



Results from DAMA/LIBRA Experiment

TAUP 2009

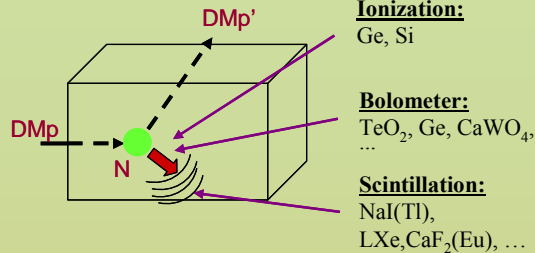
Rome – July 1-5, 2009

P. Belli
INFN-Roma Tor Vergata

Some direct detection processes:

- Scatterings on nuclei

→ detection of nuclear recoil energy



- Inelastic Dark Matter: $\mathbf{W} + \mathbf{N} \rightarrow \mathbf{W}^* + \mathbf{N}$

→ W has Two mass states χ^+ , χ^- with δ mass splitting

→ Kinematical constraint for the inelastic scattering of χ^- on a nucleus

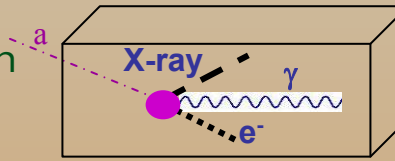
$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

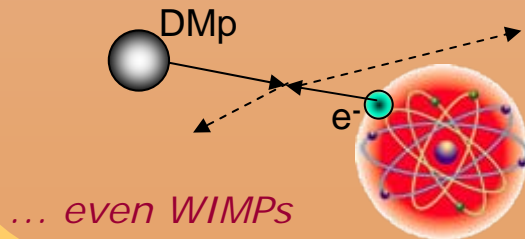
- Conversion of particle into e.m. radiation

→ detection of γ , X-rays, e^-



- Interaction only on atomic electrons

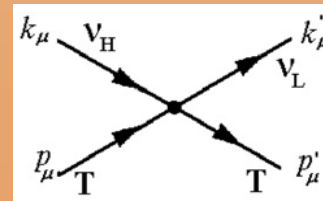
→ detection of e.m. radiation



- Interaction of light DMp (LDM) on e^- or nucleus with production of a lighter particle

→ detection of electron/nucleus recoil energy

e.g. sterile ν



e.g. signals from these candidates are **completely lost** in experiments based on “rejection procedures” of the e.m. component of their rate

... also other ideas ...

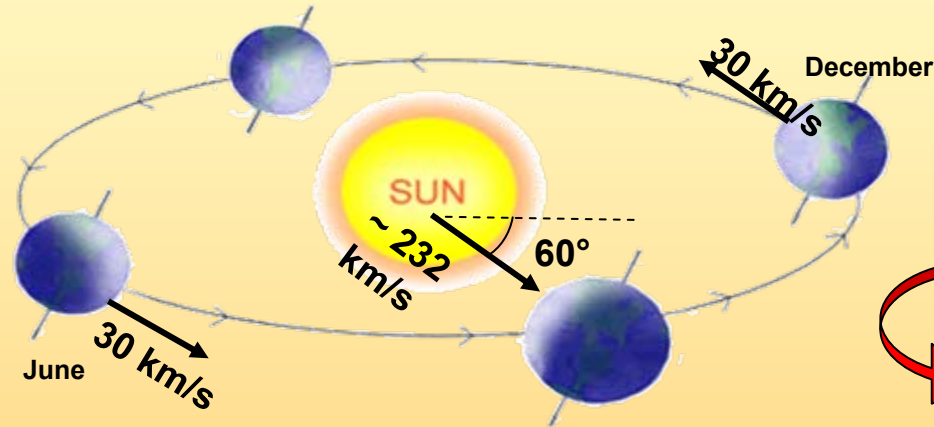
- ... and more

The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

Drukier, Freese, Spergel PRD86
Freese et al. PRD88

- $v_{\text{sun}} \sim 232 \text{ km/s}$ (Sun velocity in the halo)
- $v_{\text{orb}} = 30 \text{ km/s}$ (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ $T = 1 \text{ year}$
- $t_0 = 2^{\text{nd}} \text{ June}$ (when v_{\oplus} is maximum)



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

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

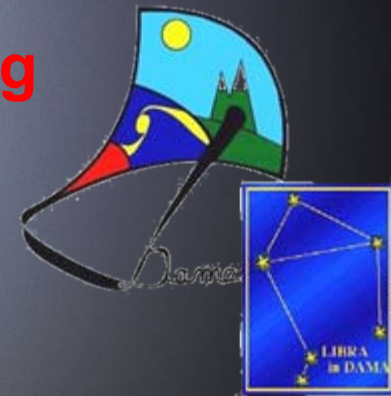
Requirements of the annual modulation

- 1) **Modulated rate according cosine**
- 2) **In a definite low energy range**
- 3) **With a proper period (1 year)**
- 4) **With proper phase (about 2 June)**
- 5) **For single hit events in a multi-detector set-up**
- 6) **With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios**

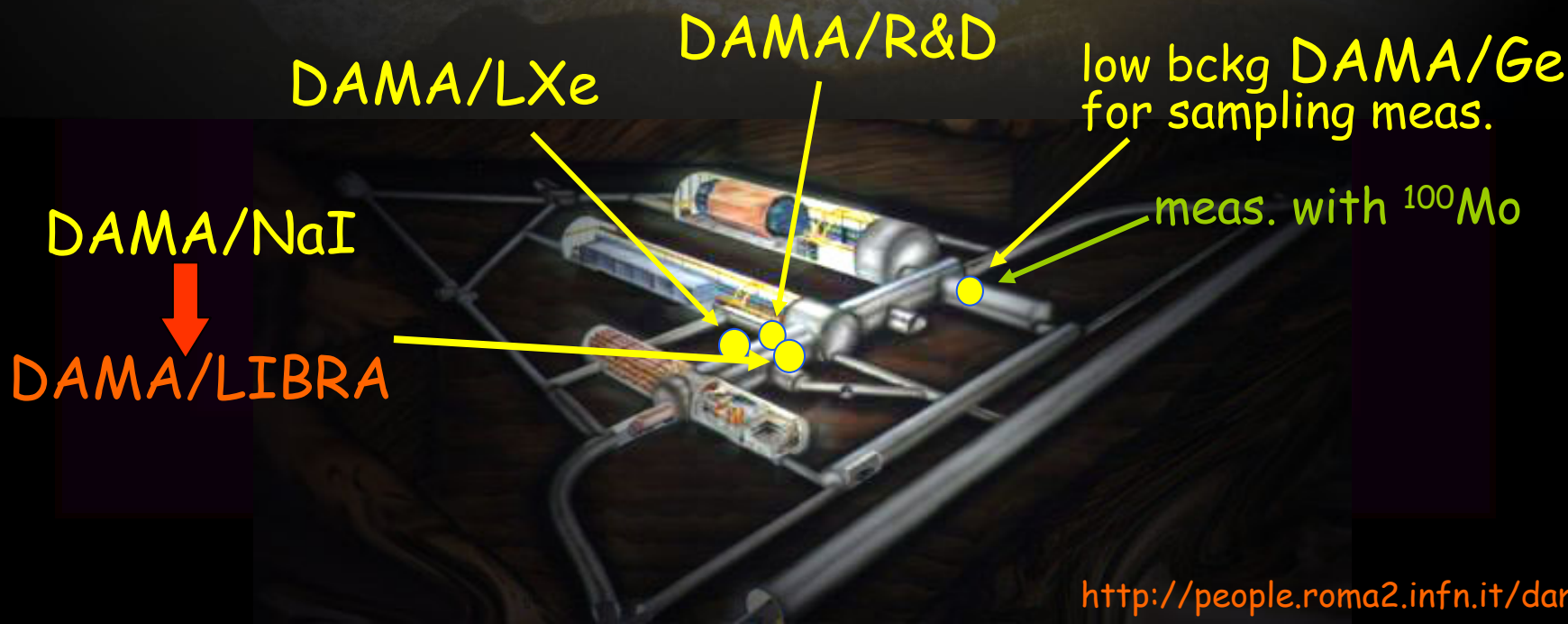
To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Roma2, Roma1, LNGS, IHEP/Beijing

- + by-products and small scale expts.: INR-Kiev
- + neutron meas.: ENEA-Frascati
- + in some studies on $\beta\beta$ decays (DST-MAE project): IIT Kharagpur, India



DAMA: an observatory for rare processes @LNGS



DAMA/NaI : ≈ 100 kg NaI(Tl)

Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283,
Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

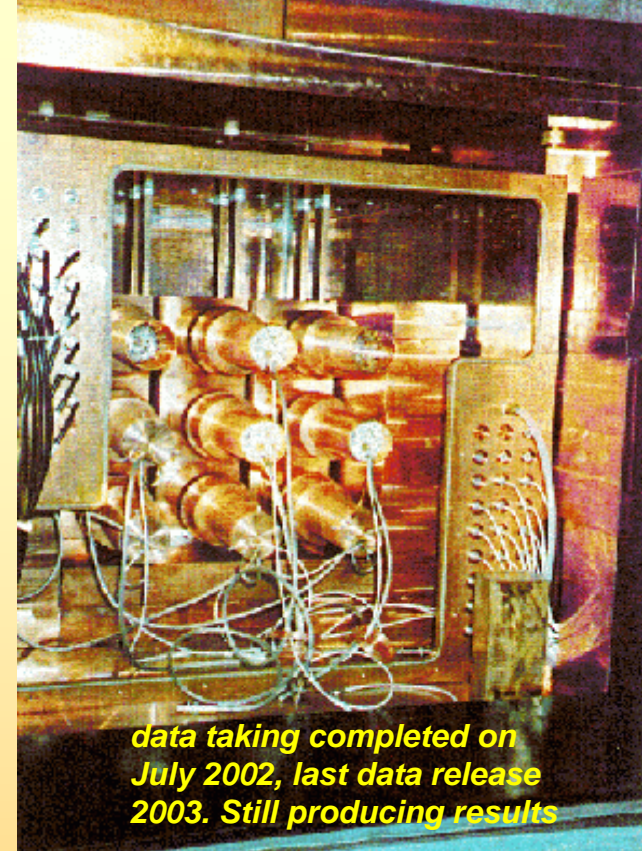
Results on rare processes:

- Possible Pauli exclusion principle violation PLB408(1997)439
- CNC processes PRC60(1999)065501
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) PLB460(1999)235
- Search for solar axions PLB515(2001)6
- Exotic Matter search EPJdirect C14(2002)1
- Search for superdense nuclear matter EPJA23(2005)7
- Search for heavy clusters decays EPJA24(2005)51

Results on DM particles:

- PSD PLB389(1996)757
- Investigation on diurnal effect N.Cim.A112(1999)1541
- Exotic Dark Matter search PRL83(1999)4918
- Annual Modulation Signature

PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283,
PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1,
IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205,
PRD77(2008)023506, MPLA23(2008)2125.



model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

total exposure (7 annual cycles) 0.29 ton x yr

The new DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RARE processes)

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)



installing DAMA/LIBRA detectors



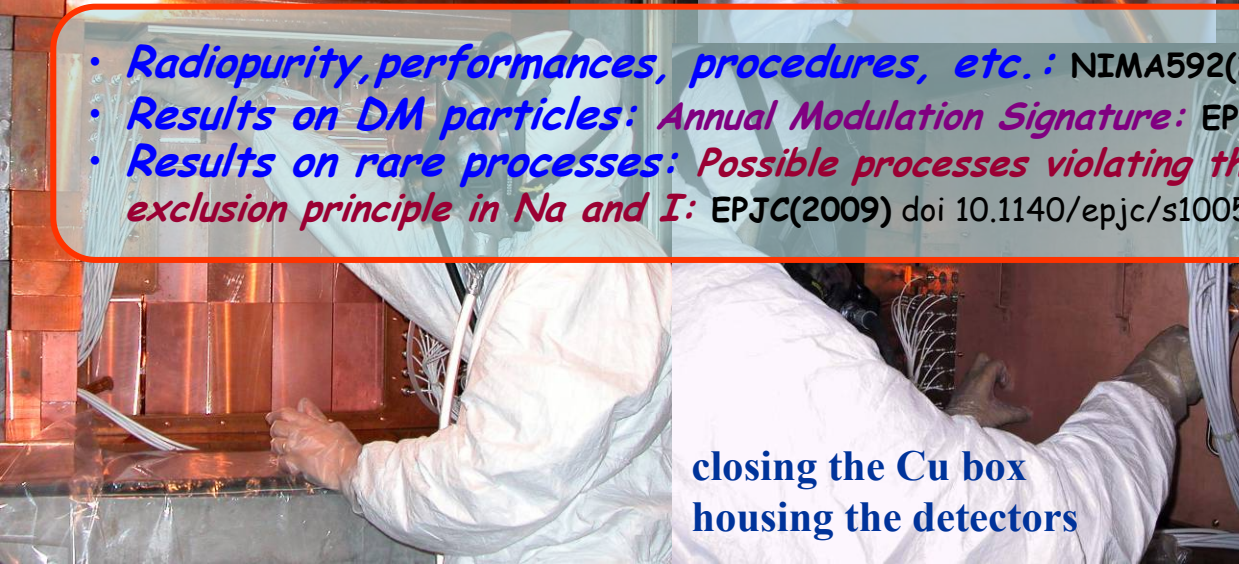
assembling a DAMA/ LIBRA detector

detectors during installation; in the
central and right up detectors the new
shaped Cu shield surrounding light
guides (acting also as optical windows)
and PMTs was not yet applied

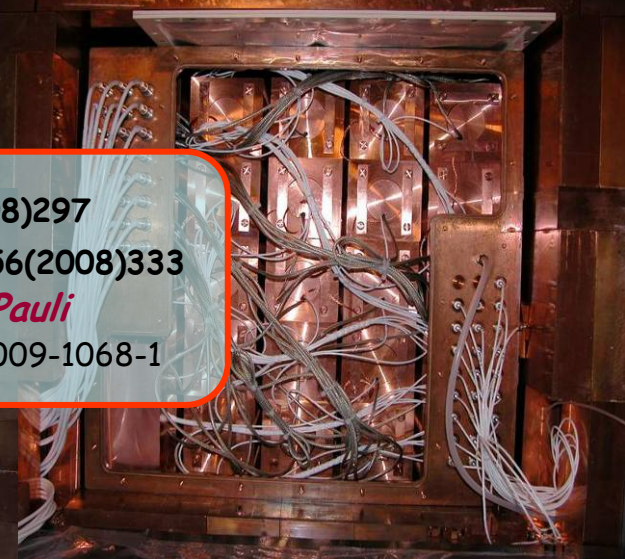


filling the inner Cu box with
further shield

- *Radiopurity, performances, procedures, etc.:* NIMA592(2008)297
- *Results on DM particles: Annual Modulation Signature:* EPJC56(2008)333
- *Results on rare processes: Possible processes violating the Pauli exclusion principle in Na and I:* EPJC(2009) doi 10.1140/epjc/s10052-009-1068-1



closing the Cu box
housing the detectors



view at end of detectors'
installation in the Cu box

DAMA/LIBRA ~250 kg NaI(Tl) **(Large sodium Iodide Bulk for RARE processes)**



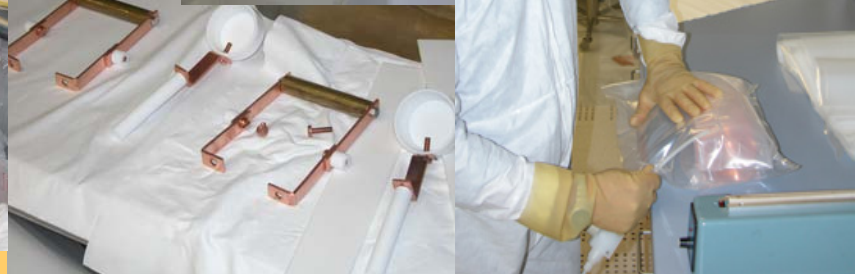
As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)



improving installation
and environment



Cu etching with
super- and ultra-
pure HCl solutions,
dried and sealed in
HP N₂



The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.

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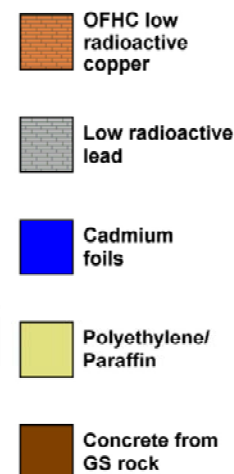
Polyethylene/
paraffin

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold

Installation

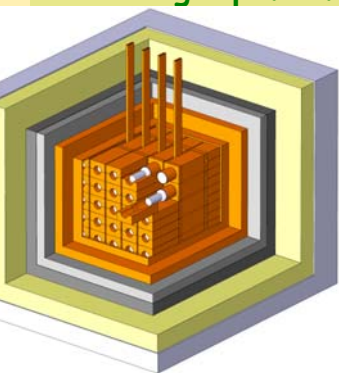
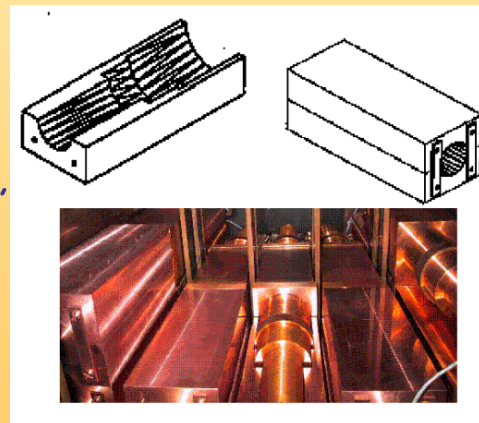
Glove-box for
calibration

Electronics +
DAQ

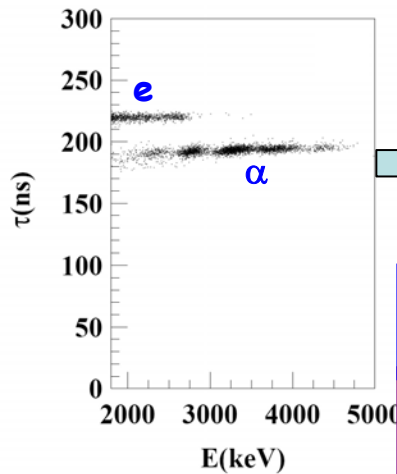


~ 1m concrete from GS rock

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waveform Analyzer TVS641A (2chs per detector), 1 Gsample/s, 8 bit, bandwidth 250 MHz
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy



Some on residual contaminants in new NaI(Tl) detectors



α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens $\alpha/\text{kg/day}$

Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling

^{232}Th residual contamination

From time-amplitude method. If ^{232}Th chain at equilibrium: it ranges from 0.5 ppt to 7.5 ppt

^{238}U residual contamination

First estimate: considering the measured α and ^{232}Th activity, if ^{238}U chain at equilibrium \Rightarrow ^{238}U contents in new detectors typically range from 0.7 to 10 ppt

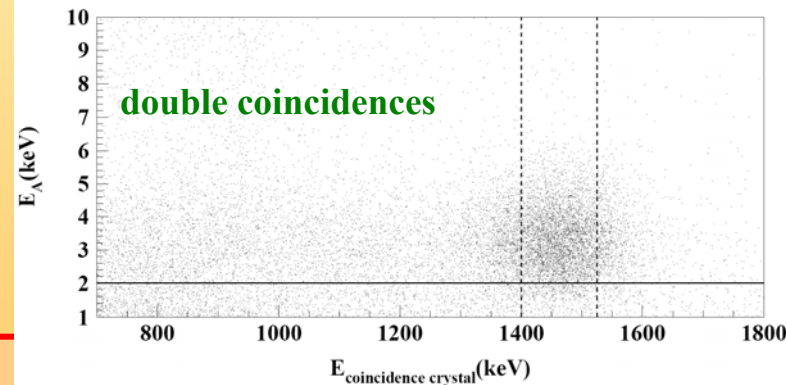
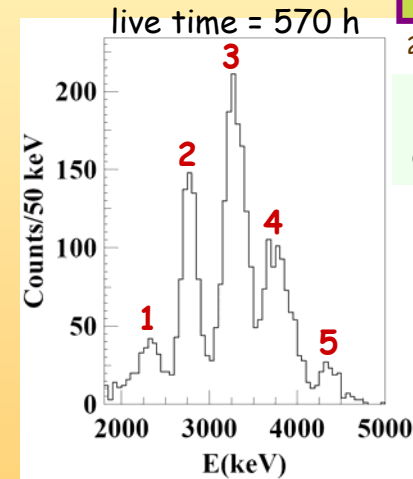
^{238}U chain splitted into 5 subchains: $^{238}\text{U} \rightarrow ^{234}\text{U} \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \rightarrow ^{210}\text{Pb} \rightarrow ^{206}\text{Pb}$

Thus, in this case: (2.1 ± 0.1) ppt of ^{232}Th ; (0.35 ± 0.06) ppt for ^{238}U

and: $(15.8 \pm 1.6) \mu\text{Bq/kg}$ for $^{234}\text{U} + ^{230}\text{Th}$; $(21.7 \pm 1.1) \mu\text{Bq/kg}$ for ^{226}Ra ; $(24.2 \pm 1.6) \mu\text{Bq/kg}$ for ^{210}Pb .

$^{\text{nat}}\text{K}$ residual contamination

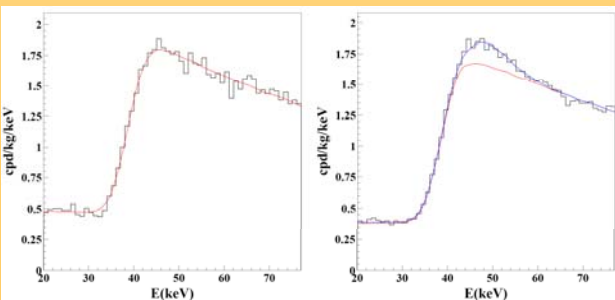
The analysis has given for the $^{\text{nat}}\text{K}$ content in the crystals values not exceeding about 20 ppb



^{129}I and ^{210}Pb

$^{129}\text{I}/^{\text{nat}}\text{I} \approx 1.7 \times 10^{-13}$ for all the new detectors

^{210}Pb in the new detectors: $(5 - 30) \mu\text{Bq/kg}$.

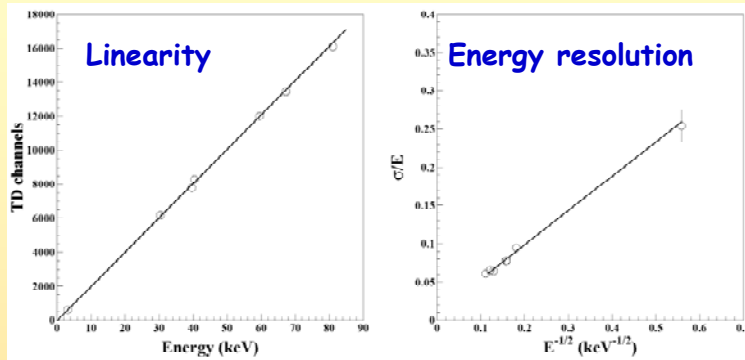


No sizeable surface pollution by Radon daughters, thanks to the new handling protocols

... more on
NIMA592(2008)297

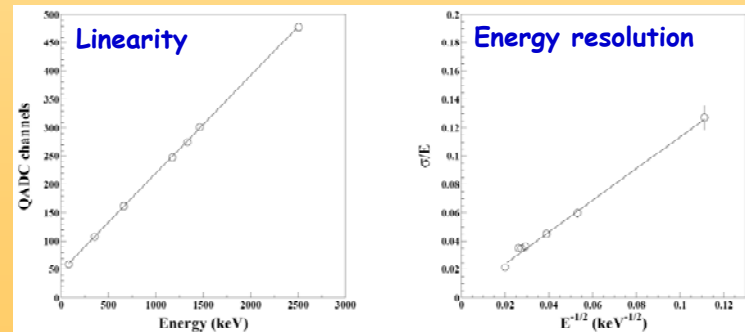
DAMA/LIBRA calibrations

Low energy: various external gamma sources (^{241}Am , ^{133}Ba) and internal X-rays or gamma's (^{40}K , ^{125}I , ^{129}I), routine calibrations with ^{241}Am



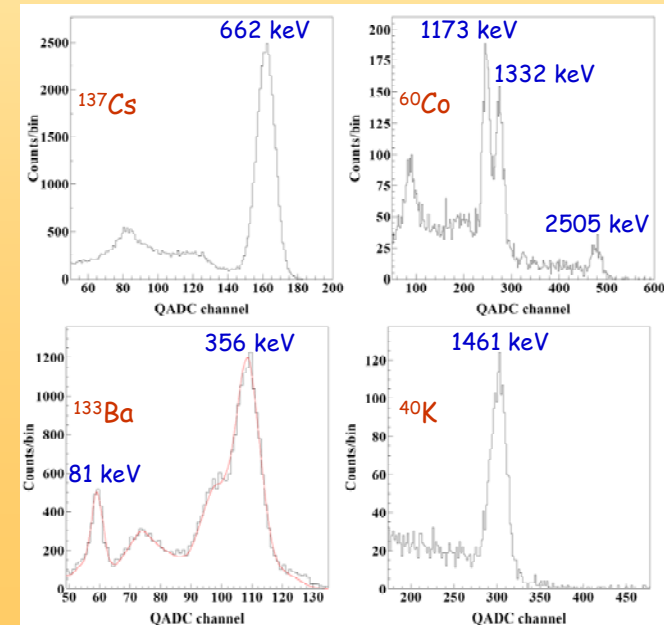
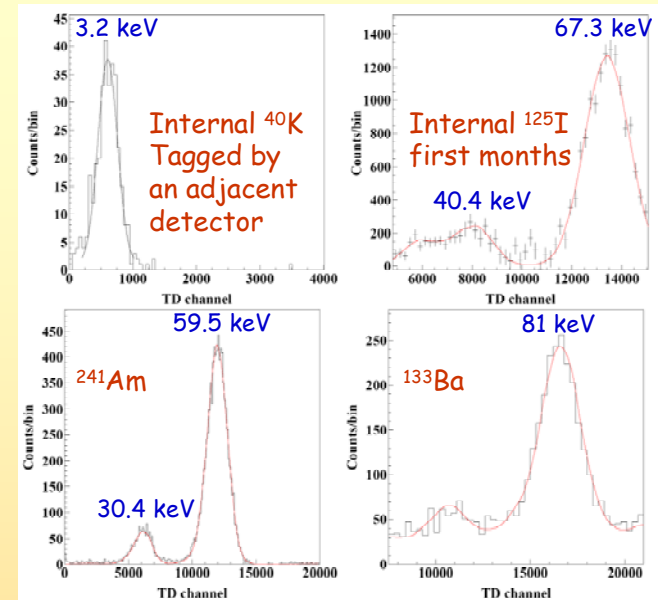
$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(\text{keV})}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

High energy: external sources of gamma rays (e.g. ^{137}Cs , ^{60}Co and ^{133}Ba) and gamma rays of 1461 keV due to ^{40}K decays in an adjacent detector, tagged by the 3.2 keV X-rays



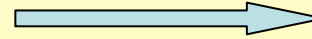
$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(\text{keV})}} + (17 \pm 23) \cdot 10^{-4}$$

The signals (unlike low energy events) for high energy events are taken only from one PMT

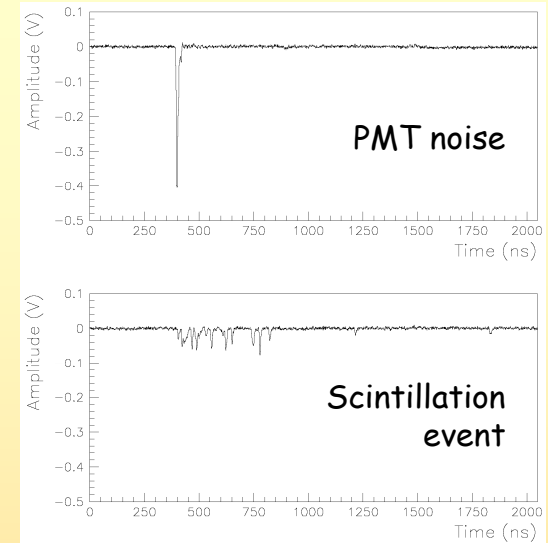


Noise rejection near the energy threshold

Typical pulse profiles of PMT noise and of scintillation event with the same area, just above the energy threshold of 2 keV



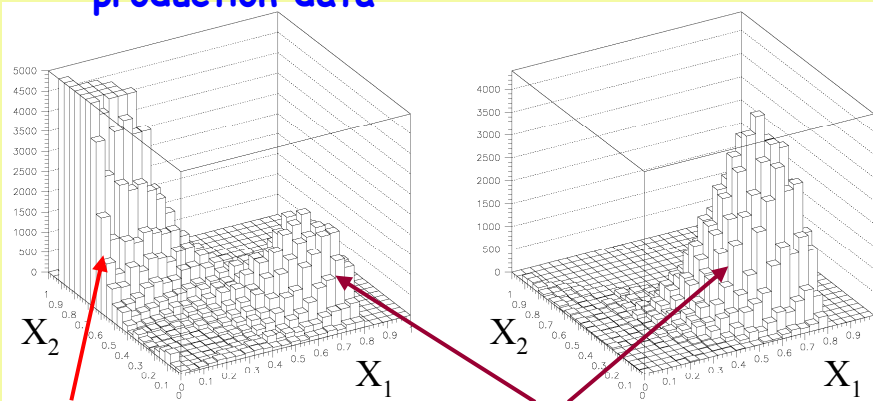
The different time characteristics of PMT noise (decay time of order of tens of ns) and of scintillation event (decay time about 240 ns) can be investigated building several variables



Single-hit
production data

γ source

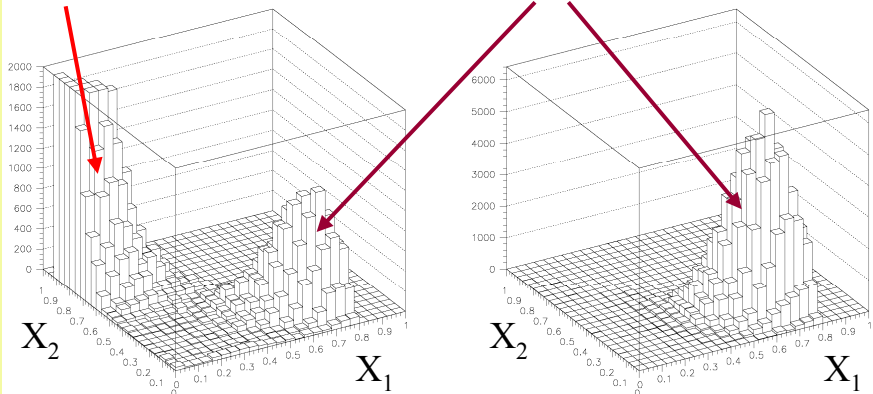
2-4 keV



PMT noise

Scintillation pulses

4-6 keV



From the Waveform Analyser
2048 ns time window:

$$X_1 = \frac{\text{Area (from 100 ns to 600 ns)}}{\text{Area (from 0 ns to 600 ns)}};$$

$$X_2 = \frac{\text{Area (from 0 ns to 50 ns)}}{\text{Area (from 0 ns to 600 ns)}}$$

- The separation between noise and scintillation pulses is very good.
- Very clean samples of scintillation events selected by stringent acceptance windows.
- The related efficiencies evaluated by calibrations with ^{241}Am sources of suitable activity in the same experimental conditions and energy range as the production data (efficiency measurements performed each ~10 days; typically 10^4 - 10^5 events per keV collected)

This is the only procedure
applied to the analysed data

Infos about DAMA/LIBRA data taking

EPJC56(2008)333

DAMA/LIBRA test runs: from March 2003 to September 2003

DAMA/LIBRA normal operation: from September 2003 to August 2004

High energy runs for TDs: September 2004
to allow internal α 's identification
(approximative exposure $\approx 5000 \text{ kg} \times \text{d}$)

DAMA/LIBRA normal operation: from October 2004

Data released here:

- four annual cycles: $0.53 \text{ ton} \times \text{yr}$
- calibrations: acquired $\approx 44 \text{ M}$ events from sources
- acceptance window eff: acquired $\approx 2 \text{ M}$ events/keV

Period		Exposure (kg \times day)	$\alpha - \beta^2$
DAMA/LIBRA-1	Sept. 9, 2003 - July 21, 2004	51405	0.562
DAMA/LIBRA-2	July 21, 2004 - Oct. 28, 2005	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 - July 18, 2006	39445	0.591
DAMA/LIBRA-4	July 19, 2006 - July 17, 2007	49377	0.541
Total		192824 $\simeq 0.53 \text{ ton} \times \text{yr}$	0.537

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

total exposure: $300555 \text{ kg} \times \text{day} = 0.82 \text{ ton} \times \text{yr}$

Two remarks:

- One PMT problems after 6 months. Detector out of trigger since Sep. 2003 (since Sept. 2008 again in operation)
- Residual cosmogenic ^{125}I presence in the first year in some detectors (this motivates the Sept. 2003 as starting time)

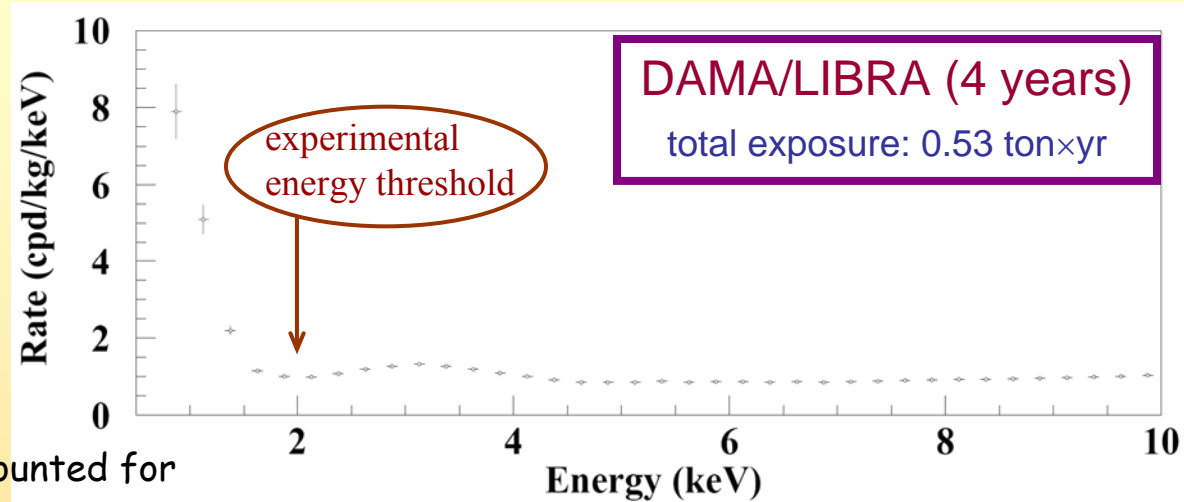
**DAMA/LIBRA is
continuously running**

Cumulative low-energy distribution of the *single-hit* scintillation events

Single-hit events = each detector has all the others as anticoincidence

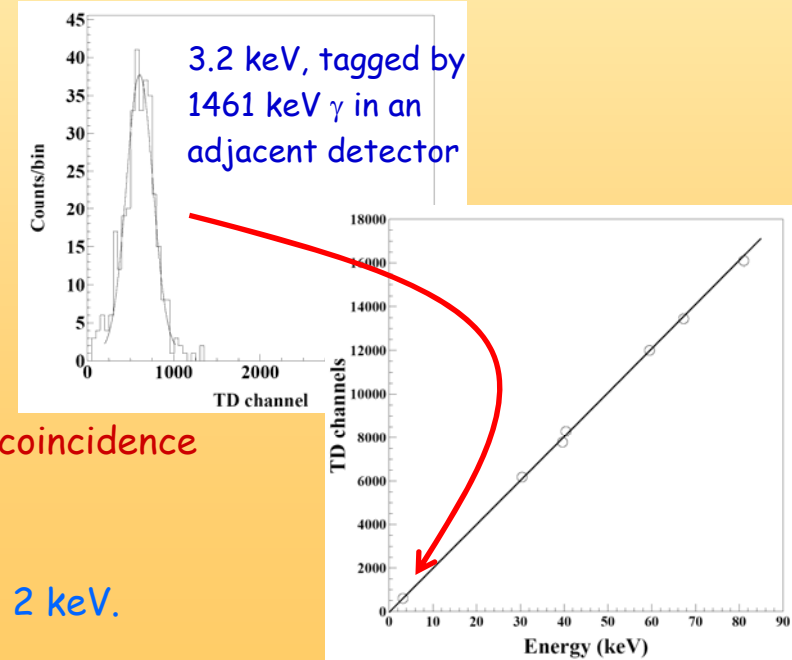
(Obviously differences among detectors are present depending e.g. on each specific level and location of residual contaminants, on the detector's location in the 5x5 matrix, etc.)

Efficiencies already accounted for



About the energy threshold:

- The DAMA/LIBRA detectors have been calibrated down to the keV region. This assures a clear knowledge of the "physical" energy threshold of the experiment.
- It obviously profits of the relatively high number of available photoelectrons/keV (from 5.5 to 7.5).
- The two PMTs of each detector in DAMA/LIBRA work in coincidence with hardware threshold at single photoelectron level.
- Effective near-threshold-noise full rejection.
- The software energy threshold used by the experiment is 2 keV.



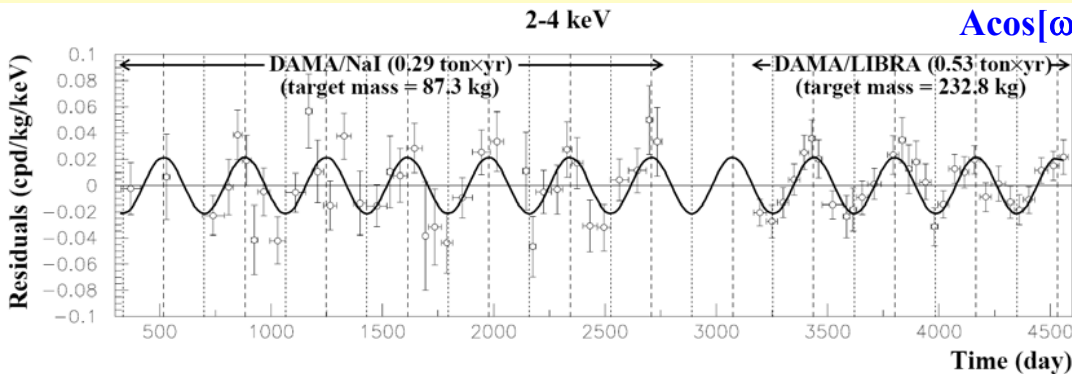
Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) Total exposure: 300555 kg×day = 0.82 ton×yr

EPJC56(2008)333

experimental single-hit residuals rate vs time and energy

$\text{Acos}[\omega(t-t_0)]$; continuous lines: $t_0 = 152.5$ d, $T = 1.00$ y



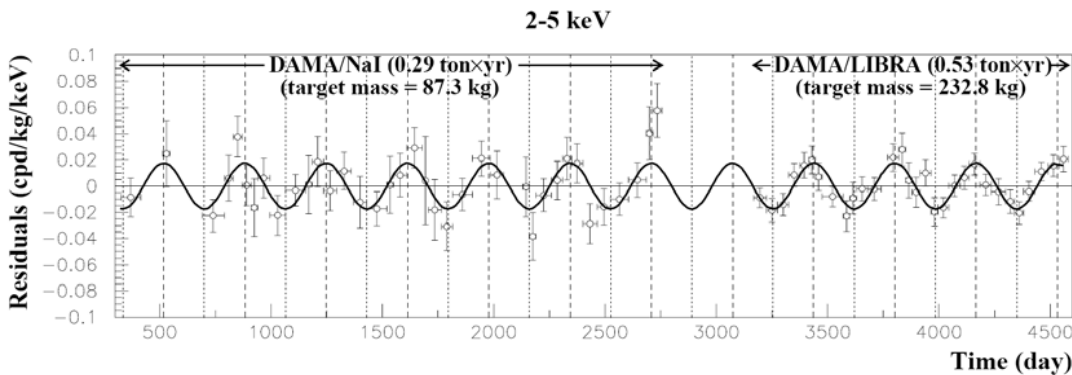
2-4 keV

$A = (0.0215 \pm 0.0026)$ cpd/kg/keV

$\chi^2/\text{dof} = 51.9/66$ **8.3 σ C.L.**

Absence of modulation? No

$\chi^2/\text{dof} = 117.7/67 \Rightarrow P(A=0) = 1.3 \times 10^{-4}$



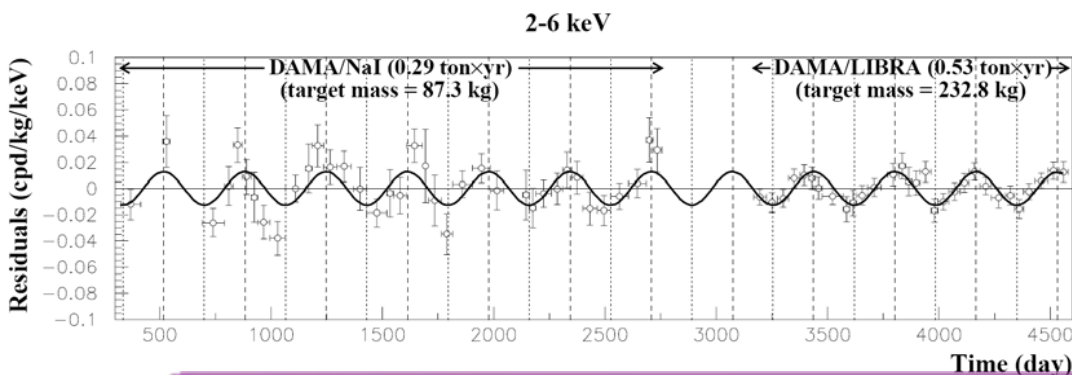
2-5 keV

$A = (0.0176 \pm 0.0020)$ cpd/kg/keV

$\chi^2/\text{dof} = 39.6/66$ **8.8 σ C.L.**

Absence of modulation? No

$\chi^2/\text{dof} = 116.1/67 \Rightarrow P(A=0) = 1.9 \times 10^{-4}$



2-6 keV

$A = (0.0129 \pm 0.0016)$ cpd/kg/keV

$\chi^2/\text{dof} = 54.3/66$ **8.2 σ C.L.**

Absence of modulation? No

$\chi^2/\text{dof} = 116.4/67 \Rightarrow P(A=0) = 1.8 \times 10^{-4}$

The data favor the presence of a modulated behavior with proper features at 8.2 σ C.L.

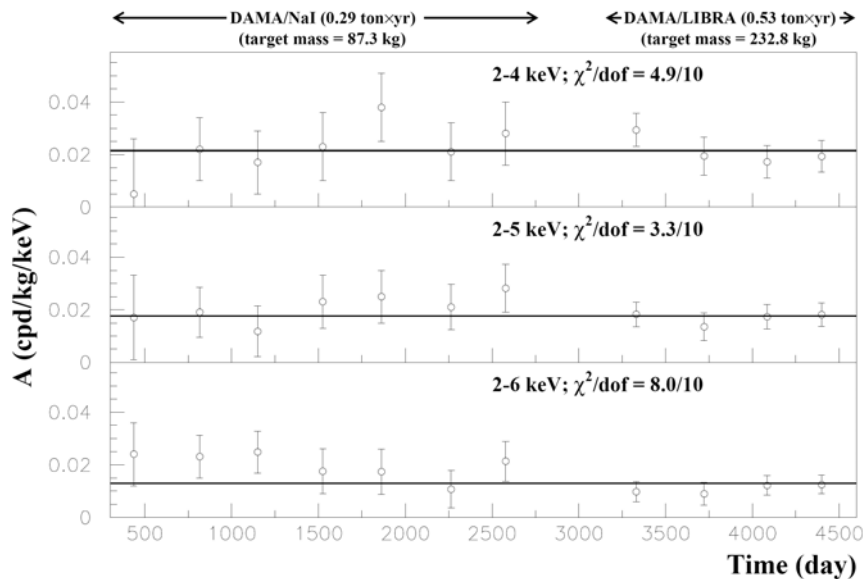
Model-independent residual rate for single-hit events

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) total exposure: 300555 kg×day = 0.82 ton×yr

Results of the fits keeping the parameters free:

Modulation amplitudes, A , of single year measured in the 11 one-year experiments of DAMA (NaI + LIBRA)

	A (cpd/kg/keV)	$T = 2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI (7 years)				
(2÷4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2÷5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2÷6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA (4 years)				
(2÷4) keV	0.0213 ± 0.0032	0.997 ± 0.002	139 ± 10	6.7σ
(2÷5) keV	0.0165 ± 0.0024	0.998 ± 0.002	143 ± 9	6.9σ
(2÷6) keV	0.0107 ± 0.0019	0.998 ± 0.003	144 ± 11	5.6σ
DAMA/NaI + DAMA/LIBRA				
(2÷4) keV	0.0223 ± 0.0027	0.996 ± 0.002	138 ± 7	8.3σ
(2÷5) keV	0.0178 ± 0.0020	0.998 ± 0.002	145 ± 7	8.9σ
(2÷6) keV	0.0131 ± 0.0016	0.998 ± 0.003	144 ± 8	8.2σ



- The modulation amplitudes for the (2 – 6) keV energy interval, obtained when fixing exactly the period at 1 yr and the phase at 152.5 days, are: (0.019 ± 0.003) cpd/kg/keV for DAMA/NaI and (0.011 ± 0.002) cpd/kg/keV for DAMA/LIBRA.
- Thus, their difference: (0.008 ± 0.004) cpd/kg/keV is $\approx 2\sigma$ which corresponds to a modest, but non negligible probability.

χ^2 test ($\chi^2/\text{dof} = 4.9/10, 3.3/10$ and $8.0/10$) and **run test** (lower tail probabilities of 74%, 61% and 11%) **accept at 90% C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.**

Compatibility among the annual cycles

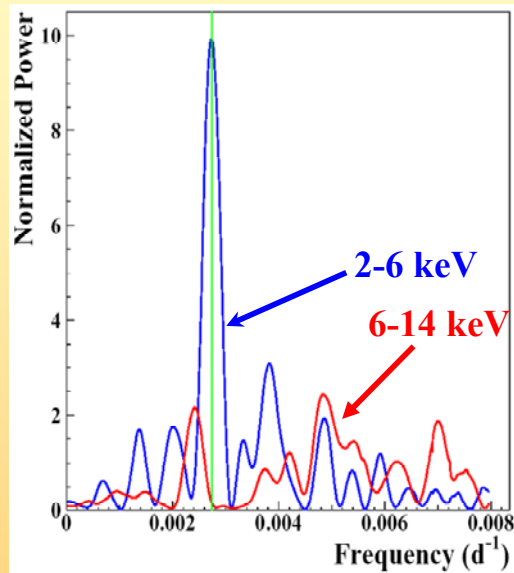
Power spectrum of single-hit residuals

(according to Ap.J.263(1982)835; Ap.J.338(1989)277)

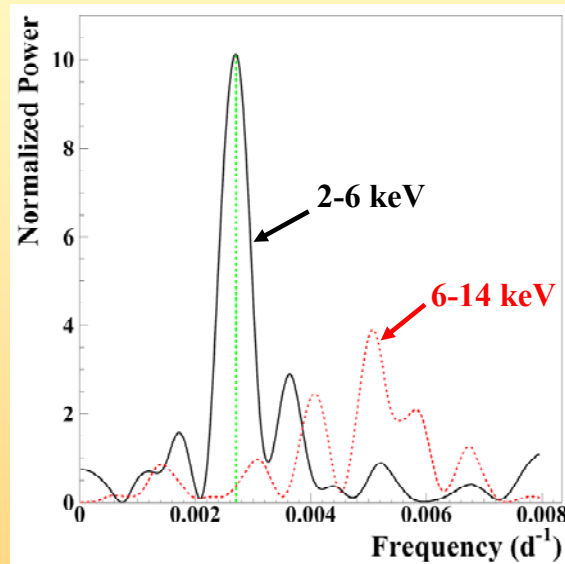
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

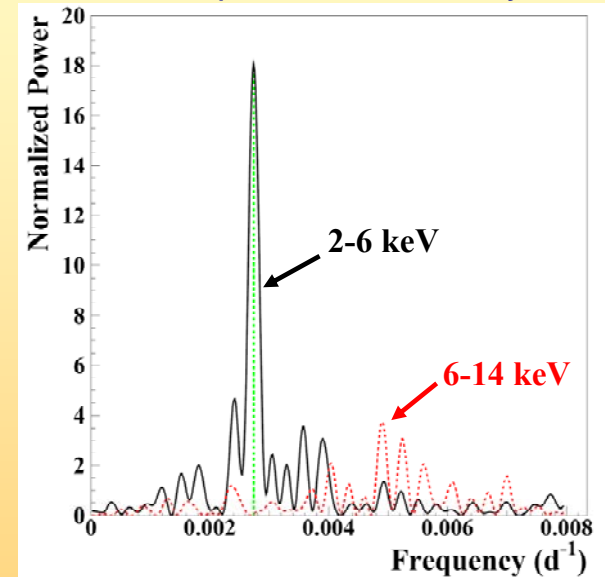
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



DAMA/LIBRA (4 years)
total exposure: 0.53 ton×yr



DAMA/NaI (7 years) +
DAMA/LIBRA (4 years)
total exposure: 0.82 ton×yr



Principal mode in the 2-6 keV region:

DAMA/NaI
 $2.737 \cdot 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}$

DAMA/LIBRA
 $2.705 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$

DAMA/NaI+LIBRA
 $2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$

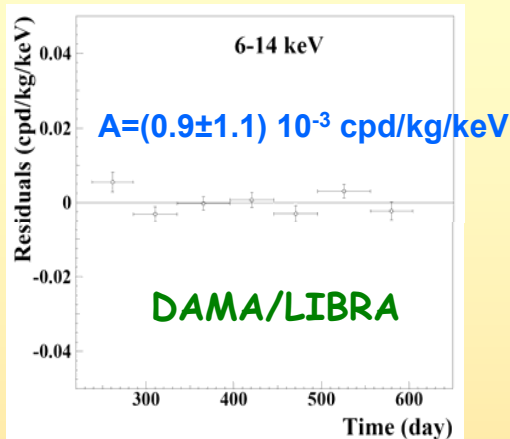
+

Not present in the 6-14 keV region (only aliasing peaks)

Clear annual modulation is evident in (2-6) keV while it is absence just above 6 keV

Can a hypothetical background modulation account for the observed effect?

• No Modulation above 6 keV



Mod. Ampl. (6-10 keV): cpd/kg/keV

- (0.0016 ± 0.0031) DAMA/LIBRA-1
- $-(0.0010 \pm 0.0034)$ DAMA/LIBRA-2
- $-(0.0001 \pm 0.0031)$ DAMA/LIBRA-3
- $-(0.0006 \pm 0.0029)$ DAMA/LIBRA-4

→ statistically consistent with zero

In the same energy region where the effect is observed: no modulation of the multiple-hits events (see next slide)

• No modulation in the whole spectrum:

studying integral rate at higher energy, R90

- R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA-1,2,3,4 running periods

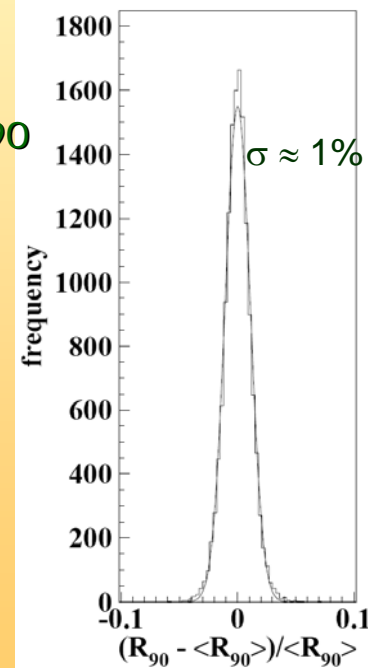
→ cumulative gaussian behaviour with $\sigma \approx 1\%$, fully accounted by statistical considerations

- Fitting the behaviour with time, adding a term modulated according period and phase expected for Dark Matter particles:

consistent with zero

Period	Mod. Ampl.
DAMA/LIBRA-1	$-(0.05 \pm 0.19) \text{ cpd/kg}$
DAMA/LIBRA-2	$-(0.12 \pm 0.19) \text{ cpd/kg}$
DAMA/LIBRA-3	$-(0.13 \pm 0.18) \text{ cpd/kg}$
DAMA/LIBRA-4	$(0.15 \pm 0.17) \text{ cpd/kg}$

+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → $R_{90} \sim \text{tens cpd/kg}$ → $\sim 100 \sigma$ far away



No modulation in the background:
these results account for all sources of bckg (+ see later)

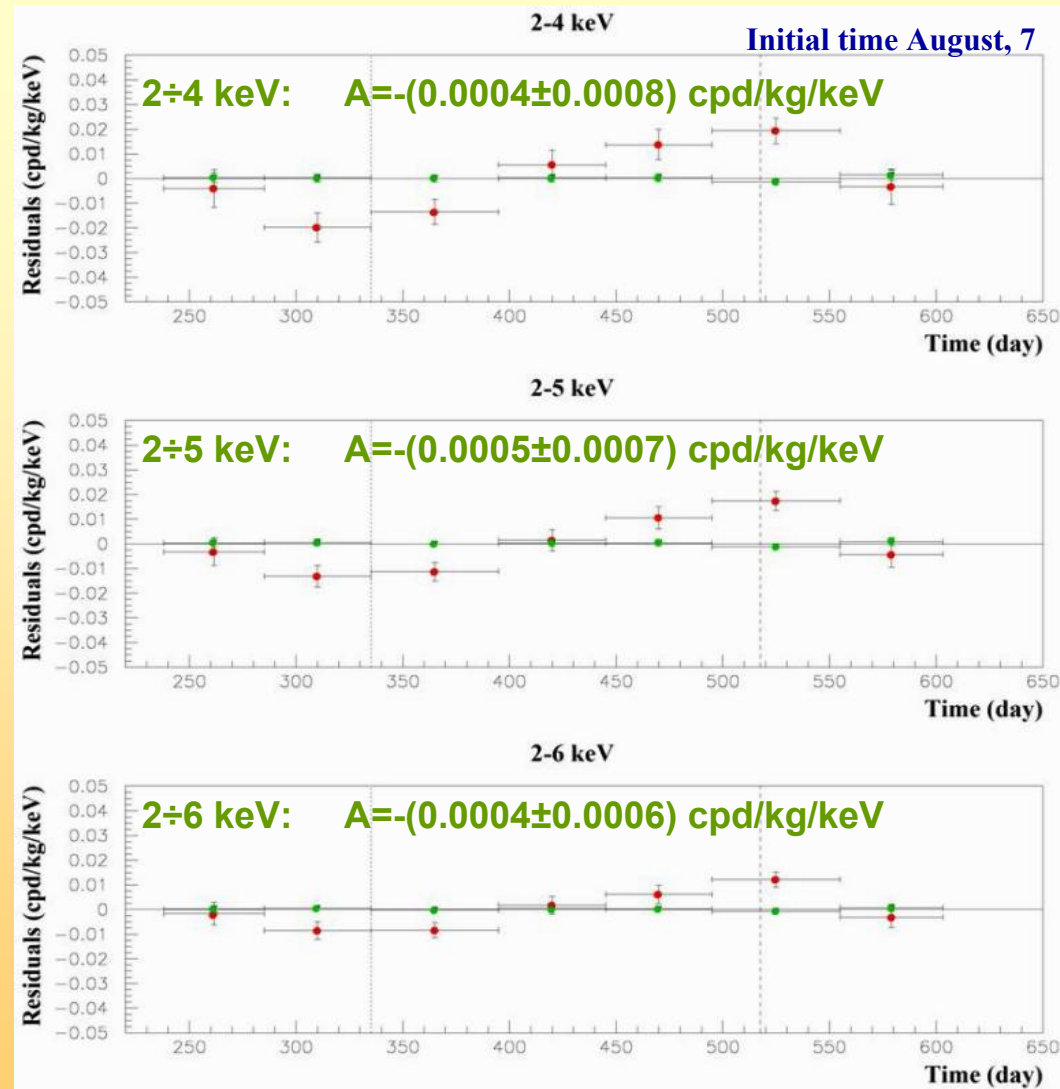
Multiple-hits events in the region of the signal - DAMA/LIBRA 1-4

- Each detector has its own TDs read-out
→ pulse profiles of multiple-hits events (multiplicity > 1) acquired (exposure: 0.53 ton×yr).
- The same hardware and software procedures as the ones followed for single-hit events

signals by Dark Matter particles
do not belong to multiple-hits
events, that is:

multiple-hits events = Dark Matter particles events "switched off"

Evidence of annual modulation with proper features as required by the DM annual modulation signature is present in the *single-hit* residuals, while it is absent in the *multiple-hits* residual rate.



This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

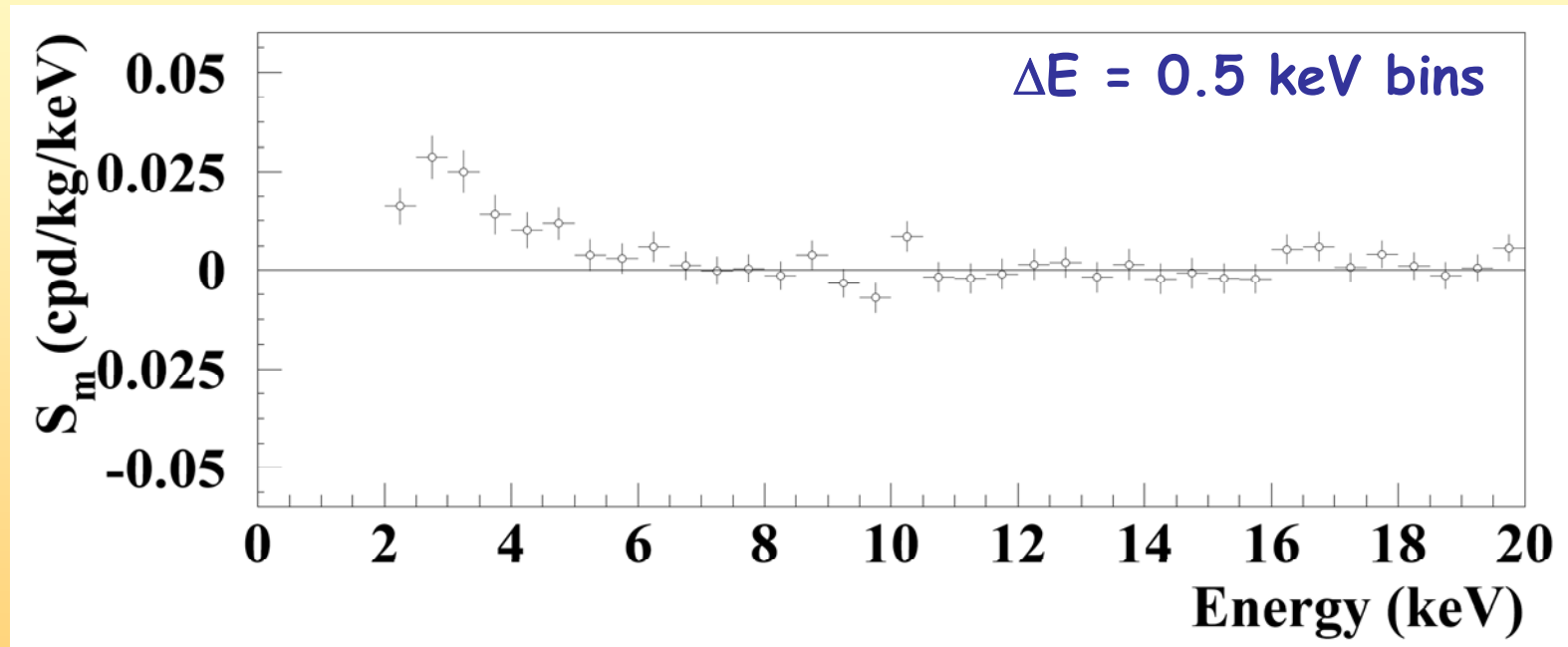
Energy distribution of the modulation amplitudes, S_m , for the total exposure

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

total exposure: 300555 kg×day = 0.82 ton×yr

here $T=2\pi/\omega=1$ yr and $t_0=152.5$ day



A clear modulation is present in the (2-6) keV energy interval, while S_m values compatible with zero are present just above

In fact, the S_m values in the (6-20) keV energy interval have random fluctuations around zero with χ^2 equal to 24.4 for 28 degrees of freedom

Statistical distributions of the modulation amplitudes (S_m)

a) S_m values for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

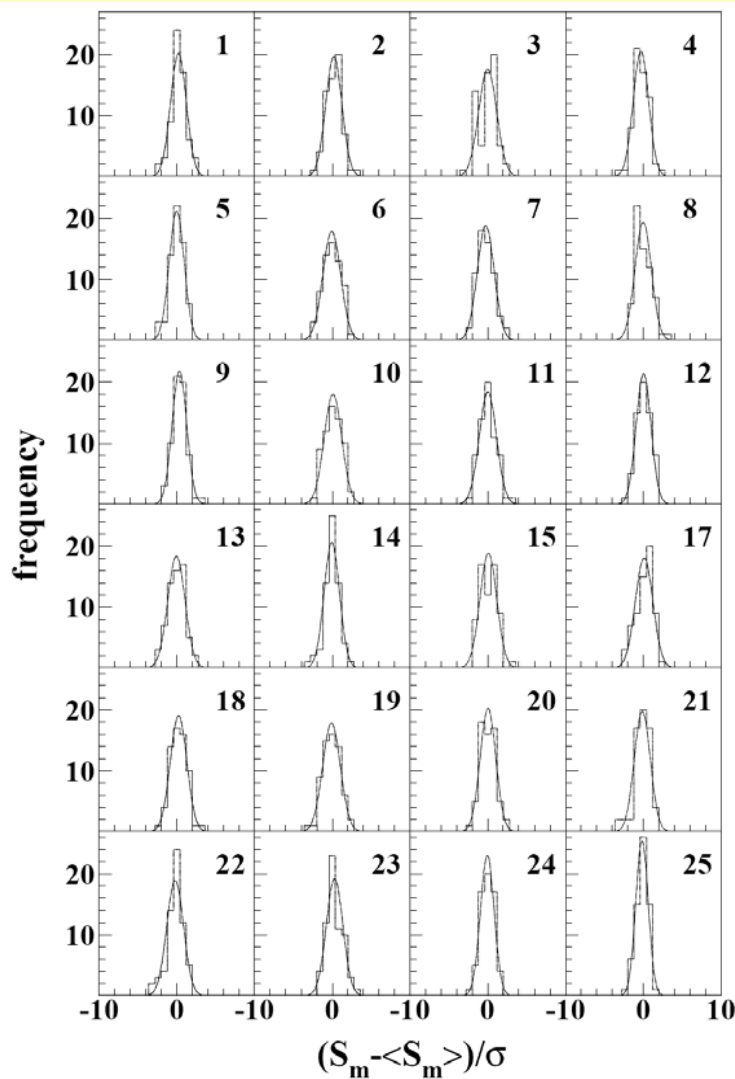
b) $\langle S_m \rangle$ = mean values over the detectors and the annual cycles for each energy bin; σ = errors associated to each S_m

DAMA/LIBRA (4 years)

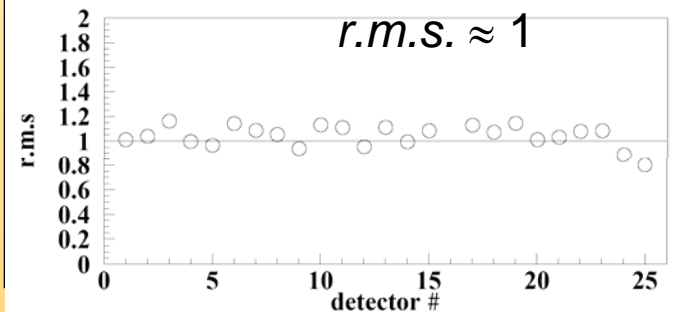
total exposure: 0.53 ton \times yr

Each panel refers to each detector separately; 64 entries = 16 energy bins in 2-6 keV energy interval \times 4 DAMA/LIBRA annual cycles

2-6 keV



Standard deviations of the variable
 $(S_m - \langle S_m \rangle) / \sigma$
 for the DAMA/LIBRA detectors



$r.m.s. \approx 1$

$0.80 < r.m.s. < 1.16$

Individual S_m values follow a normal distribution since $(S_m - \langle S_m \rangle) / \sigma$ is distributed as a Gaussian with a unitary standard deviation (r.m.s.)



S_m statistically well distributed in all the detectors and annual cycles

Statistical analyses about modulation amplitudes (S_m)

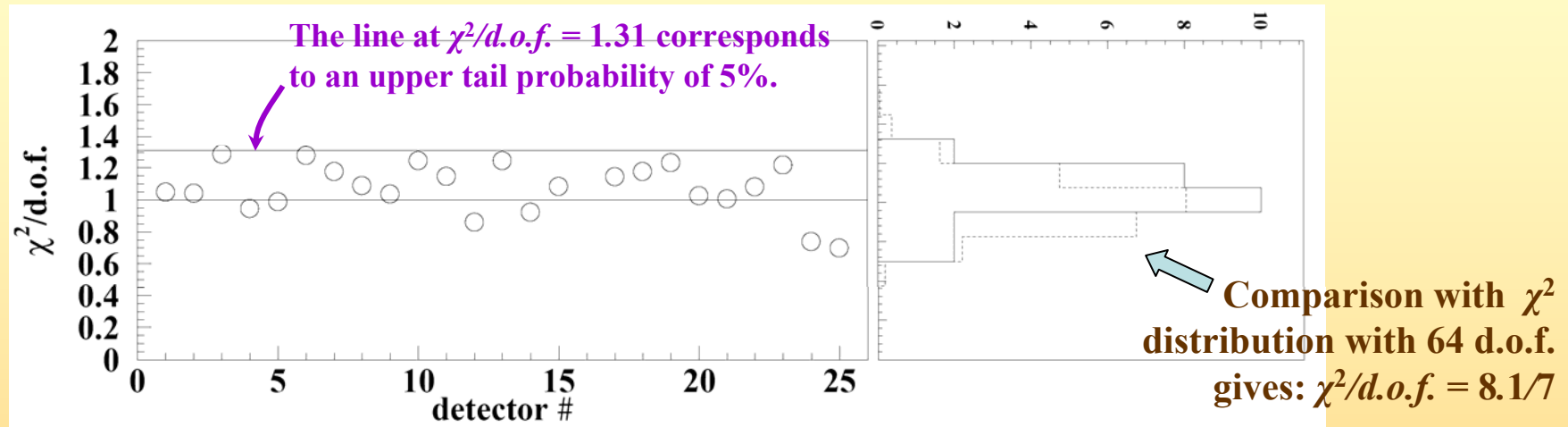
$$x = (S_m - \langle S_m \rangle) / \sigma,$$

$$\chi^2 = \sum x^2$$

$\chi^2/d.o.f.$ values of S_m distributions for each DAMA/LIBRA detector in the (2–6) keV energy interval for the four annual cycles.

DAMA/LIBRA (4 years)

total exposure: 0.53 ton×yr



The $\chi^2/d.o.f.$ values range from 0.7 to 1.28 (64 d.o.f. = 16 energy bins \times 4 annual cycles)
 \Rightarrow at 95% C.L. the observed annual modulation effect is well distributed in all the detectors.

- The mean value of the twenty-four points is 1.072, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 5 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 7 \times 10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error ($\leq 4.7\%$ or $\leq 0.7\%$, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

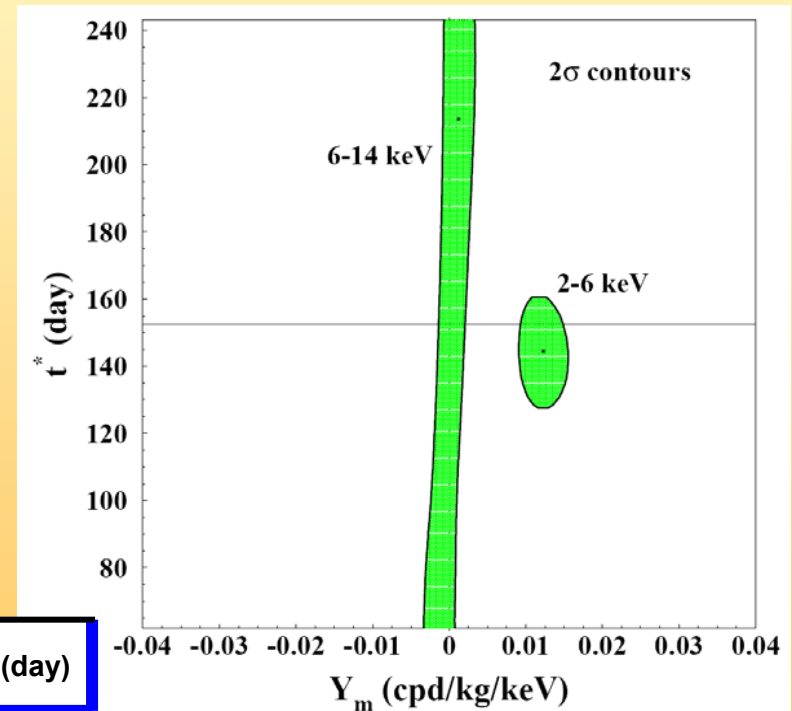
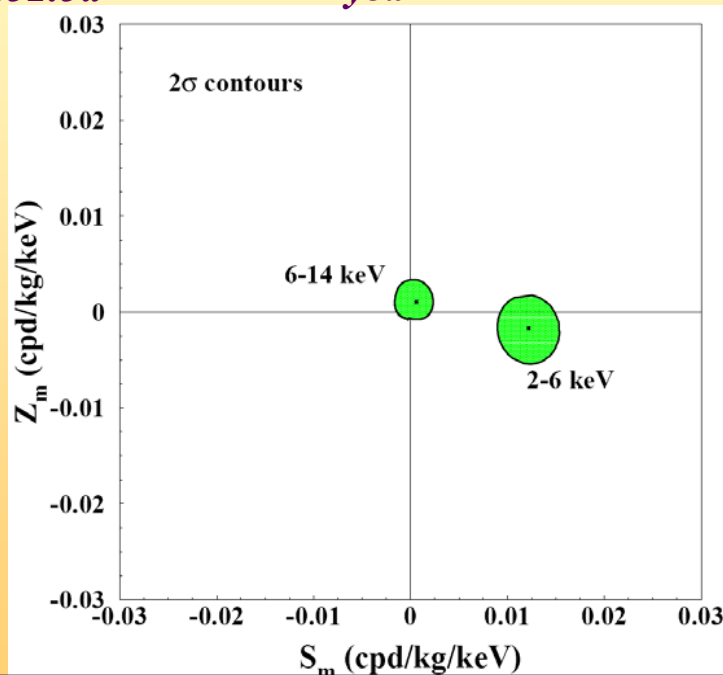
Is there a sinusoidal contribution in the signal? Phase $\neq 152.5$ day?

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $\omega = 2\pi/T$
- $t^* \approx t_0 = 152.5d$
- $T = 1 \text{ year}$

Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)



E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t^* (day)
2-6	0.0122 ± 0.0016	-0.0019 ± 0.0017	0.0123 ± 0.0016	144.0 ± 7.5
6-14	0.0005 ± 0.0010	0.0011 ± 0.0012	0.0012 ± 0.0011	--

The analysis at energies above 6 keV, the analysis of the multiple-hit events and the statistical considerations about S_m already exclude any sizeable presence of systematical effects.

Additional investigations on the stability parameters

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation

Running conditions stable
at a level better than 1%

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
Temperature	$-(0.0001 \pm 0.0061) ^\circ\text{C}$	$(0.0026 \pm 0.0086) ^\circ\text{C}$	$(0.001 \pm 0.015) ^\circ\text{C}$	$(0.0004 \pm 0.0047) ^\circ\text{C}$
Flux N_2	$(0.13 \pm 0.22) \text{ l/h}$	$(0.10 \pm 0.25) \text{ l/h}$	$-(0.07 \pm 0.18) \text{ l/h}$	$-(0.05 \pm 0.24) \text{ l/h}$
Pressure	$(0.015 \pm 0.030) \text{ mbar}$	$-(0.013 \pm 0.025) \text{ mbar}$	$(0.022 \pm 0.027) \text{ mbar}$	$(0.0018 \pm 0.0074) \text{ mbar}$
Radon	$-(0.029 \pm 0.029) \text{ Bq/m}^3$	$-(0.030 \pm 0.027) \text{ Bq/m}^3$	$(0.015 \pm 0.029) \text{ Bq/m}^3$	$-(0.052 \pm 0.039) \text{ Bq/m}^3$
Hardware rate above single photoelectron	$-(0.20 \pm 0.18) \times 10^{-2} \text{ Hz}$	$(0.09 \pm 0.17) \times 10^{-2} \text{ Hz}$	$-(0.03 \pm 0.20) \times 10^{-2} \text{ Hz}$	$(0.15 \pm 0.15) \times 10^{-2} \text{ Hz}$

All the measured amplitudes well compatible with zero

+none can account for the observed effect

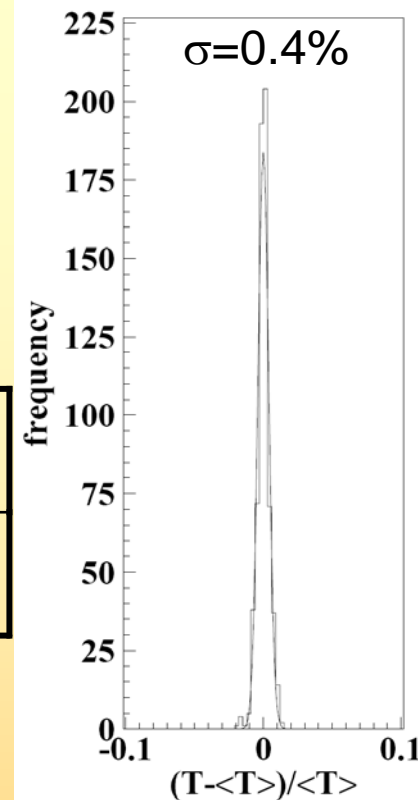
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

Temperature

- Detectors in Cu housings directly in contact with multi-ton shield
→ huge heat capacity ($\approx 10^6$ cal/ $^{\circ}\text{C}$)
- Experimental installation continuously air conditioned (2 independent systems for redundancy)
- Operating T of the detectors continuously controlled

Amplitudes for annual modulation in the operating T of the detectors **well compatible with zero**

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
T ($^{\circ}\text{C}$)	$-(0.0001 \pm 0.0061)$	(0.0026 ± 0.0086)	(0.001 ± 0.015)	(0.0004 ± 0.0047)



Distribution of the relative variations of the operating T of the detectors

Distribution of the root mean square values of the operating T within periods with the same calibration factors (typically ≈ 7 days):

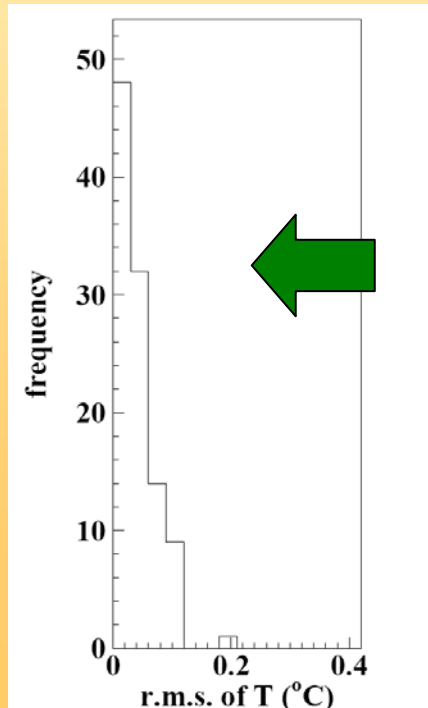
mean value $\approx 0.04^{\circ}\text{C}$

Considering the slope of the light output $\approx -0.2\% / ^{\circ}\text{C}$:
relative light output variation $< 10^{-4}$:

$< 10^{-4}$ cpd/kg/keV ($< 0.5\%$ S_m^{observed})

An effect from temperature can be excluded

+ Any possible modulation due to temperature would always fail some of the peculiarities of the signature



Can a possible thermal neutron modulation account for the observed effect?

NO

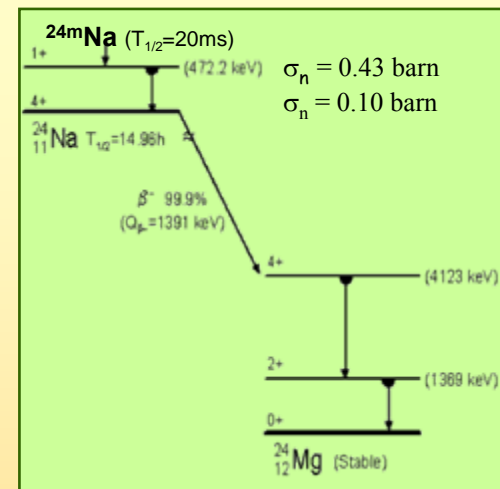
- Thermal neutrons flux measured at LNGS :

$$\Phi_n = 1.08 \cdot 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \text{ (N.Cim.A101(1989)959)}$$

- Experimental upper limit on the thermal neutrons flux “surviving” the neutron shield in DAMA/LIBRA:
 - studying triple coincidences able to give evidence for the possible presence of ^{24}Na from neutron activation:

$$\Phi_n < 1.2 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \text{ (90\%C.L.)}$$

- Two consistent upper limits on thermal neutron flux have been obtained with DAMA/NaI considering the same capture reactions and using different approaches.



Evaluation of the expected effect:

► Capture rate = $\Phi_n \sigma_n N_T < 0.022 \text{ captures/day/kg}$

HYPOTHESIS: assuming very cautiously a 10% thermal neutron modulation:

⇒ $S_m^{(\text{thermal n})} < 0.8 \times 10^{-6} \text{ cpd/kg/keV} (< 0.01\% S_m^{\text{observed}})$

In all the cases of neutron captures (^{24}Na , ^{128}I , ...) a possible thermal n modulation induces a variation in all the energy spectrum

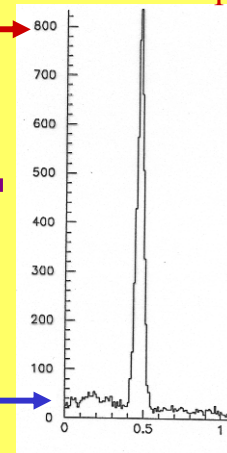
Already excluded also by R_{90} analysis

MC simulation of the process

When $\Phi_n = 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1}$:

$7 \cdot 10^{-5} \text{ cpd/kg/keV}$

$1.4 \cdot 10^{-3} \text{ cpd/kg/keV}$



E (MeV)

Can a possible fast neutron modulation account for the observed effect?

NO

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield

Measured fast neutron flux @ LNGS:

$$\Phi_n = 0.9 \cdot 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \text{ (Astropart.Phys.4 (1995)23)}$$

By MC: differential counting rate above 2 keV $\approx 10^{-3}$ cpd/kg/keV

HYPOTHESIS: assuming - very cautiously - a 10% neutron modulation: $\Rightarrow S_m^{(\text{fast n})} < 10^{-4} \text{ cpd/kg/keV} (< 0.5\% S_m^{\text{observed}})$

• Experimental upper limit on the fast neutrons flux “*surviving*” the neutron shield in DAMA/LIBRA:

➤ through the study of the inelastic reaction $^{23}\text{Na}(n,n')^{23}\text{Na}^*(2076 \text{ keV})$ which produces two γ 's in coincidence (1636 keV and 440 keV):

$$\Phi_n < 2.2 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \text{ (90\%C.L.)}$$

➤ well compatible with the measured values at LNGS. This further excludes any presence of a fast neutron flux in DAMA/LIBRA significantly larger than the measured ones.

Moreover, a possible fast n modulation would induce:

▶ a variation in all the energy spectrum (steady environmental fast neutrons always accompanied by thermalized component)

already excluded also by R_{90}

▶ a modulation amplitude for multiple-hit events different from zero

already excluded by the multiple-hit events

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS


Can (whatever) possible cosmogenic products be considered as side effects?

Hypothesis (all the following items must be satisfied):

- the surviving muons can produce by spallation either unstable isotopes or exotic products;
- their decay or de-excitation or whatever else (mean-life: τ) can produce:
 - only events at low energy,
 - only *single-hit* events,
 - no sizeable effect in the *multiple-hit* counting rate

?

The muon flux at LNGS ($\approx 20 \mu \text{ m}^{-2} \text{ d}^{-1}$) is yearly modulated ($\pm 2\%$) with phase roughly around middle of July



We expect in this hypothesis an annual modulation of the counting rate with a period one year (OK), but a phase (much) larger than July, 15th

DAMA/NaI + DAMA/LIBRA

measured a phase of roughly May, 25th ± 10 days

• if $\tau \ll T/2\pi$:

$$t_{\text{side}} = t_{\mu} + \tau$$

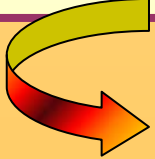
• if $\tau \gg T/2\pi$:

$$t_{\text{side}} = t_{\mu} + T/4$$


Also this hypothesis can be ruled out!

Summary of the results obtained in the additional investigations of possible systematics or side reactions (DAMA/LIBRA - NIMA592(2008)297, EPJC56(2008)333)

<i>Source</i>	<i>Main comment</i>	<i>Cautious upper limit (90% C.L.)</i>
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5 \times 10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1-2 \times 10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV <i>multiple-hits</i> events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured by MACRO	$<3 \times 10^{-5}$ cpd/kg/keV



+ even if larger they cannot satisfy all the requirements of annual modulation signature



Thus, they can not mimic the observed annual modulation effect

Model-independent evidence by DAMA/NaI and DAMA/LIBRA

well compatible with several candidates (in several of the many astrophysical, nuclear and particle physics scenarios); other ones are open

Neutralino as LSP in SUSY theories

Various kinds of WIMP candidates with several different kind of interactions
Pure SI, pure SD, mixed + Migdal effect + channeling, ... (from low to high mass)

a heavy ν of the 4-th family

Pseudoscalar, scalar or mixed light bosons with axion-like interactions

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

Dark Matter (including some scenarios for WIMP) electron-interacting

Sterile neutrino

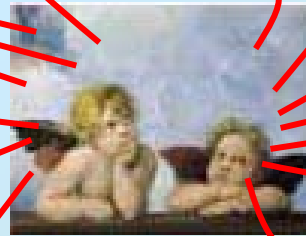
Self interacting Dark Matter

Elementary Black holes such as the Daemons

heavy exotic candidates, as "4th family atoms", ...

Kaluza Klein particles

... and more

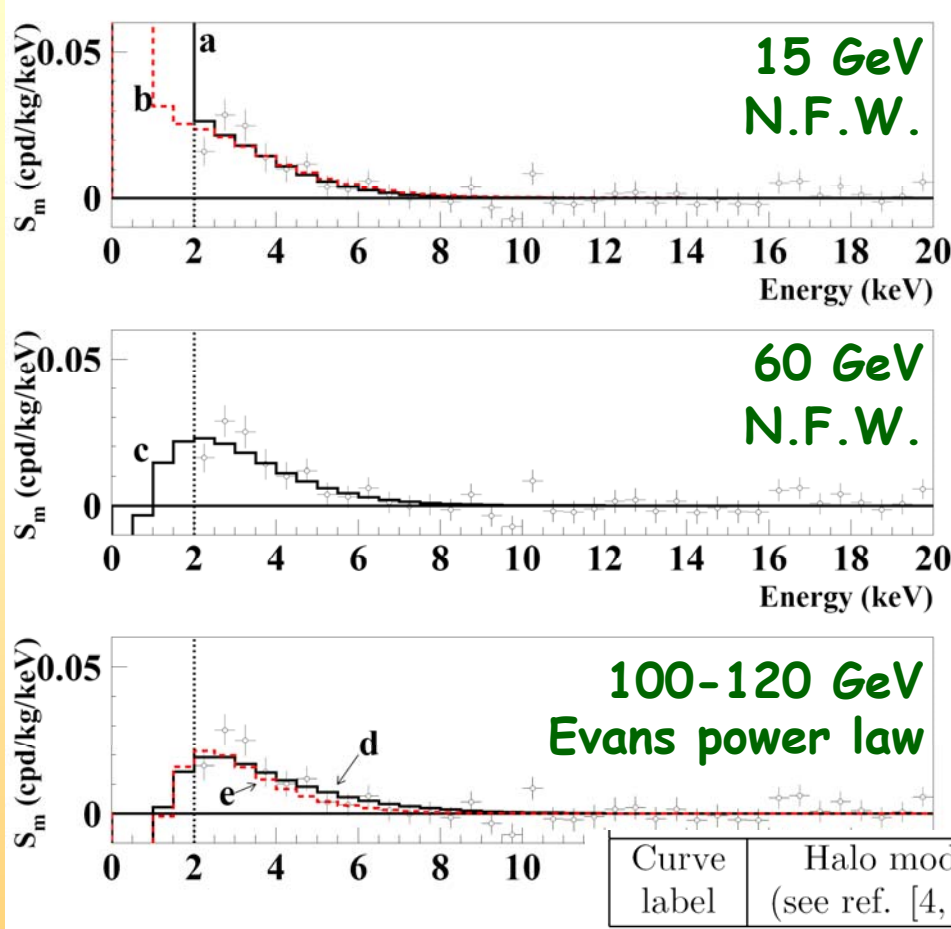


Possible model dependent positive hints from indirect searches not in conflict with DAMA results

(but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.)

Available results from direct searches using different target materials and approaches do not give any robust conflict

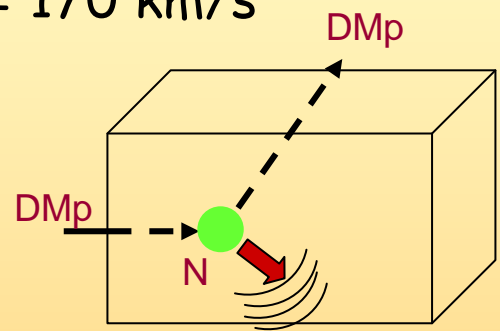
Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$



WIMP DM candidate (as in [4])
considering elastic scattering on nuclei

SI dominant coupling

$v_0 = 170 \text{ km/s}$



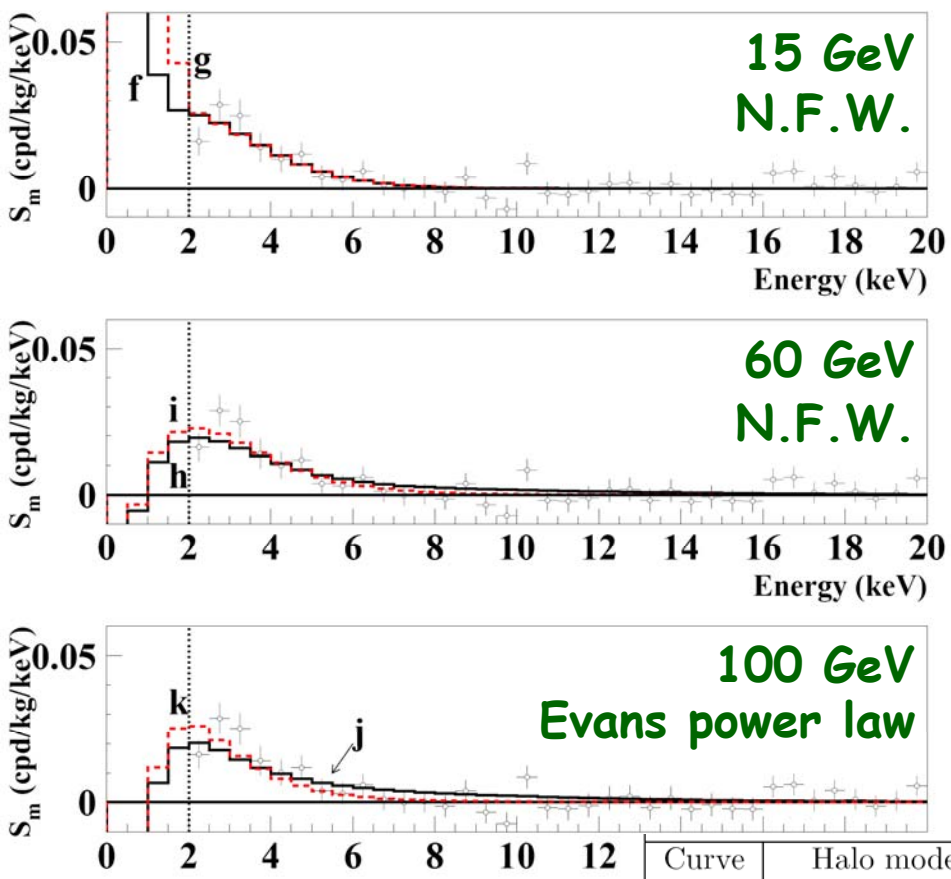
- Not best fit
- About the same C.L.

...scaling from NaI

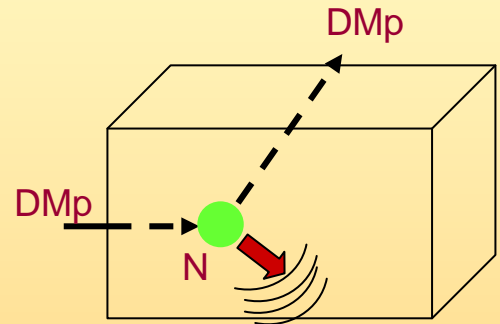
channeling contribution as in EPJC53(2008)205 considered for curve *b*

Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm ³)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)
<i>a</i>	A5 (NFW)	0.2	A	15 GeV	3.1×10^{-4}
<i>b</i>	A5 (NFW)	0.2	A	15 GeV	1.3×10^{-5}
<i>c</i>	A5 (NFW)	0.2	B	60 GeV	5.5×10^{-6}
<i>d</i>	B3 (Evans power law)	0.17	B	100 GeV	6.5×10^{-6}
<i>e</i>	B3 (Evans power law)	0.17	A	120 GeV	1.3×10^{-5}

Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$



WIMP DM candidate (as in [4])
 Elastic scattering on nuclei
 SI & SD mixed coupling
 $v_0 = 170 \text{ km/s}$

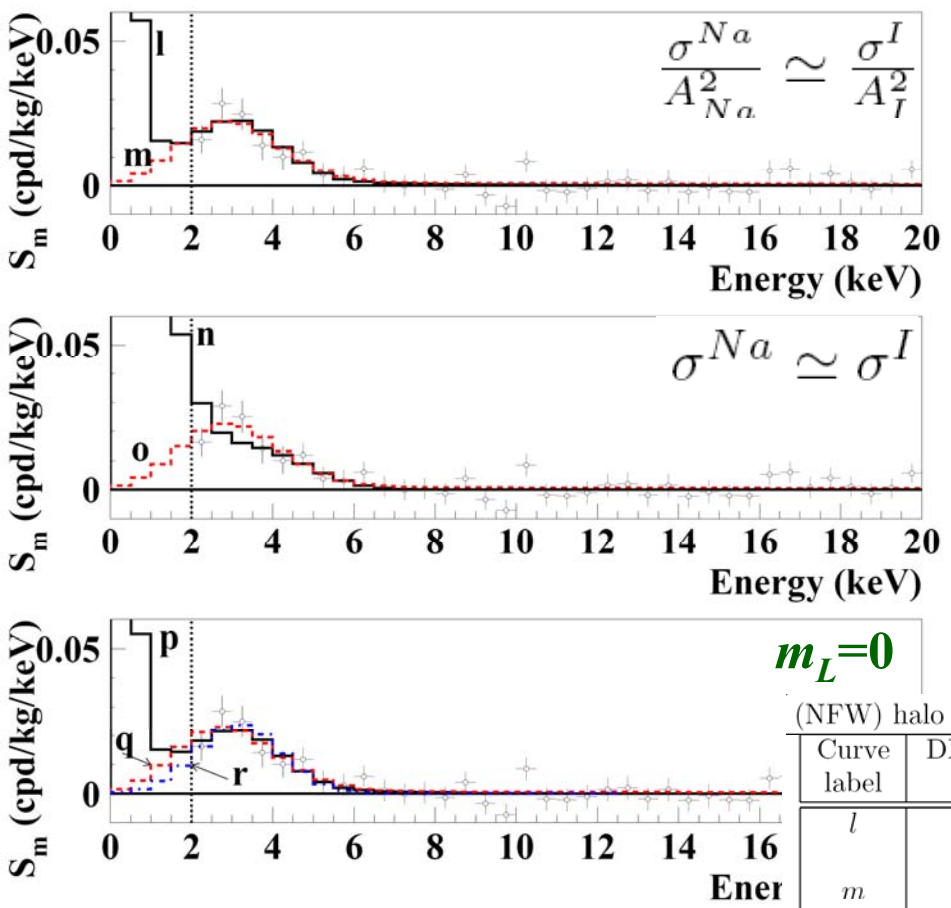


- Not best fit
 - About the same C.L.
- ...scaling from NaI

$\theta = 2.435$

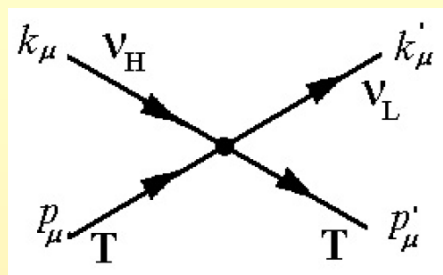
Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm ³)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)	$\xi\sigma_{SD}$ (pb)
<i>f</i>	A5 (NFW)	0.2	A	15 GeV	10^{-7}	2.6
<i>g</i>	A5 (NFW)	0.2	A	15 GeV	1.4×10^{-4}	1.4
<i>h</i>	A5 (NFW)	0.2	B	60 GeV	10^{-7}	1.4
<i>i</i>	A5 (NFW)	0.2	B	60 GeV	8.7×10^{-6}	8.7×10^{-2}
<i>j</i>	B3 (Evans power law)	0.17	A	100 GeV	10^{-7}	1.7
<i>k</i>	B3 (Evans power law)	0.17	A	100 GeV	1.1×10^{-5}	0.11

Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$



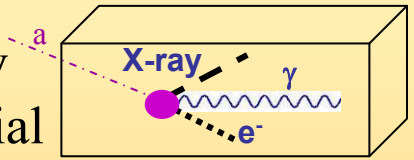
curve *r*: also pseudoscalar axion-like candidates (e.g. majoron)
 $m_a=3.2$ keV $g_{aee}=3.9 \cdot 10^{-11}$

LDM candidate
 (as in MPLA23(2008)2125):
 inelastic interaction
 with electron or nucleus
 targets



Light bosonic candidate
 (as in IJMPA21(2006)1445):
 axion-like particles totally
 absorbed by target material

- Not best fit
- About the same C.L.



(NFW) halo model as in [4, 34], local density = 0.17 GeV/cm³, local velocity = 170 km/s

Curve label	DM particle	Interaction	Set as in [4]	m_H	Δ	Cross section (pb)
<i>l</i>	LDM	coherent on nuclei	A	30 MeV	18 MeV	$\xi\sigma_m^{coh} = 1.8 \times 10^{-6}$
<i>m</i>	LDM	coherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{coh} = 2.8 \times 10^{-6}$
<i>n</i>	LDM	incoherent on nuclei	A	30 MeV	3 MeV	$\xi\sigma_m^{inc} = 2.2 \times 10^{-2}$
<i>o</i>	LDM	incoherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{inc} = 4.6 \times 10^{-2}$
<i>p</i>	LDM	coherent on nuclei	A	28 MeV	28 MeV	$\xi\sigma_m^{coh} = 1.6 \times 10^{-6}$
<i>q</i>	LDM	incoherent on nuclei	A	88 MeV	88 MeV	$\xi\sigma_m^{inc} = 4.1 \times 10^{-2}$
<i>r</i>	LDM	on electrons	–	60 keV	60 keV	$\xi\sigma_m^e = 0.3 \times 10^{-6}$

where DAMA is ...

- DAMA/LIBRA over 4 annual cycles (0.53 ton×yr) confirms the results of DAMA/NaI (0.29 ton×yr)
- The cumulative confidence level for the model independent evidence for presence of DM particle in the galactic halo is 8.2σ (total exposure 0.82 ton × yr)



- First upgrading of the experimental set-up in Sept. 2008



Phase 1

- Mounting of the “clean room” set-up in order to operate in HP N₂ atmosphere
- Opening of the shield of DAMA/LIBRA set-up in HP N₂ atmosphere
- Replacement of some PMTs in HP N₂ atmosphere
- Closing of the shield

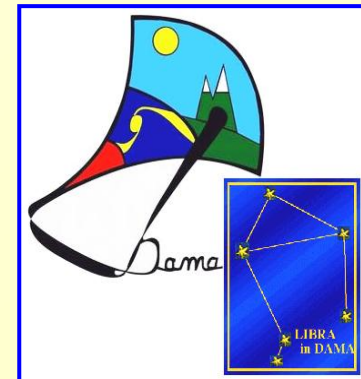


Phase 2

- Dismounting of the Tektronix TDs (Digitizers + Crates)
- Mounting of the new Acqiris TD (Digitizers + Crate)
- Mounting of the new DAQ system with optical read-out
- Test of the new TDs (*hardware*) and of the new required DAQ system (*software*)



• *Since Oct. 2008 again in data taking*





... and where DAMA is going to

- Continuing the data taking
- Update corollary analyses in some of the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..

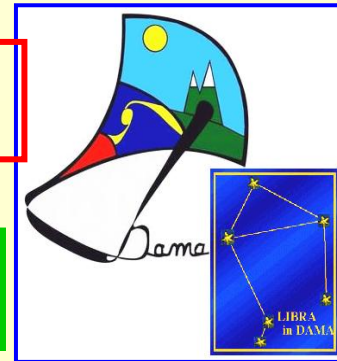
- Next upgrading: replacement of all the PMTs with higher Q.E. ones.
- Production of new high Q.E. PMTs in progress
- Goals:
 - better separation under 2 keV in the rejection plane between noise and single-hit scintillation events
 - lowering the energy threshold (presently, at 2 keV)
 - improvement of the acceptance efficiency near energy threshold
 - increase of the sensitivity in the *model independent* analysis (amplitude, phase, second order effects, ...)
 - improvement of the sensitivity in the *model dependent* analyses, allowing to better disentangle several astrophysical, particle physics and nuclear physics scenarios

- Analyses/data taking to investigate also other rare processes in progress/foreseen

- Long term data taking to improve the investigation, to disentangle at least some of the many possibilities, to investigate other features of DM particle component(s), second order effects, etc..

A possible highly radiopure NaI(Tl) multi-purpose set-up
DAMA/1 ton (proposed by DAMA in 1996) at R&D phase

to deep investigate Dark Matter
phenomenology at galactic scale



Felix qui potuit rerum cognoscere causas (Virgilio, Georgiche, II, 489)