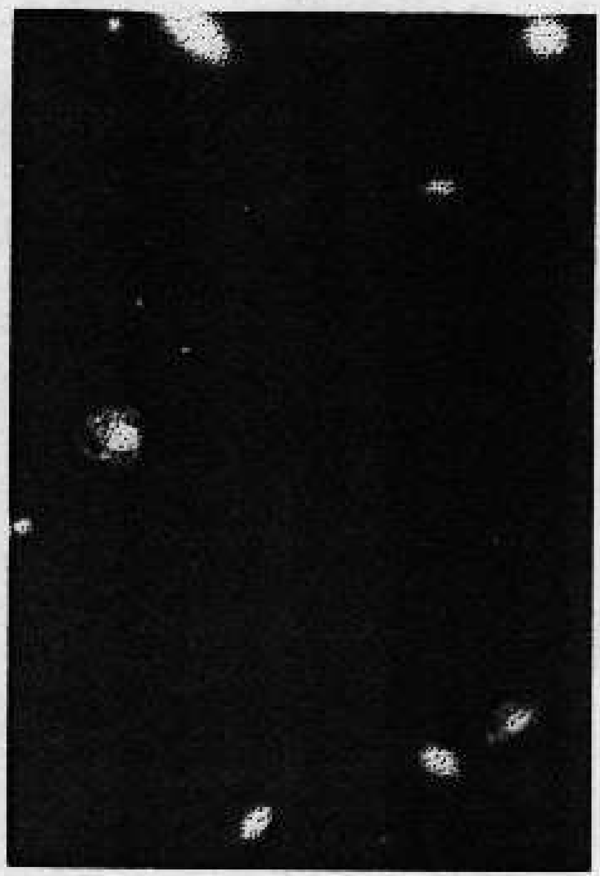
Searching for signals from the Dark Universe: recent results from DAMA



> 90% of the Universe is dark
What is the nature of our Universe?
What is the future?

Roma2/Roma/Beijing

R. BERNABEI
Trieste, April 27, 2000

The WIMPs

Relic CDM particles from primordial Universe

- in thermal equilibrium in the early stage of Universe
- non relativistic at decoupling time
- $<\sigma_{ann} \cdot v> \sim \frac{10^{-26}}{\Omega_{WIMP} h^2}$ $cm^3 s^{-1} \rightarrow \sigma_{ordinary\ matter} \sim \sigma_{weak}$
- expected flux: $\Phi \sim 10^7 \cdot \frac{1 GeV}{M_W}$ $cm^{-2}\ s^{-1}$
  ($0.2 < \rho_{halo} < 0.7$ GeV cm^{-3})
- form a dissipationless gas trapped in the gravitational field of the Galaxy ($v \sim 10^{-3}$ c)

..... searching for a candidate

- neutral, stable (or with $\tau \sim$ age of Universe) and massive particle

→ the most favoured candidate ...

- MSSM +SUGRA
- R-parity conserved → the LSP is stable
- LSP=χ

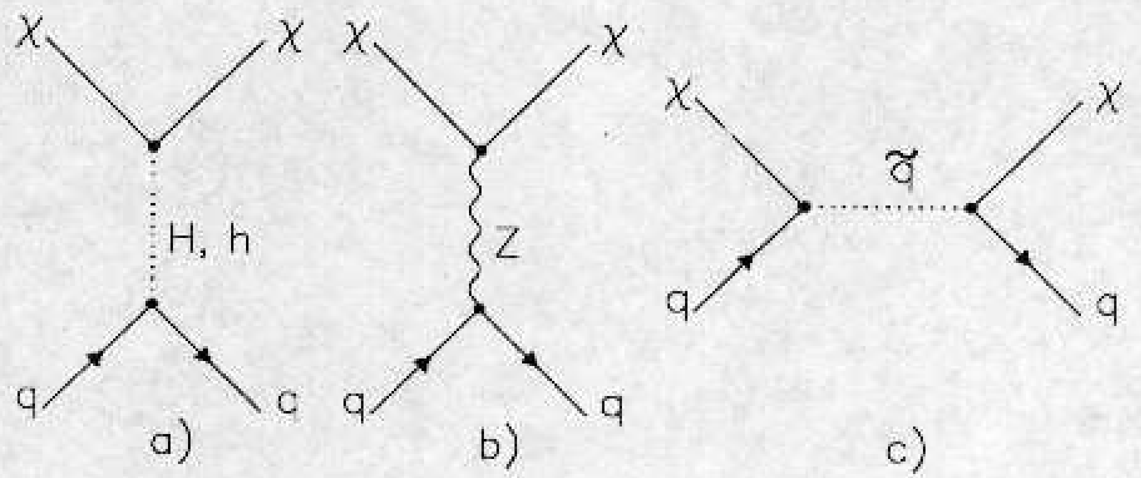
.... the χ

The χ

- spin 1/2 - Majorana LSP

$$\chi = a_1 \tilde{\gamma} + a_2 \tilde{Z} + a_3 \tilde{H}_1 + a_4 \tilde{H}_2$$

- relevant diagrams for cross section on ordinary matter:



a) coherent contribution:

higgsino-Zino mixture: $\sigma \propto A^2$

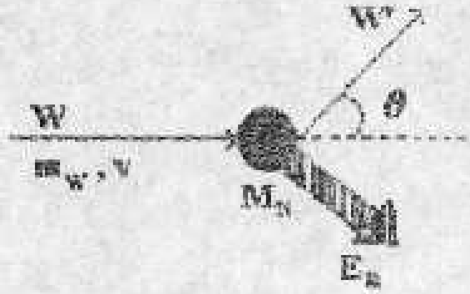
b) spin-dependent contribution:

higgsino component: $\sigma \propto \lambda^2 J(J+1)$

c) spin and coherent contribution

The WIMP *wind*

Direct detection mainly
° by elastic scattering on target-nuclei



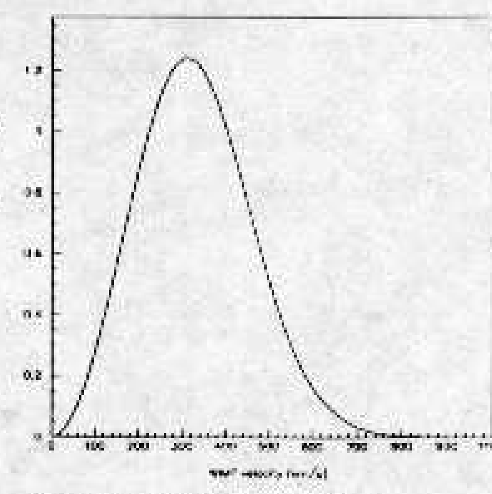
Energy spectrum

$$\circ\ \frac{dR}{dE_R} = N_T \frac{\rho_W}{M_W} \int_{v_{min}}^{v_{max}} v f(v|v_\oplus) \frac{\sigma_{point\text{-}like}}{E_{R_{max}}} F^2(E_R)\, dv$$

with $v_{min} = \sqrt{\frac{M_{nucleus} E_R}{2 m_{red}^2}}$; $E_{R_{max}} = \frac{2 m_{red}^2 v^2}{M_{nucleus}}$;

$v_\oplus$ = **Earth velocity in the galactic frame**

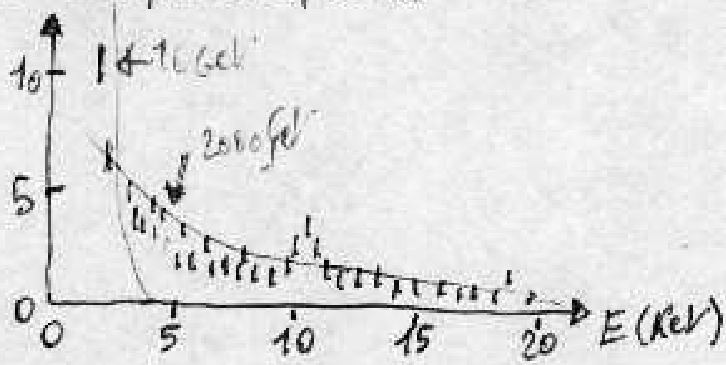
WIMP velocity distribution = Maxwellian with cut-off at v_{escape} **and** $v_0 = \sqrt{\frac{2}{3}} v_{r.m.s.}$ **= 220 km /s**



measured quantity: E_R in the keV region
(quasi-exponential behaviour)

Usual approach

- Experimental vs Expected spectra



low activity materials; particle and nuclear physics, cosmological evolution of particles

detector; form factor

$$(dR/dE_R)_{exp} \leftrightarrow (dR/dE_R)_{Theo} = f(\rho_W, \beta_W, \sigma_W, M_W)\, F(E_R)$$

underground laboratory; nucleon spin factor

calibration of detector; galaxy model

⇓

← + in the limit of the used experimental and theoretical assumptions and of the proper "handling" of all the involved uncertainties.

Intrinsic uncertainties when comparing exclusion plots from different experiments

- **the same carefull knowledge and control of the "physical" energy threshold and of technical quantities such as quenching factors, sensitive volume, efficiencies, energy calibrations, ... ?**
- **stability with time of all these quantities (also for expts measuring only counting rates) at the same level of accuracy?**
- **the same carefull knowledge and control of the quantities involved in recoil/background discrimination and related efficiencies? use of Montecarlo subtraction ???**
- **uncertainties in the astrophysical parameters**
- **uncertainties in the form factors**
- **uncertainties in different contributions from possible systematics and their proper "handling", mainly when different techniques are used**

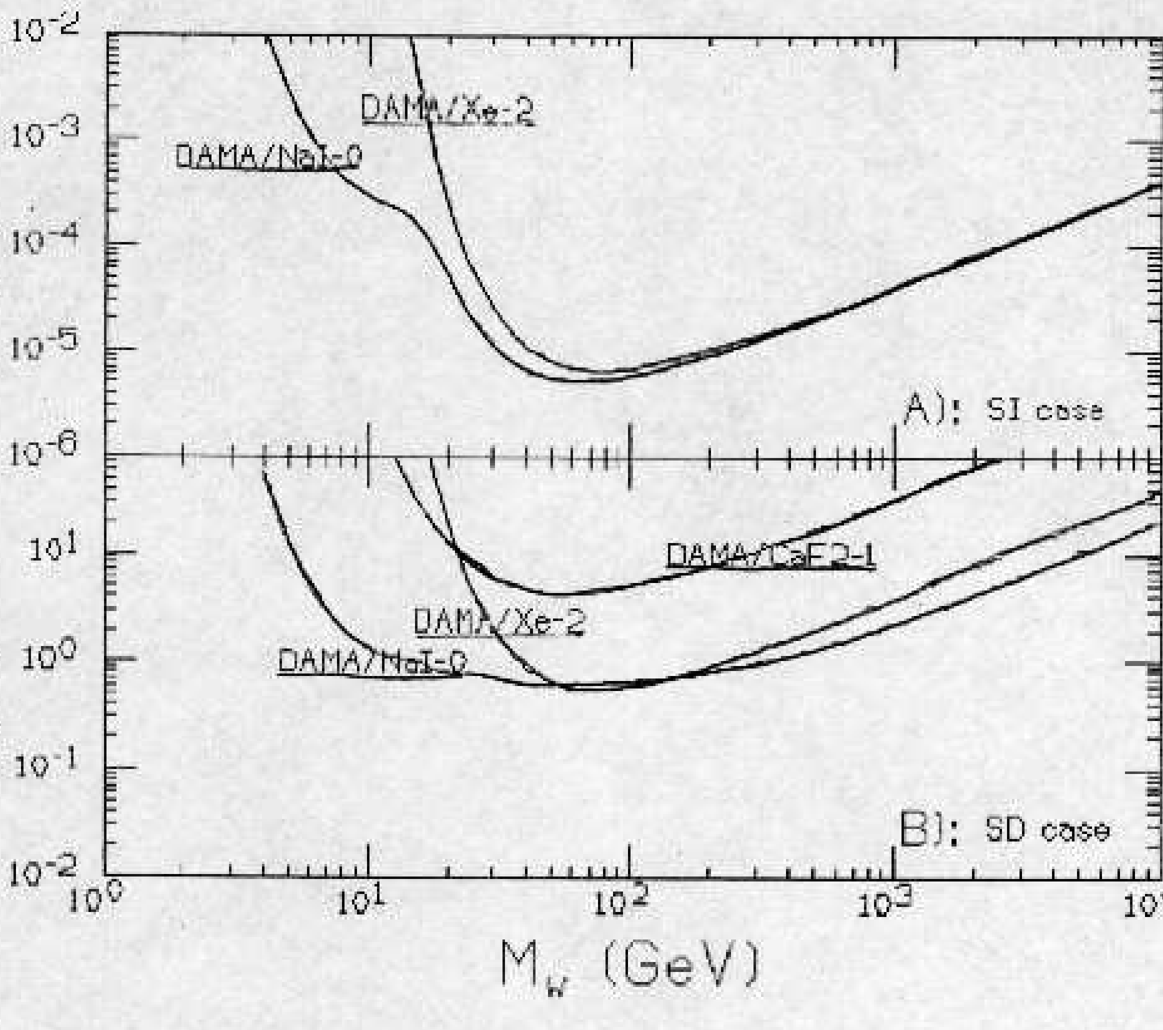
etc. etc. etc. etc.

- **to compare experiment with different target nuclei scaling laws to cross section on proton are necessary**
- **no discovery pontentiality (also in case of discrimination concurrent processes from neutron, end-range alphas, etc. are undistinguishable and reliable ways to handle that do not exist!)**

⇓

a signature is needed !

DAMA exclusion plots
90% C.L.



A signature is needed !

- Comparison of the results from different experiments.

  (SI: $R \propto A^2$; SD: $R \propto C\lambda^2 J(J+1)$; $\langle Er \rangle = f(M_N)$ for each M_W)

  not feasible – different backgrounds
  different possible systematics
  - - -

- **Directionality.**

  Correlation of nuclear recoil track with the Earth's galactic motion due to the distribution of WIMP velocities

  Very hard to realize

- **Diurnal modulation**

  Daily variation of the rate due to different Earth depth crossed by Wimps

  only for high σ

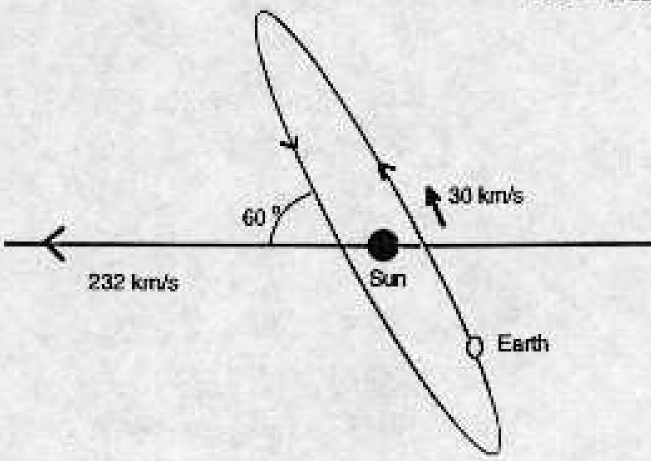
- **Annual modulation of the signal**

  annual variation of the rate due to Earth motion around the Sun

  The only feasible one

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)

γ = $\pi/3$

ω = $2\pi/T$ with T=1 year

t_0 = 2^{nd} 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:

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

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

- 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 $\leq 7\%$.

YES!

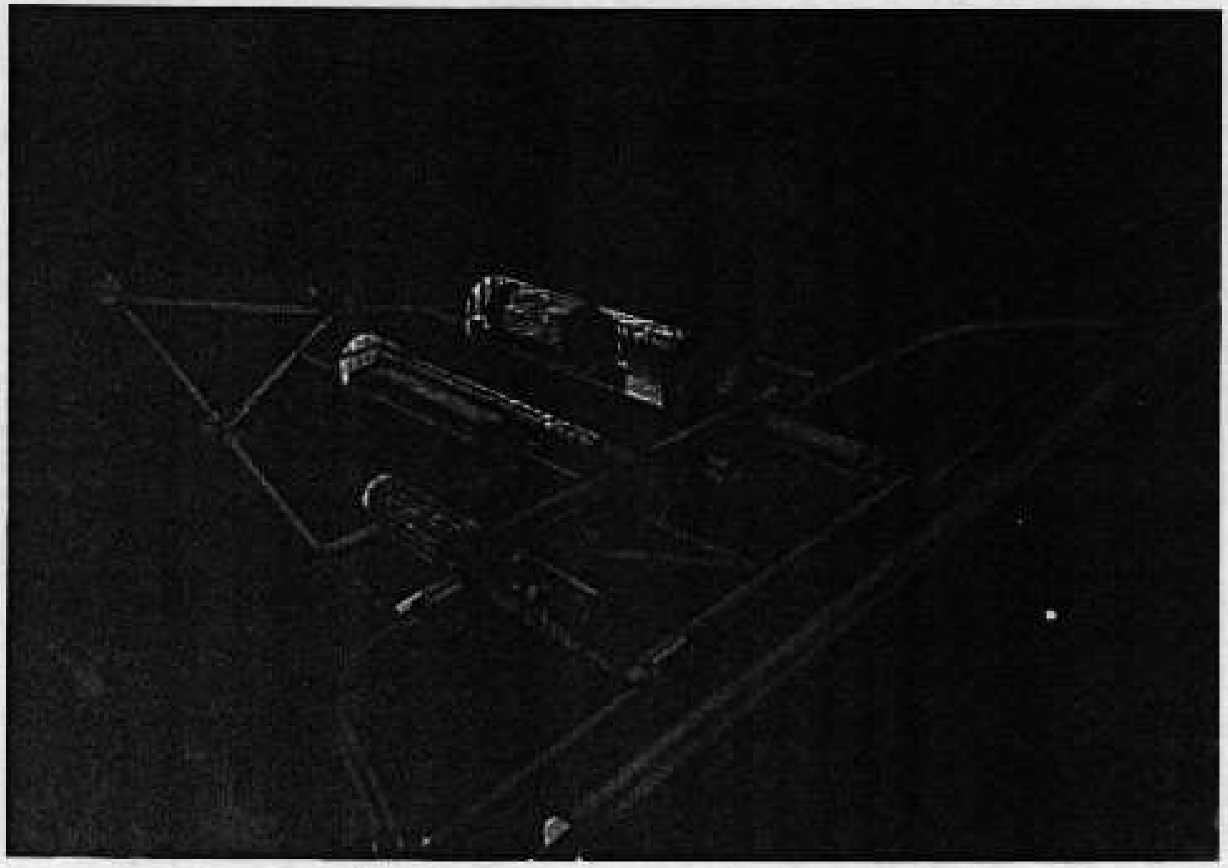
⇓

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

Scintillators as target-detectors

- Known technology
- Cost/Mass relatively low
- Large mass $\rightarrow$ suitable statistics for annual modulation
- Statistical discrimination of recoil nuclei e.g. in NaI(Tl) and LXe
- A large set of target-detectors nuclei
- Sensitive also to spin-dependent interactions

DAMA ACTIVITIES @LNGS



Recent References

- **~100 kg NaI(Tl)**

PLB389 (1996) 757; PLB408 (1997) 439; PLB424 (1998) 195; PLB450 (1999) 448; N.Cim.A112 (1999) 545; PRD61 (2000) 023512; PRL83 (1999) 4918; N.Cim.A112 (1999) 1541; ROM2F/2000-01 and INFN/AE-00/01 To appear on PLB

- **~ 6.5 kg LXe**

N.Cim.C19 (1996)537; PLB387(1996) 222; PLB436(1998) 379; ROM2F/2000-05

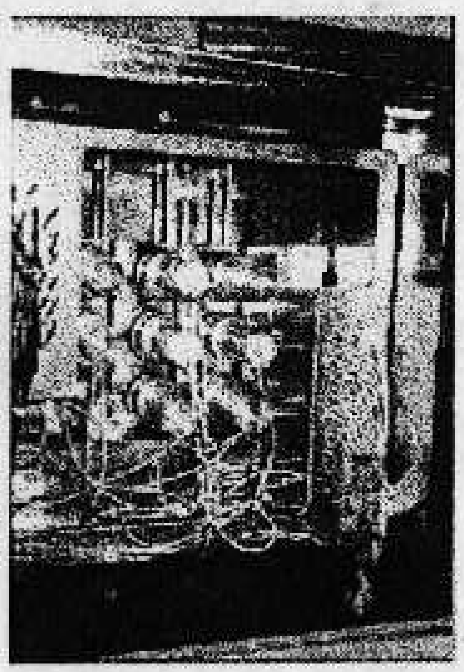
- **CaF_2(Eu) + by-products + others**

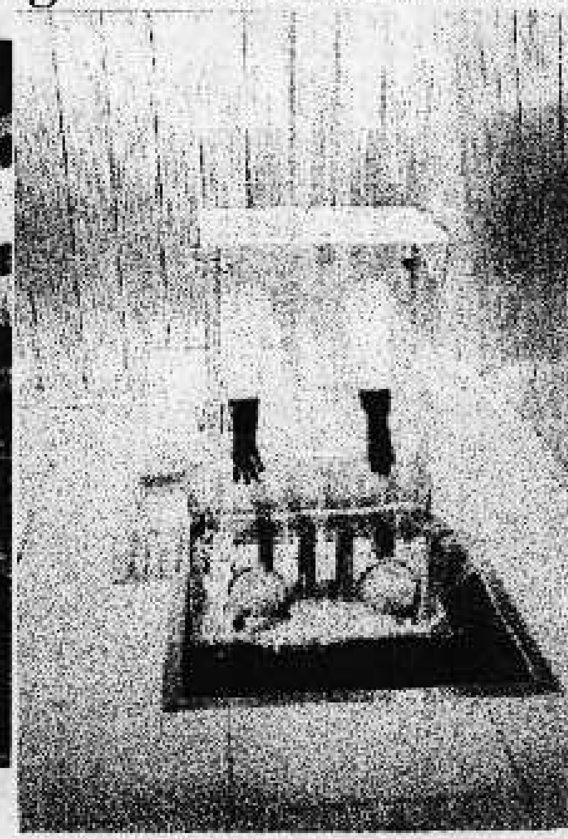
Astrop.Phys.5(1996) 217; Astrop.Phys. 7(1997)73; N.Cim.A110 (1997)189; PLB408(1997)439; Astrop. Phys. 10 (1999) 115; NPB546 (1999) 19; PLB460 (1999) 235; NPB563 (1999) 97; PRC60 (1999) 065501; PLB465 (1999), 315; ROM2F/99/32

The ~100 kg NaI(Tl) experiment

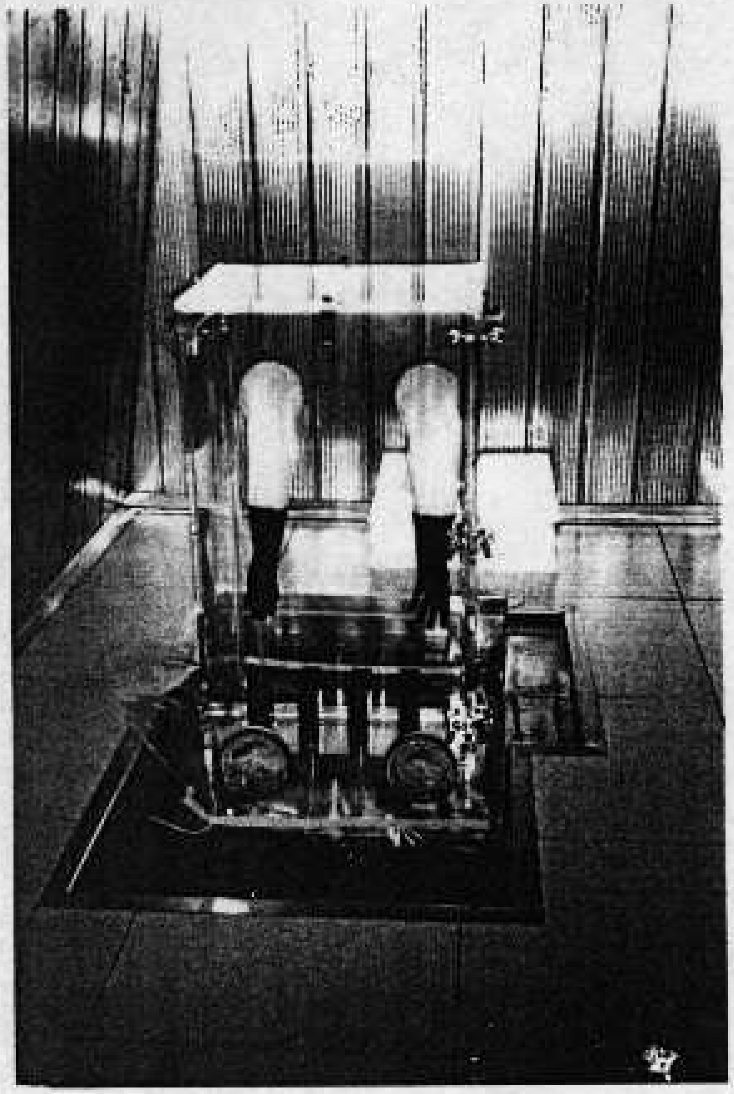
Unique in the world for exposed mass

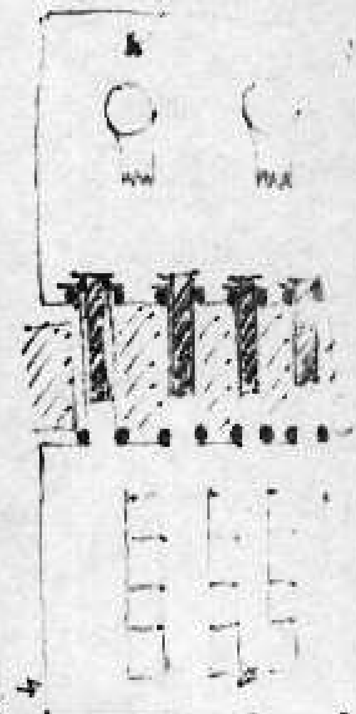
The NaI(Tl) crystals..... the installation and ..... the glove-box for calibration

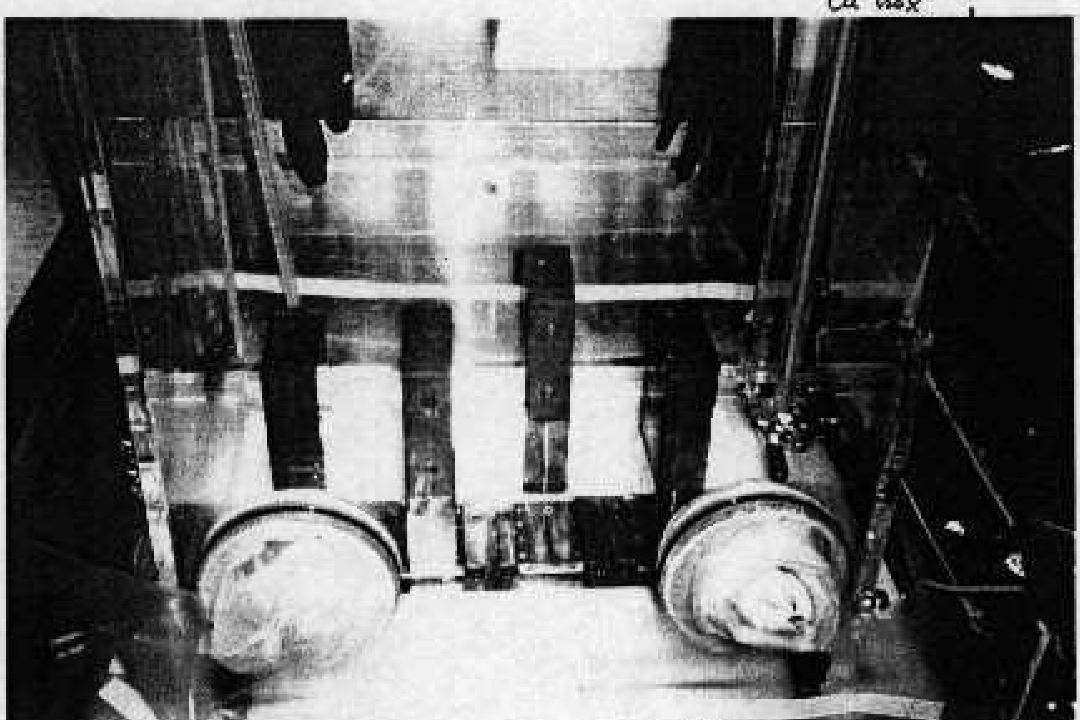




EXPERIMENTAL DETAILS ON: Nuovo Cim. A 112 (1999), 545.




sealed
Cu box


NaI
Detector

Main Features

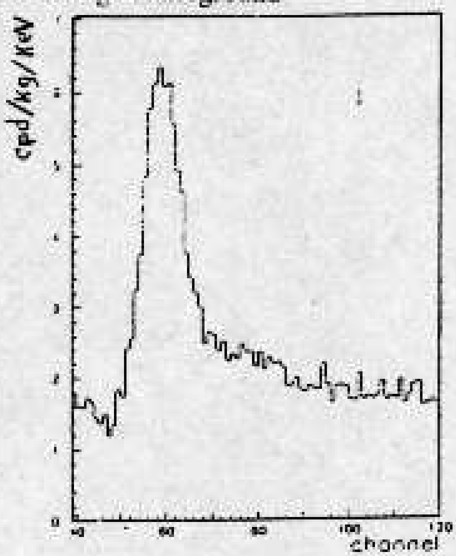
(full description in Il Nuovo Cim. A112 (1999), 545)

- 9x9.70kg NaI(Tl) (WIMP exp) + 4x7.05kg NaI(Tl) (old SIMP exp) in sealed Cu box flushed with HP N_2 from bottles
- Reduced standard contaminants (e.g. U/Th of order of ppt) by material selection and growth/handling protocols.
- Each detector coupled - through 10cm long light guides - to two low background EMI9265B53/FL 3" diameter PMTs working in coincidence (selected materials).
- Low Radioactive Shields: 10cm of high radiopurity copper inner; 15cm of very low radioactivity lead outer; 1.5mm Cd foil and polyethylen/paraffin for neutron shield.
- Further external sealing of the shield from environmental air.
- Installation with conditioned temperature.
- Calibration in sealed environment using the upper glove-box: no air pollution + in the same conditions as the production runs.
- Single PMT working at single photoelectron level. Usual software energy threshold: 2 keV.
- Pulse shape recorded over 3250ns by a 200 Msample/s Transient Digitizer.
- Monitoring and control of several stability parameters.
- Control and alarm system continuously operating by self-controlled computer processes.
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy.

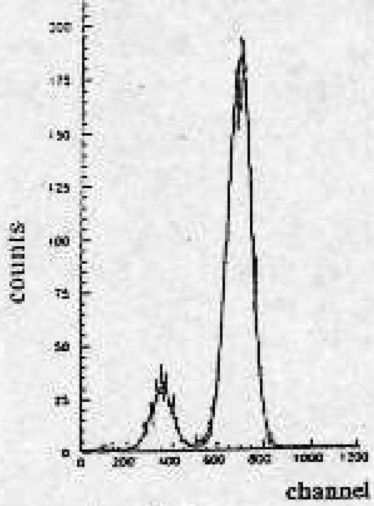
Energy scale monitoring

Calibration stability control mainly by $^{210}Pb^{(*)}$ peak (46.5 keV) each ~ week: peak position and energy resolution.

(*) Mainly external contamination at beginning of the storage underground



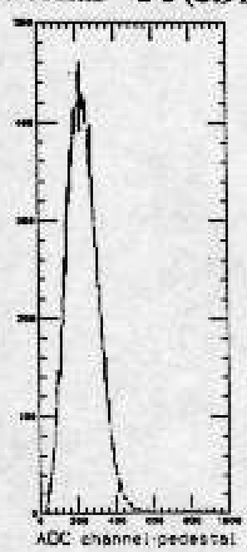
^{241}Am source (59.5keV)

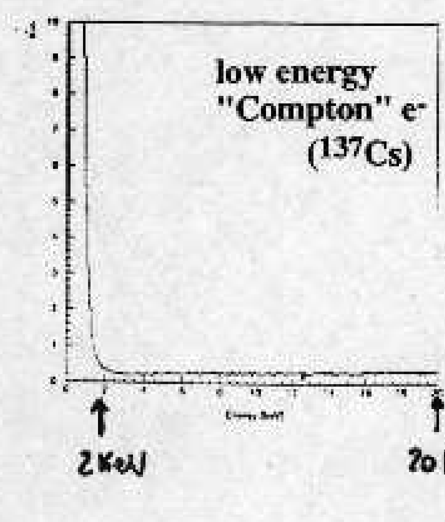


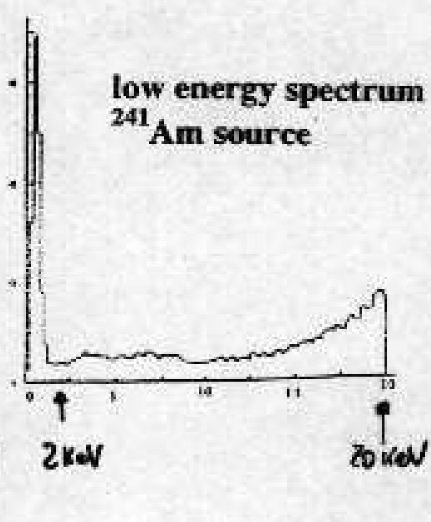
The energy threshold

- Using the sealed glove-box: γ sources down to keV range through low Z MIB window on detector housing + keV range "Compton" electrons
- Hardware threshold @ single photoelectron level
- 5.5 - 7.5 photoelectrons/keV

External ^{55}Fe (5.9keV)



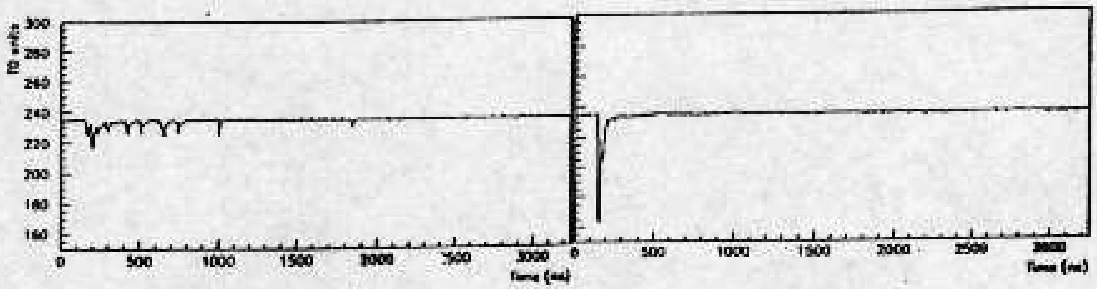




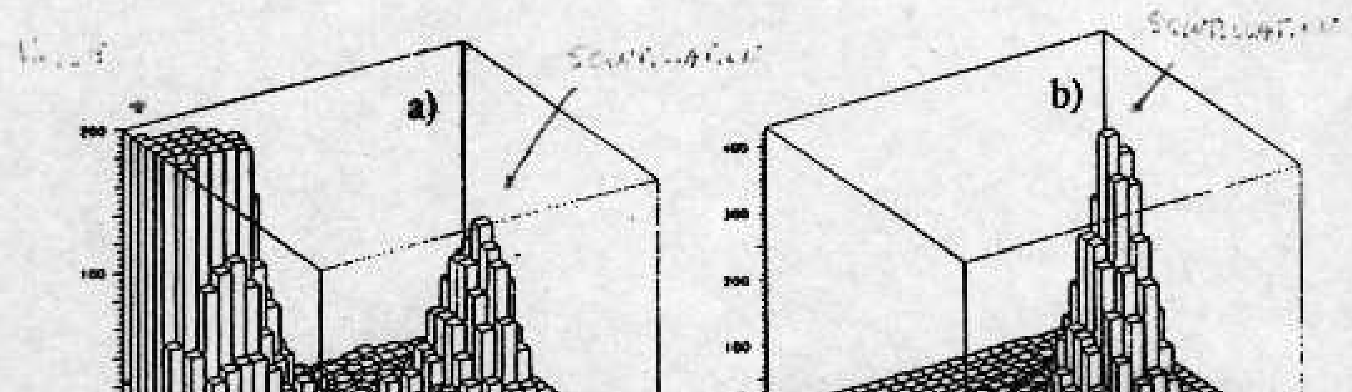
Residual noise rejection above software energy threshold

In our NaI(Tl) set-up:

- **Absence of microphonic noise.**
- **Photoelectrons/keV from 5.5 to 7.5 (depending on the detector)**
- **Scintillation pulses time distribution with τ of $\approx$ 240 ns.**
- **PMT noises: fast single photoelectrons with τ of order of tens ns.**



$\rightarrow$ **PMT noise rejectable by the study of pulse profile recorded by TD.**
Several variables can be built from the considered low energy data (2-20 keV) to reject noise from scintillation pulses, such as e.g.

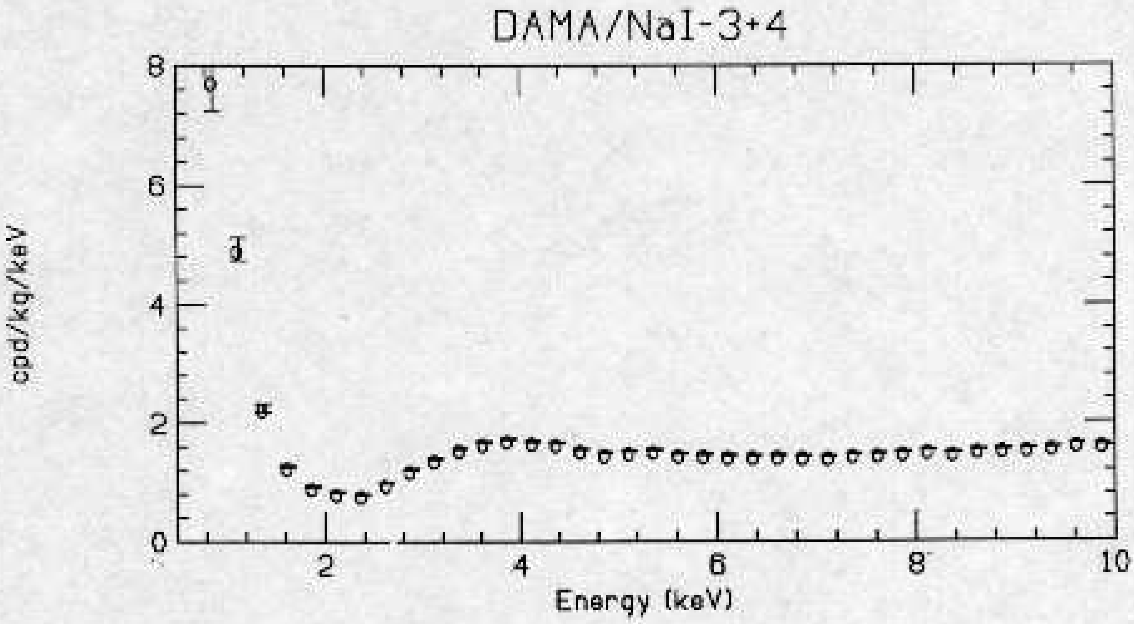


x_1 **expected values:** close to 0 **for noise** and close to $\approx$0.7 for scintillation pulses
x_2 **expected values:** close to 1 for noise and close to $\approx$0.5 for scintillation pulses

Typical energy spectrum

The DAMA/NaI-3&4 running periods

- **The 9 NaI(Tl) detectors all together**
- **<u>Single-hit</u> <u>events</u> → low energy Compton events and X-rays/Auger electrons correlated with higher energy escaping γ's vetoed by the close detectors (impossible when a single detector is used).**
- **<u>Never</u> used neutron source in the set-up.**
- **Electronics optimized and environmental background contributions well reduced.**



Discussed in the seminars at CERN by R.Bernabei on april 1999; Beyond99; included in the paper N.Cim.A112(1999),1541; energy spectra [3,6]keV on PLB460(1999),236 and up to 500keV on PRC60(1999) 065501.

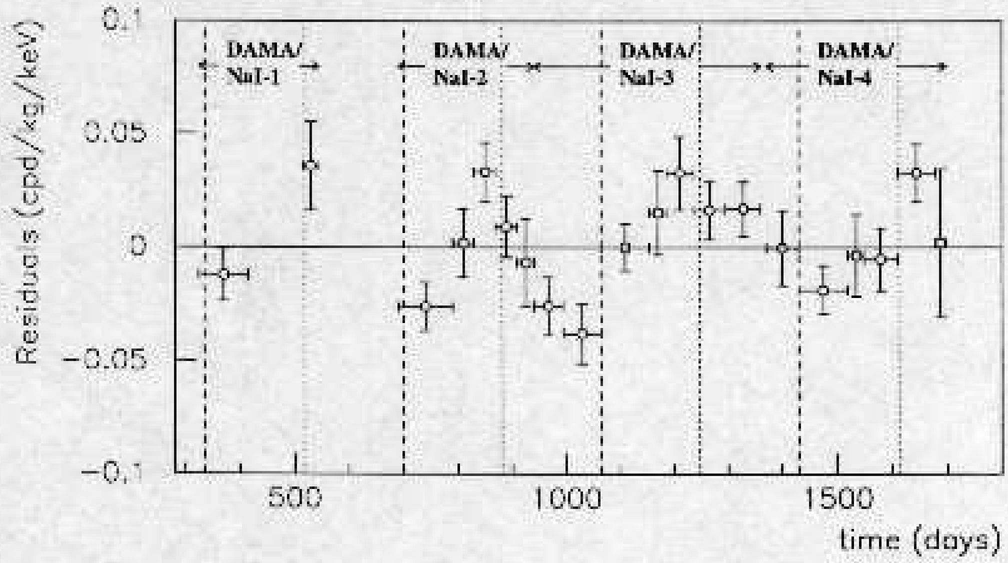
The running periods for annual modulation search

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**	**INFN/AE-00/01 to appear on PLB**
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 x 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
χ^2/dof = 23/18

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

Residuals vs time

$$\textbf{Residual}_i = \langle \mathbf{r}_{ijk} - \mathbf{flat}_{jk} \rangle_{jk}$$

- The average is made on all the detectors (***j***) and on all the 1 keV bins (***k***) which constitute the considered energy interval.
- $\mathbf{r}_{ijk}$ is the rate in the considered i th time interval for the j th detector in the k th energy bin
- $\mathbf{flat}_{jk}$ is the rate of the j th detector in the k th energy bin averaged over the cycles.

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)

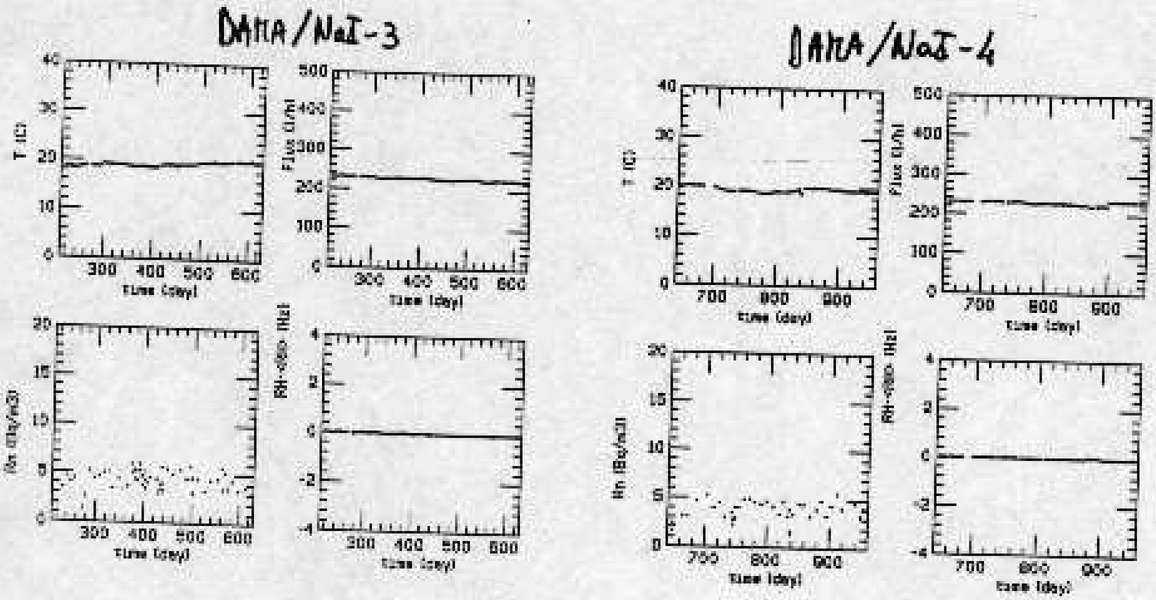
=

Compatibility with presence of WIMP in the Galactic halo

Investigation on possible systematics and side reactions for the new DAMA/NaI-3 and DAMA/NaI-4 running periods

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

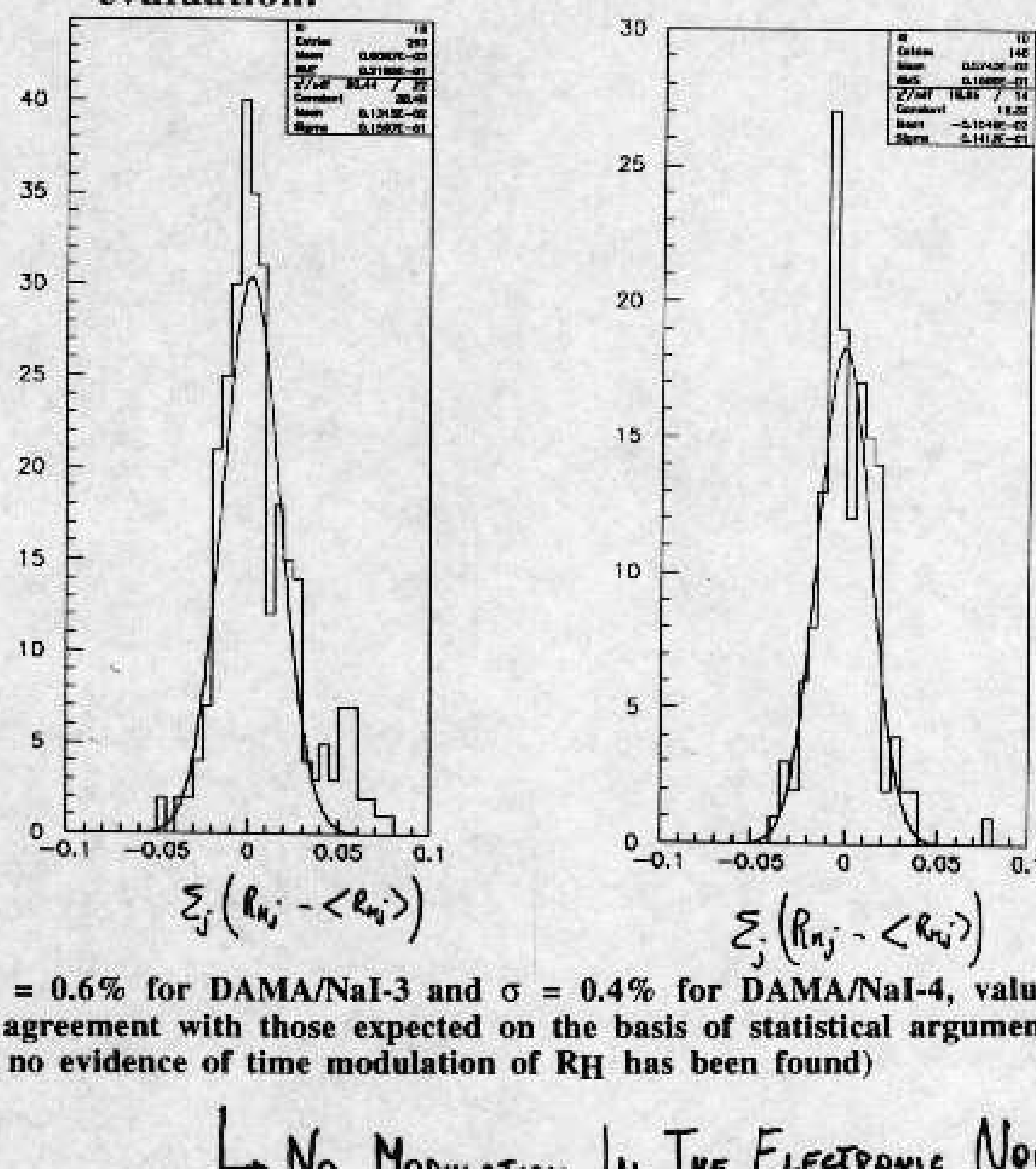
  (0.12 ± 0.20) Bq/m^3 DAMA/NaI-4 → consistent with zero

  ↳ NO MODULATION IN THE PARAMETERS

The stability control (2)

• **Distribution of total hardware rates of the 9 crystals over the single ph.el. threshold (that is from noise to "infinity"):**

shows a cumulative gaussian behaviour fully accounted by expected statistical spread arising from the sampling time used for the rate evaluation.



(σ = 0.6% for DAMA/NaI-3 and σ = 0.4% for DAMA/NaI-4, values in agreement with those expected on the basis of statistical arguments + no evidence of time modulation of R_H has been found)

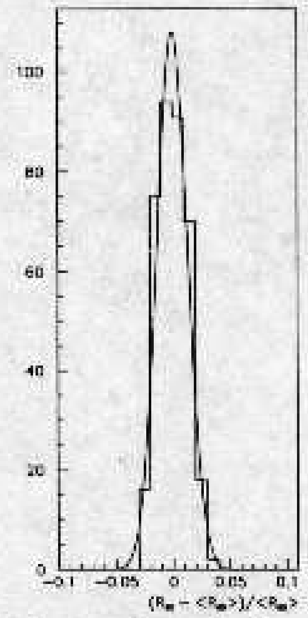
↳ NO MODULATION IN THE ELECTRONIC NOISE

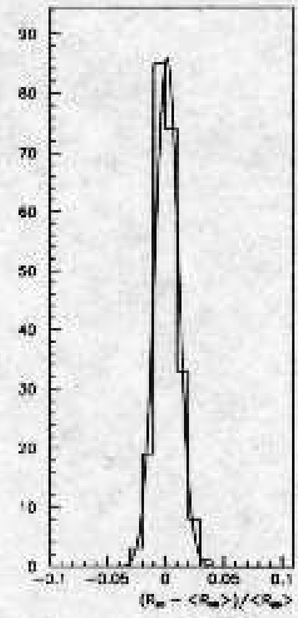
HE spectrum stability (3)

1 -Rates at higher energy (above 90 keV), R_{90}:

a - R_{90} percentage variations with respect to their mean values for single crystal

→ cumulative gaussian behaviour with $\sigma \approx 1.3\%$ (DAMA/NaI-3) and $\approx 1\%$ (DAMA/NaI-4) - fully accounted by statistical considerations





b -Fitting the behaviour with time, adding a term modulated according to T=1 year and t_0 = 152.5 day (as for Wimps) one gets as modulated amplitude
R_{90} = (-0.11 ± 0.33) cpd/kg for DAMA/NaI-3
R_{90} = (-0.35 ± 0.32) cpd/kg for DAMA/NaI-4

→ consistent with zero + if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

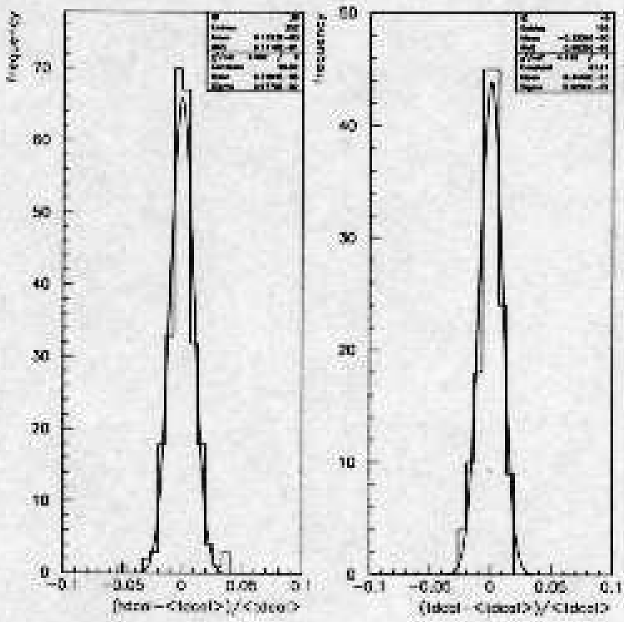
2 - Focusing the attention on an energy region nearer to the one of possible signal (10-20 keV), the modulated amplitudes: A = (-0.0044 ± 0.0044) cpd/kg/keV for DAMA/NaI-3 and A = (-0.0071 ± 0.0044) cpd/kg/keV for DAMA/NaI-4 are found

→ they can be considered statistically consistent with zero.

↳ NO MODULATION IN THE BACKGROUND

The stability control (4)

- **Relative variations of the energy calibration factors (tdcal) from the ^{210}Pb peak - without applying any correction - for all the 9 detectors during the whole DAMA/NaI-3 and DAMA/NaI-4 data takings**



gaussian behaviour with $\sigma = (0.95 \pm 0.04)\%$

↓

Uncertainties on tdcal for each detector <1% within each ≈7 days period → Negligible effect because of the routine calibration corrections and energy resolution at low energy: overall additional relative energy spread ≤3 10^{-4} @ 2 keV and ≤3 10^{-3} @ 20 keV

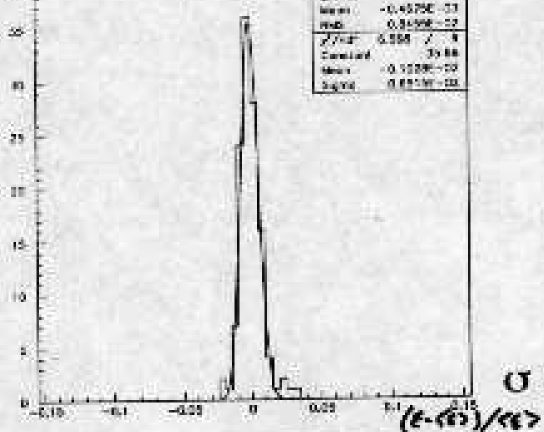
↳ NO MODULATION IN THE ENERGY SCALE

The efficiency stability

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

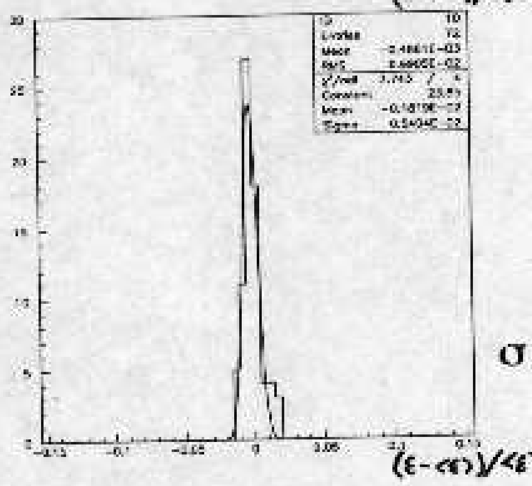
(2-4)+(4-6)+(6-8) keV

- **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	$(1.0 \pm 1.0)\ 10^{-3}$
4-6 keV	$(0.1 \pm 0.7)\ 10^{-3}$
6-8 keV	$-(0.2 \pm 0.5)\ 10^{-3}$

↳ 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 $<3\ 10^{-4}$ @ 2 keV and $<3\ 10^{-3}$ @ 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

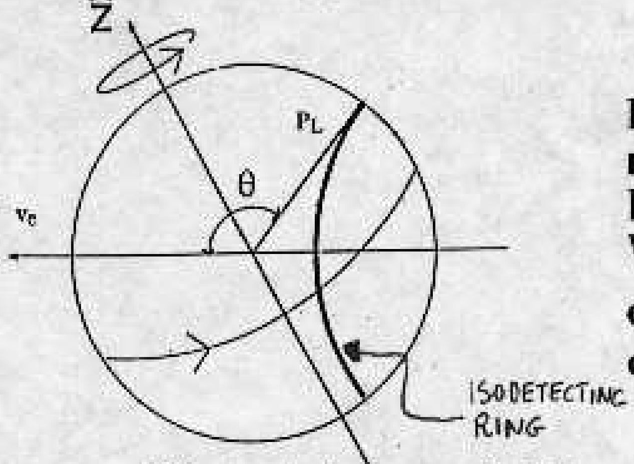
° expected modulated amplitude << 10^{-4} cpd/kg/keV

??Suggestions??

...while collecting further statistics for the annual modulation studies...

ROM2F/99/26 [redacted] N. Cim. A112 (1999) 1541

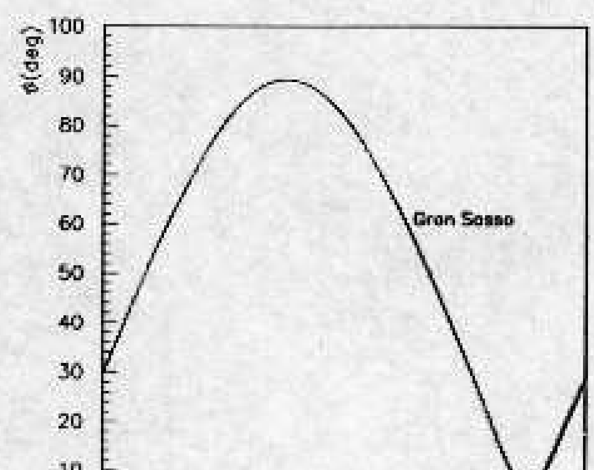
- **Investigation of possible rate diurnal modulation in the DAMA/NaI-2 data: 14962 kg day**



Daily variation of the rate due to different Earth depth crossed by WIMP. Appreciable only for high σ_p candidates

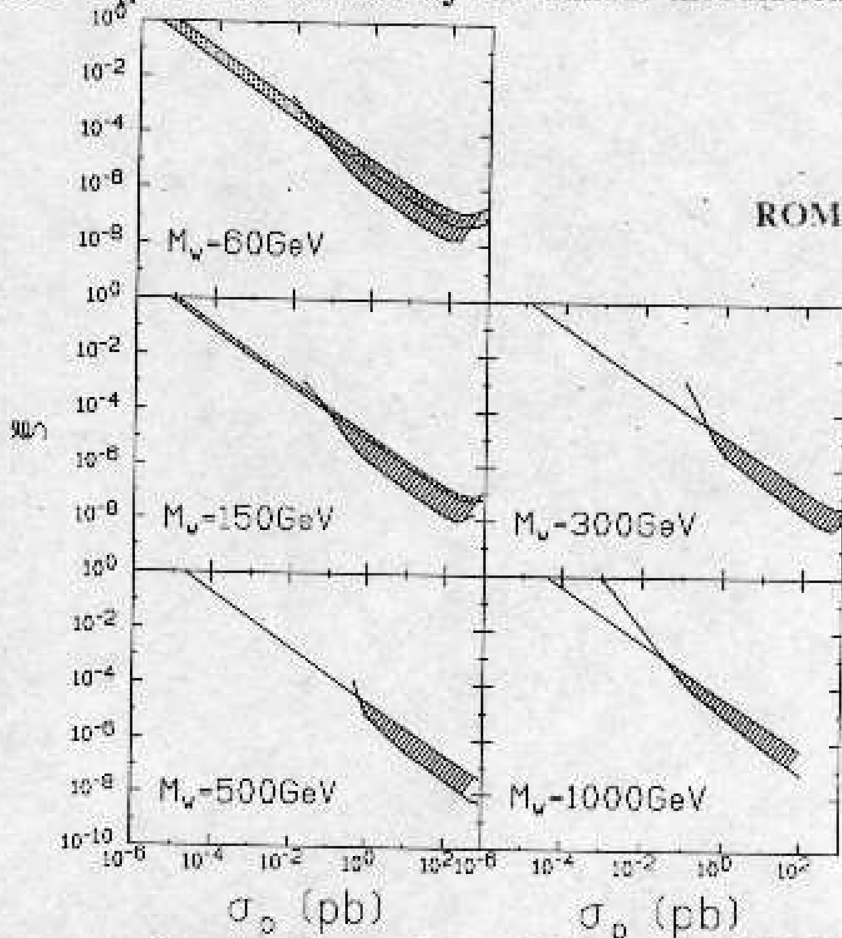
→ **To test the possibility of a high σ_p relic component with small halo fraction $\xi<10^{-3}$**

- **"Sidereal time" vs "θ":**



Limits on halo fraction (ξ) vs σ_p plane for SI coupled candidates for several M_W.

- **Slanted lines: best existing limits on $\xi\sigma_p$.**
- **Dashed regions are excluded by the diurnal variation analysis**
- **Dotted regions are allowed by the annual modulation analysis**



ROM2F/99/26
To appear etc
N. Cim. A
112 (1999), 1541

- **Absence of rate diurnal variation in DAMA/NaI-2 excludes the presence of:**
  - <u>high cross section</u> **Dark Matter particle component** (with small halo fraction)
  - **spurious effects correlated with the diurnal sidereal time.**

(similar conclusions when correlation analysis with solar time is used)

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**

Analysis strategy

MAXIMUM LIKELIHOOD METHOD:

→ studying the differential energy spectrum with **$\Delta E = 1$keV**

(best compromise between an high S/N and available statistics)

FORMULATION:

° **grouping the events in cells of 1 day (i), 1 keV(k) for each detector (j) : N_{ijk}**

° **Compare the Nijk with the expectations:**

$$\mu_{ijk} = (b_{jk} + S_{0,k} + S_{m,k} \cos\omega(t_i - t_0))\, M_j\, \Delta t_i\, \Delta E\, \varepsilon_{jk}$$

b_{jk} = time independent background

$S_{0,k} = \xi\sigma_p S'_{0,k}(M_W)$

$S_{m,k} = \xi\sigma_p S'_{m,k}(M_W)$

($\xi = \frac{\rho_W}{0.3\,\mathrm{GeV/cm^3}}$; S' according to standard hyphoteses)

° **Minimize the function:**

$$y = -2\ln(L) - \text{const} \qquad \textbf{with } L = \Pi_{ijk} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!} = \Pi_{ijk} l_{ijk}$$

° **Final results by minimizing y with respect to σ_p, M_W, b_{jk}'s** *(remind always ΔE = 1keV !)*

GOODNESS OF THE METHOD:

→ extracts a possible signal in energy bins where the sensitivity is maximal (generally at lower energy) + consistency in higher energy bins (where a possible signal is fallen down) offers a further strenght to the result.

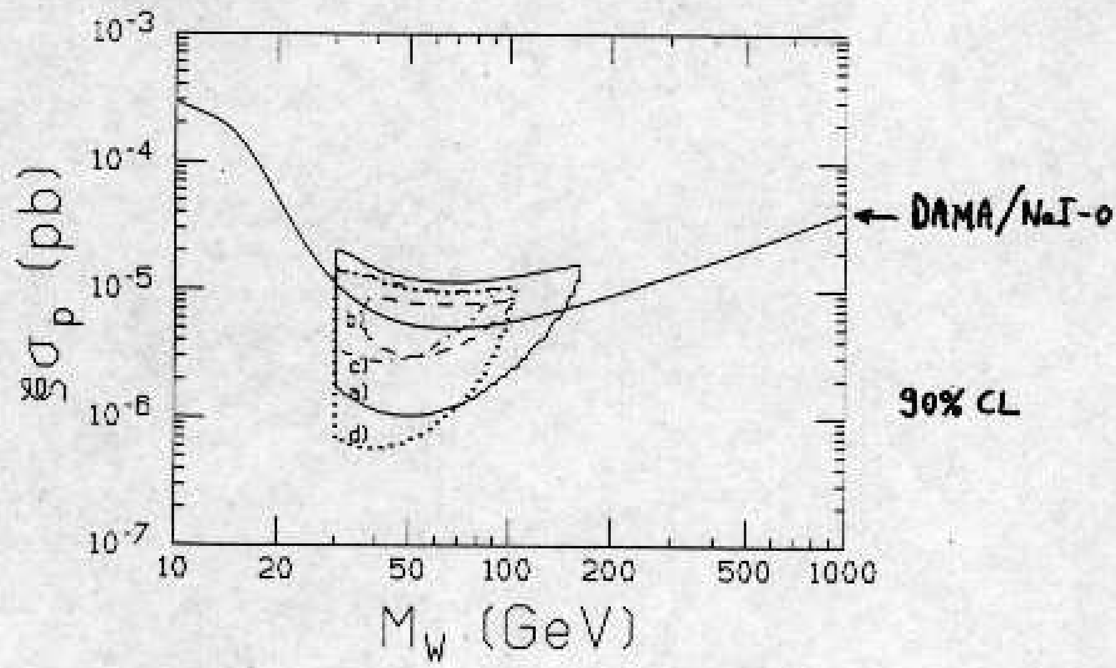
→ does not requires any *a priori* choice of the most sensitive energy interval.

New results: DAMA/NaI-3&4

- Framework: SI candidate; standard astrophysical parameters (e.g. v_0=220 km/s); detector parameters included; standard scaling law for cross sections; Helm SI Iodine form factor; $b_{jk} \geq 0$; 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 ROM2F/2000-01 INFN/AE-00/01 to appear on PLB	22455 from middle August to end of September	56^{+18}_{-26}	$(9.7^{+0.3}_{-3.5})\,10^{-6}$	98.3%
DAMA/NaI-4 ROM2F/2000-01 INFN/AE-00/01 to appear on PLB	16020 middle October to second half of August	44^{+32}_{-14}	$(6.9^{+3.9}_{-3.8})\,10^{-6}$	92.8%



DAMA/NaI-3 & 4 statistical evaluations

1) **Maximum likelihood ratio:**

DAMA/NaI-3:
$(-2\ \ln\lambda) = 5.67$ is asymptotically distributed as a χ^2

DAMA/NaI-4:
$(-2\ \ln\lambda) = 3.23$ is asymptotically distributed as a χ^2

→ in favour of the hypothesis of presence of modulation with given $\xi\sigma_p$, M_w at 98.3% C.L. and at 92.8% C.L. respectively

2) **z-test:**

using the variable $z = \frac{1}{N}\sum_{ijk}\left[2\left(\mu_{ijk} - N_{ijk}\right) + 2N_{ijk}\ln\left(\frac{N_{ijk}}{\mu_{ijk}}\right)\right]$ **(PDP)**

(Similar conclusions obtained with other chosen variables)

- N number of considered {ijk} bins (d.o.f.).
- z variable would be a χ^2/d.o.f. for sufficiently large N_{ijk} which is not always the case here.
- expected distribution of the z variable by a MonteCarlo code (simulation of 10^4 independent experiments with the same statistics as each one of the considered periods)
- DAMA/NaI-3: z = 1.036 when using the best fitted values
- DAMA/NaI-4: z = 1.009 when using the best fitted values

→ z MonteCarlo distribution gives a probability of 19% and 99.8% to get worse z value

GLOBAL ANALYSIS

• Framework: **SI candidate; standard astrophysical parameters (e.g. v_0=220 km/s); detector parameters included; standard scaling law for cross sections; Helm SI Iodine form factor; $b_{jk} \geq 0$; M_W>30GeV to account for results at accelerators**

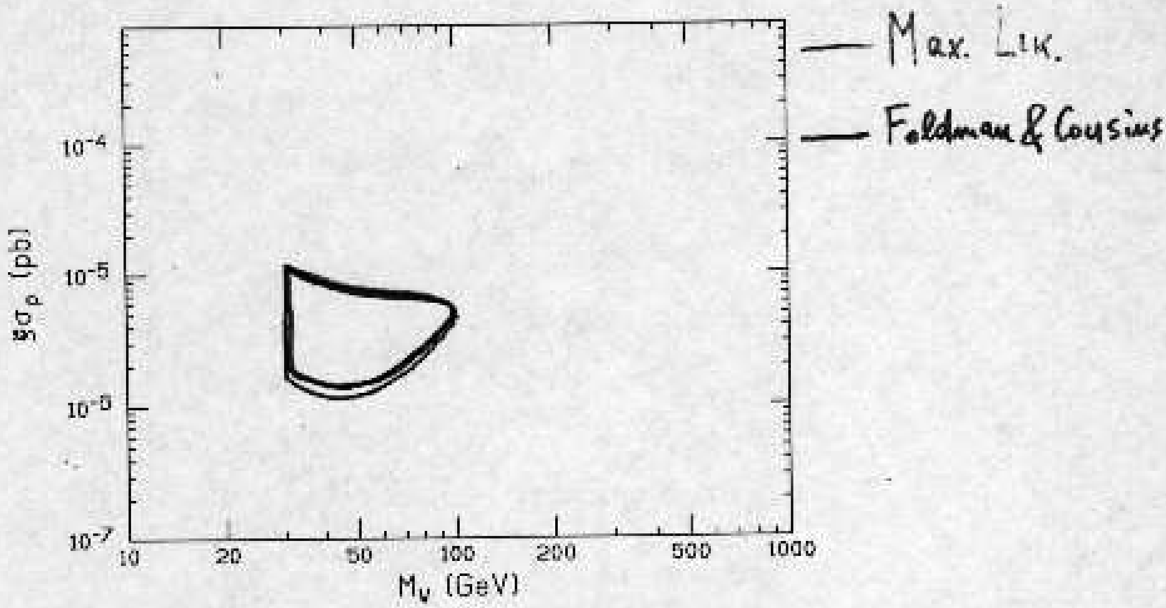
experimental $N_{ijk} \Leftrightarrow \mu_{ijk}$ expected from the model

running period	statistics (kg d)	M_w (GeV)	$\xi\sigma_p$ (pb)	C.L. (m.l.r)
DAMA/NaI-1 to DAMA/NaI-4	57986	52^{+10}_{-8}	$(7.2^{+0.4}_{-0.9})10^{-6}$	4 σ
>>> DAMA/NaI-1 to DAMA/NaI-4 + constraint from DAMA/NaI-0*	57986	44^{+12}_{-9}	$(5.4\pm1.0)10^{-6}$	~ 4 σ <<<<

* **It completely accounts for all the DAMA results on WIMP search: constraint from exclusion plot of DAMA/NaI-0** (PSD)

Result
with the Feldman and Cousins approach
(standard assumptions)
DAMA/NaI-0 to 4

- **Allowed at 3 σ**
- **v_0 = 220 km/s**



$M_W = (43^{+13}_{-9})$ GeV,
$\xi\sigma_p = (5.4 \pm 1.0)\ 10^{-6}$ pb
at ~4 σ C.L.

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

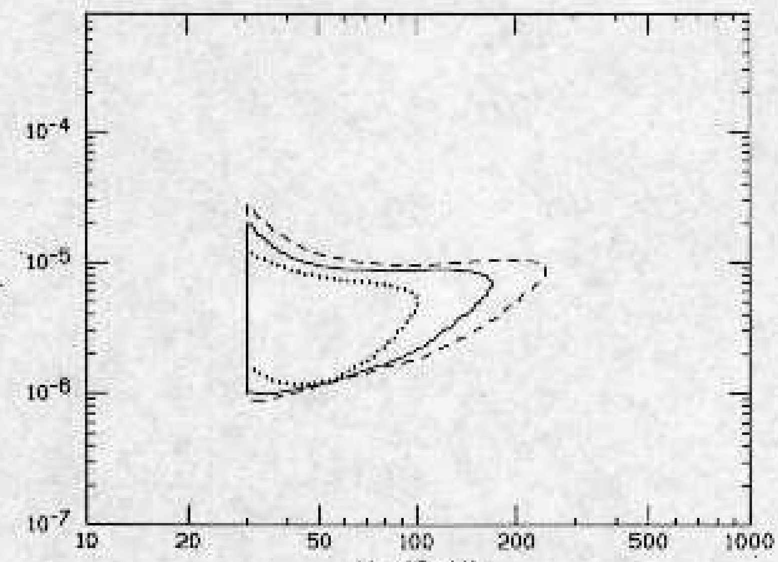
- v_0 = 220 km/s (dotted)
- v_0 = (220±50) km/s (90% C.L.) (continuous)

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

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

- Including possible Dark halo rotation (dashed)

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

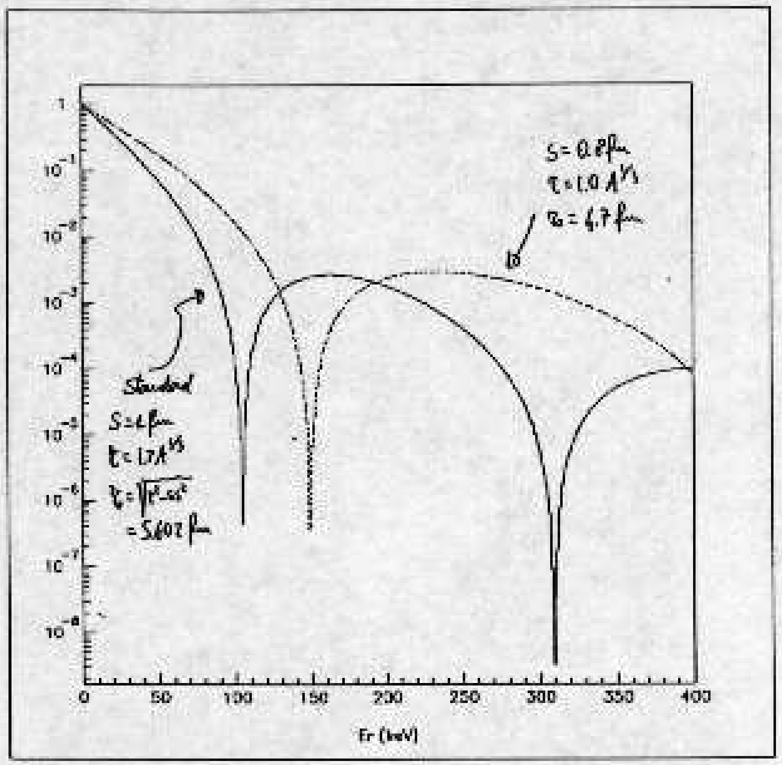


A similar analysis was performed for DAMA/NaI-1&2:

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

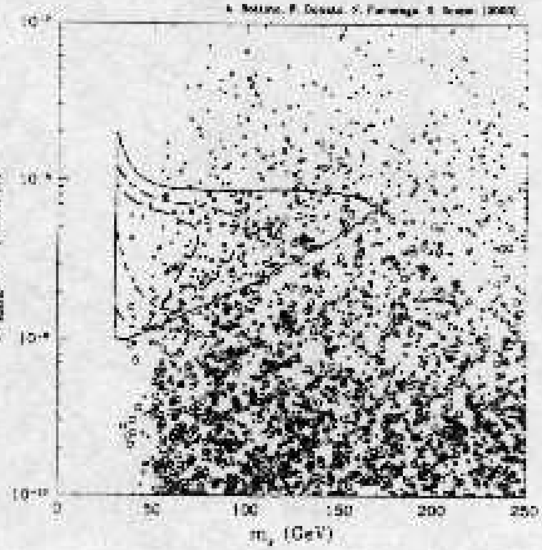
⇓

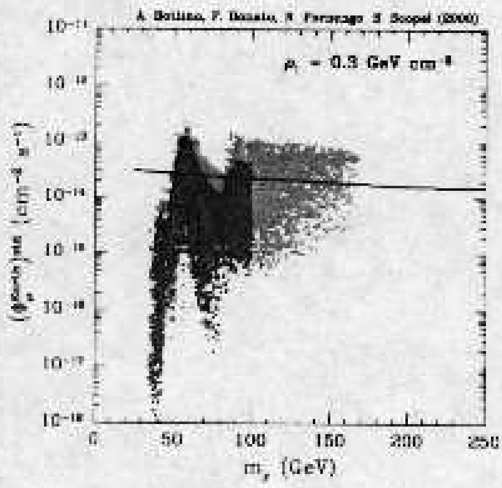
Is a neutralino with mass and cross section in the region presently allowed by DAMA of cosmological interest?

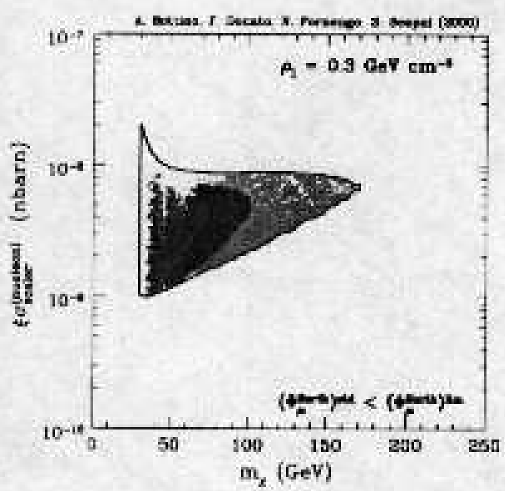
⇒ (from A.Bottino et al.)

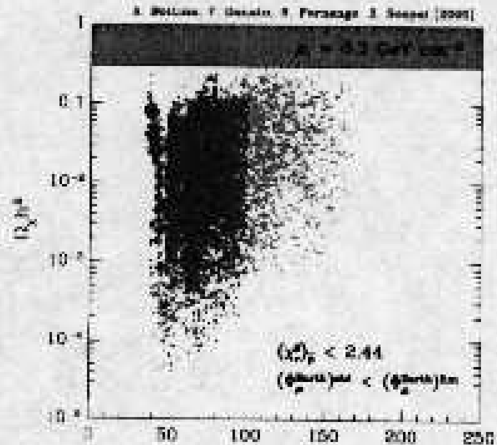
⇒ ⇒ ⇒

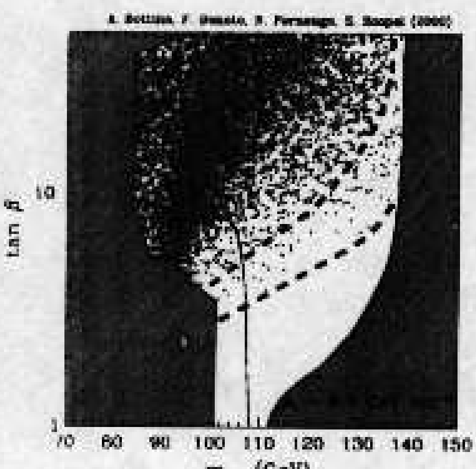
- MSSM
- DIRECT VS INDIRECT SEARCHES
- COSMOLOGICAL ABUNDANCE
- WHAT EXPECTED FROM ACCELERATORS?











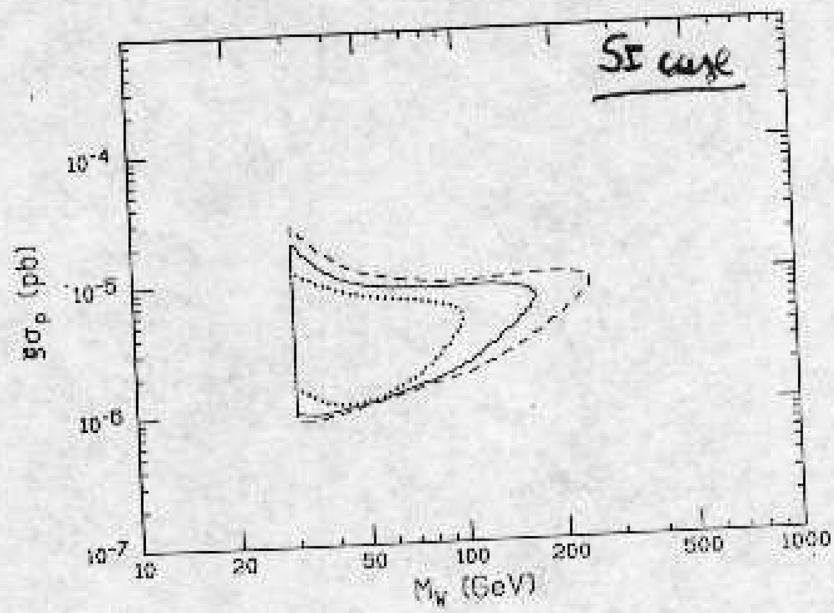
↑ 95% CL REACHABLE AT LEP2 (NO DISCOVERY of neutral HIGGS boson)

A. Bottino et al., hep-ph/0001309

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. a χ in the DAMA allowed region will be of cosmological interest)



investigation on other possible uncertainties on the astrophysical, nuclear and particle physics parameters in progress (e.g. FF)

→ it could enlarge the allowed region.

↓

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

→ wait for more ......