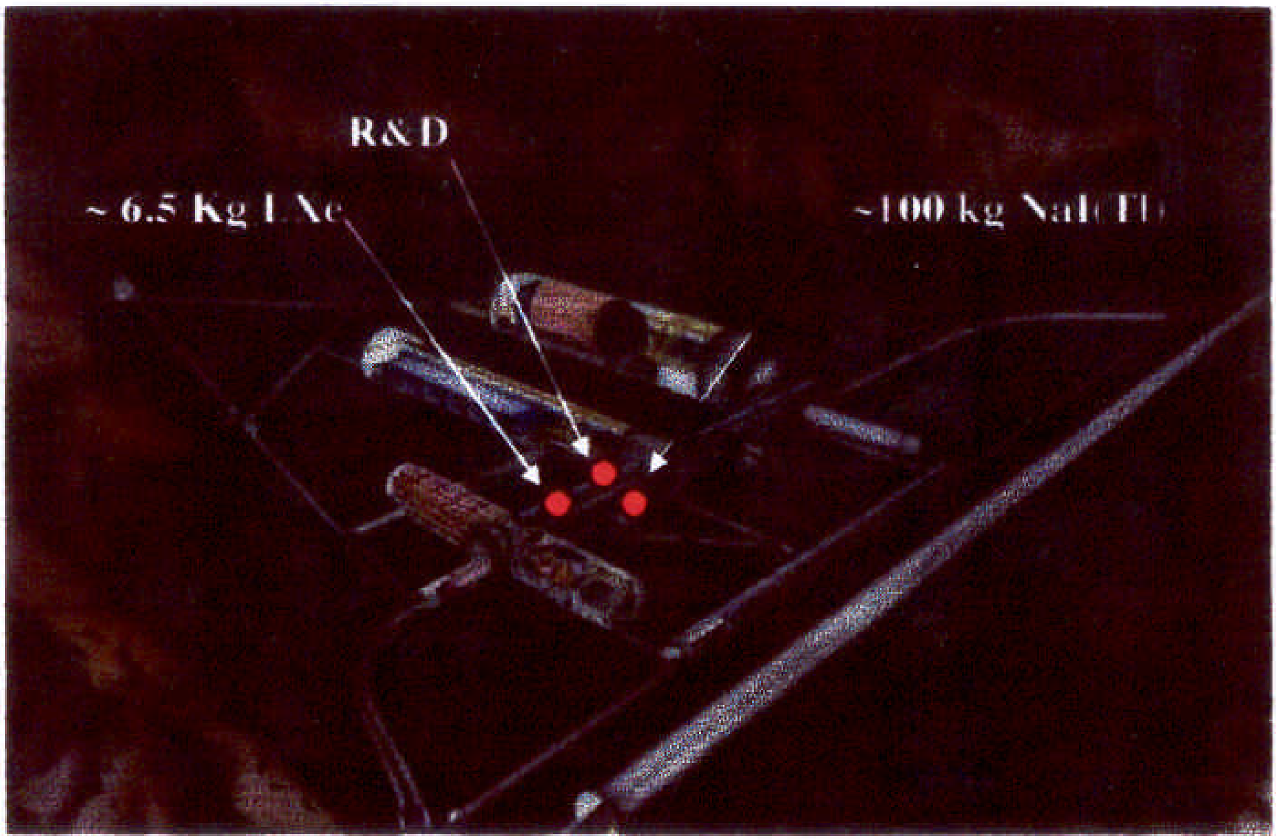
Searching for signals from the Dark Universe by DAMA at Gran Sasso

Roma2 & Roma & IHEP/Beijing
(+ other coll. on special topics)

http://www.lngs.infn.it/lngs/htexts/dama/

R. Bernabei
ν 2000
Sudbury June, 2000

DAMA ACTIVITIES @ LNGS



Recent References

• ~ 100 Kg NaI(Tl)

PLB389 (1996) 757; PLB408 (1997) 439; P:B424 (1998) 195; PLB450 (1999) 448; N.CimA112 (1999) 545; PRD61 (2000) 023512; PRL83 (1999) 4918; N.CimA112 (1999) 1541; PLB480 (2000) 23; ROM2F/2000/15

• ~ 6.5 Kg Lxe (filled with Xe enriched in ^{129}Xe)

N.Cim.C19 (1996) 537; PLB387 (1996) 222; PLB436 (1998) 379; ROM2F/2000-05 to appear on New Journal of Physics.

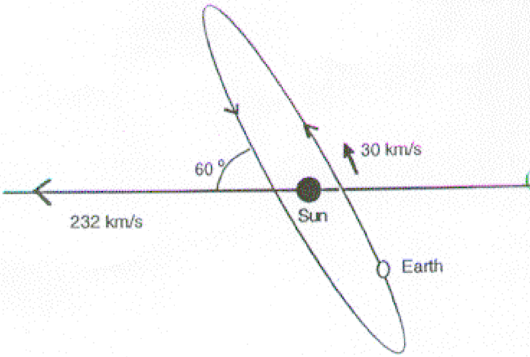
(since June 2000 filled with Xe enriched in ^{136}Xe)

• CaF_2(Eu) + by-products + others

Astrop.Phys.5 (1996) 217; Astrop.Phys.7 (1997) 73; N.Cim.A110 (1997) 189; PLB408 (1997) 439; Astrop.Phys.10 (1999) 115; NPB546 (1999) 235; NPB563 (1999) 97; PRC60 (1999) 065501; PLB465 (1999) 315; Phys.Rev. D61 (2000) 117301.

Identifying signals from the WIMP *wind*

In practice only one signature can be exploited:
the annual modulation of the rate



$v_\odot = v_0 + 12$ km/s
(Sun velocity in the halo)

$v_{orb} = 30$ km/s
(Earth orbital velocity around the Sun)

$\gamma = \pi/3$

$\omega = 2\pi/T$ with T=1 year

$t_0 =$ 2nd June
(when $v_\oplus$ is at maximum)

change in $\frac{dR}{dE_R}$ along the year because of the yearly motion of the Earth around the Sun moving in the Galaxy:

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

$$\eta(t) = \frac{v_\oplus(t)}{v_0} = \eta_0 + \Delta\eta \cos[\omega(t-t_0)]$$

with $\eta_0 \cong 1.05$ and $\Delta\eta \cong 0.07$ → large mass needed

Expected rate in given energy bin at time t of the year:

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_k[\eta_0] + \left[\frac{\partial S_k}{\partial \eta}\right]_{\eta_0} \Delta\eta \cos[\omega(t-t_0)] =$$

$$= S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

PRD33(1986),3495 ← . Drukier, Freese, Spergel PRD86
. Freese et al. PRD88

Is the annual modulation signature well distinctive?

1) Modulated rate according to cosine function

2) only in a defined low energy range

3) with proper period (1 year)

4) with proper phase (about 2 june)

5) for single hit events in a multi-detector set-up

6) with modulated amplitude in the region of maximal sensitivity ≤ 7%.

YES!

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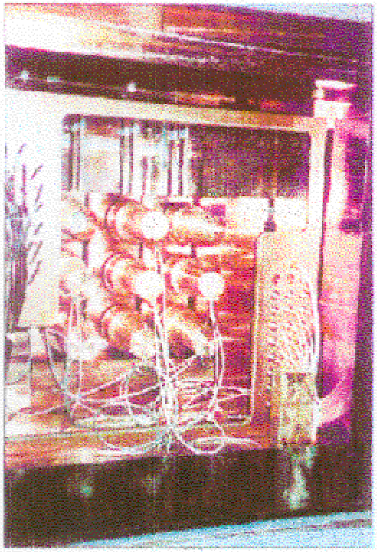
To fake this signature, the spurious effects and side reactions must satisfy contemporaneously all the 1 to 6 requirements

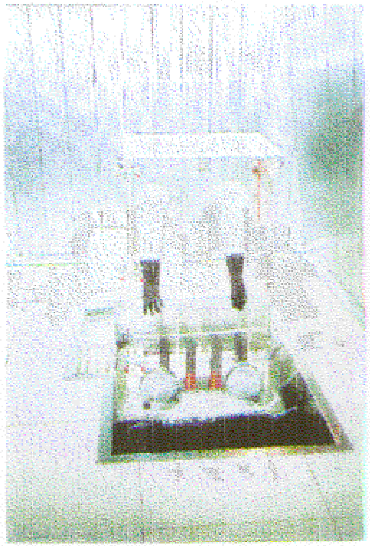
The ~100 kg NaI(Tl) experiment

NaI(Tl) crystals



The installation

Glove-box for calibration



full description in: Il Nuovo Cim. A112(1999), 545-575

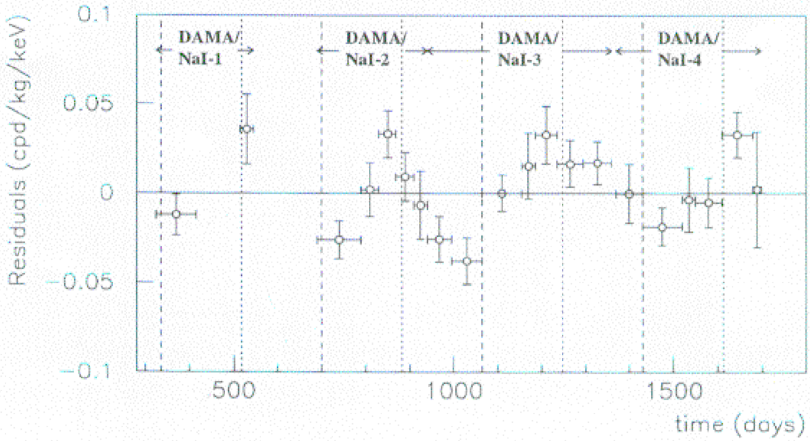
The running periods for annual modulation search

period	statistics (kgday)	references
DAMA/NAI-1	3363.8 winter + 1185.2 summer	PLB424 (1998), 195
DAMA/NaI-2	14962 ~ november → end of July	PLB450 (1999), 440
DAMA/NaI-3	22455 ~ middle August → end of September	PLB480 (2000), 23
DAMA/NaI-4	16020 ~ middle October → second half of August	idem
Total statistics	57986	idem
+ DAMA/NaI-0 (properly included in the final result)	limits on recoils fraction by PSD	PLB389 (1996), 757

Model independent result from DAMA

- 4 yearly cycles
- Exposure of 57986 kgday
- Residuals of rate vs time
- Low energy region: 2-6 keV interval

Zero of the time scale:
January 1st of the first year of data taking



$$A \cos[\omega(t-t_0)]$$

$\chi^2_0(A=0)/dof = 48/20$ (P = 4×10^{-4})

1) t_0 = 152.5 days (fixed)
   A = (0.022±0.005)cpd/kg/keV
   T = $2\pi/\omega$ = (1.00±0.01) years
   $\chi^2/dof \approx 23/18$

2) T = 1 year (fixed)
   A=(0.022±0.005)cpd/kg/keV
   t_0 = (144±13) days
   $\chi^2/dof \approx 23/18$

SIMILAR RESULTS, BUT WITH LARGER ERRORS IN CASE ALL PARAMETERS ARE KEPT FREE

Residuals vs time

Presence of annual modulation in the low energy counting rate

(see "Residuals vs time")

+

Stability controls

No modulation in the:

- parameters (as T, Rn, ...)
- electronic noise
- background
- energy scale
- efficiency

+ they fail some of the 6 requirements

(see "Stability control")

+

Side reactions

No one found able to give the observed modulation and to satisfy the 6 requirements

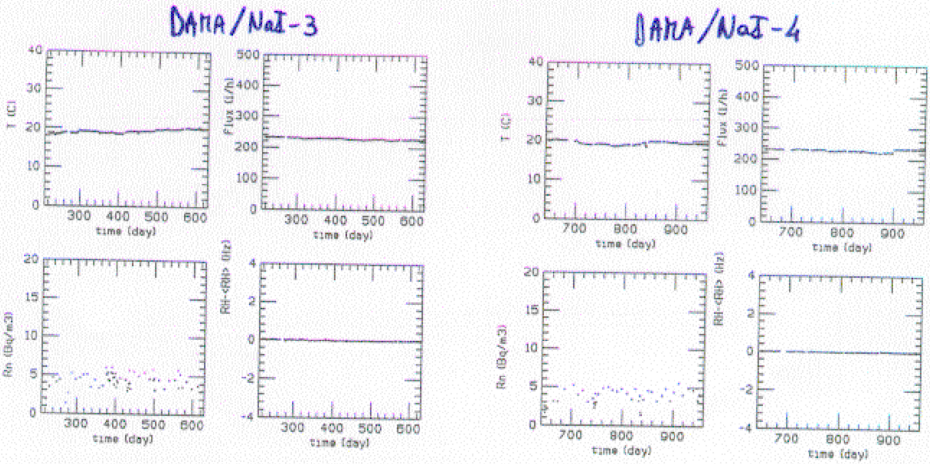
(see later)

=

Compatibility with presence of WIMP in the Galactic halo

The stability control (1)

- Several parameters monitored and acquired by CAMAC to know the set-up working conditions



- **Sizeable temperature variations could cause (PSA not used!) only small light response variation: average slope of the light output ≈ -0.2%/°C in our operating temperature range.**

  → **modulated amplitude (T and φ as for Wimp):**

  (0.021 ± 0.046) °C DAMA/NaI-3

  (0.064 ± 0.058) °C DAMA/NaI-4 → consistent with zero

- **Detectors excluded from environmental air! + time correlation analysis of the external Radon level with time → modulated amplitude (T and φ as for Wimp):**

  (0.14 ± 0.25) Bq/m^3 DAMA/NaI-3

  (0.12 ± 0.20) Bq/m^3 DAMA/NaI-4 → consistent with zero

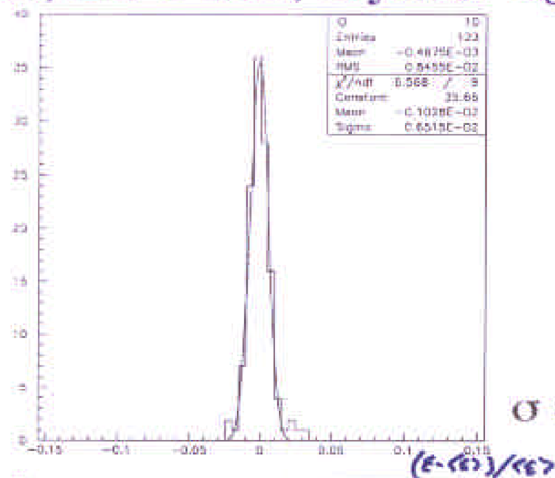
↳ NO MODULATION IN THE PARAMETERS

The efficiency stability

2-8 keV 65 different sets; ΔE=2 keV; crystals together.

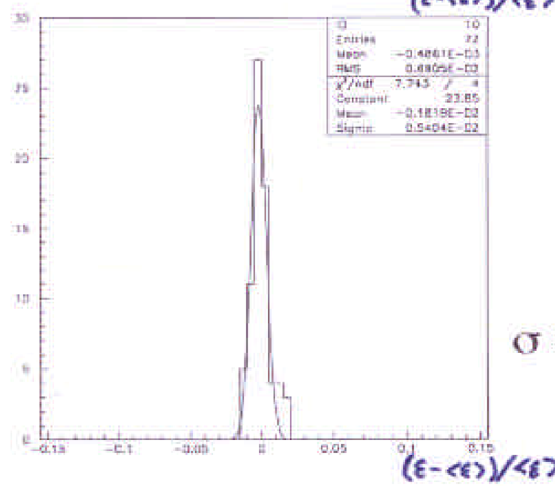
(2-4)+(4-6)+(6-8) keV

- **DAMA/NaI-3:** 41 different sets



$\sigma = 0.6\%$

- **DAMA/NaI-4:** 24 different sets



$\sigma = 0.5\%$

If T and Φ as for WIMP:

Energy	Modulated amplitude DAMA/NaI-3 + 4
2-4 keV	$(1.0\pm1.0)\ 10^{-3}$
4-6 keV	$(0.1\pm0.7)\ 10^{-3}$
6-8 keV	$-(0.2\pm0.5)\ 10^{-3}$

↳ NO MODULATION IN THE EFFICIENCY

Level of known systematic uncertainties

- **Temperature variations**

  $<<$ 0.1% random variation in the light response along the year + calibration and energy resolution + time correlation analysis gives modulated contribution compatible with zero

- **Radon variations**

  Detectors excluded from environmental air. Moreover, time correlation analysis gives modulated contribution compatible with zero

- **Energy calibration**

  Uncertainties negligible with the respect to the energy resolution at low energy: overall additional relative energy spread $<3 \cdot 10^{-4}$ @ 2 keV and $<3 \cdot 10^{-3}$ @ 20 keV

- **Efficiency**

$$\frac{\varepsilon - \langle\varepsilon\rangle}{\langle\varepsilon\rangle} \lesssim 6 \times 10^{-3}$$

all detectors in 2-8 keV

- **Background variations**

  i) No evidence of modulation in total hardware rate above single photoel. (no noise modulation);

  ii) No evidence of modulation in rate above 90keV, $R_{90} \lesssim 0.3$ cpd/kg;

  iii) S_m compatible with zero above the first pole of the Helm FF;

↓

even if larger cannot satisfy
all the 1 to 6 requirements
of the annual modulation signature

"Side reactions"

- **They must simulate the WIMP signal features: yearly modulation of "single hit" rate with t_0 and only in the lowest energy region.**

- Up to now not suitable candidate found:

  MACRO μ modulation:
  - ° all the needed requirements not satisfied
  - ° expected modulated amplitude $<< 10^{-4}$ cpd/kg/keV

??Suggestions??

CONCLUSION #1

presence of modulation with the proper features for a WIMP induced effect
+
absence of known sources of possible systematics and side reactions able to fake this modulation

⇓

presence of a WIMP contribution to the experimental rate is candidate by these data independently on its nature and coupling with ordinary matter

⇓

At this point one can investigate a possible candidate

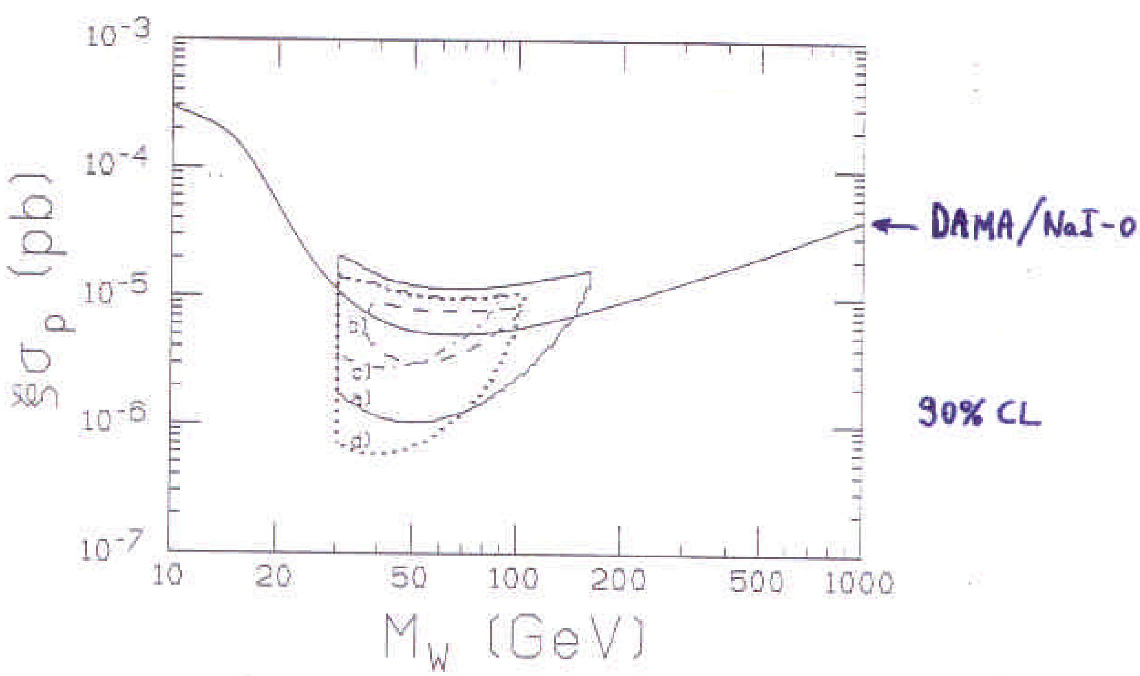
→ **for that a model is needed as well as an effective energy and time correlation analysis strategy**

Each single cycle alone in the simple framework:

SI candidate; fixed values for astrophysical (e.g. v_0=220 km/s) nuclear and particle physics parameters; detector parameters included; standard scaling law for cross sections; $b_{jk} \geq 0$; M_W>30GeV to account for results at accelerators.

experimental $N_{ijk} \Leftrightarrow \mu_{ijk}$ expected from the model

running period	statistics (kg d)	M_W (GeV)	$\xi\sigma_p$ (pb)	C.L. (m.l.r)
DAMA/NaI-1 PLB424 (1998), 195	3363.8 winter + 1185.2 summer	59^{+36}_{-19}	$(1.0^{+0.1}_{-0.4})10^{-5}$	90%
DAMA/NaI-2 PLB450 (1999), 448	14962 from middle november to the subsequent july	59^{+22}_{-14}	$(7.0^{+0.4}_{-1.7})10^{-6}$	98.5%
DAMA/NaI-3 PLB4580 (2000), 23	22455 from middle August to end of September	56^{+18}_{-26}	$(9.7^{+0.3}_{-3.5})10^{-6}$	98.3%
DAMA/NaI-4 PLB4580 (2000), 23	16020 middle October to second half of August	44^{+32}_{-14}	$(6.9^{+3.9}_{-3.8})10^{-6}$	92.8%



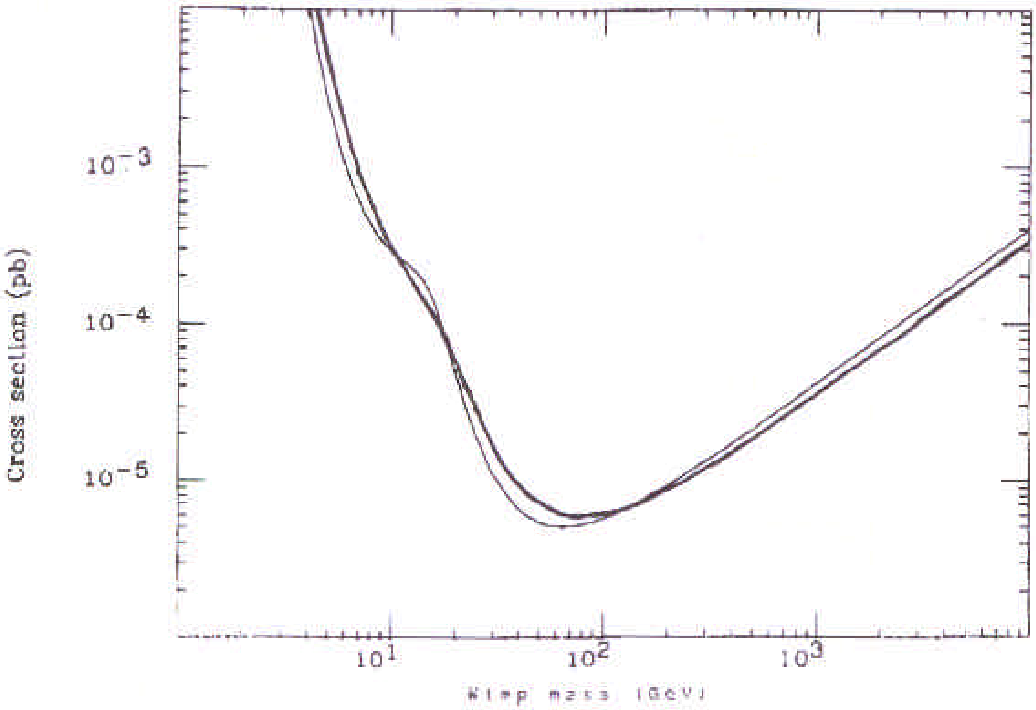
GLOBAL ANALYSIS
in the same framework:

SI candidate; fixed values for astrophysical (e.g. v_0=220 km/s) nuclear and particle physics parameters; detector parameters included; standard scaling law for cross sections; $b_{jk} \geq 0$; M_W>30GeV to account for results at accelerators (4 cycles **total statistics: 57986 kg d**).

experimental $N_{ijk} \Leftrightarrow \mu_{ijk}$ expected from the model

running period	M_W (GeV)	$\xi\sigma_p$ (pb)	C.L. (m.l.r)
the "simple" scenario: DAMA/NaI-1 to DAMA/NaI-4	52^{+10}_{-8}	$(7.2^{+0.4}_{-0.9})\,10^{-6}$	4 σ
requiring consistency with measured upper limits on recoils: DAMA/NaI-0 to DAMA/NaI-4	44^{+12}_{-9}	$(5.4\pm1.0)\,10^{-6}$	~ 4 σ

- Case of NaI(Tl) PSD result (DAMA/NaI-0)
- Standard method to calculate the exclusion plot (each energy bin of each crystal as independent) **vs** a maximum likelihood method (considering all the bins together with their effective weights) excluding the first energy bin.



- Discussed at DM98 Int. Workshop and at 1-day satellite Workshop on "detailed Techniques in direct detection of Dark Matter at DM98, USA, Marina del Rey, Feb. 98

as quoted (and presented also) on Proc. 3K Cosmology p. 65 (1998) and Proc. of Int. Workshop on "Identification of Dark Matter" p. 293 (1998)

On "Anomalous" or "unknown" events

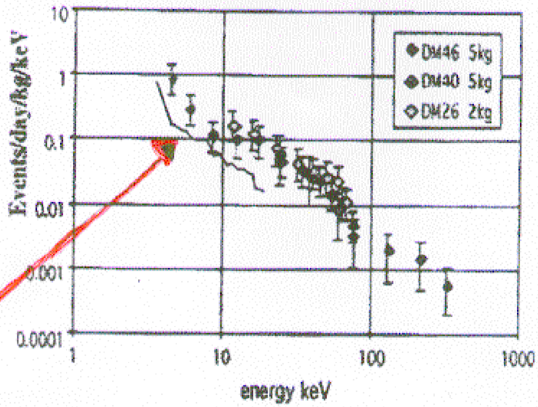
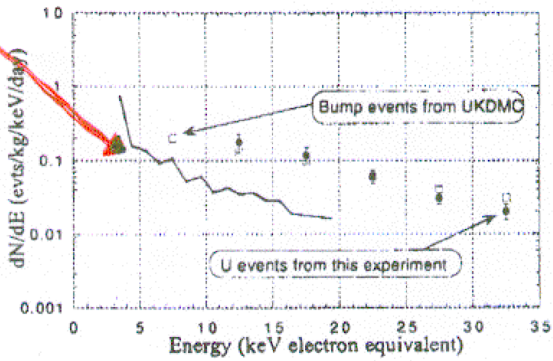


Figure 2. Energy spectra of anomalous events. Data from several crystals is shown to be consistent.

UK coll. Nucl. Phys. B (Proc. Sup.) 87 (2000) 64

DAMA/NaI-0 PLB389(1996),757



Gerbier et al. Nucl. Phys. B (Proc. Sup.) 87 (2000), 61

Figure 4. Energy spectra of U events (from this experiment) and Bump events from UKDMC result [3].

As it can be easily understood from the PLB389(1996),757 this method was sensitive to similar events. Their presence will cause the presence of sizeable fraction of recoil candidates → excluded by these data up to "high" region (where no noise cut at all is applied).

Extending the DAMA/NaI-0 to 4 region by accounting for the v_0 uncertainties

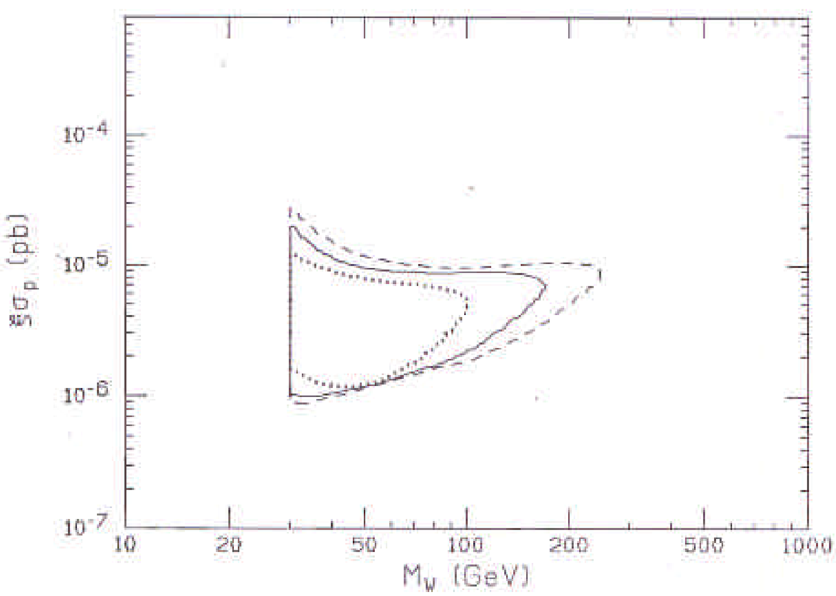
- v_0 = 220 km/s (dotted)
- v_0 = (220±50) km/s (90% C.L.) (continuous)

{ v_{esc} = (550±100) km/s (90% C.L.) ← negligible effect}

at 1σ C.L. 30 GeV $\lesssim m_\chi \lesssim$ 105 GeV

- Including possible Dark halo rotation (dashed)

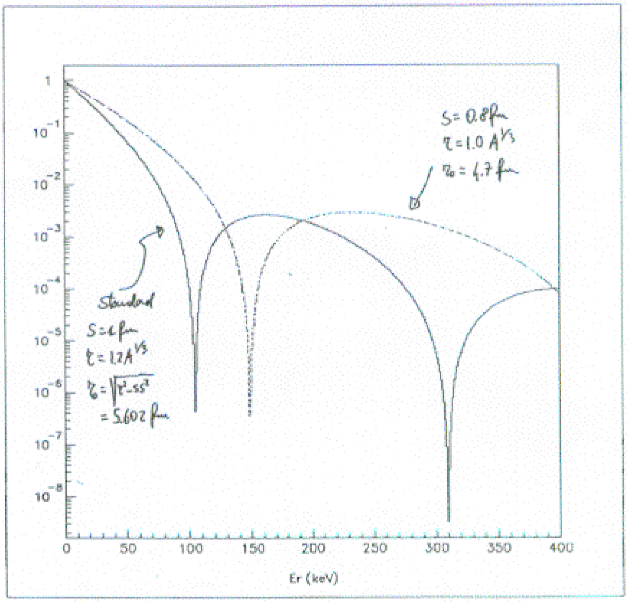
at 1σ C.L. 30 GeV $\lesssim m_\chi \lesssim$ 132 GeV



A similar analysis was performed for DAMA/NaI-1&2:
PR D61 (2000) 023512

Accounting for further uncertainties can enlarge the allowed region

- **example:**
  the Iodine Form Factor (by Helm)



e.g.: varying the standard values of the FF parameters by 20%:

1 - the region moves toward larger M_W and lower σ_p

2 - the S_m(2-6 keV) increases of ≈15%

CONCLUSION #2

The comparison of the experimental data
with the model for
a spin-independent coupled **WIMP**
with mass larger than 30 GeV (such as the
neutralino) allows to put it as a candidate for the
observed effect

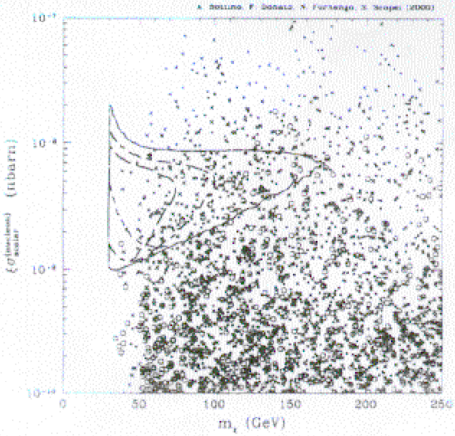
⇓

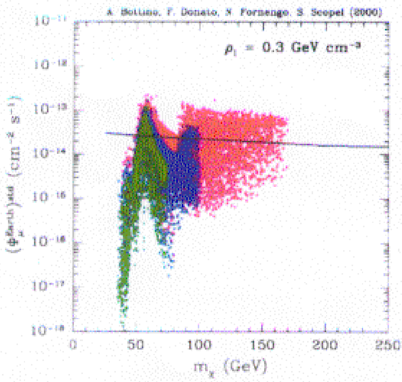
Is a neutralino with mass and cross section in the region presently allowed by DAMA of cosmological interest?

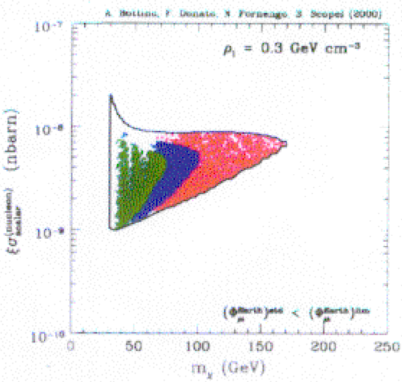
→ (from A.Bottino et al.)

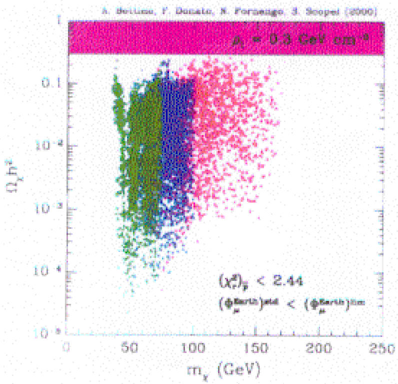
→ → →

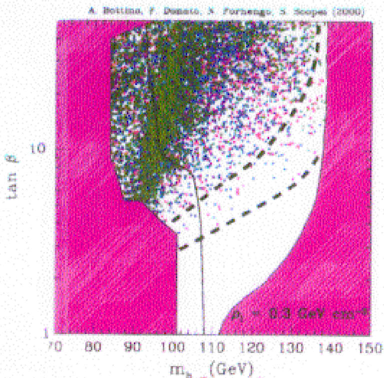
- MSSM
- Direct vs Indirect Searches
- Cosmological Abundance
- What Expected From Accelerators?









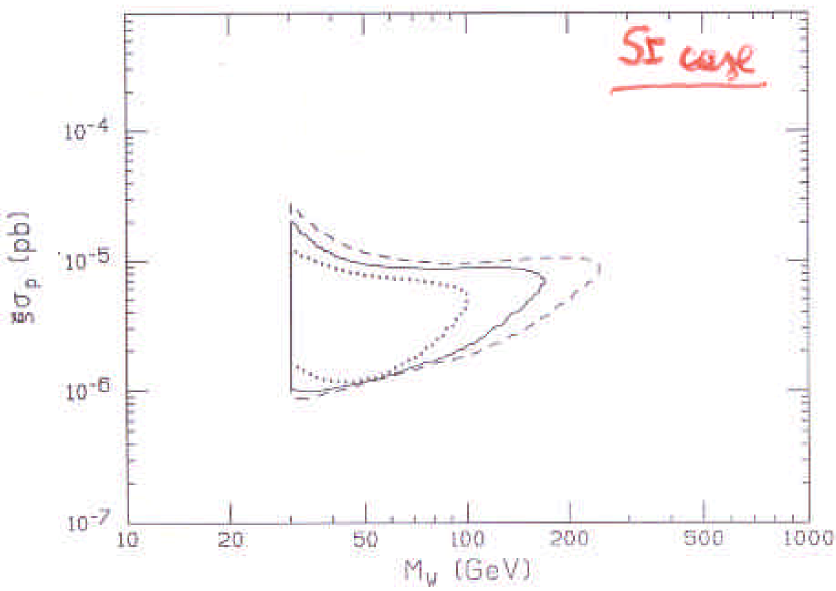


↑ 95% CL REACHABLE AT LEP2 (No DISCOVERY of neutral HIGGS boson)

A. Bottino et al., hep-ph/0001309
To appear on Phys. Rev. D

Conclusions

- **A WIMP contribution to the measured rate is candidate by the model independent residuals and by the investigation of known sources of systematics**
- **The global full correlation analysis in terms of a SI candidate with mass > 30 GeV favours the modulation at ~4σ C.L. (+ shown by Bottino et al. that a χ in this allowed region is of cosmological interest)**



in progress: investigation on the role of other possible uncertainties on the used parameters (e.g. FF) → it could enlarge the allowed region given above + on model framework

↓

- **data taking in progress**
- **new electronics and DAQ installation on July 2000 (exploiting further peculiarities)**
- **fulfil the present installation up to 250 kg**

(new much higher radiopure detectors & R&D successfull

→ **wait for more ......**