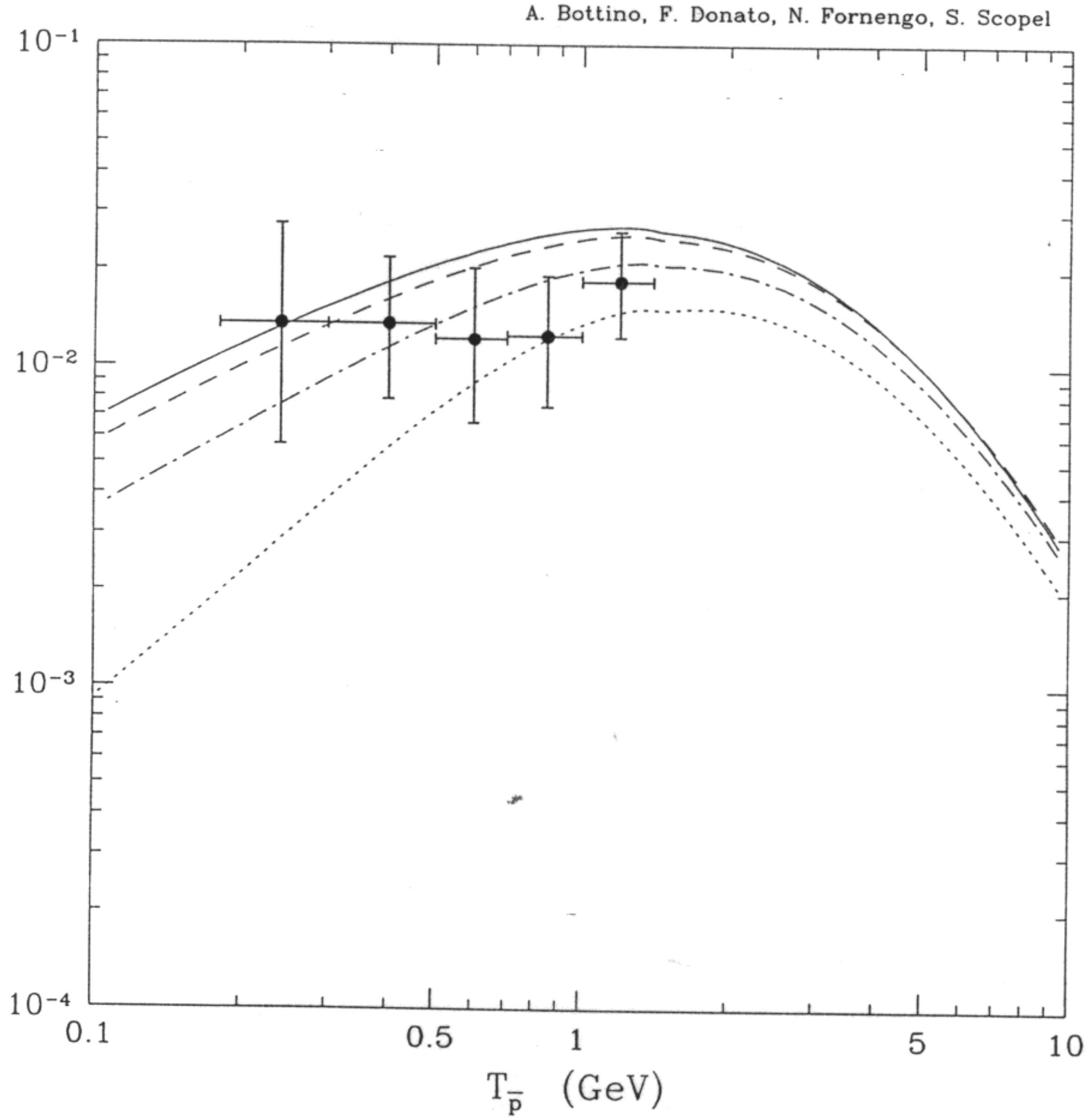
A. Bottino, F. Donato, N. Fornengo, S. Scopel
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\Phi_{\bar{p}}$ (m^{-2} s^{-1} sr^{-1} GeV^{-1})
0.1
0.5
1
5
10
$T_{\bar{p}}$ (GeV)

Figure 4

Extending the DAMA region and the relevant Susy configurations by accounting for the range in v_0

DAMA Collaboration

&

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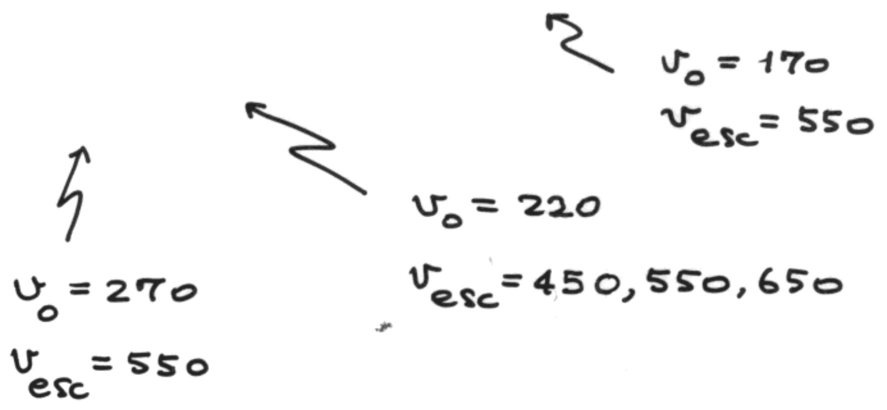
Dependence of location of the DAMA region on the values of v_0 and v_{esc}

$$v_0 = 220 \pm 30 \ \mathrm{km \cdot s^{-1}} \quad (1\text{-}\sigma \ \mathrm{C.L.})$$

$$450 \ \mathrm{km \cdot s^{-1}} \leq v_{esc} \leq 650 \ \mathrm{km \cdot s^{-1}} \quad (90\% \ \mathrm{C.L.})$$

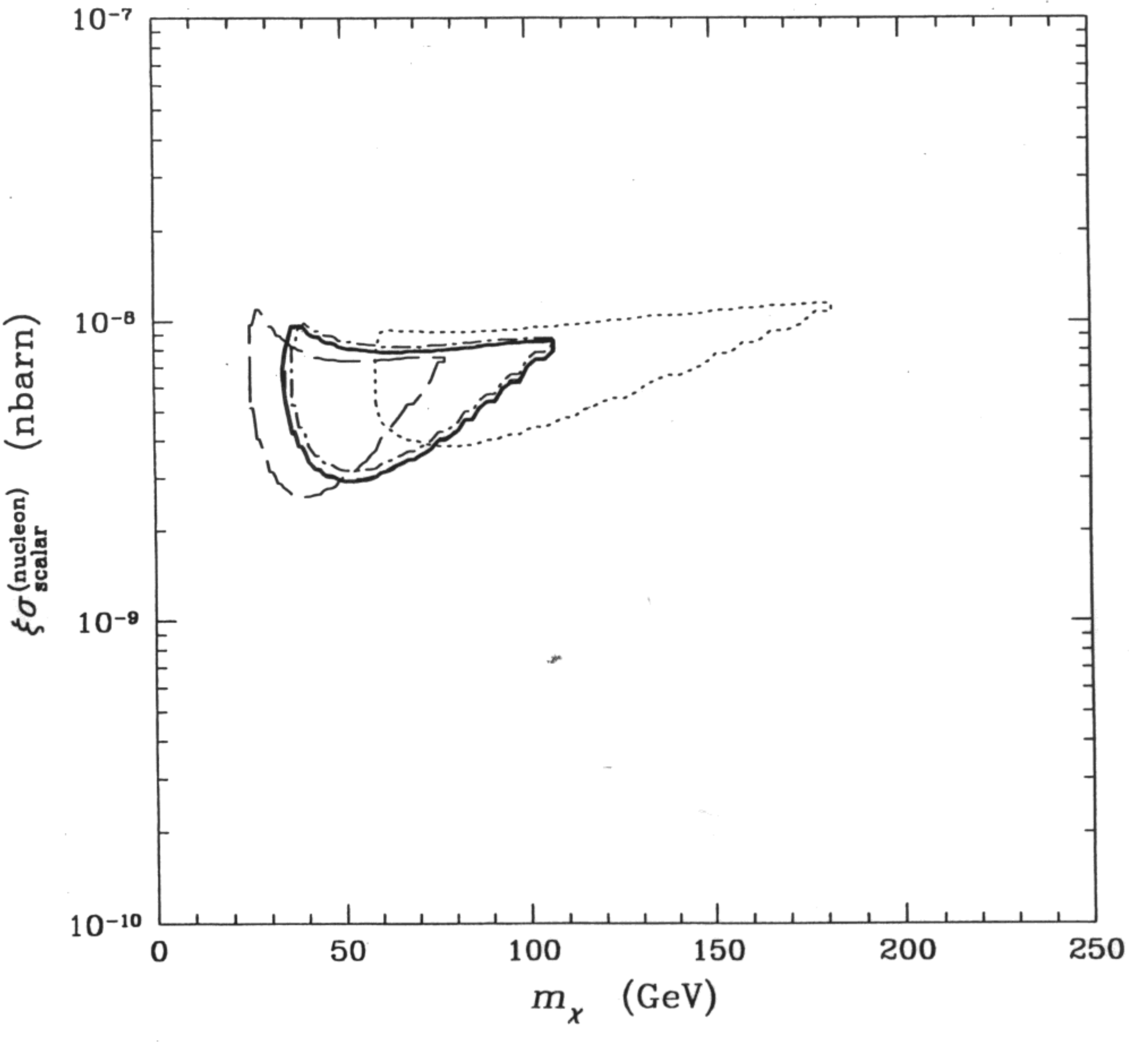


velocities in units of $\mathrm{km \cdot s^{-1}}$

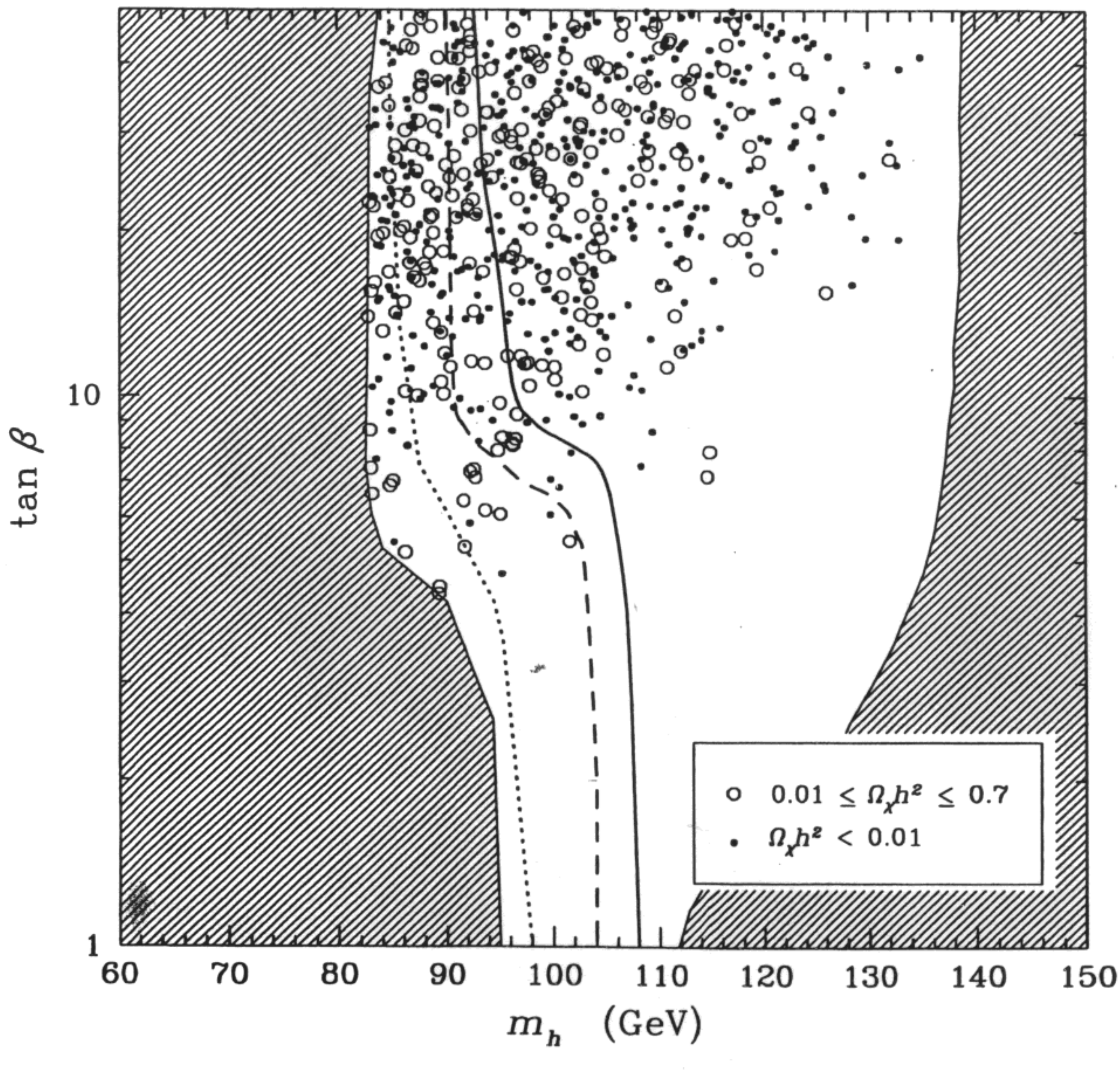
▷ range of m_χ very sensitive to v_0: the range of v_0 extends the range of m_χ to

$$35 \ \mathrm{GeV} \leq m_\chi \leq 130 \ \mathrm{GeV} \quad (1\text{-}\sigma \ \mathrm{C.L.})$$

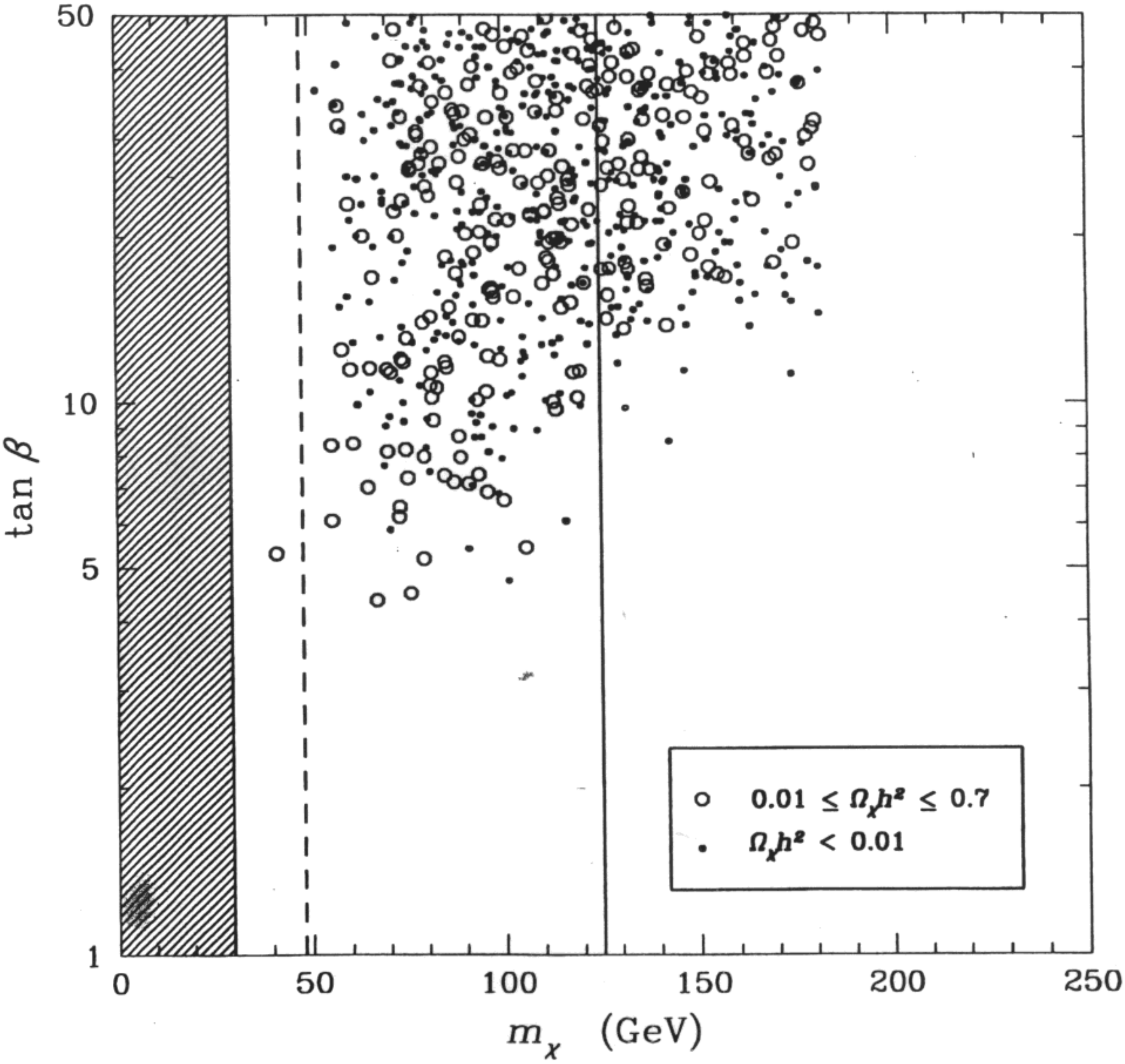
▷ location of the region quite insensitive to v_{esc}



10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\xi\sigma^{(nucleon)}_{scalar}$ (nbarn)
0
50
100
150
200
250
m_χ (GeV)



tan β
10
1
60
70
80
90
100
110
120
130
140
150
m_h (GeV)
0.01 ≤ $\Omega_\chi h^2$ ≤ 0.7
$\Omega_\chi h^2$ < 0.01



50
10
5
1
tan β
0
50
100
150
200
250
m_χ (GeV)
0.01 ≤ Ω_χh² ≤ 0.7
Ω_χh² < 0.01

Conclusions

- ▷ The indication of an annual modulation effect, singled out by the DAMA/NaI experiment, is widely compatible with an interpretation in terms of a relic neutralino as a major component of DM
- ▷ A sizeable fraction of the relevant Susy configurations:
  - * provides signals detectable at ν-telescopes and as $\bar{p}$'s in CRs
  - * is explorable at accelerators
- ▷ Compatibility with SUGRA schemes
- ▷ We eagerly await confirmation of the yearly modulation effect by further investigation in WIMP direct search.