DAMA/LIBRA results

WONDER 2010

LNGS – March 22-23, 2010

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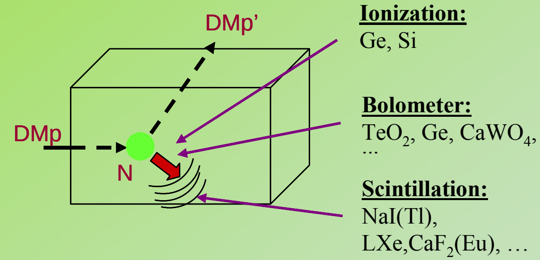
Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



- Inelastic Dark Matter: **W + N → W* + N**

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

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

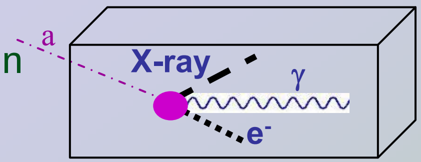
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

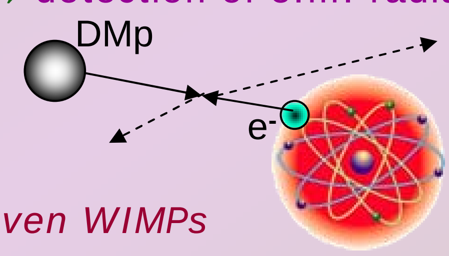
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

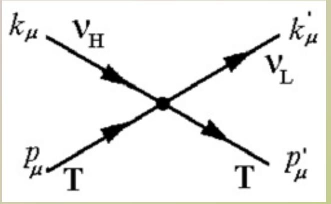


… even WIMPs

- 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

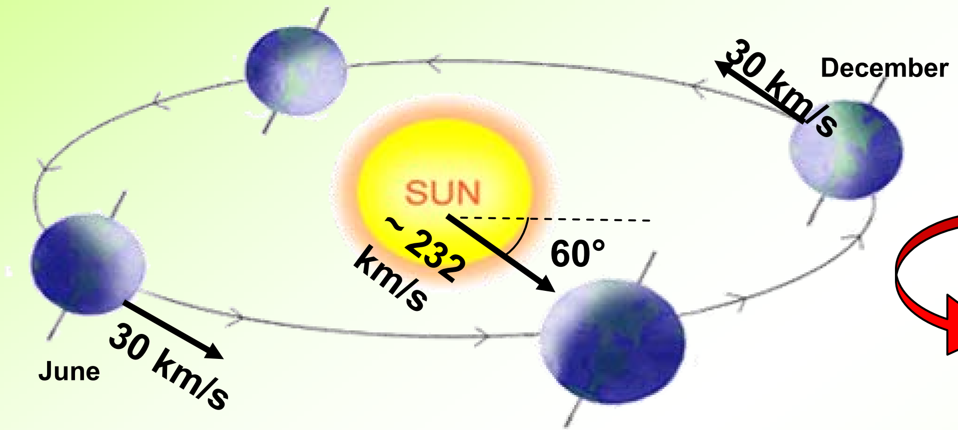
… also other ideas …

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

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

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

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) **Just 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

The DM annual modulation signature has a different origin and, thus, different peculiarities (e.g. the phase) with respect to those effects connected with the seasons instead

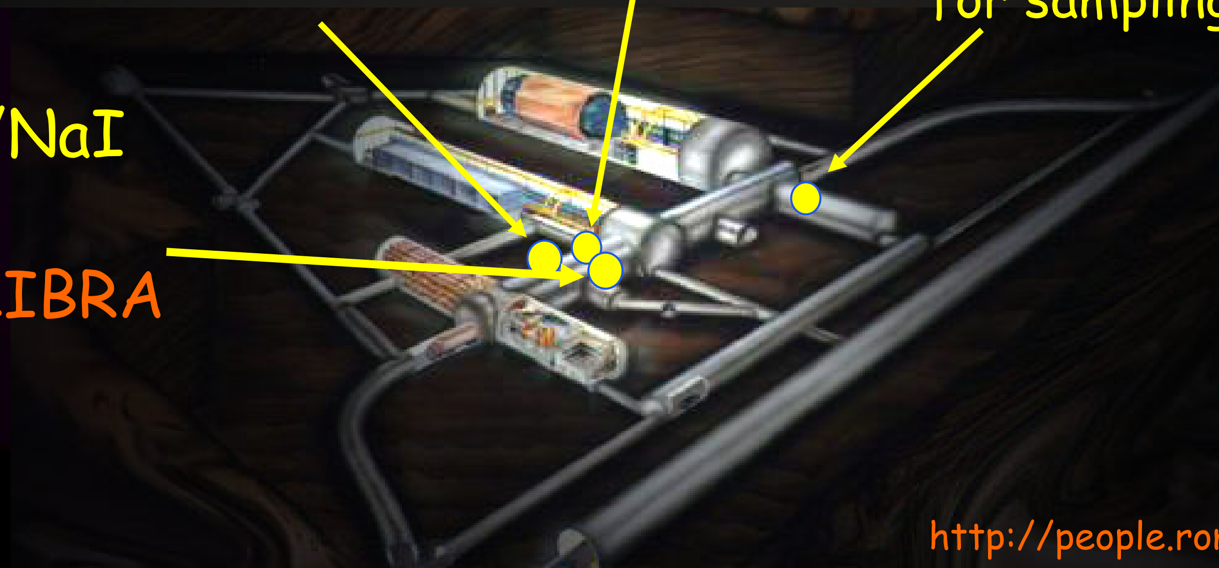
Competitiveness of ULB NaI(Tl) set-up

- Well known technology
- High duty cycle
- Large mass possible
- "Ecological clean" set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- High light response (5.5 -7.5 ph.e./keV)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios on the contrary of other proposed target-materials (and approaches)
- Sensitive to both high (mainly by Iodine target) and low mass (mainly by Na target) candidates
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up
- Etc.

<u>A low background NaI(Tl) also allows the study of several other rare processes</u> **:** possible processes violating the Pauli exclusion principle, CNC processes in ^{23}Na and ^{127}I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar axion search, ...

High benefits/cost

DAMA: an observatory for rare processes @LNGS



http://people.roma2.infn.it/dama

A brief history …

- DAMA proposal by the italian group and first funding on 1990
- First measurements with commercial NaI(Tl) underground in 1989.
- Technological research on liquid Xenon operative within INFN CSN5 since end of 80's (XELIDON project); realized various LXe prototypes and R&D using ^{nat}Xe
- Dark Matter investigation using NaI(Tl), liquid Xenon and other scintillators

- Dark Matter investigation
- investigation on ββ decay processes in ^{136}Xe and ^{134}Xe
- electron decay
- charge-non-conserving processes
- nucleon, di-nucleon and tri-nucleon decay into invisible channels

DAMA/LXe

- Since 1990, pure liquid scintillator (direct collection of UV light, no other material apart from xenon present in the sensitive volume, assuring high radiopurity level, high light response and PSD capability, no liquid-gas interface between liquid and PMTs, UHV technique) low background developments and applications to dark matter investigation (since N.Cim.A103(1990)767)
  - A significant upgrade occurred at the end of 1995;
  - Set-up deeply modified in 2000;
  - Suspended at end of August 2002 after the Borexino accident for the request to not use cryogenic liquids underground
- Further upgrade in 2003
- New measurement from May to Dec 2004
- From 2005 to 2007 waiting for the restart of LNGS cooling water plant operation and local water refrigeration system
- New data taking from Nov 2007 to Jan 2009
- Maintenance and small upgrade
- Further data taking from Sept 2009 to Jan 2010

Kr-free enriched in ^{129}Xe at 99.5% and in ^{136}Xe at 68.8%

New data taking foreseen with the aim to further investigate rare processes, ββ decay in ^{136}Xe and ^{134}Xe and Dark Matter particles comparing SI vs SD contribution

DAMA membership

Overall membership in the DAMA activities

Spokesperson: R. Bernabei

P. Belli, R. Bernabei, A. Bussolotti*, F. Montecchia, F. Nozzoli
Dip. di Fisica, Univ. Roma "Tor Vergata" and INFN, sez. Roma Tor Vergata, Italy

F. Cappella, A. d'Angelo, A. Incicchitti, A. Mattei*, D. Prosperi
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R. Cerulli, V. Caracciolo, A. di Marco
INFN - Laboratori Nazionali del Gran Sasso, Italy

C.J. Dai, H.L. He, X.H. Ma, X.D. Sheng, R.G. Wang, Z.P. Ye**
IHEP, Chinese Academy, China;

+ in some by-product results and small scale experiments:

F. Danevich, B.V. Grinyov, V.V. Kobychev, V.M. Kudovbenko, S.S. Nagorny, L.L. Nagornaya, D.V. Poda, R.B. Podviyanuk, O.G. Polischuk, V.I. Tretyak, I. M. Vyshnevskyi, S.S. Yurchenko and coll.
Institute for Nuclear Research of Kiev, Ukraine

M. Laubenstein, S. Nisi
INFN - Laboratori Nazionali del Gran Sasso, Italy

S. d'Angelo
Dip. di Fisica and INFN, Università di Roma "Tor Vergata", Italy

+ in some studies on $\beta^+\beta^+$, EC/β^+, EC/EC decay modes (under the joint Indo-Italian DST-MAE project):

P.K. Raina, A.K. Singh, P.K. Rath, A. Shukla
Indian Institute of Technology, Kharagpur, India.

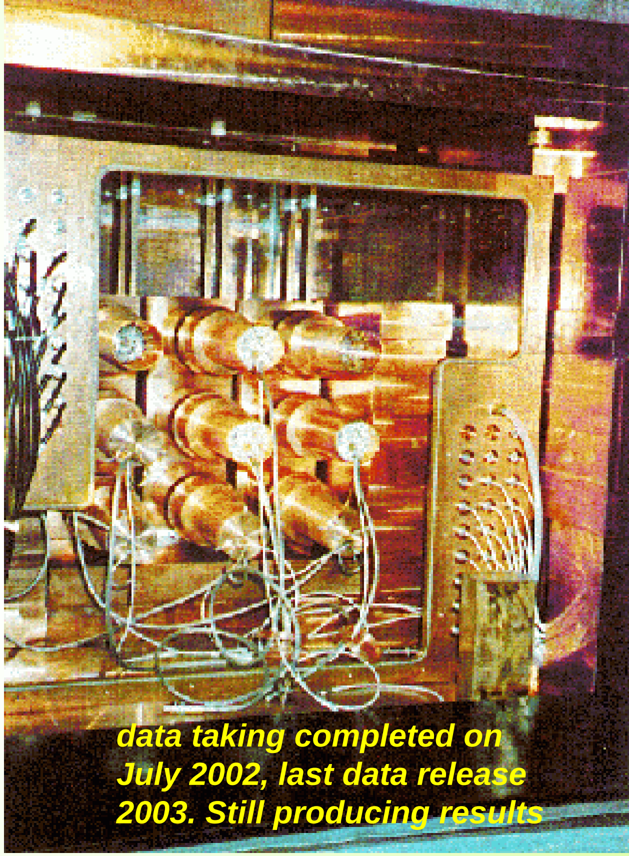
+ in neutron measurements:

M. Angelone, P. Batistoni, M.Pillon
ENEA - C. R. Frascati, Italy

* Technical staff; ** also University of Jing Gangshan, Jiangxi, China.

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



data taking completed on July 2002, last data release 2003. Still producing results

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 6.3 σ C.L.

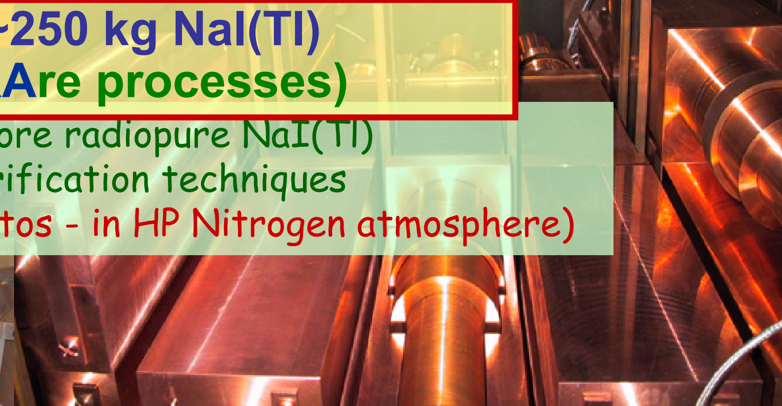
total exposure (7 annual cycles) 0.29 ton x yr

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

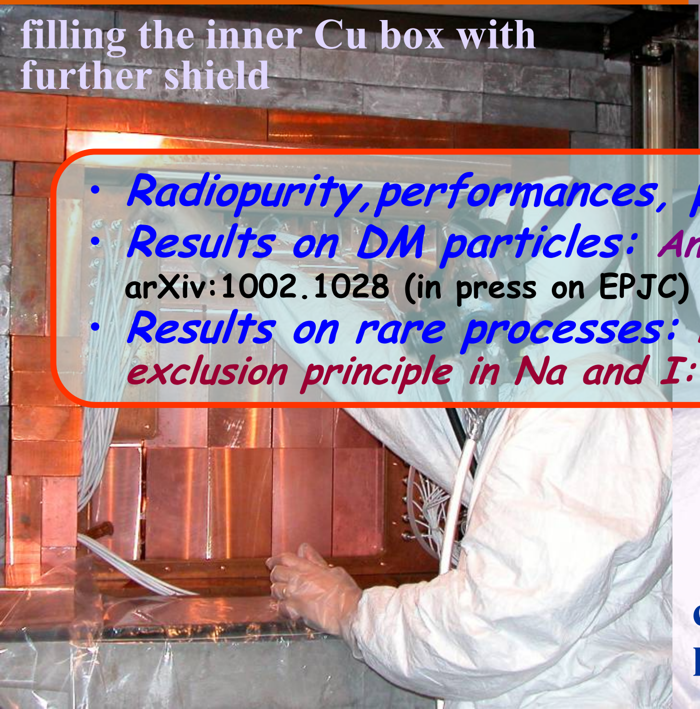
As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

installing DAMA/LIBRA detectors

assembling a DAMA/ LIBRA detector

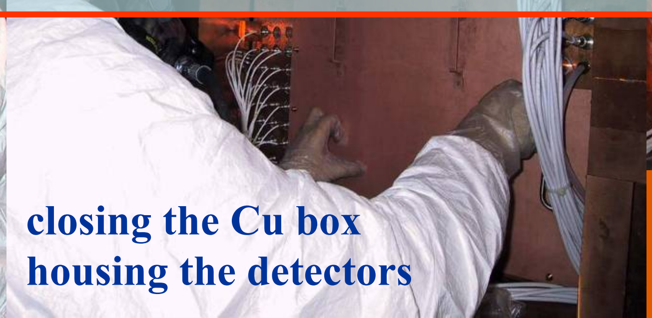


detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied



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, arXiv:1002.1028 (in press on EPJC)
- *Results on rare processes: Possible processes violating the Pauli exclusion principle in Na and I:* EPJC62(2009)327



closing the Cu box housing the detectors

view at end of detectors' installation in the Cu box

DAMA/LIBRA ~250 kg ULB 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

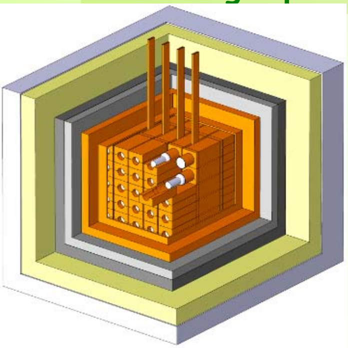
Cu etching with super- and ultra-pure HCl solutions, dried and sealed in HP N_2

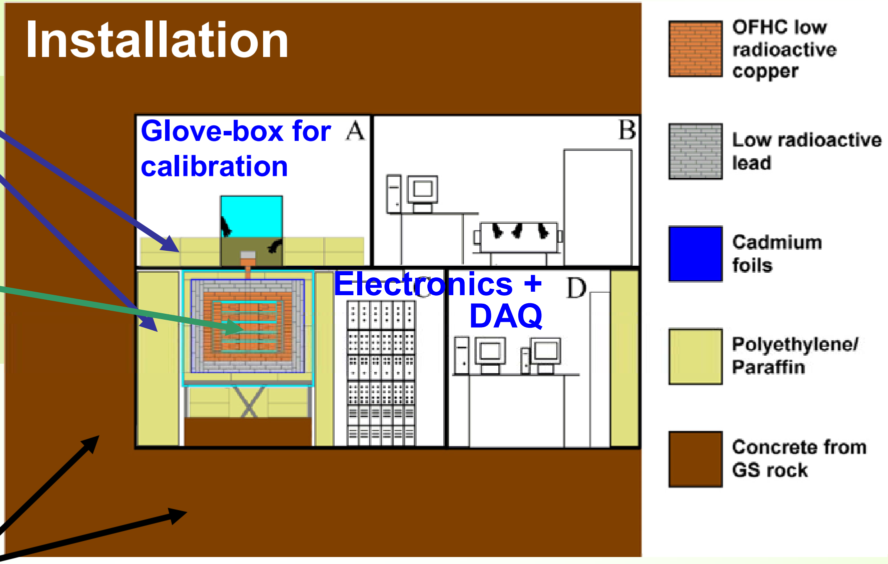
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.
NIMA592(2008)297

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



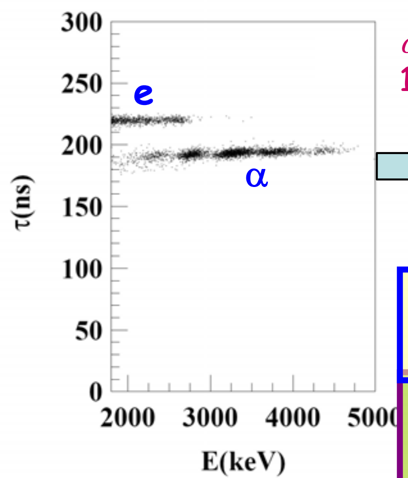


5.5-7.5 phe/keV

~ 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 Waweform Analyzer Acqiris DC270 (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 ULB NaI(Tl) detectors



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

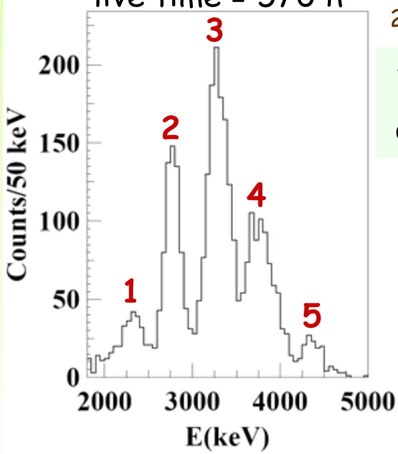
The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/day

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

live time = 570 h



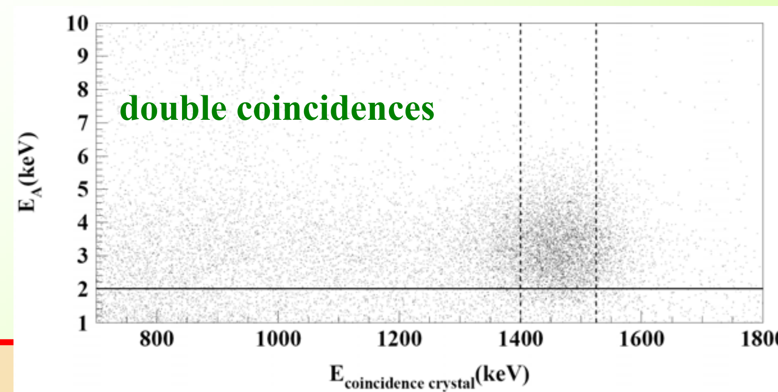
^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

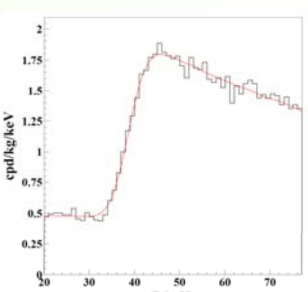
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

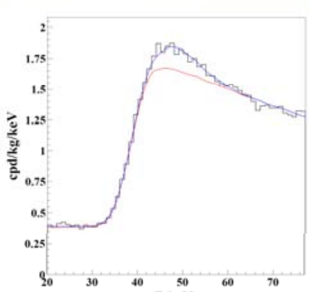
and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{nat}K residual contamination

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







^{129}I and ^{210}Pb

$^{129}I/^{nat}I \approx 1.7\times10^{-13}$ for all the new detectors

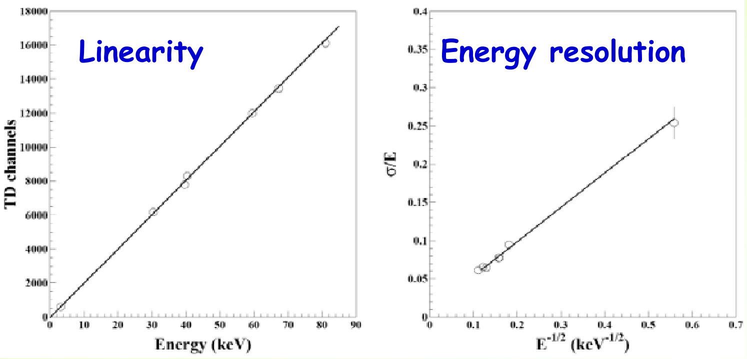
^{210}Pb in the new detectors: (5 – 30) μBq/kg.

No sizable surface pollution by Radon daugthers, thanks to the new handling protocols

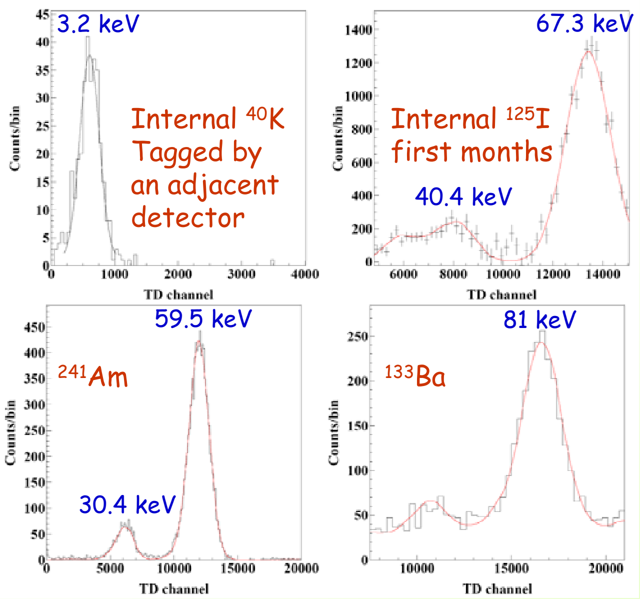
... more on NIMA592(2008)297

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

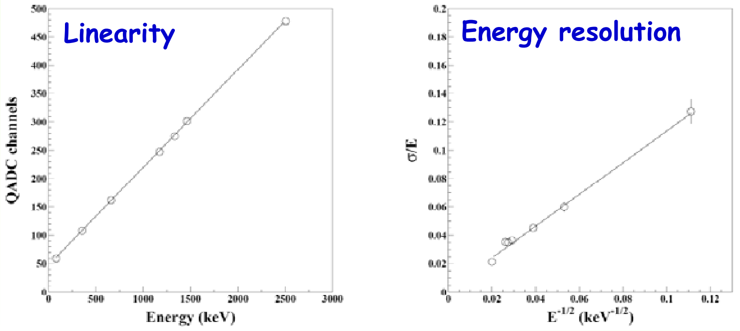


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$



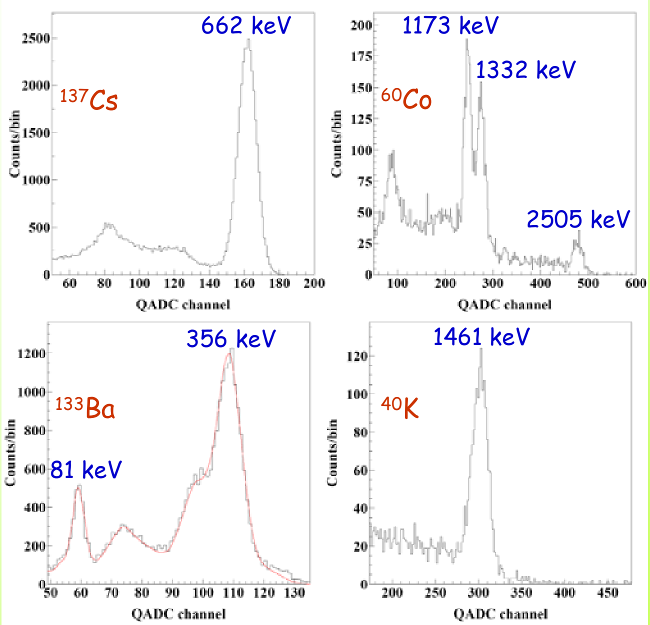
The curves superimposed to the experimental data have been obtained by simulations

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



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

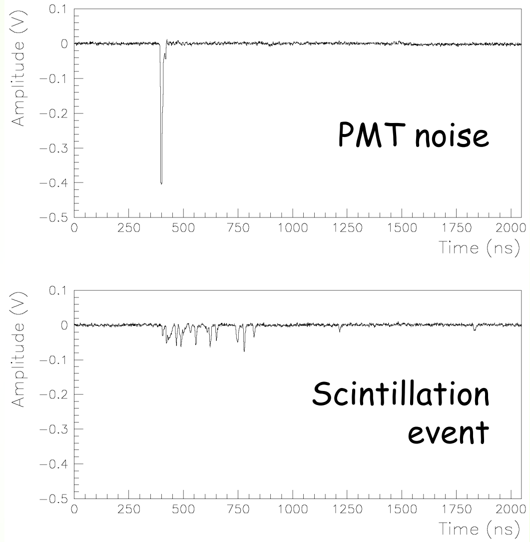
$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23) \cdot 10^{-4}$$



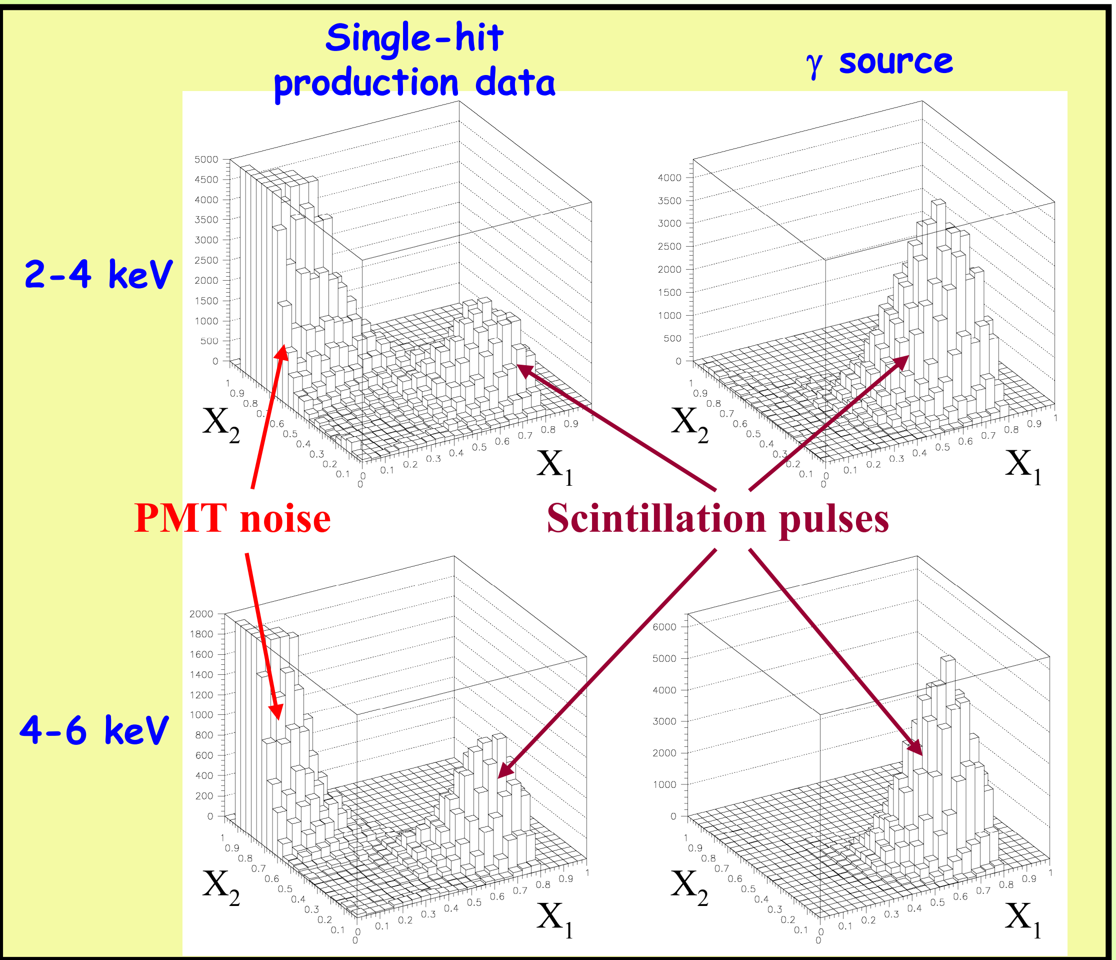
Thus, here and hereafter keV means keV electron equivalent

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



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

Period		Mass (kg)	Exposure (kg × day)	α-β²
DAMA/LIBRA-1	Sep. 9, 2003 – July 21, 2004	232.8	51405	0.562
DAMA/LIBRA-2	July 21, 2004 – Oct. 28, 2005	232.8	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 – July 18, 2006	232.8	39445	0.591
DAMA/LIBRA-4	July 19, 2006 – July 17, 2007	232.8	49377	0.541
DAMA/LIBRA-5	July 17, 2007 – Aug. 29, 2008	232.8	66105	0.468
DAMA/LIBRA-6	Nov. 12, 2008 – Sep. 1, 2009	242.5	58768	0.519
DAMA/LIBRA-1 to -6	**Sep. 9, 2003 – Sep. 1, 2009**		**317697 = 0.87 ton×yr**	**0.519**

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

total exposure: 425428 kg×day = 1.17 ton×yr

- **calibrations: ≈72 M events from sources**
- **acceptance window eff: 82 M events (≈3M events/keV)**

- **EPJC56(2008)333**
- **arXiv:1002.1028 (in press on EPJC)**

- **First upgrade on Sept 2008:**
  - replacement of some PMTs in HP N_2 atmosphere
  - restore 1 detector to operation
  - new Digitizers installed (U1063A Acqiris 1GS/s 8-bit High-Speed cPCI)
  - new DAQ system with optical read-out installed

- **New upgrade foreseen on fall 2010**

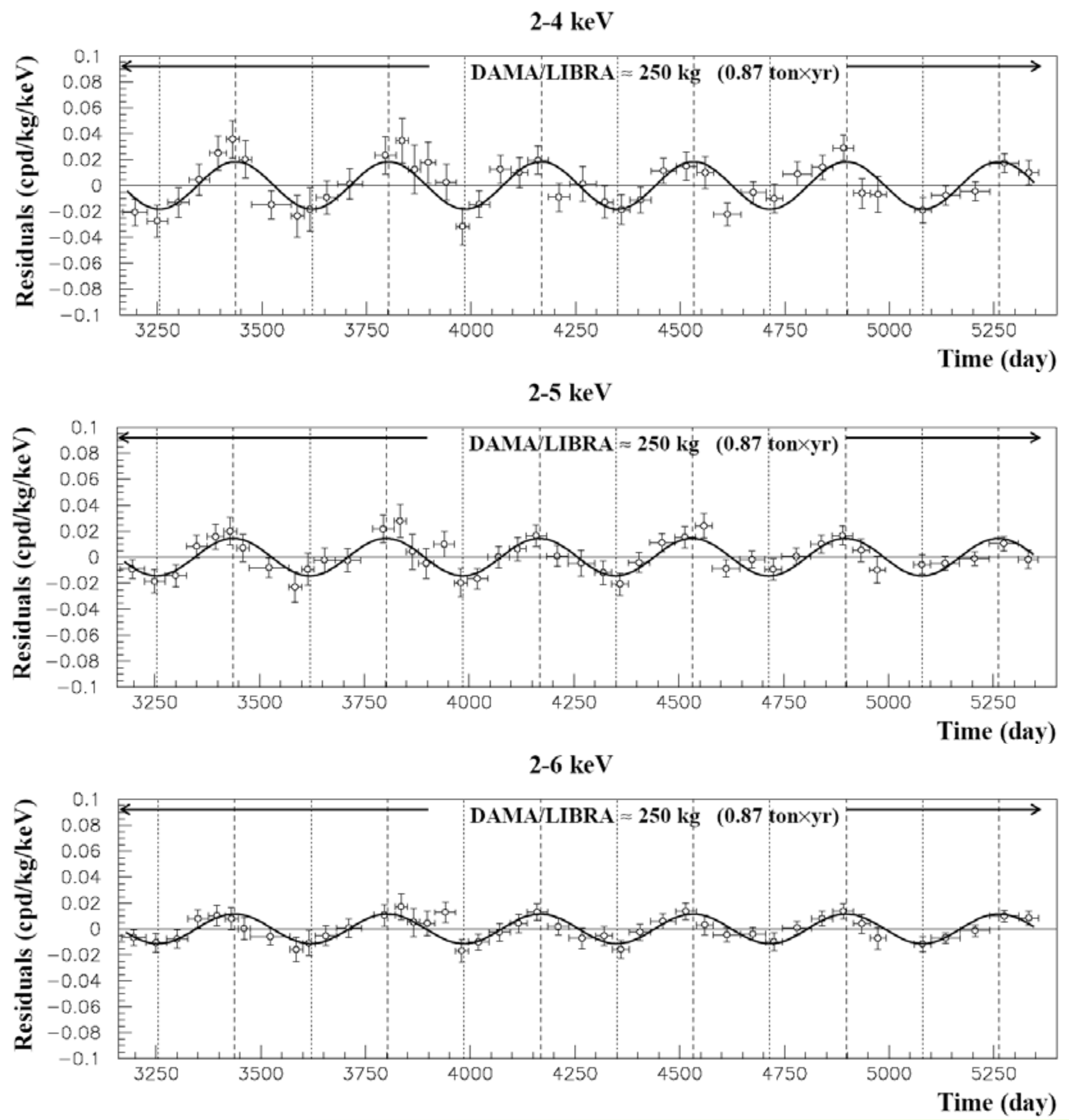
... continuously running

DAMA/LIBRA-1 to 6 Model Independent Annual Modulation Result

experimental single-hit residuals rate vs time and energy

$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

DAMA/LIBRA-1,2,3,4,5,6 (0.87 ton × yr)



The fit has been done on the DAMA/NaI & DAMA/LIBRA data (1.17 ton × yr)

2-4 keV

A=(0.0183±0.0022) cpd/kg/keV

χ^2/dof = 75.7/79 **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=147/80 ⇒ P(A=0) = 7×10^{-6}

2-5 keV

A=(0.0144±0.0016) cpd/kg/keV

χ^2/dof = 56.6/79 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=135/80 ⇒ P(A=0) = 1.1×10^{-4}

2-6 keV

A=(0.0114±0.0013) cpd/kg/keV

χ^2/dof = 64.7/79 **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=140/80 ⇒ P(A=0) = 4.3×10^{-5}

The data favor the presence of a modulated behavior with proper features at 8.8σ C.L.

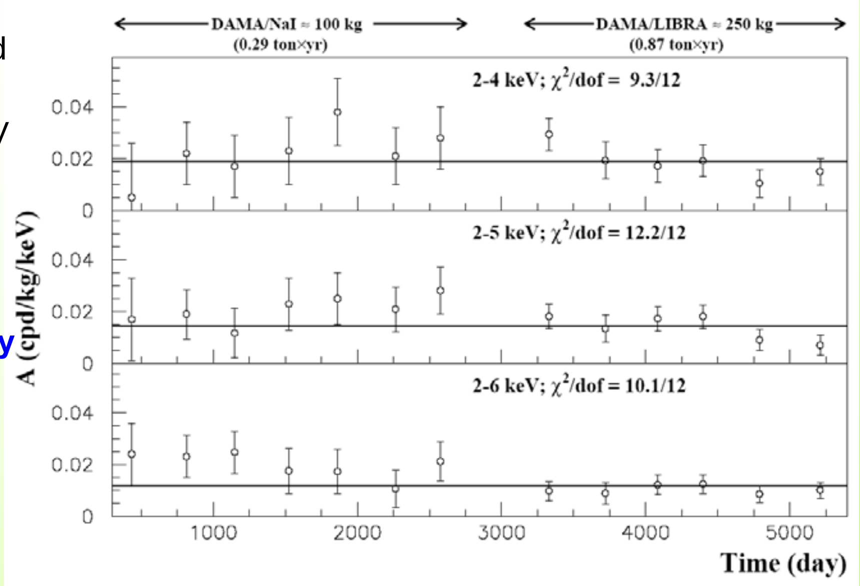
Modulation amplitudes measured in each one of the 13 one-year experiments (DAMA/NaI and DAMA/LIBRA)

	A (cpd/kg/keV)	T= 2π/ω (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 (6 years)				
(2÷4) keV	0.0180 ± 0.0025	0.996 ± 0.002	135 ± 8	7.2σ
(2÷5) keV	0.0134 ± 0.0018	0.997 ± 0.002	140 ± 8	7.4σ
(2÷6) keV	0.0098 ± 0.0015	0.999 ± 0.002	146 ± 9	6.5σ
DAMA/NaI + DAMA/LIBRA				
(2÷4) keV	0.0194 ± 0.0022	0.996 ± 0.002	136 ± 7	8.8σ
(2÷5) keV	0.0149 ± 0.0016	0.997 ± 0.002	142 ± 7	9.3σ
(2÷6) keV	0.0116 ± 0.0013	0.999 ± 0.002	146 ± 7	8.9σ

DAMA/NaI (7 annual cycles: 0.29 ton x yr) +
DAMA/LIBRA (6 annual cycles: 0.87 ton x yr)
total exposure: 425428 kg×day = 1.17 ton×yr

A, T, t_0 obtained by fitting the single-hit data with **$A\cos[\omega(t-t_0)]$**

- The modulation amplitudes for the (2 – 6) keV energy interval, obtained when fixing the period at 1 yr and the phase at 152.5 days, are: (0.019±0.003) cpd/kg/keV for DAMA/NaI and (0.010±0.002) cpd/kg/keV for DAMA/LIBRA.
- Thus, their difference: (0.009±0.004) cpd/kg/keV is *≈2σ* which corresponds to a modest, but non negligible probability.



The χ^2 test (χ^2 = 9.3, 12.2 and 10.1 over 12 *d.o.f.* for the three energy intervals, respectively) and the *run test* (lower tail probabilities of 57%, 47% and 35% for the three energy intervals, respectively) accept at 90% C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.

Compatibility among the annual cycles

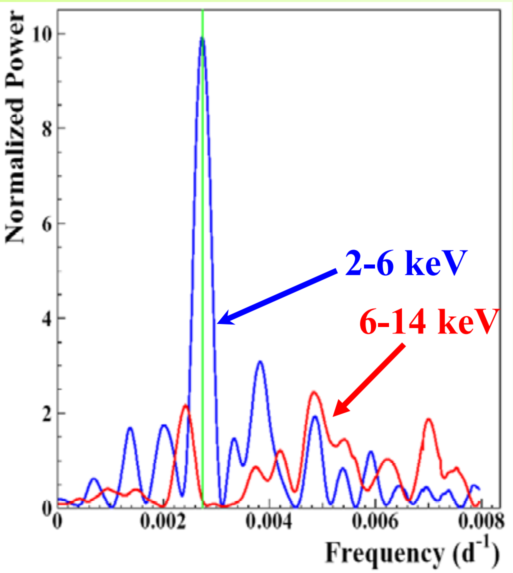
Power spectrum of single-hit residuals

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

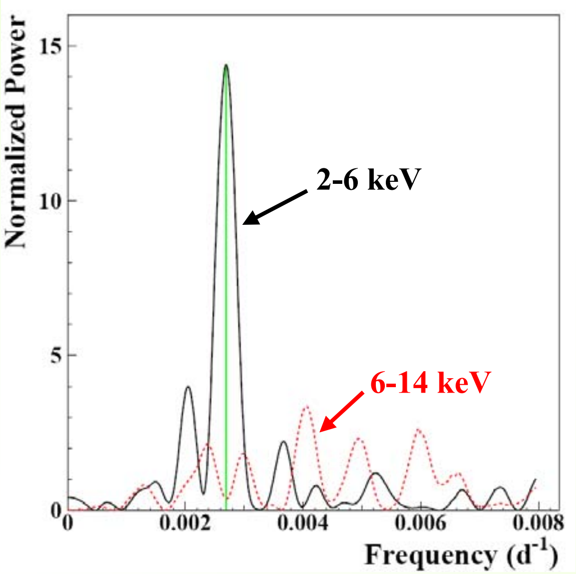
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

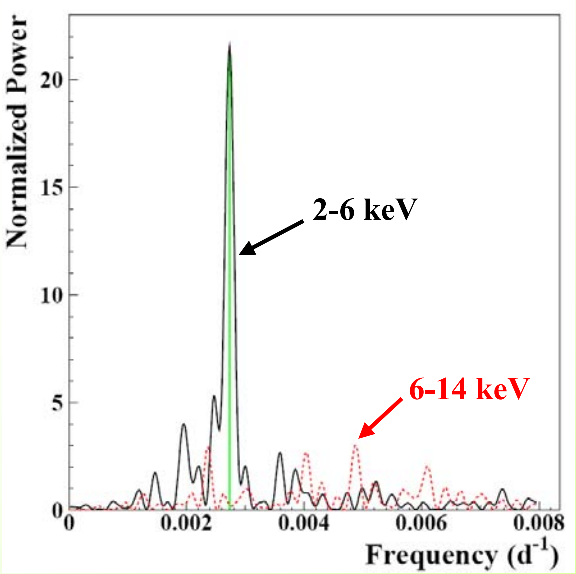
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



DAMA/LIBRA (6 years)
total exposure: 0.87 ton×yr



DAMA/NaI (7 years) + DAMA/LIBRA (6 years)
total exposure: 1.17 ton×yr



Principal mode in the 2-6 keV region:

DAMA/NaI	DAMA/LIBRA	DAMA/NaI+LIBRA
$2.737 \cdot 10^{-3}$ d^{-1} ≈ 1 y^{-1}	2.697×10^{-3} d^{-1} ≈ 1 yr^{-1}	2.735×10^{-3} d^{-1} ≈ 1 yr^{-1}

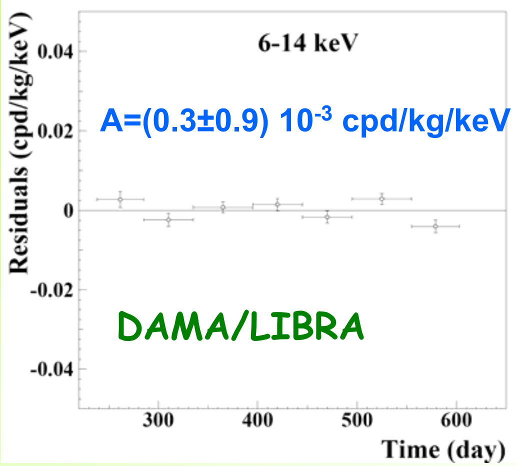
+

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

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

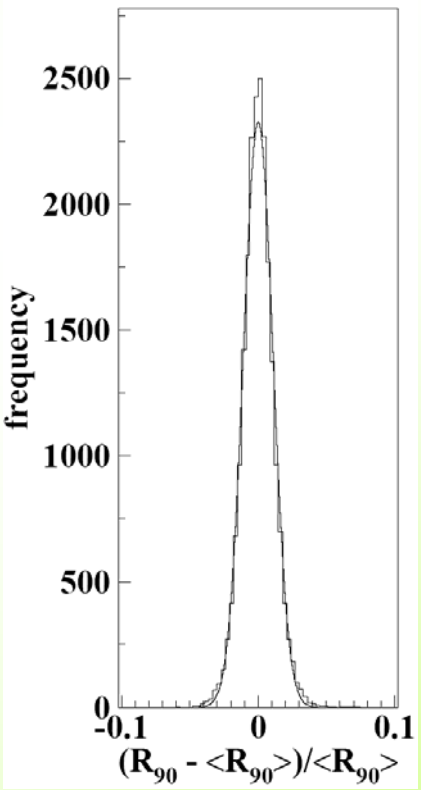
Rate behaviour above 6 keV

- **No Modulation above 6 keV**



Mod. Ampl. (6-10 keV): cpd/kg/keV
(0.0016 ± 0.0031) DAMA/LIBRA-1
-(0.0010 ± 0.0034) DAMA/LIBRA-2
-(0.0001 ± 0.0031) DAMA/LIBRA-3
-(0.0006 ± 0.0029) DAMA/LIBRA-4
-(0.0021 ± 0.0026) DAMA/LIBRA-5
(0.0029 ± 0.0025) DAMA/LIBRA-6
→ statistically consistent with zero

DAMALIBRA-1 to -6



$\sigma \approx 1\%$, fully accounted by statistical considerations

- **No modulation in the whole energy spectrum:** studying integral rate at higher energy, R_{90}
  - R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods
  - Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:

consistent with zero

Period	Mod. Ampl.
DAMA/LIBRA-1	-(0.05±0.19) cpd/kg
DAMA/LIBRA-2	-(0.12±0.19) cpd/kg
DAMA/LIBRA-3	-(0.13±0.18) cpd/kg
DAMA/LIBRA-4	(0.15±0.17) cpd/kg
DAMA/LIBRA-5	(0.20±0.18) cpd/kg
DAMA/LIBRA-6	-(0.20±0.16) cpd/kg

+ 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

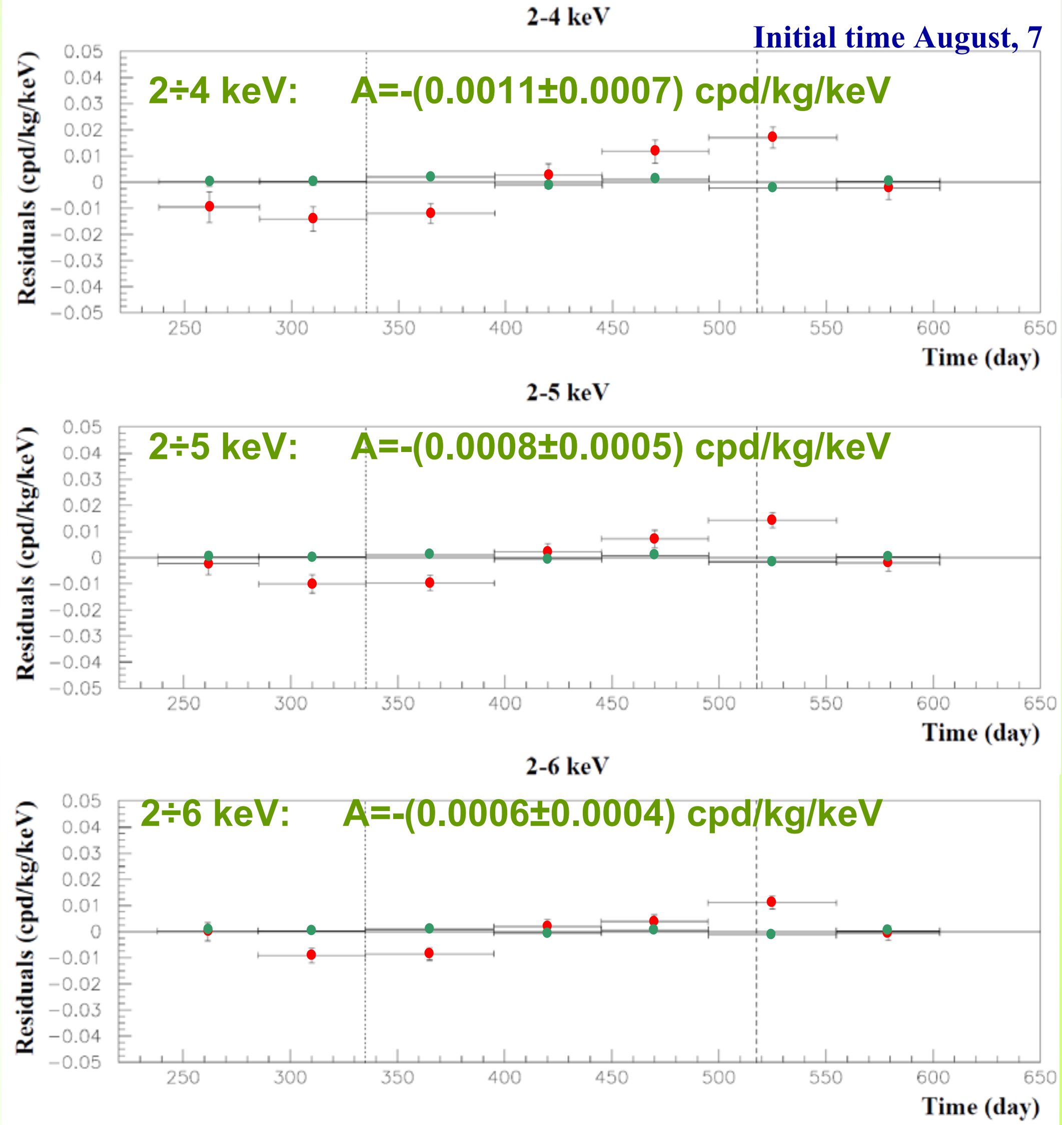
No modulation above 6 keV
This accounts for all sources of bckg and is consistent with studies on the various components

Multiple-hits events in the region of the signal, DAMA/LIBRA 1-6

- Each detector has its own TDs read-out → pulse profiles of multiple-hits events (multiplicity > 1) acquired (exposure: 0.87 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

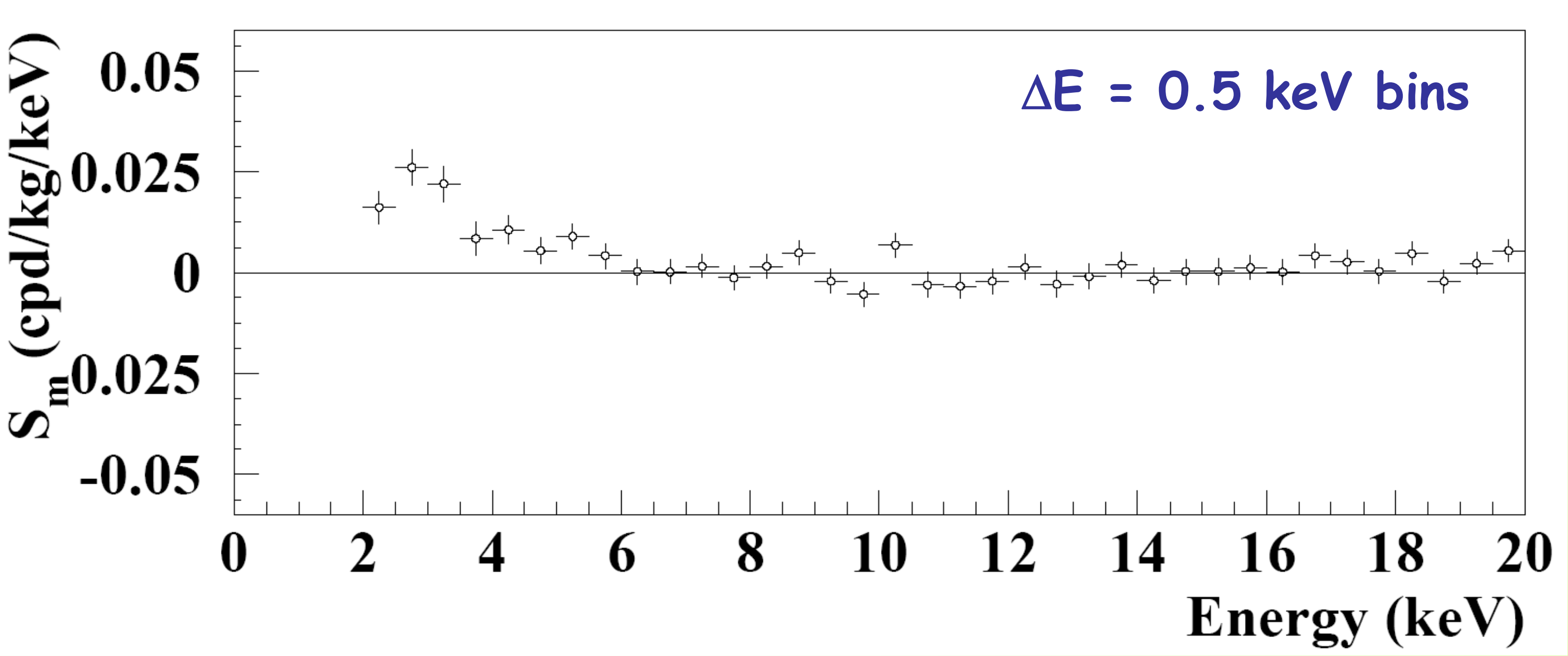
Energy distribution of the modulation amplitudes

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

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

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

total exposure: 425428 kg×day ≈1.17 ton×yr



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

The S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom

Statistical distributions of the modulation amplitudes (S_m)

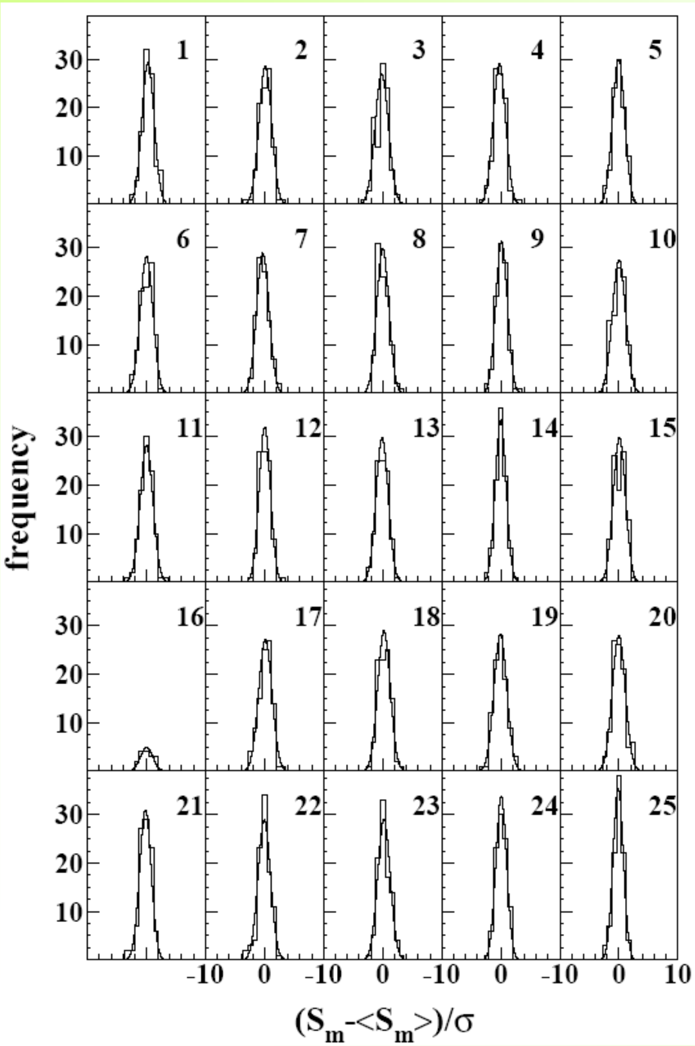
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

b) $<S_m>$ = mean values over the detectors and the annual cycles for each energy bin; σ = error associated to the S_m

DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr

Each panel refers to each detector separately; 96 entries = 16 energy bins in 2-6 keV energy interval × 6 DAMA/LIBRA annual cycles (for crys 16, 1 annual cycle, 16 entries)

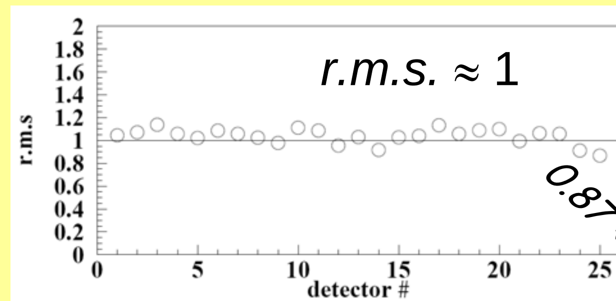


2-6 keV

Standard deviations of the variable

$(Sm-\langle Sm\rangle)/\sigma$

for the DAMA/LIBRA detectors



0.87 < r.m.s. < 1.14

$x=(S_m-<S_m>)/\sigma,$

$\chi^2=\Sigma x^2$

Individual S_m values follow a normal distribution since $(S_m-<S_m>)/\sigma$ 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)

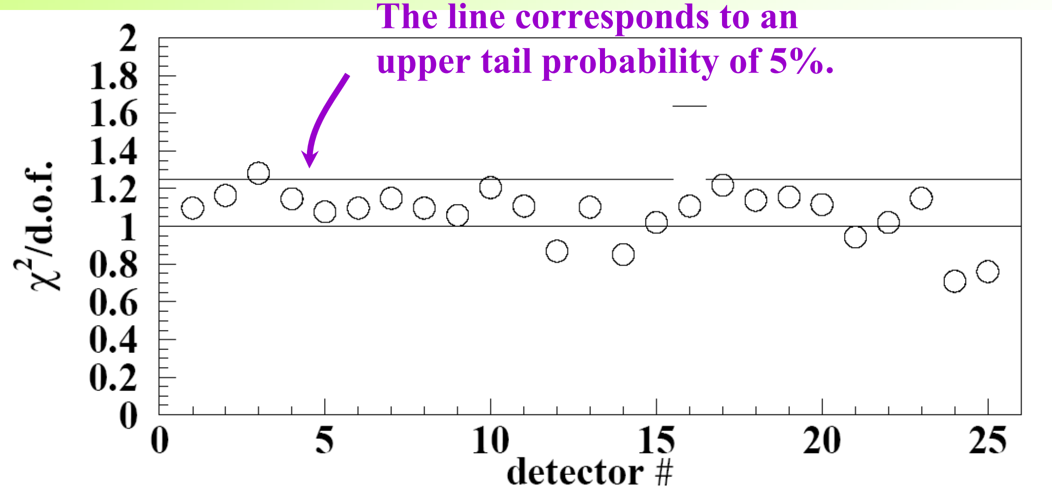
$x=(S_m-\langle S_m\rangle)/\sigma$,

$\chi^2=\Sigma x^2$

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

DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr



The $\chi^2/d.o.f.$ values range from 0.7 to 1.22 (96 *d.o.f.* = 16 energy bins × 6 annual cycles) for 24 detectors ⇒ at 95% C.L. the observed annual modulation effect is well distributed in all these detectors.

The remaining detector has $\chi^2/d.o.f.$ = 1.28 exceeding the value corresponding to that C.L.; this also is statistically consistent, considering that the expected number of detectors exceeding this value over 25 is 1.25.

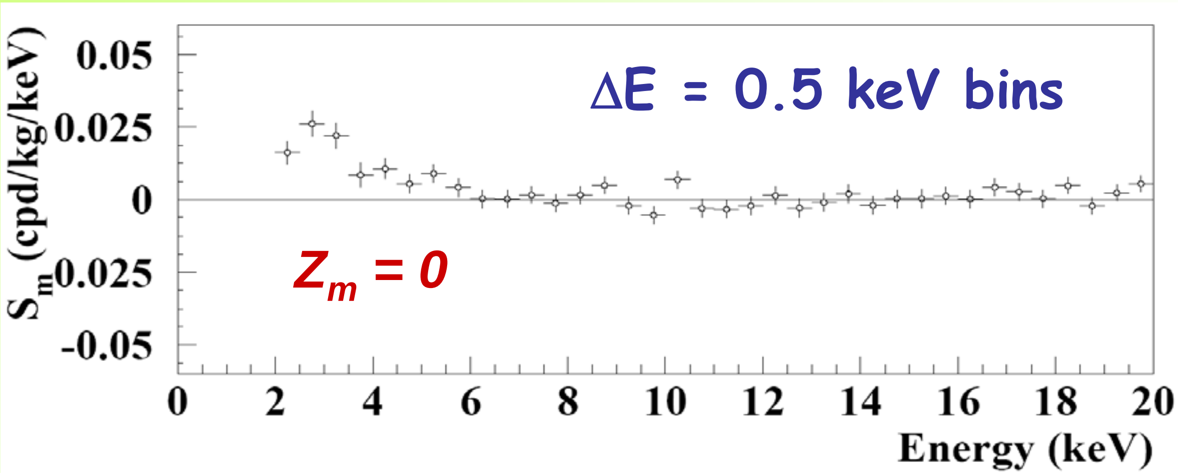
- The mean value of the twenty-five points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 4\times10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 5\times10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (**≤ 4 %** or **≤ 0.5%**, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

Energy distributions of cosine (S_m) and sine (Z_m) modulation amplitudes

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

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

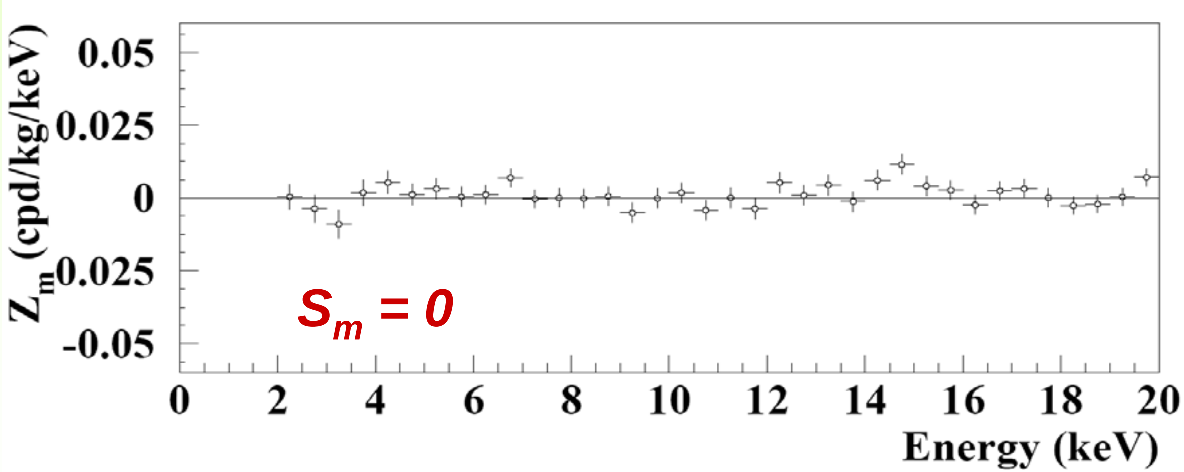
total exposure: 425428 kg×day = 1.17 ton×yr



***t_0 = 152.5 day* (2° June)**

***maximum at* 2° June**

as for DM particles



***maximum at* 1° September**

***T/4* days after 2° June**

The χ^2 test in the (2-14) keV and (2-20) keV energy regions (χ^2/dof = 21.6/24 and 47.1/36, probabilities of 60% and 10%, respectively) supports the hypothesis that the $Z_{m,k}$ values are simply fluctuating around zero.

Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

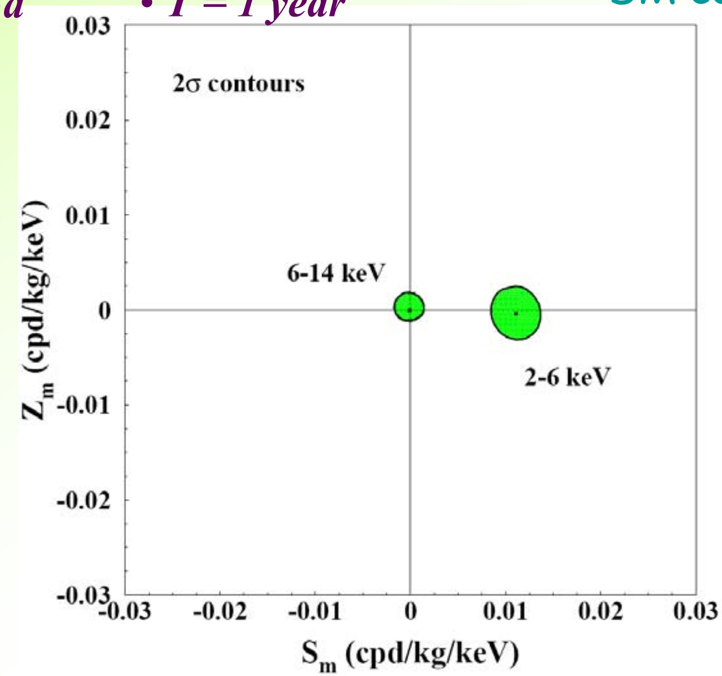
total exposure: 425428 kg×day = 1.17 ton×yr

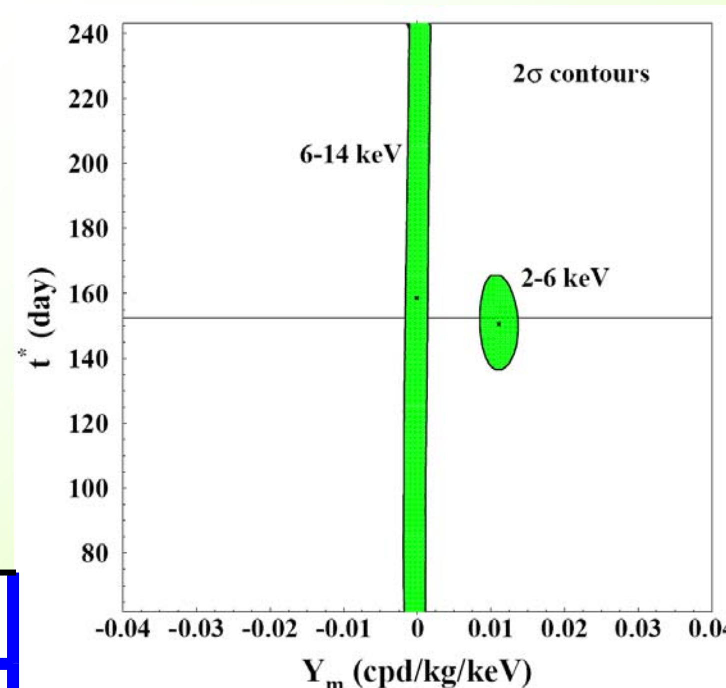
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $t^* \approx t_0 = 152.5d$
- $\omega = 2\pi/T$
- $T = 1$ 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	0.0111 ± 0.0013	-0.0004 ± 0.0014	0.0111 ± 0.0013	150.5 ± 7.0
6-14	-0.0001 ± 0.0008	0.0002 ± 0.0005	-0.0001 ± 0.0008	--

Phase as function of energy

$$R(t) = S_0 + Y_m \cos\left[\omega\left(t - t^*\right)\right]$$

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

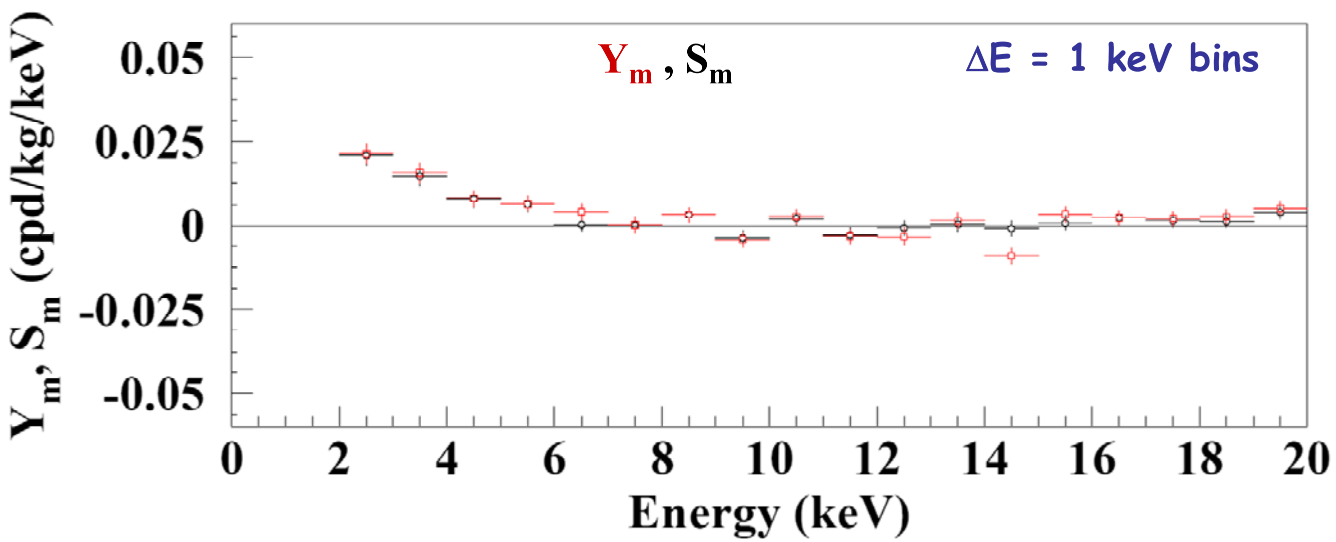
total exposure: 425428 kg×day = 1.17 ton×yr

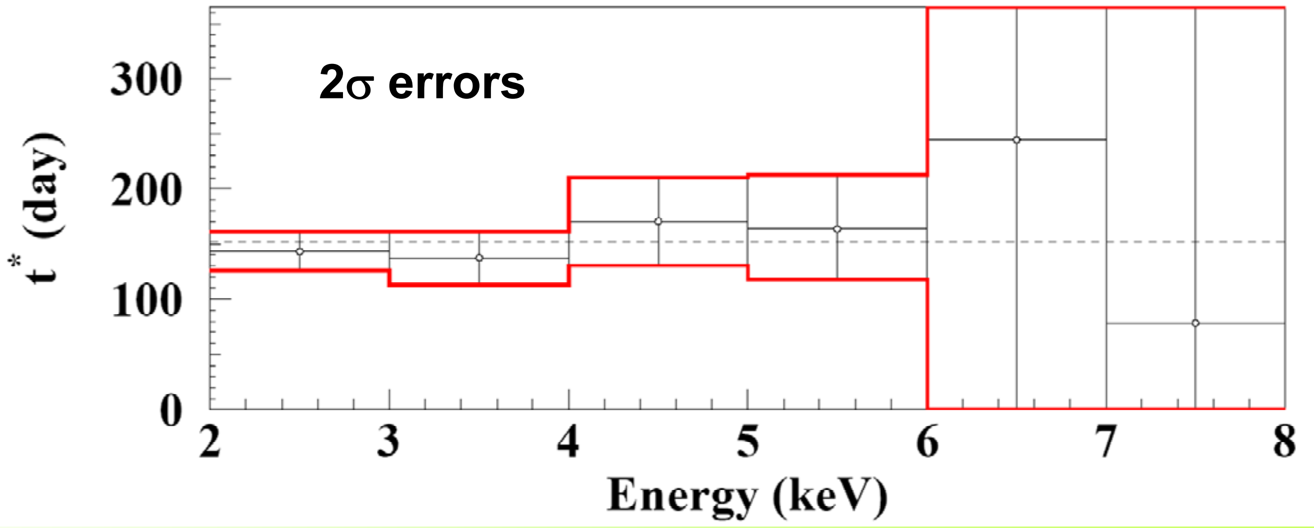
For DM signals:

$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

$\omega = 2\pi/T; \quad T = 1\ year$

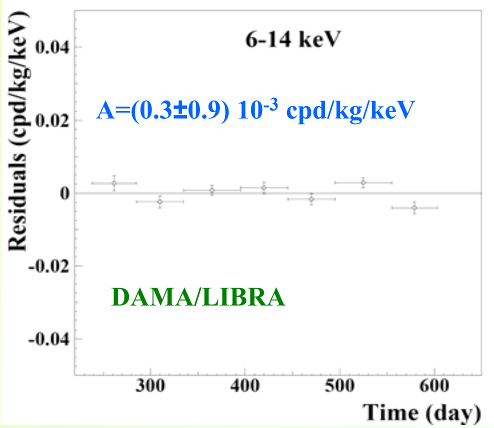




Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as the SagDEG stream)

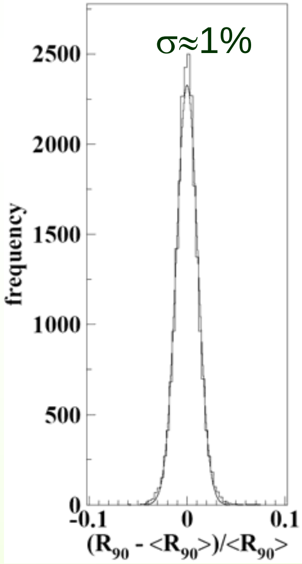
Summarizing on a hypothetical background modulation in DAMA/LIBRA 1-6

- **No Modulation above 6 keV**

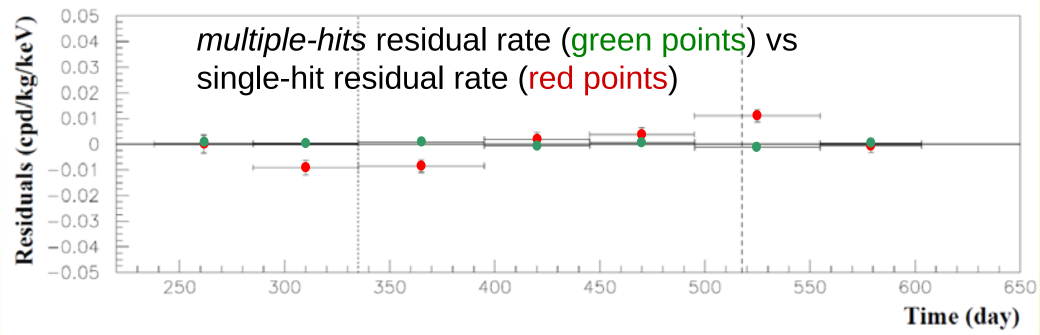


- **No modulation in the whole energy spectrum**

+ 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



- **No modulation in the 2-6 keV *multiple-hits* residual rate**



No background modulation (and cannot mimic the signature): all this accounts for the all possible sources of bckg

Nevertheless, additional investigations performed ...

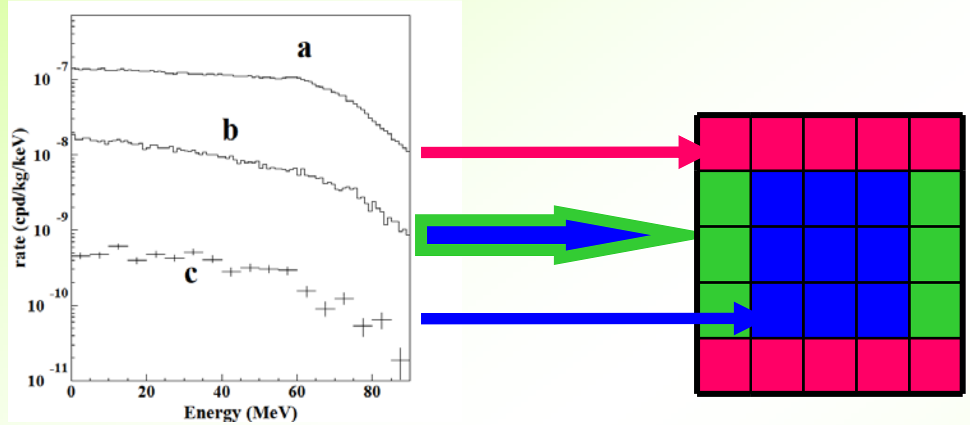
Three examples for specific cases in the following:

1. The muon case
2. The ^{40}K case
3. The neutron case

The μ case

MonteCarlo simulation
- muon intensity distribution
- Gran Sasso rock overburden map

events where just one detector fires



Case of fast neutrons produced by μ

Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±2% modulated)
Measured neutron Yield @ LNGS: Y=1÷7 10^{-4} n/μ/(g/cm^2)
R_n = (fast n by μ)/(time unit) = Φ_μ Y M_{eff}

Annual modulation amplitude at low energy due to μ modulation:

$$S_m^{(\mu)} = R_n\ g\ \varepsilon\ f_{\Delta E}\ f_{single}\ 2\% / (M_{setup}\ \Delta E)$$

g = geometrical factor; ε = detection effic. by elastic scattering
$f_{\Delta E}$ = energy window (E>2keV) effic.; f_{single} = single hit effic.

Hyp.: M_{eff} = 15 tons; g ≈ ε ≈ $f_{\Delta E}$ ≈ f_{single} ≈ 0.5 (cautiously)
Knowing that: M_{setup} ≈ 250 kg and ΔE=4keV

→ **$S_m^{(\mu)} < (0.4 \div 3) \times 10^{-5}$ cpd/kg/keV**

Moreover, this modulation also induces a variation in other parts of the energy spectrum
It cannot mimic the signature: already excluded also by R_{90} + different phase, etc.

Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:
- only events at low energy,
- only *single-hit* events,
- no sizable effect in the *multiple-hit* counting rate?

?

But, its phase should be (much) larger than μ phase, t_μ :

- if $\tau \ll T/2\pi$: $t_{side} = t_\mu + \tau$
- if $\tau \gg T/2\pi$: $t_{side} = t_\mu + T/4$

The muon flux at LNGS (≈ 20 μ m^{-2} d^{-1}) is yearly modulated (±2%) with phase roughly around middle of July and largely variable from year to year. Last meas. by LVD partially overlapped with DAMA/NaI and fully with DAMA/LIBRA: 1.5% modulation and phase=July 5th ± 15 d.

→ DAMA/NaI + DAMA/LIBRA
measured a stable phase: May, 26th ± 7 days

This phase is 7.3 σ far from July 15th and is 5.9 σ far from July 5th

NO

No role for ^{40}K in the S_m spectrum

see arXiv:0912.0660

not evidence for any 3 keV peak in the S_m distribution. Behaviour compatible with a **monotonic behaviour** and with a **"structure"** as expected for many Dark Matter candidates (also for WIMP)

^{40}K decay cannot give any modulation, unless evoking new exotic physics.

No modulation has been observed in other energy regions where ^{40}K decay contributes

No modulation in multiple-hit events in 2-6 keV (^{40}K can give double events in two adjacent detectors and multi-site events due to Compton scatterings)

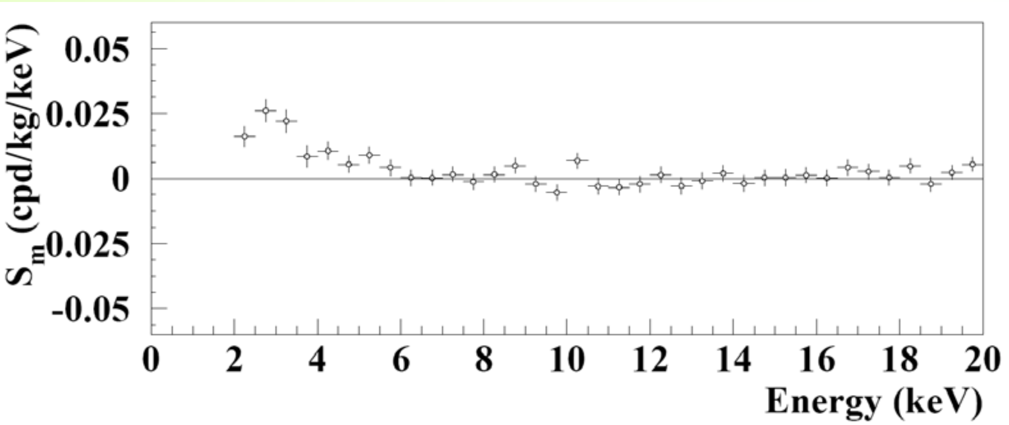
No modulation of the **double coincidence events**, 1461 keV-3 keV

The annual modulation signal is present in the outer and in the inner detectors.

(no dependence on the veto capability, that is different – for geometrical reasons – among the detectors)

Stability of efficiency

The annual modulation signal is equally distributed over all the detectors



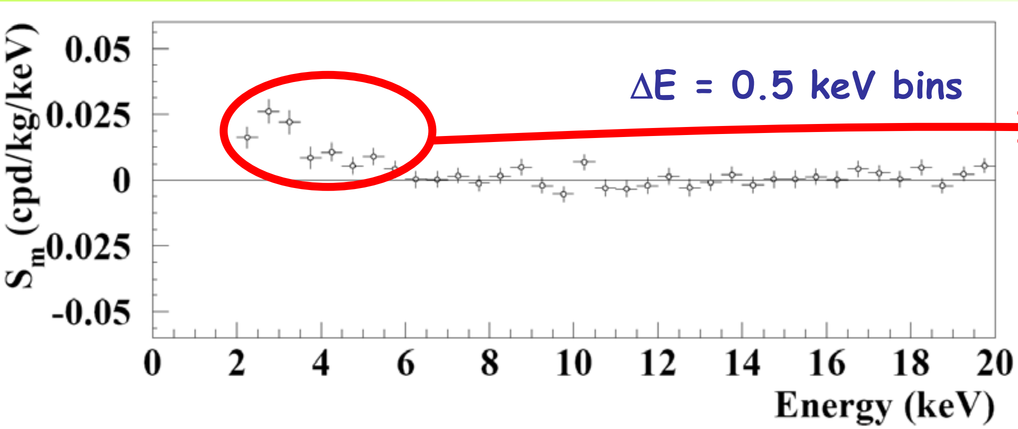
The analysis of the double coincidences rules out at more than 10 σ any modulation around 3 keV in the *single-hit* events from the hypothetical cases of : i) ^{40}K "exotic" modulation decay; ii) spill-out from double to single events and viceversa.

Even assuming the arXiv:0808.3283 scenario:

- the expected single hit modulation amplitude would be much below the measured modulation amplitude
- the phase (3 jan) would be well different from the measured phase (26 may±7 day).

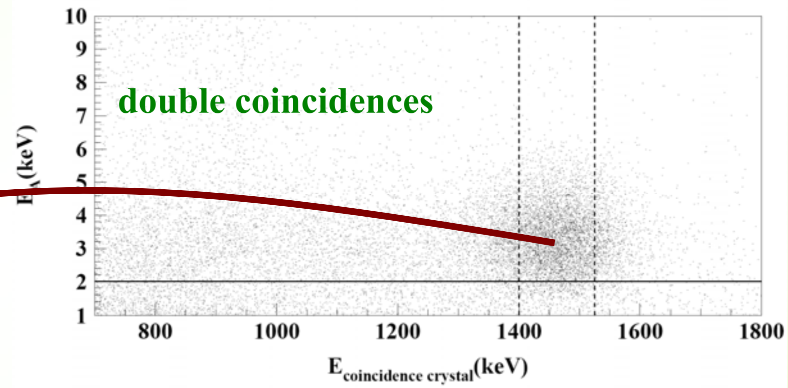
No role for ^{40}K in the experimental S_m

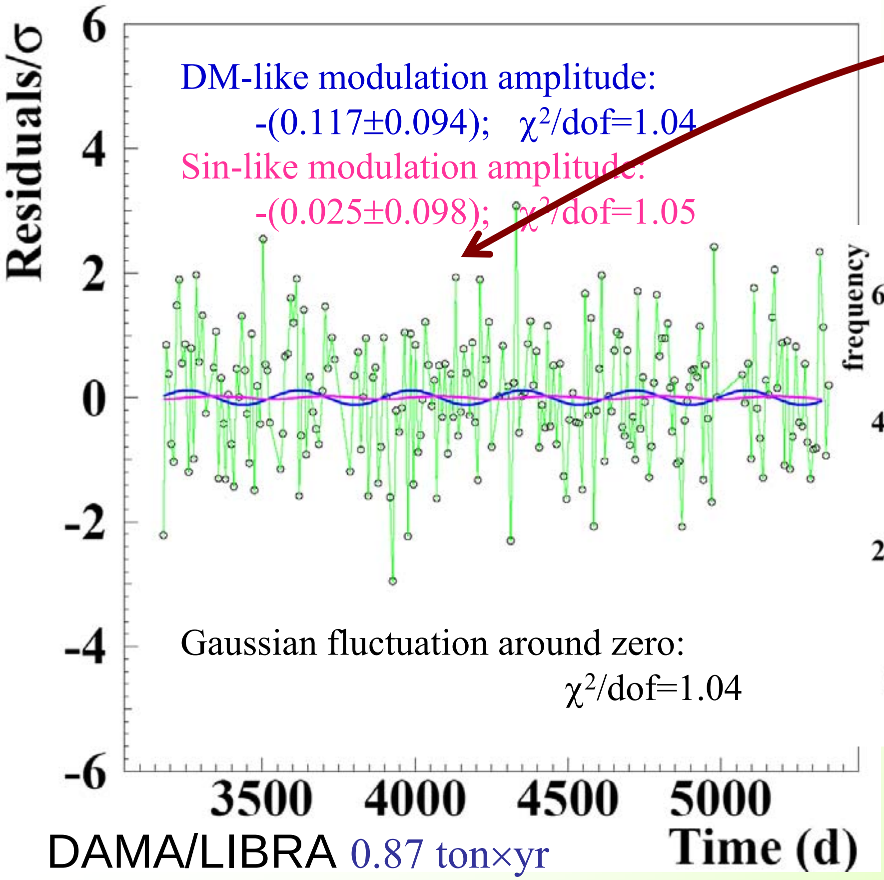
also see arXiv:0912.0660

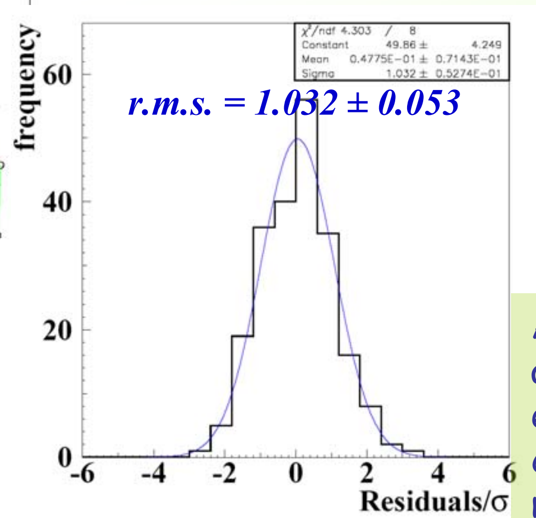


The experimental S_m cannot be due to ^{40}K for many reasons.

No modulation of the double coincidence events (1461 keV-3 keV).







The ^{40}K double coincidence events are not modulated

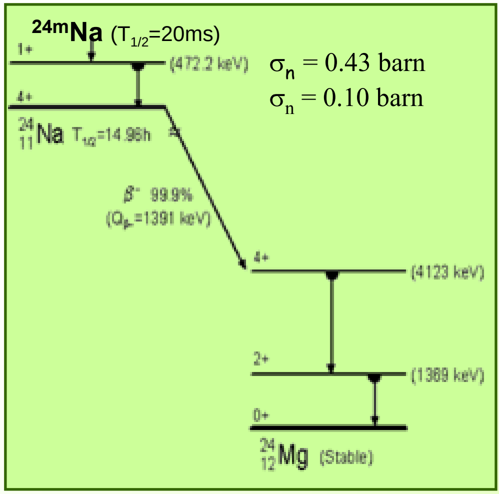
Any modulation contribution around 3 keV in the single-hit events from the hypothetical cases of: i) ^{40}K "exotic" modulated decay; ii) spill-out effects from double to single events and viceversa, is ruled out at more than 10 σ

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

NO

- Thermal neutrons flux measured at LNGS :

  $\Phi_n = 1.08\ 10^{-6}$ n cm^{-2} s^{-1} (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:

    $\Phi_n < 1.2 \times 10^{-7}$ n cm^{-2} s^{-1} (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 captures/day/kg

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

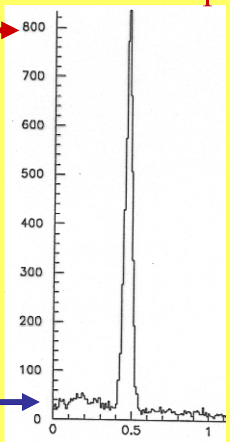
$S_m^{(\text{thermal n})} < 0.8 \times 10^{-6}$ cpd/kg/keV (< 0.01% S_m^{observed})

MC simulation of the process

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

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

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



E (MeV)

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

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

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

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

- **Experimental upper limit on the fast neutrons flux "*surviving*" the neutron shield in DAMA/LIBRA:**
  - through the study of the inelastic reaction ^{23}Na(n,n′)^{23}Na*(2076 keV) which produces two γ's in coincidence (1636 keV and 440 keV):

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

  - 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 accompained 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

Summary of the results obtained in the additional investigations of possible systematics or side reactions: DAMA/LIBRA-1 to 6

(previous exposure and details see: NIMA592(2008)297, EPJC56(2008)333, arXiv:0912.4200)

Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ 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 + instrinsic calibrations	**$<1\text{-}2\times10^{-4}$ 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 *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect

Summarizing

- Presence of modulation for 13 annual cycles at 8.9σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 13 independent experiments of 1 year each one
- The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.17 ton × yr (13 annual cycles)
- In fact, as required by the DM annual modulation signature:

1) **The *single-hit* events show a clear cosine-like modulation, <u>as expected for the DM signal</u>**

2) **Measured period is equal to (0.999±0.002) yr, well compatible with the 1 yr period, <u>as expected for the DM signal</u>**

3) **Measured phase (146±7) days is well compatible with the roughly about 152.5 days <u>as expected for the DM signal</u>**

4) **The modulation is present only in the low energy (2—6) keV energy interval and not in other higher energy regions, <u>consistently with expectation for the DM signal</u>**

5) **The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones <u>as expected for the DM signal</u>**

6) **The measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2-6) keV energy interval is: (0.0116±0.0013) cpd/kg/keV (8.9σ C.L.).**

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

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

well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

No other experiment whose result can be directly compared in model independent way with those of DAMA/NaI and DAMA/LIBRA available

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

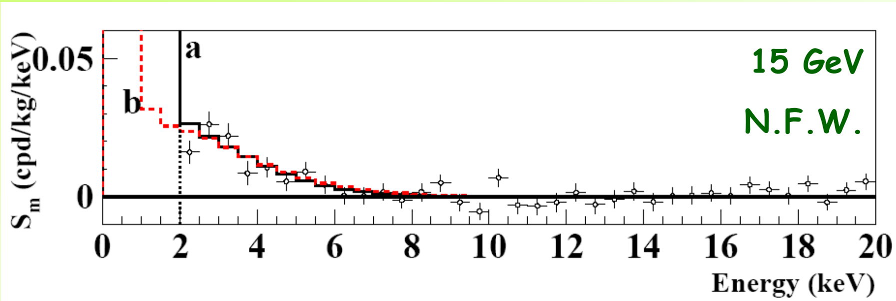
Possible model dependent positive hints from indirect searches not in conflict with DAMA; but interpretation and the evidence itself depend e.g. on bckg modeling (also including pulsars, supernovae remnants, ...), on DM spatial velocity distribution, either on forced boost factor or on unnatural clumpiness, etc.

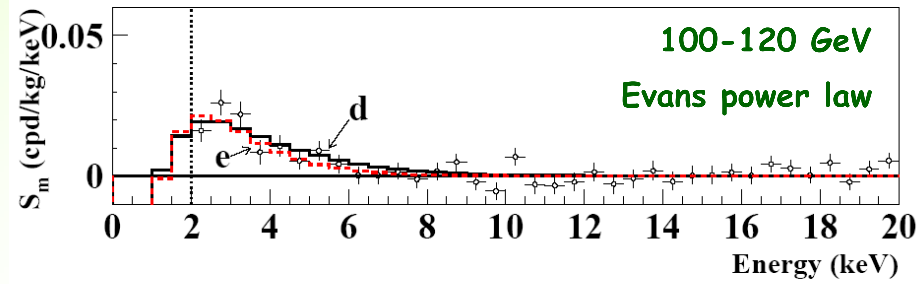
Moreover, some possible hints from direct searches must be interpreted; in any case large room of compatibility with DAMA is present

Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

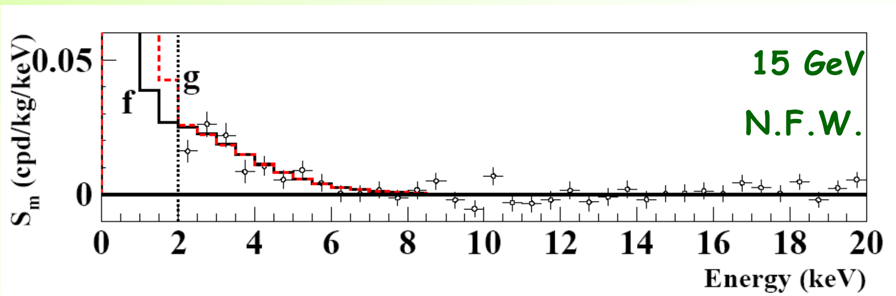
- Not best fit
- About the same C.L.

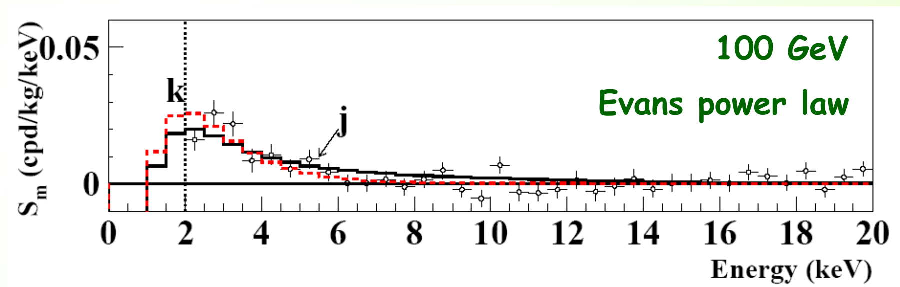
WIMP: SI



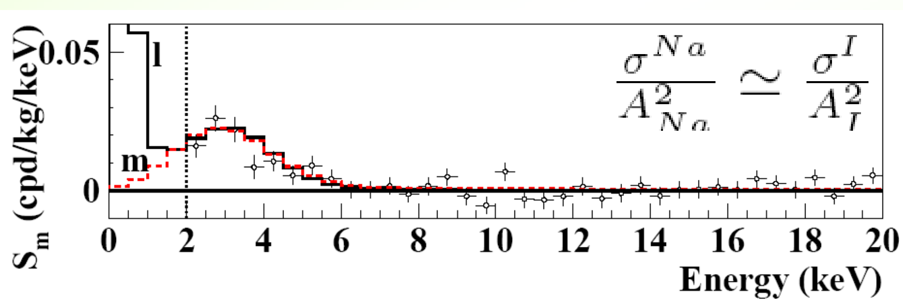


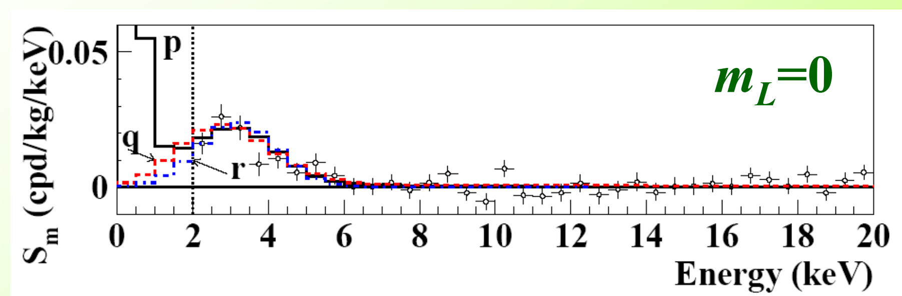
WIMP: SI & SD $\theta = 2.435$





LDM, bosonic DM





EPJC56(2008)333

Compatibility with several candidates; other ones are open

About interpretation

Exclusion plots are **model-dependent**: selecting just one model framework by fixing many parameters and by adopting several (astrophysical, nuclear and particle physics) assumptions

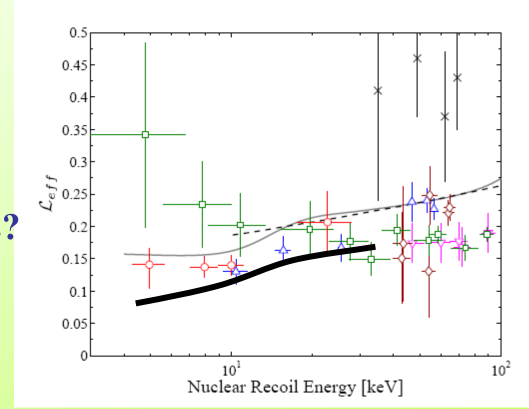
- **which particle?**
- **which interaction couplings?**
- **which Form Factors for each target-material?**
- **which Spin Factors?**
- **which nuclear model framework?**
- **which scaling laws?**
- **which halo model, profile and parameters?**
- **is there a presence of non-thermalized components in the halo parameters?**
- **which velocity distribution?**
- **which parameters for velocity distribution?**
- **which instrumental quantities?**
- **...**

Exclusion plots have no "universal validity" (they depend on the recipe)

… and experimental aspects …

- **Marginal and "selected" exposures**
- **Threshold, small detector response (few phe/keV), energy scale and energy resolution; calibrations in other energy region. Stability of all the operating conditions.**
- **Selections of detectors and of data**
- **Handling of (many) "subtraction" procedures and stability in time of all the selection windows and related quantities, etc. Efficiencies**
- **Fiducial volume vs disuniformity of detector, response in liquids?**
- **Used values in the calculation (q.f., etc.)**
- **Used approximations**
- **...**

For example, which L_{eff} in liquid Xenon experiments? arXiv:0909.1063



No experiment can be directly compared in model independent way with DAMA

Perspectives of DAMA/LIBRA

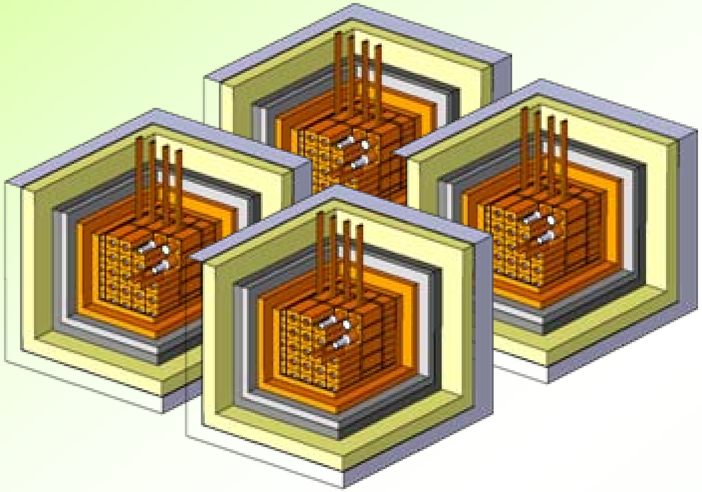
- Continuously running
- *Next upgrade*: replacement of all the PMTs with higher Quantum Efficiency (Q.E.) PMTs.
- New PMTs with higher Q.E. in production: 16 prototypes already tested; five of them have been accepted; 4 new prototypes at hand now
- Continuing data taking for many years in the new configuration.
- Special data taking for other rare processes.
- Update corollary analyses with the new data to disentangle among the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..

- Goals:
  - lowering the energy threshold (presently, at 2 keV)
  - improvement of the acceptance efficiency
  - increase 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

Towards possible DAMA/1ton: now at R&D stage

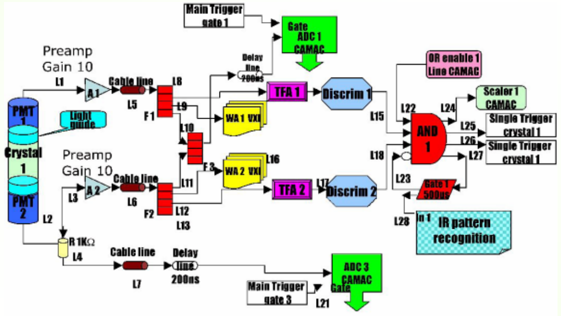
1) Proposed since 1996 (DAMA/NaI and DAMA/LIBRA intermediate steps)
2) Technology largely at hand (large experiences and fruitful collaborations among INFN and companies/industries)
3) Still room for further improvements in the low-background characteristics of the set-up (NaI(Tl) crystals, PMTs, shields, etc.)
4) 1 ton detector: the cheapest, the highest duty cycle, the clear signature, fast realization in few years

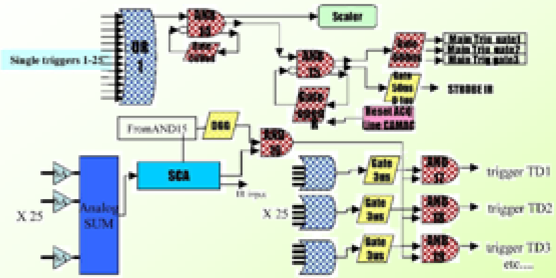
A possible design: DAMA/1 ton can be realized by four replicas of DAMA/LIBRA:



- the detectors could be of similar size than those already used
- the features of low-radioactivity of the set-up and of all the used materials would be assured by many years of experience in the field
- electronic chain and controls would profit by the previous experience and by the use of compact devices already developopped, tested and used.
- new digitizers will offer high expandibility and high performances
- the daq can be a replica of that of DAMA/LIBRA

Collaboration and outlook in Appec data sheet





- R&Ds on PMTs and crystals in progress
- detector prototypes ready for measurements

Electronic chain and example of the trigger system

Program of DAMA/LIBRA, DAMA/1ton and DAMA/10ton set-ups in incoming years

Goals of high-mass and high-sensitivity NaI detector:

- Extremely high C.L. for the model independent signal
- Highly precise determination of all the modulation parameters (possible dependence of the phase on energy, ...)
- Model independent investigation on other peculiarities of the signal
- High exposure: investigation & test of different astrophysical, nuclear, particle physics models

Increasing the competitiveness in DM investigation with respect to DAMA/LIBRA

- **Further investigation on Dark Matter candidates (further on neutralino, bosonic DM, mirror DM, inelastic DM, neutrino of 4th family, etc.):**

✓ **high exposure can better disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, particle conversion processes, …, form factors, spin-factors and more on new scenarios)**

✓ **scaling laws and cross sections**

✓ **multi-component DM particles halo?**

+

- **Further investigation on astrophysical models:**

✓ **velocity and position distribution of DM particles in the galactic halo**

✓ **effects due to:**

i. **satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";**
ii. **caustics in the halo;**
iii. **gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");**
iv. **possible structures as small scale size clumpiness;**

Also high sensitivities investigation on other rare processes: *possible PEP violating processes, various possible CNC processes in ^{23}Na and ^{127}I, nucleon and di-nucleon decay into invisible channels with new approach in ^{23}Na and ^{127}I, exotic particles (e.g. SIMPs, neutral nuclearities, Q-balls), solar axions by Primakoff effect in NaI(Tl), rare nuclear processes in ^{23}Na, ^{127}I, hypothesized neutral particles (new QED phase) in ^{241}Am decays, etc.*

... towards a 100 ton highly radiopure NaI(Tl) set-up for high-resolution full-spectroscopy solar neutrinos (Astrop.Phys.4(1995)45)

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo now supported at 8.9 σ C.L. by the cumulative 1.17 ton $\times$ yr exposure over 13 annual cycles by the former DAMA/NaI and the present DAMA/LIBRA
- The modulation parameters determined with better precision
- Full sensitivity to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation
- Updated/new model dependent corollary investigations on the nature of the DM particle in progress also in the light of some recent strongly model dependent claims
- Investigations other than DM

What next?

- Upgrade in fall 2010 substituting all the PMTs with new ones having higher Q.E. to lower the experimental energy threshold, improve general features and disentangle among at least some of the possible scenarios
- Collect a suitable exposure in the new running conditions
- Investigate second order effects
- R&D toward a 1 ton ULB NaI(Tl) set-up experiment proposed in 1996 as a further step for an ultimate multi-ton & multi-purpose NaI(Tl) experiment

Twenty years from now you will be more disappointed by the things that you didn't do than by the ones you did do [M. Twain]