The DAMA/LIBRA results

Light Dark Matter
University of California Davis
April 30-May 1 2010

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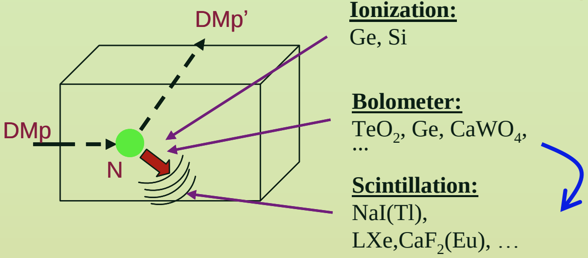
INFN - Roma

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, …

Scintillation:
NaI(Tl),
LXe, CaF_2(Eu), …

- 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

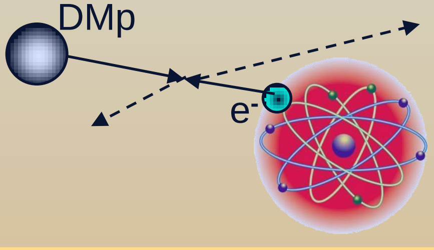
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

- Interaction only on atomic electrons

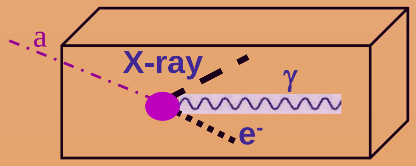
  → detection of e.m. radiation



… even WIMPs

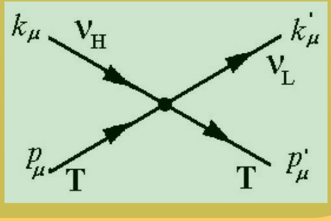
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



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

  → detection of electron/nucleus recoil energy



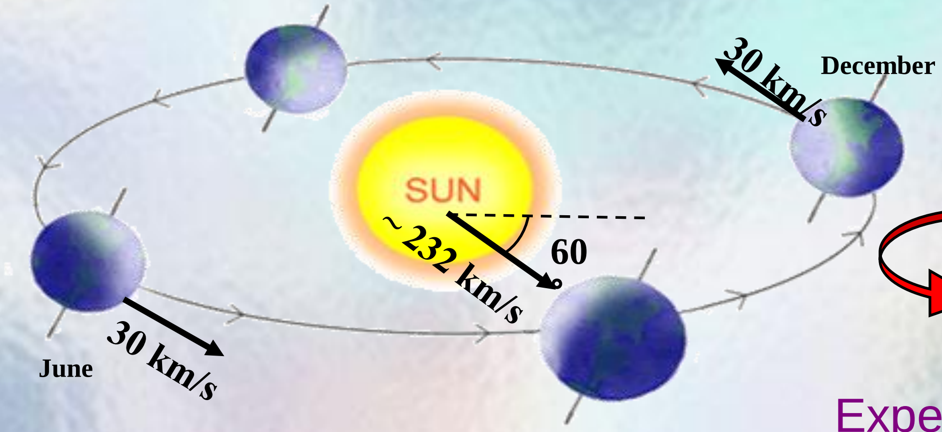
e.g. sterile ν

e.g. signals from these candidates are completely lost in experiments based on "rejection procedures" of the electromagnetic component of their counting rate

- **… and more**

Investigating the presence of a DM particle component in the galactic halo by the model independent annual modulation signature

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 of the Earth's motion around the Sun moving in the Galaxy

Requirements:

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 be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

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

Competitiveness of ULB NaI(Tl) set-up

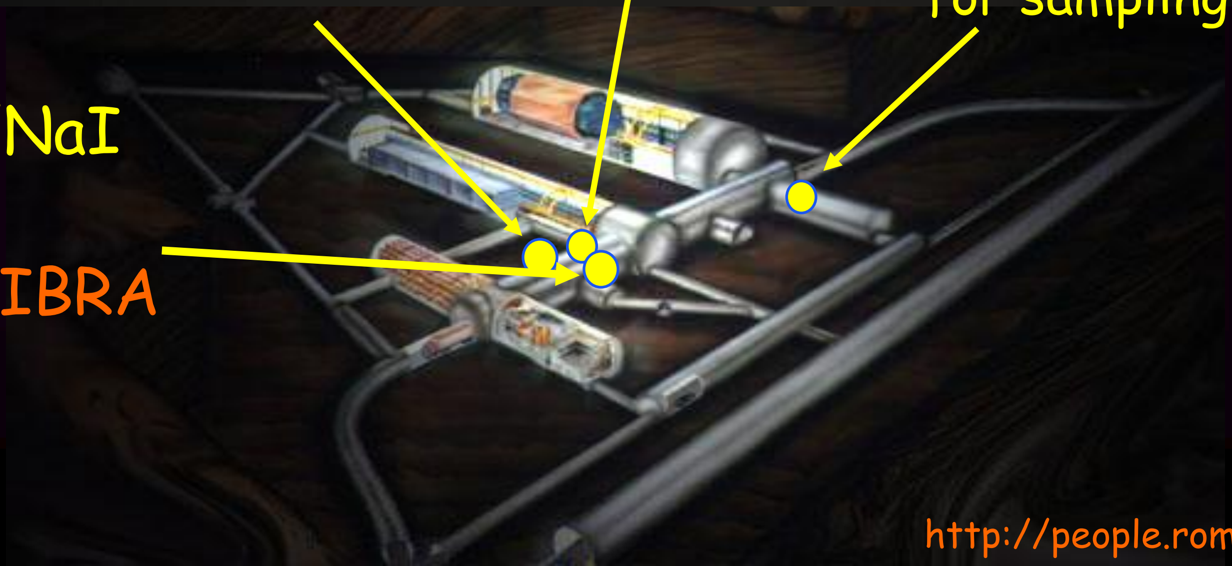
- Well known technology
- High duty cycle
- Large mass possible
- “Ecological clean” set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational 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.

A low background NaI(Tl) also allows the study of several other rare processes :
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

Roma2,Roma1,LNGS,IHEP/Beijing

DAMA: an observatory for rare processes @LNGS



DAMA/R&D

DAMA/LXe

low bckg DAMA/Ge
for sampling meas.

DAMA/NaI
↓
DAMA/LIBRA

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

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: total exposure (7 annual cycles) 0.29 ton x yr

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.

DAMA/LIBRA $\sim$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)

PMT
+HV
divider

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

etching staff at work in clean room

storing new crystals

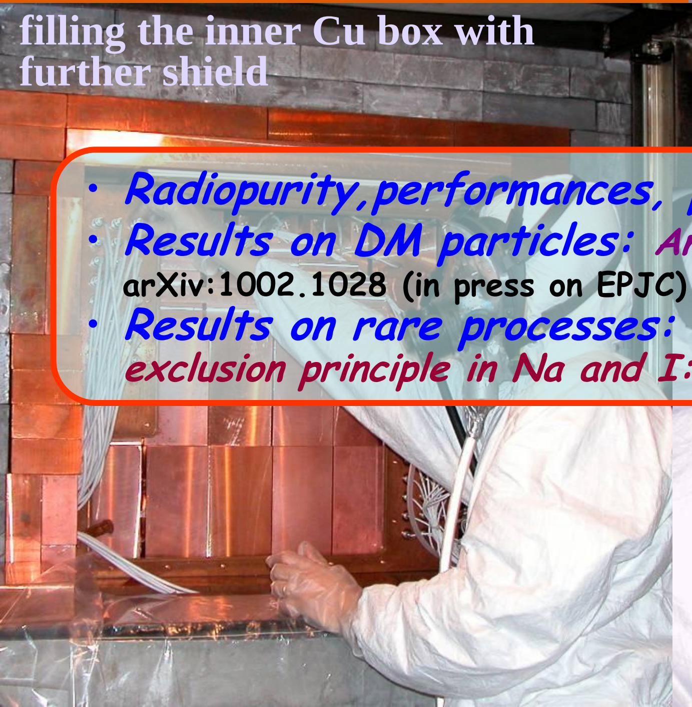
improving installation and environment

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

installing DAMA/LIBRA detectors

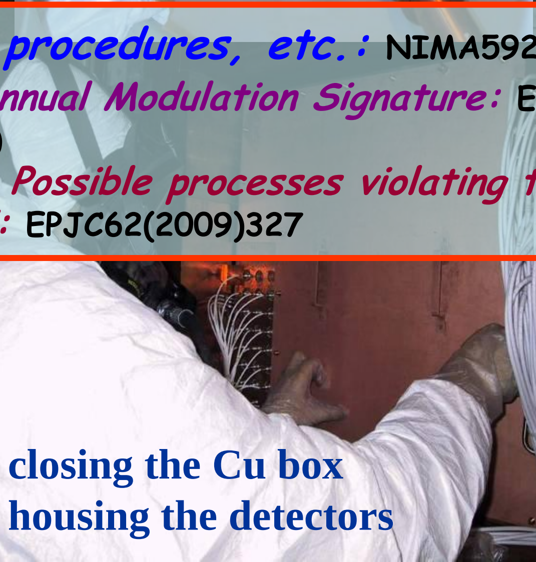
assembling a DAMA/ LIBRA detector

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

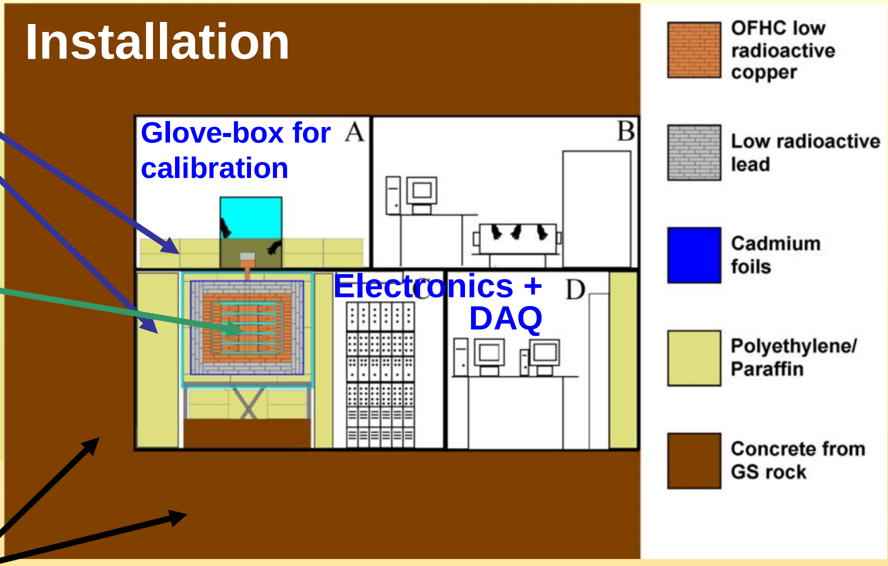
The DAMA/LIBRA set-up

For details, radiopurity,performances, procedures, etc.
see 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

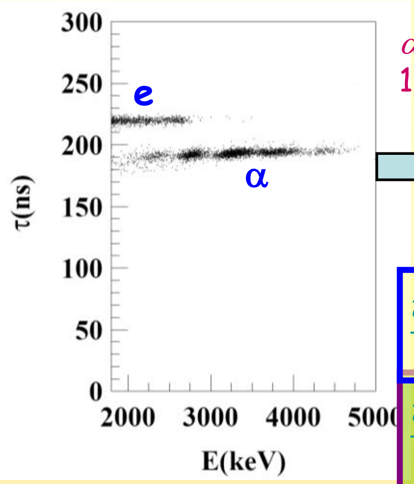
~ 1m concrete from GS rock



- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield
- 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 *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

The calibration system

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 α/kg/keV

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

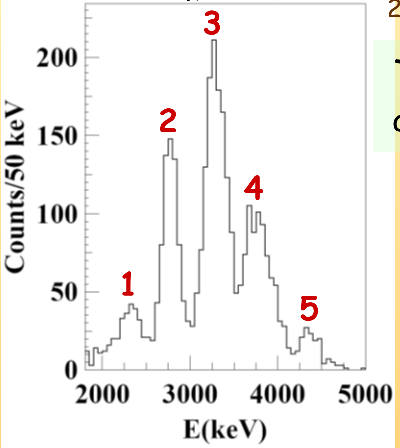
^{232}Th residual contamination

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



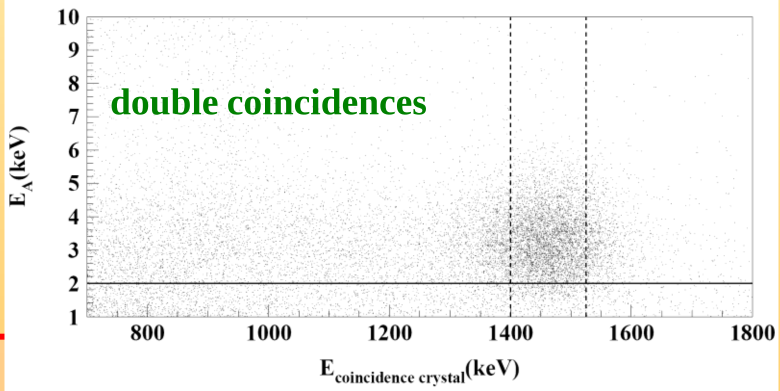
^{238}U chain splitted into 5 subchains: $^{238}\text{U} \rightarrow {}^{234}\text{U} \rightarrow {}^{230}\text{Th} \rightarrow {}^{226}\text{Ra} \rightarrow {}^{210}\text{Pb} \rightarrow {}^{206}\text{Pb}$

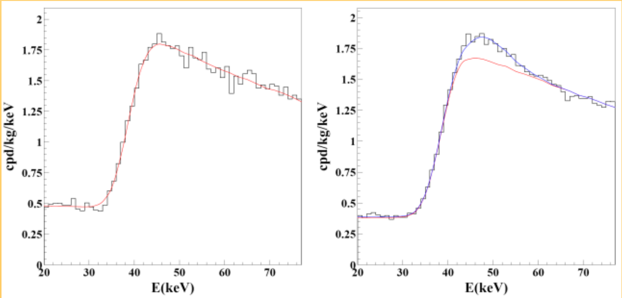
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

and: (15.8±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 ≈1.7×10^{-13} for all the new detectors

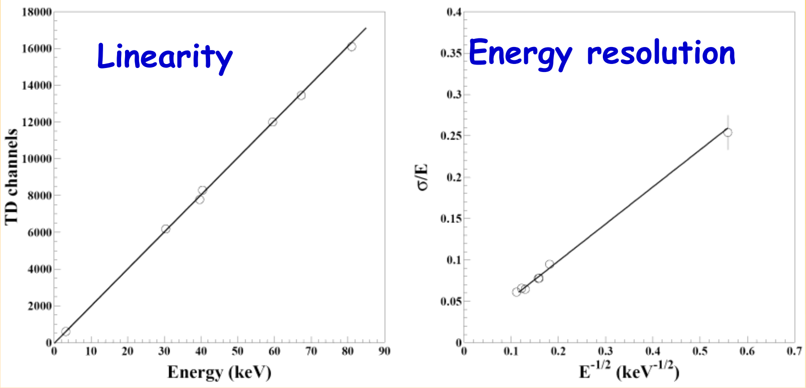
^{210}Pb in the new detectors: (5 – 30) μBq/kg.

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

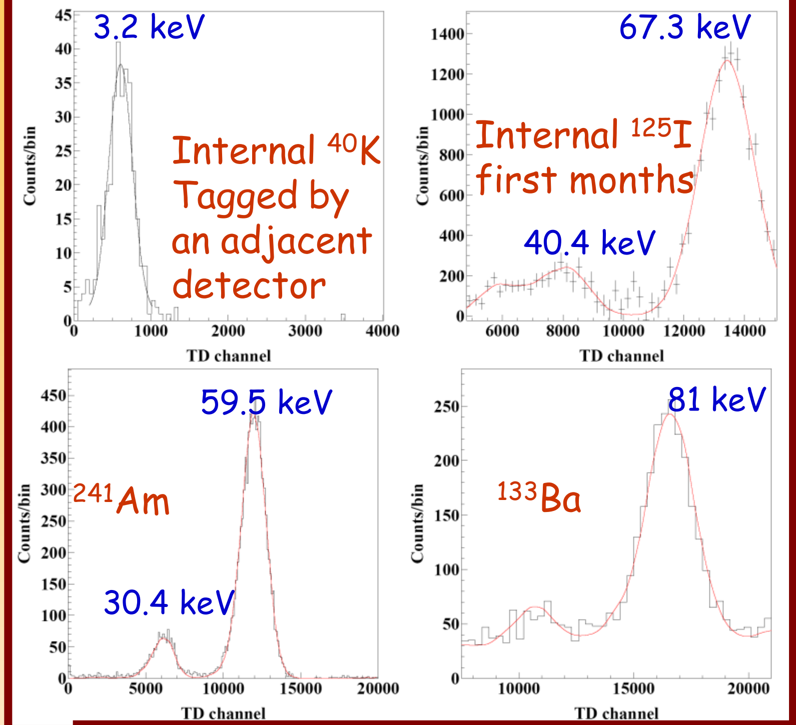
... more on NIMA592(2008)297

DAMA/LIBRA calibrations

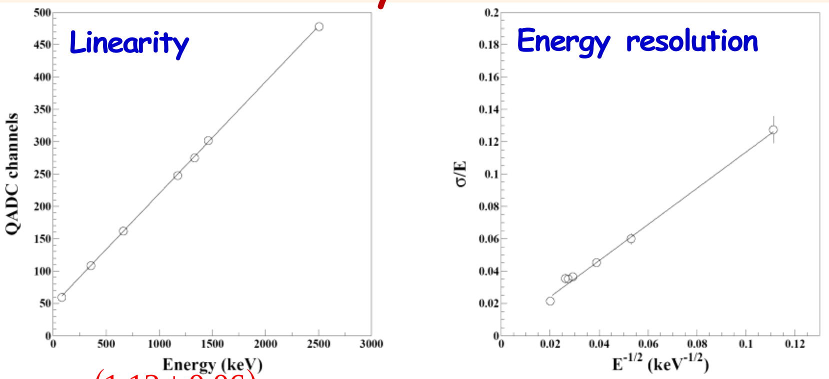
Low energy: various external γ sources (^{241}Am, ^{133}Ba) and internal X-rays or γ's (^{40}K, ^{125}I, ^{129}I), routine calibrations with ^{241}Am



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



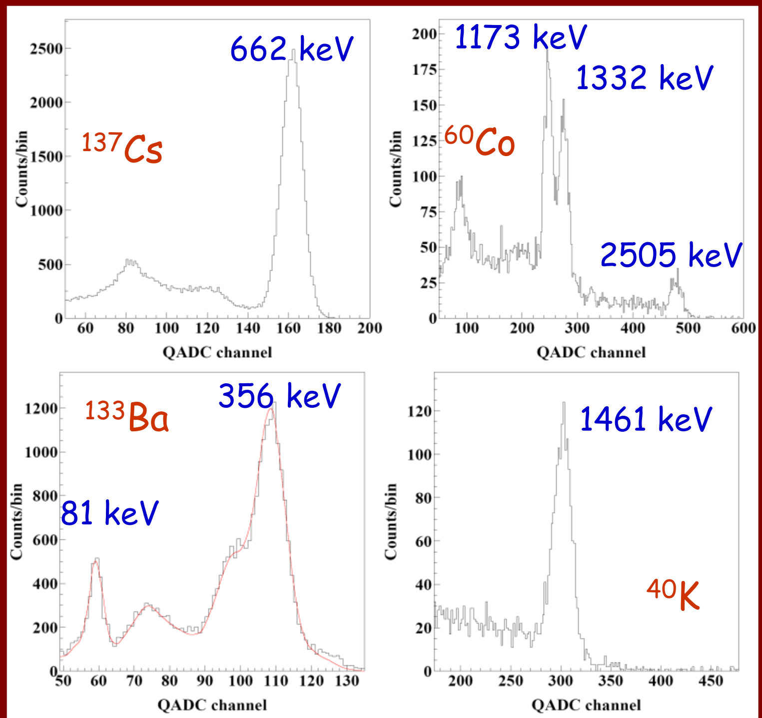
High energy: external sources of γ rays (e.g. ^{137}Cs, ^{60}Co and ^{133}Ba) and γ rays of 1461 keV due to ^{40}K decays in an adjacent detector, tagged by the 3.2 keV X-rays



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

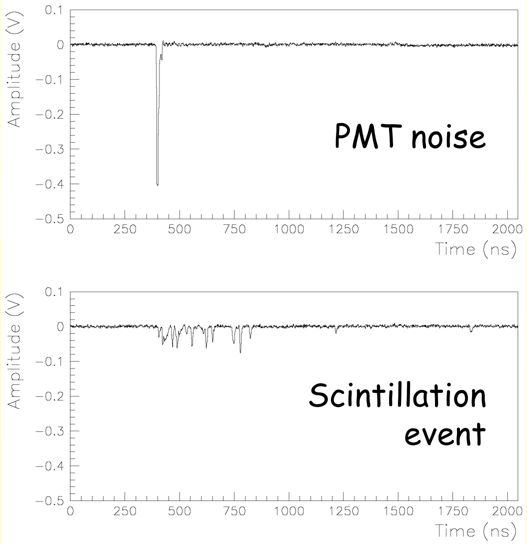
$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23)\cdot 10^{-4}$$

Thus, here and hereafter keV means keV electron equivalent

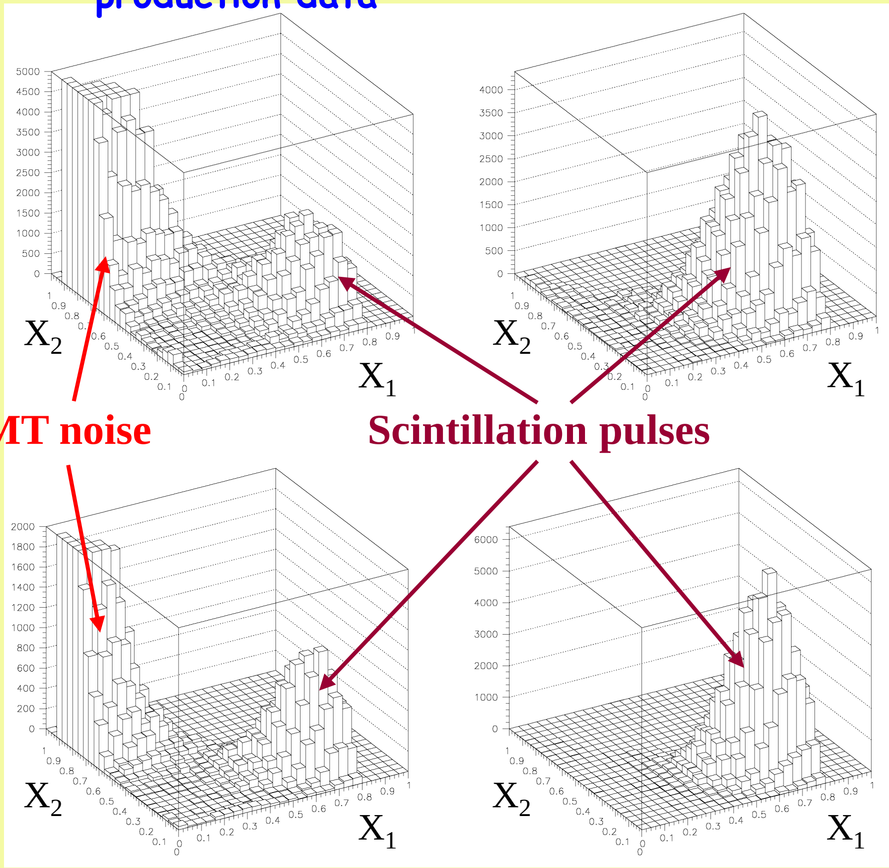


Noise rejection near the energy threshold

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



Single-hit production data

γ source

2-4 keV

4-6 keV

PMT noise

Scintillation pulses

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

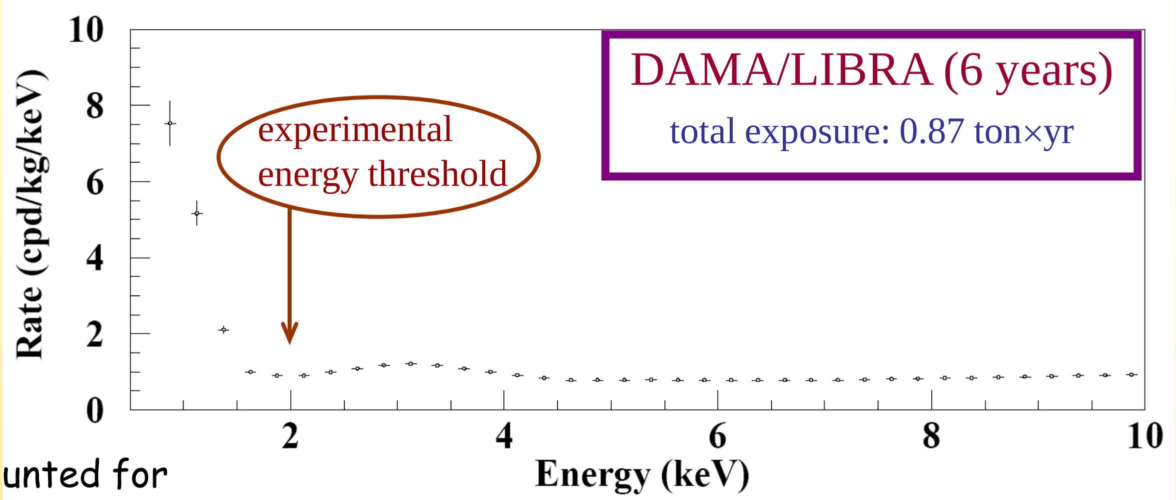
- **New upgrade foreseen on fall 2010**

... continuously running

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

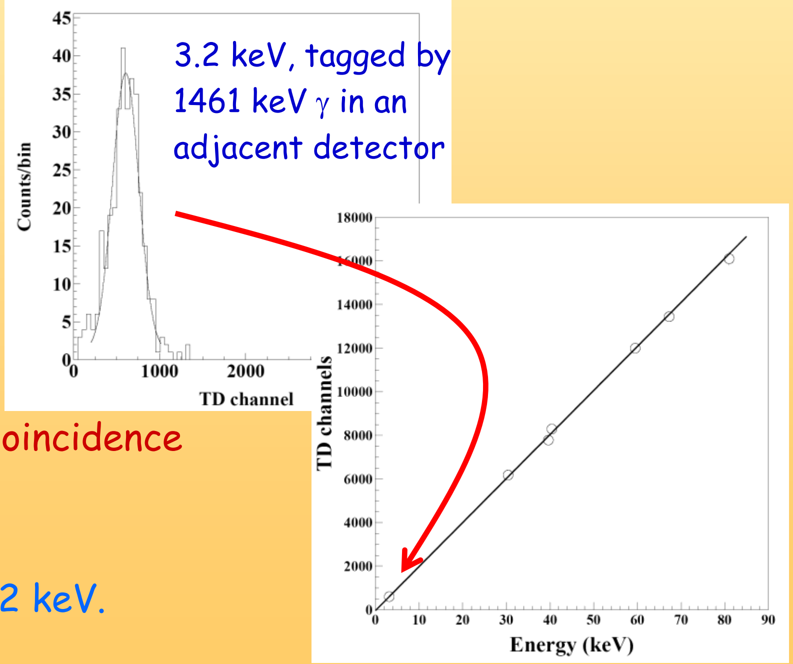
Single-hit events = each detector has all the others as anticoincidence

(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:



3.2 keV, tagged by 1461 keV γ in an adjacent detector

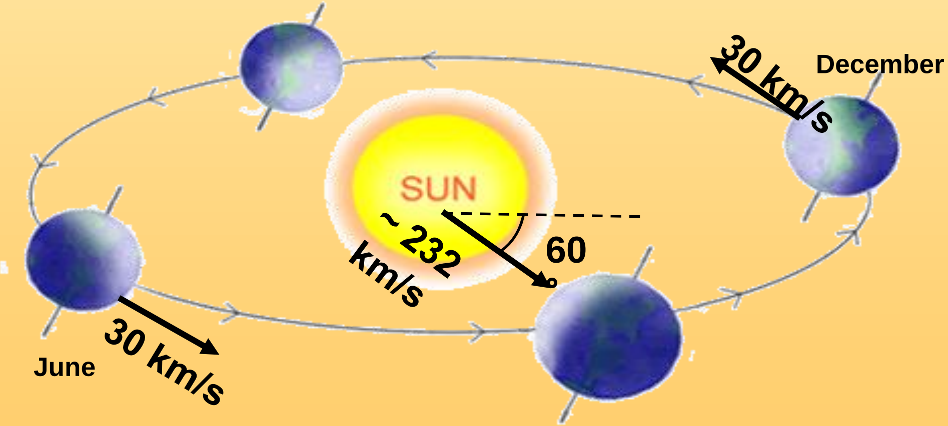
- The DAMA/LIBRA detectors have been calibrated down to the keV region. This assures a clear knowledge of the "physical" energy threshold of the experiment.
- It profits of the relatively high number of available photoelectrons/keV (from 5.5 to 7.5).
- The two PMTs of each detector in DAMA/LIBRA work 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.

Experimental *single-hit* residuals rate vs time and energy

- Model-independent investigation of the annual modulation signature has been carried out by exploiting the time behaviour of the residual rates of the *single-hit* events in the lowest energy regions of the DAMA/LIBRA data.

- These residual rates are calculated from the measured rate of the *single-hit* events (obviously corrections for the overall efficiency and for the acquisition dead time are already applied) after subtracting the constant part:

$$\left\langle r_{ijk} - flat_{jk} \right\rangle_{jk}$$



- r_{ijk} is the rate in the considered *i-th* time interval for the *j-th* detector in the *k-th* energy bin

- $flat_{jk}$ is the rate of the *j-th* detector in the *k-th* energy bin averaged over the cycles.

- The average is made on all the detectors (*j* index) and on all the energy bins (*k* index)

- The weighted mean of the residuals must obviously be zero over one cycle.

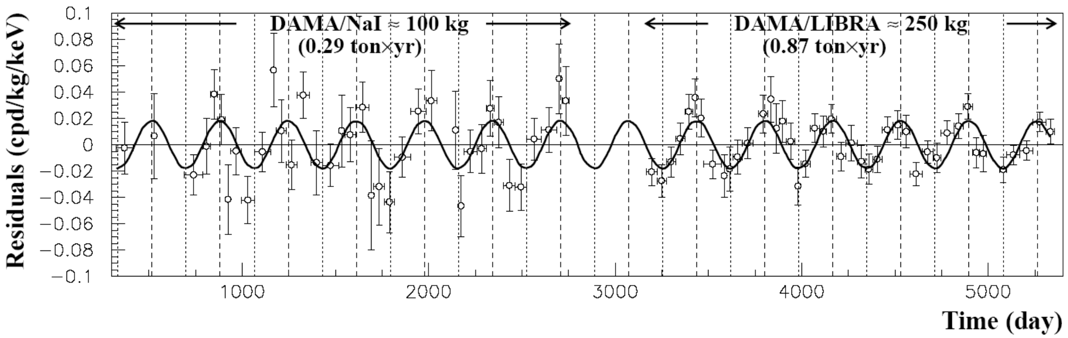
Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (6 years) Total exposure: 425428 kg×day = 1.17 ton×yr

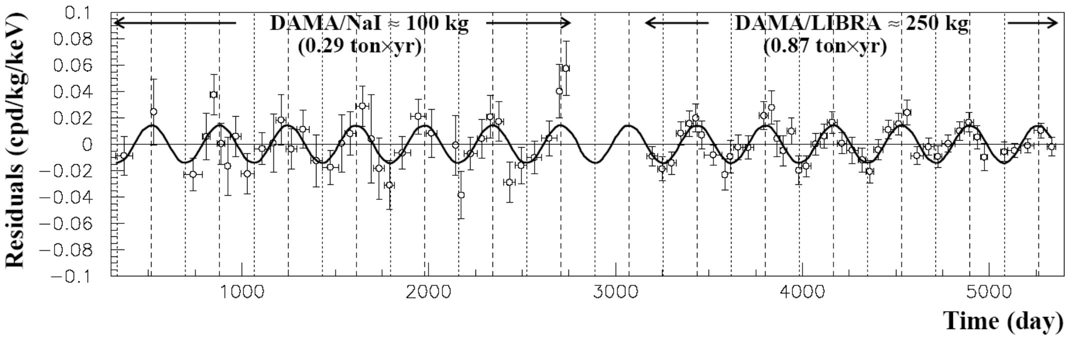
experimental single-hit residuals rate vs time and energy

Acos[w(t-t_0)] ; continuous lines: t_0 = 152.5 d, T = 1.00 y

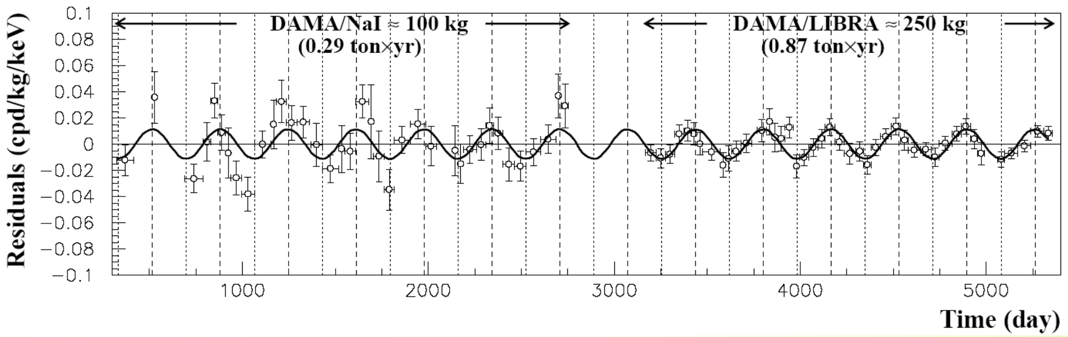
2-4 keV



2-5 keV



2-6 keV



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}

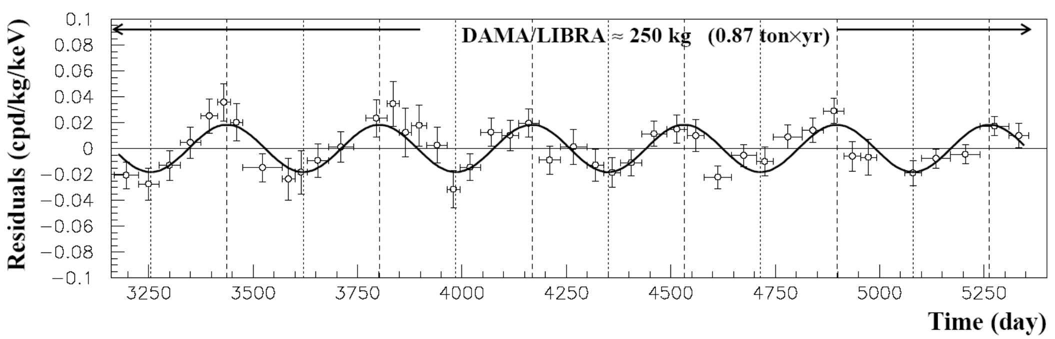
The data favor the presence of a modulated behavior with proper features at 8.8σ C.L.

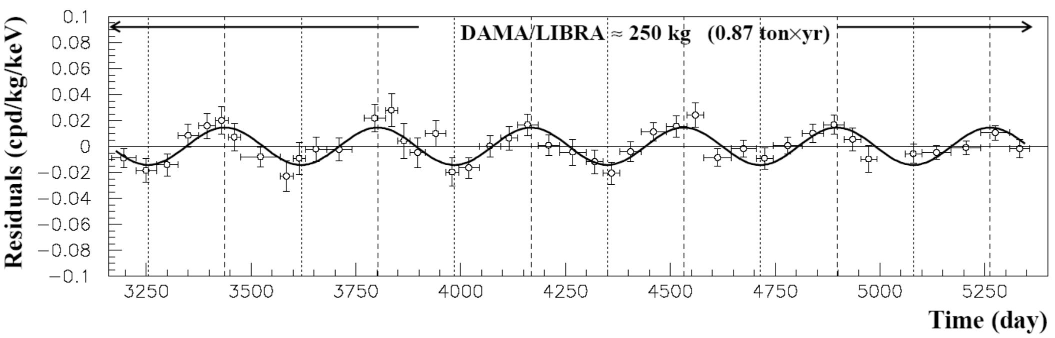
DAMA/LIBRA-1 to 6 Model Independent Annual Modulation Result

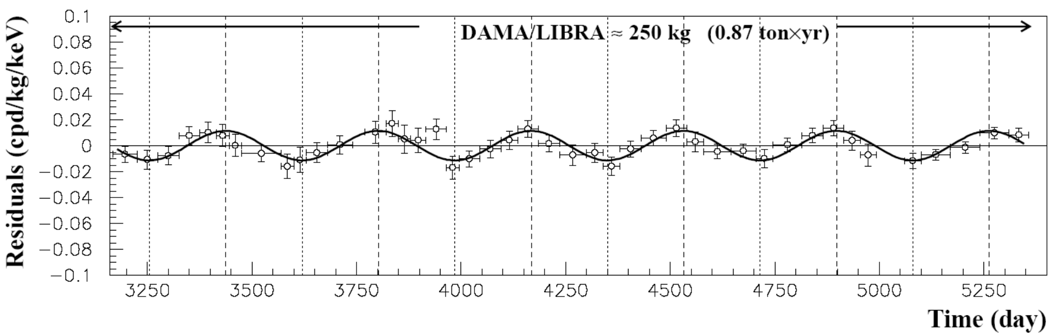
DAMA/LIBRA-1,2,3,4,5,6 (0.87 ton × yr)

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

experimental single-hit residuals rate vs time and energy


2-4 keV


2-5 keV


2-6 keV

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

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

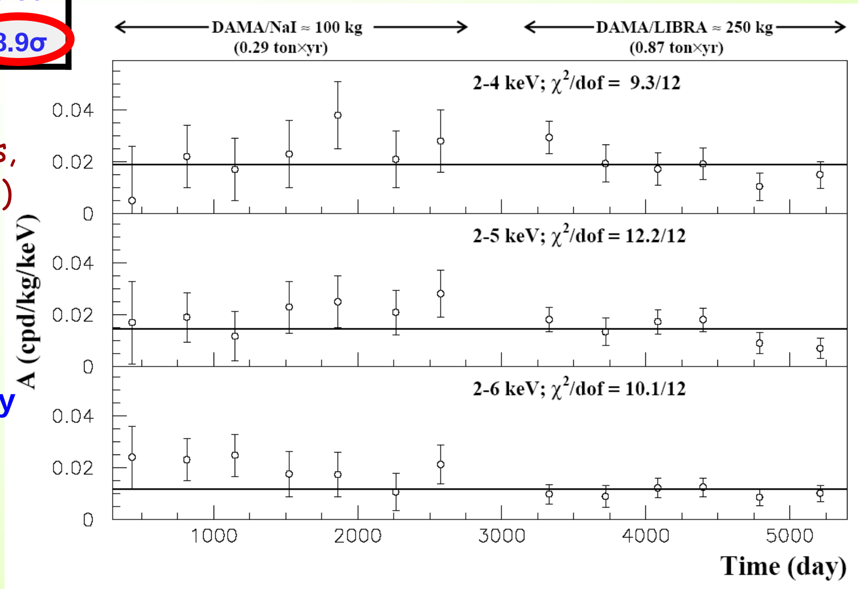
Modulation amplitudes measured in each one of the 13 one-year experiments (DAMA/NaI and DAMA/LIBRA)

	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

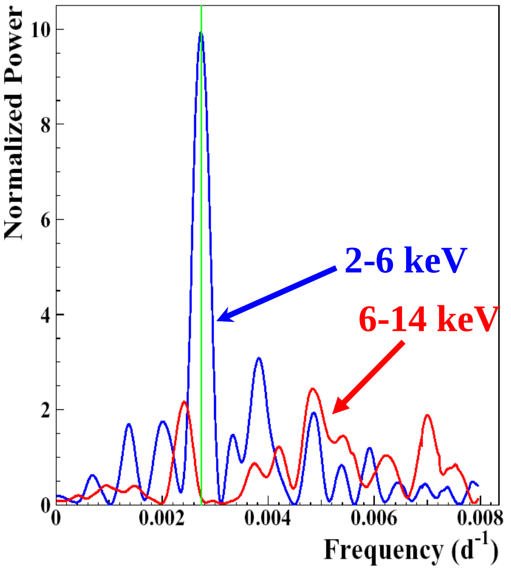
Power spectrum of single-hit residuals

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

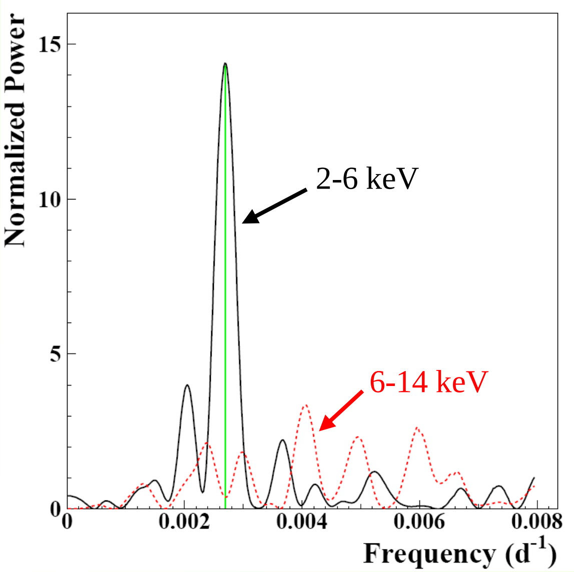
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

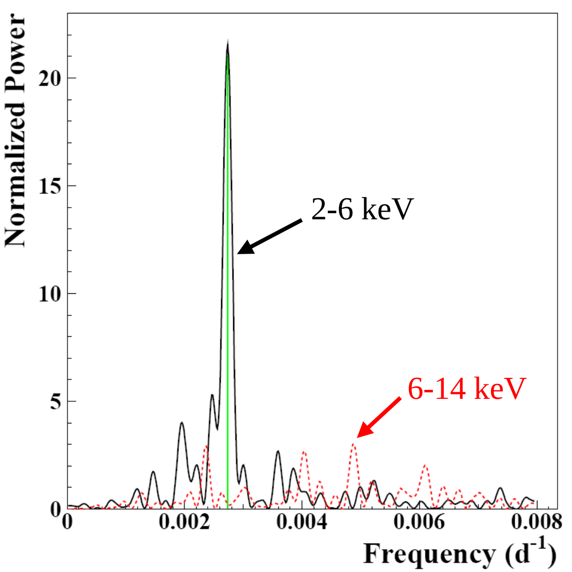
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



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}

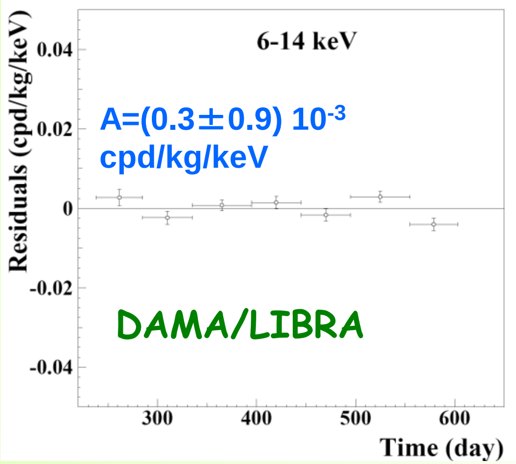
+

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



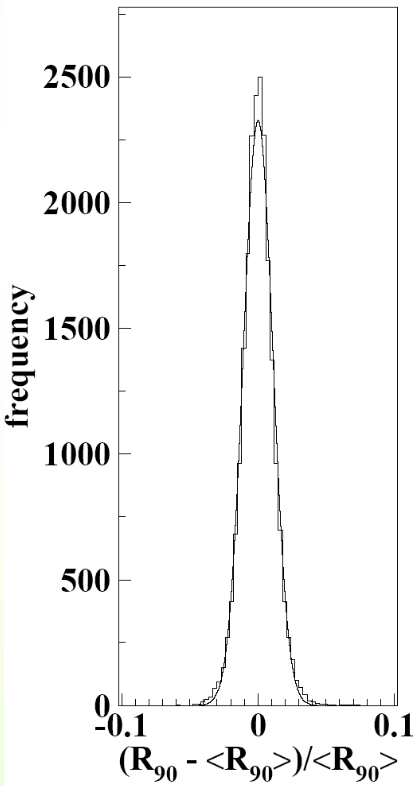
Mod. Ampl. (6-10 keV): cpd/kg/keV
(0.0016 ± 0.0031) DAMA/LIBRA-1
-(0.0010 ± 0.0034) DAMA/LIBRA-2
-(0.0001 ± 0.0031) DAMA/LIBRA-3
-(0.0006 ± 0.0029) DAMA/LIBRA-4
-(0.0021 ± 0.0026) DAMA/LIBRA-5
(0.0029 ± 0.0025) DAMA/LIBRA-6
→ statistically consistent with zero

- 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

DAMALIBRA-1 to -6



σ ≈ 1%, fully accounted by statistical considerations

+ 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

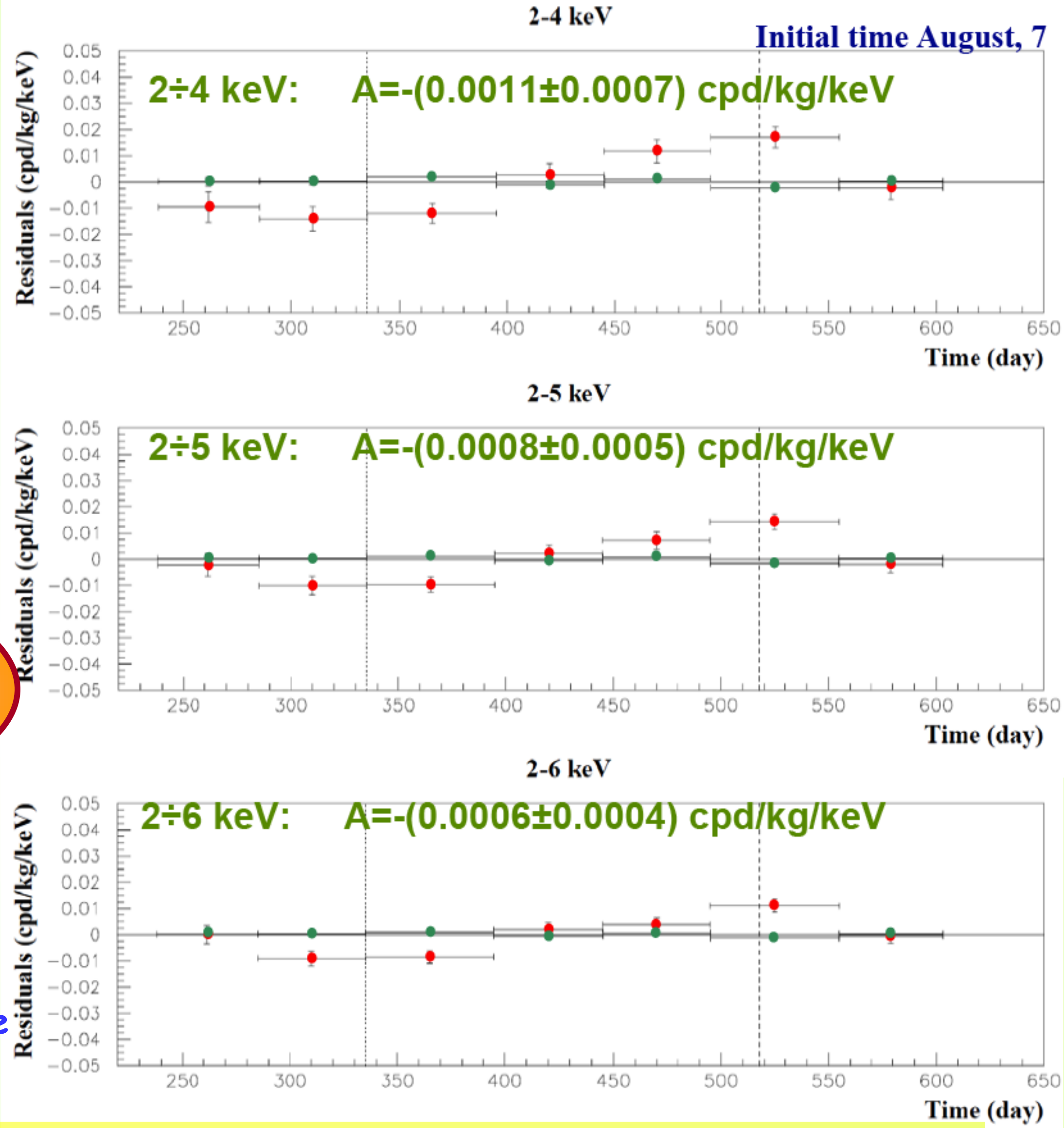
Multiple-hits events in the region of the signal, DAMA/LIBRA 1-6

- 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

Modulation amplitudes, $S_{m,k}$, as function of the energy

The likelihood function of the *single-hit* experimental data in the *k-th* energy bin is defined as:

$$L_k = \prod_{ij} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!}$$

N_{ijk} is the number of events collected in the *i-th* time interval, by the *j-th* detector and in the *k-th* energy bin.

N_{ijk} follows a Poissonian distribution with expectation value:

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

The b_{jk} are the background contributions, M_j is the mass of the *j-th* detector, Δt_i is the detector running time during the *i-th* time interval, ΔE is the chosen energy bin, ε_{jk} is the overall efficiency.

The usual procedure is to minimize the function $y_k = -2\ln(L_k) - const$ for each energy bin; the free parameters of the fit are the $(b_{jk} + S_{0,k})$ contributions and the $S_{m,k}$ parameter.

The $S_{m,k}$ is the modulation amplitude of the modulated part of the signal obtained by maximum likelihood method over the data considering $T=2\pi/\omega=1$ yr and $t_0= 152.5$ day.

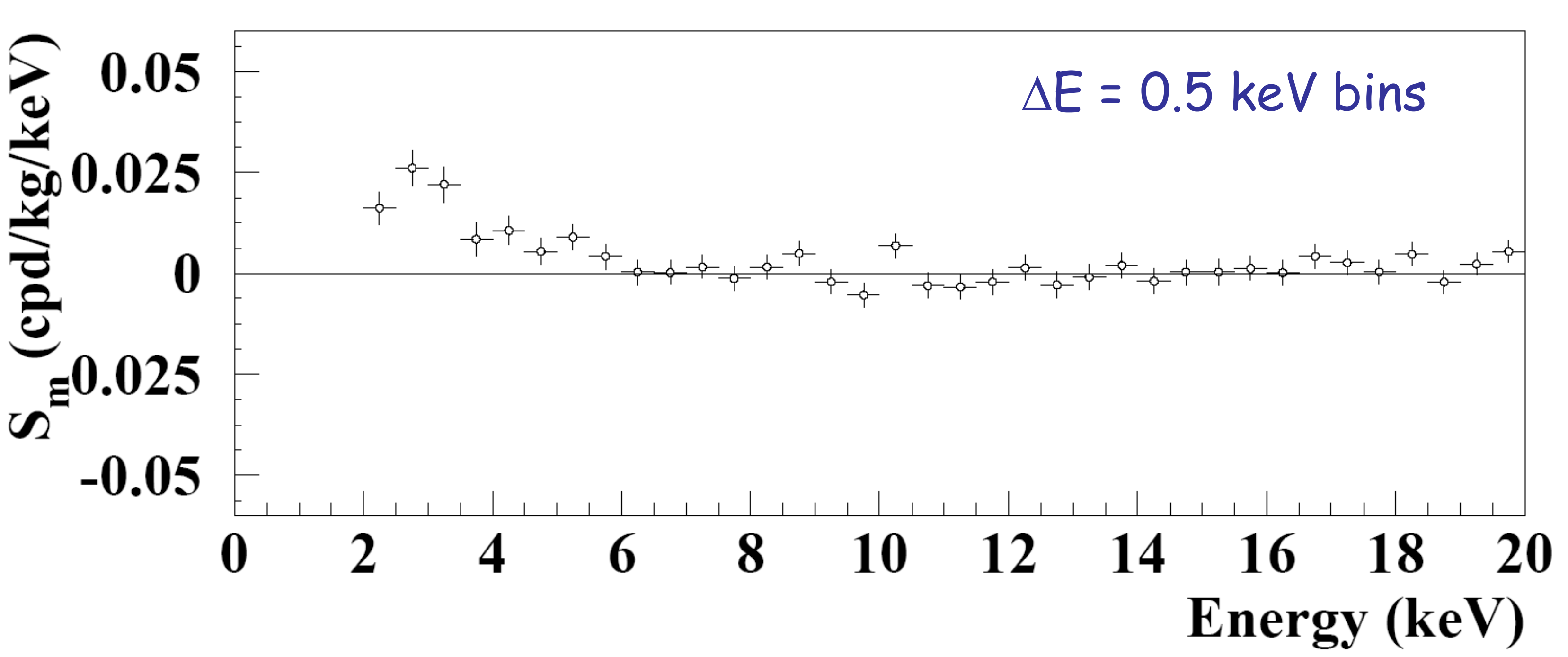
Energy distribution of the modulation amplitudes

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

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)

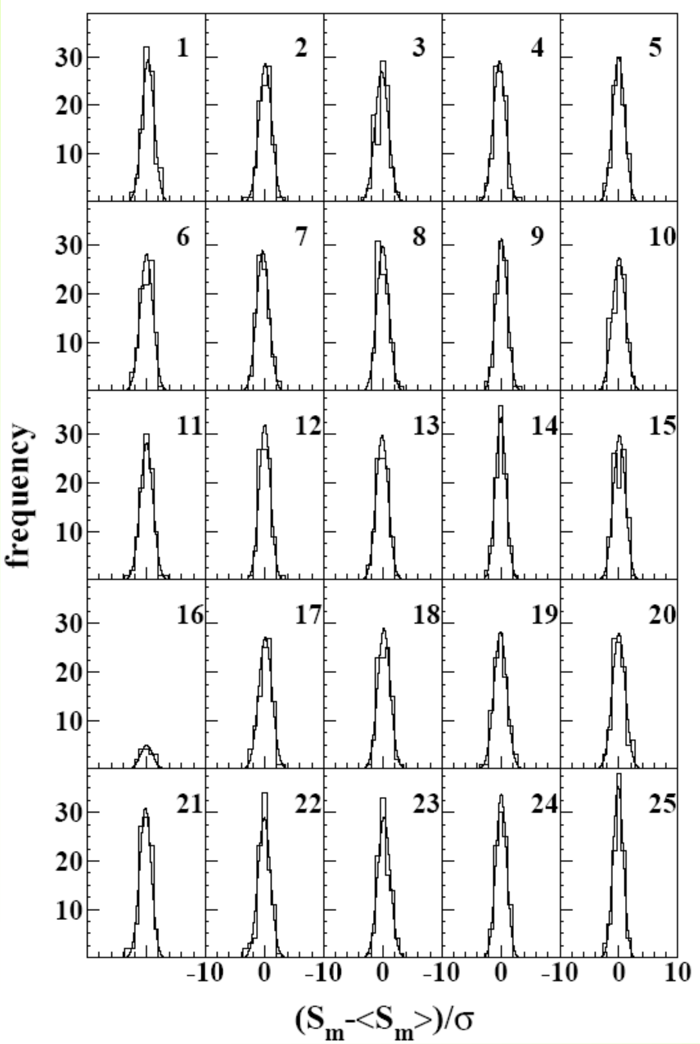
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

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)

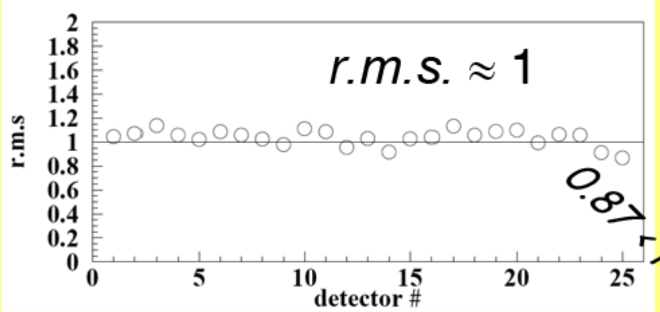


2-6 keV

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)

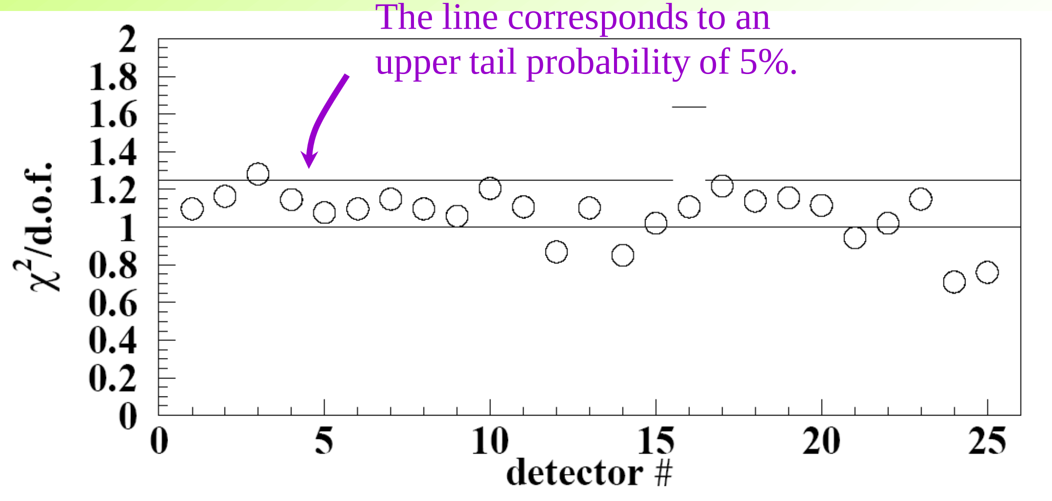
$x=(S_m-\langle S_m\rangle)/\sigma$,

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

$\chi^2/d.o.f.$ 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 line corresponds to an upper tail probability of 5%.

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.

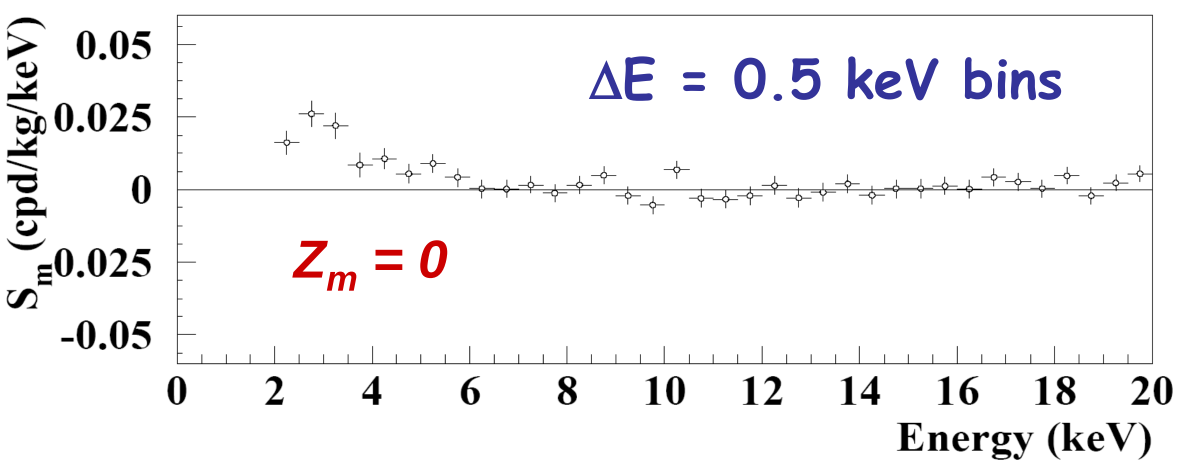
- The mean value of the twenty-five points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 4 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 5 \times 10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (≤ 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)

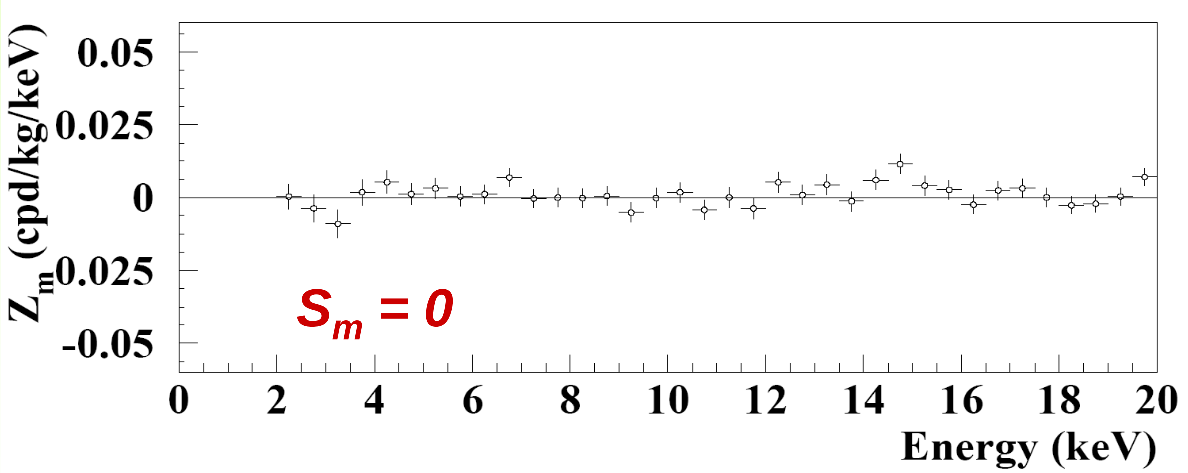
total exposure: 425428 kg×day = 1.17 ton×yr



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)

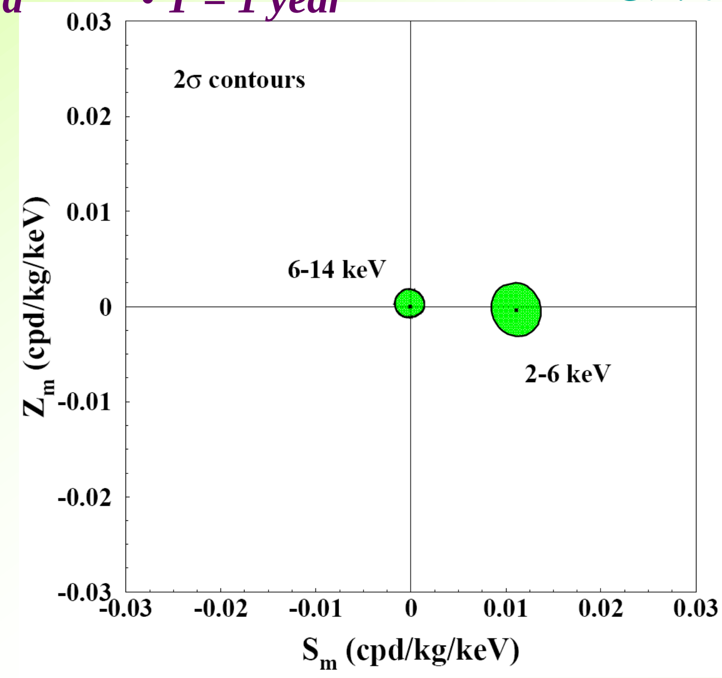
total exposure: 425428 kg×day = 1.17 ton×yr

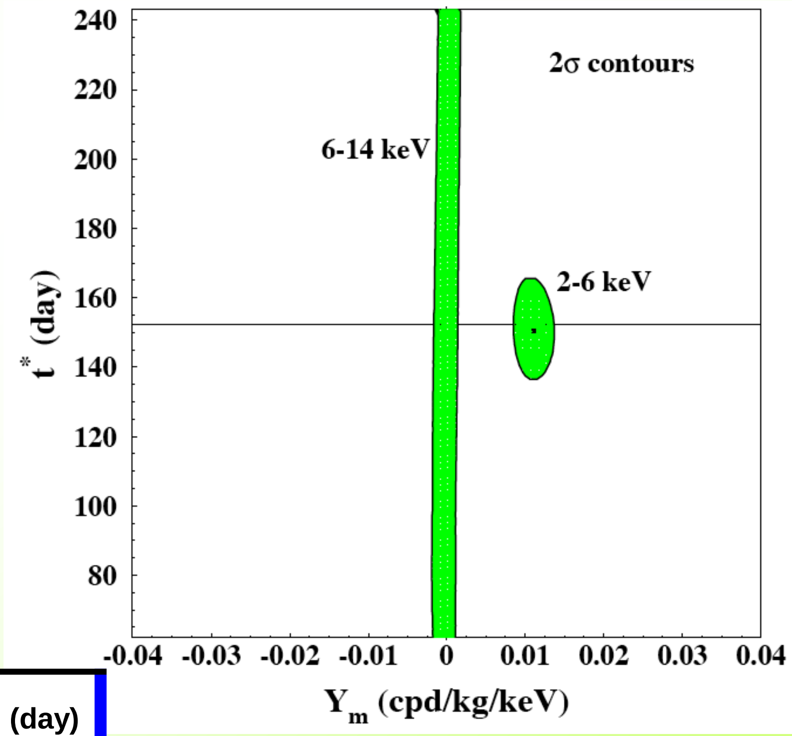
$$R(t) = S_0 + S_m \cos[\omega(t-t_0)] + Z_m \sin[\omega(t-t_0)] = S_0 + Y_m \cos[\omega(t-t^*)]$$

For Dark Matter signals:

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

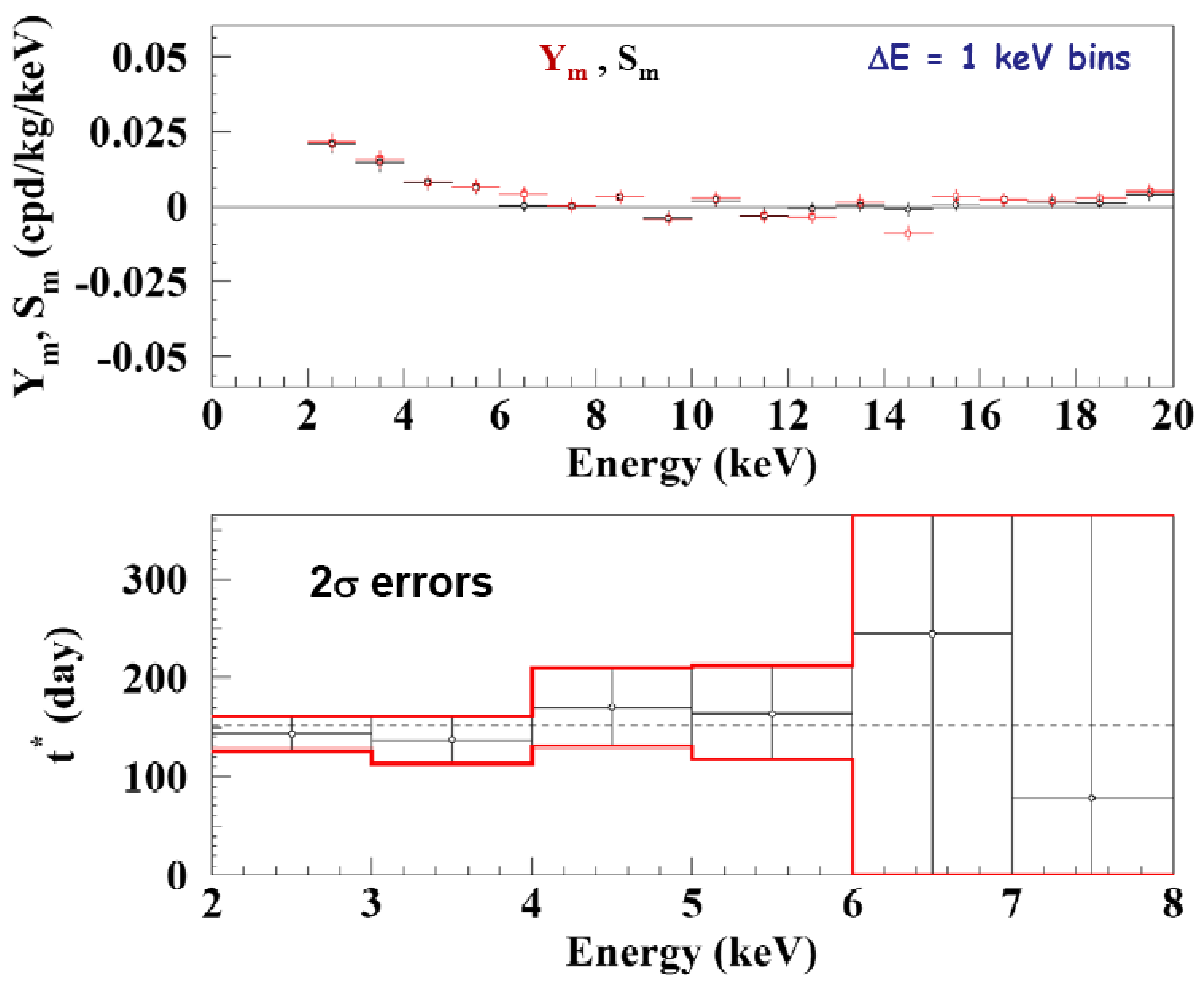
For DM signals:

$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

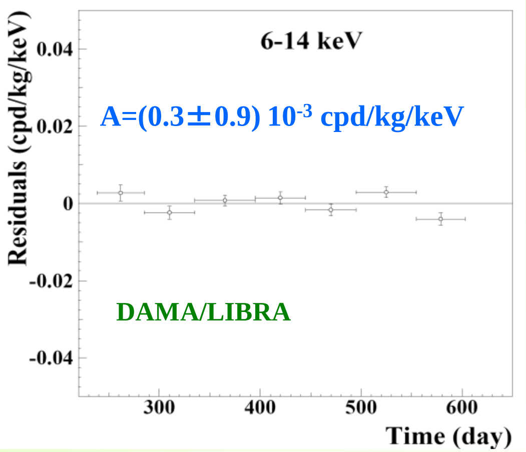
$\omega = 2\pi/T; \quad T = 1\ year$

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



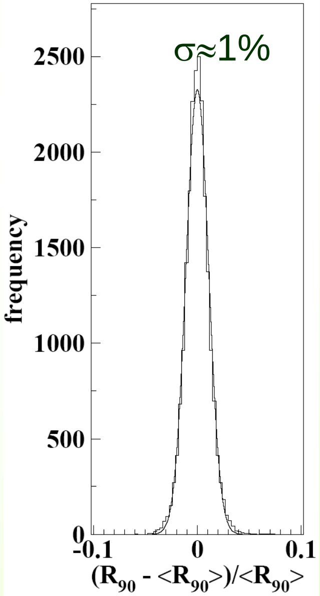
Summarizing on
a hypothetical background modulation in DAMA/LIBRA 1-6

- **No Modulation above 6 keV**



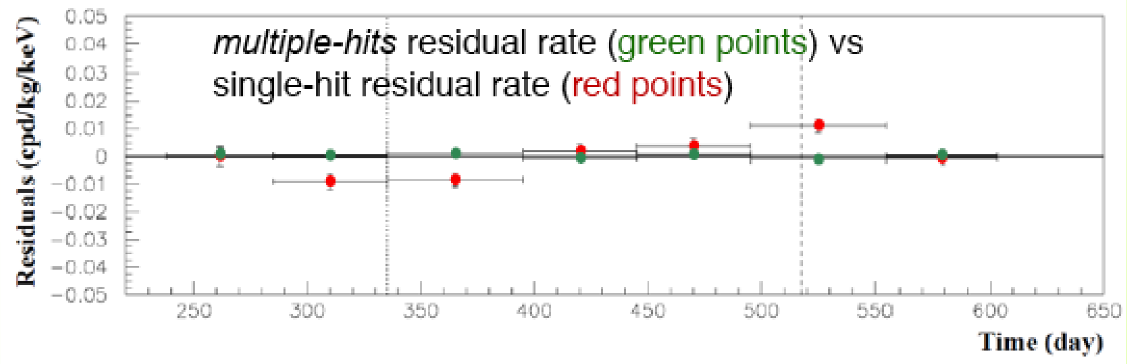
- **No modulation in the whole energy spectrum**

+ 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



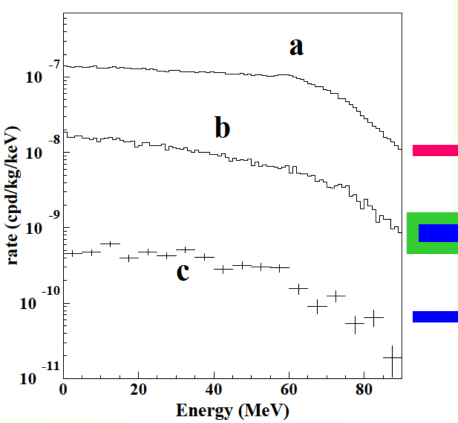
Nevertheless, additional investigations performed ...

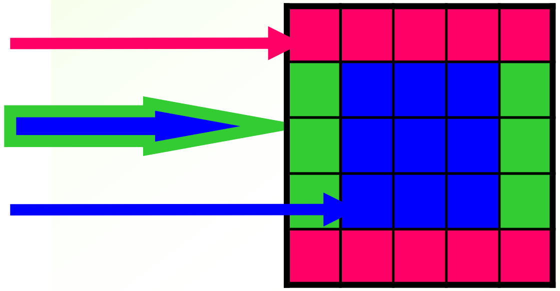
examples for specific cases such as: The muon case, the neutron case

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/cm²)
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; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)
Knowing that: $M_{setup} \approx 250$ 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 and in the *multi-hits* events

It cannot mimic the signature: already excluded also by R_{90}, by *multi-hits* analysis + 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 $\tau \gg T/2\pi$: $t_{side} = t_\mu + T/4$

It cannot mimic the signature, e.g.: different phase

The phase of the muon flux at LNGS is 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

+ R_{90}, multi-hits, phase, and other analyses

NO

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

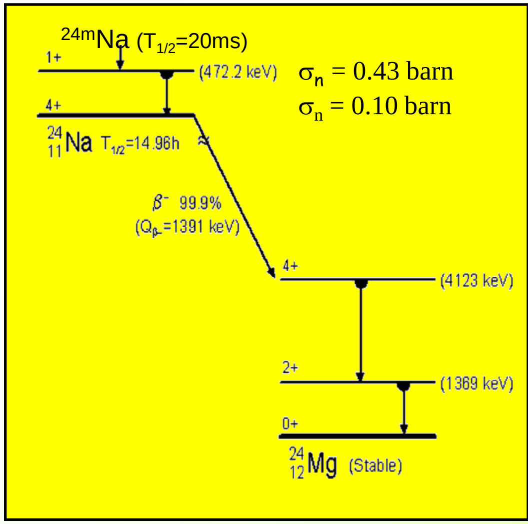
NO

- **Thermal neutrons flux measured at LNGS :**

Φ_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:

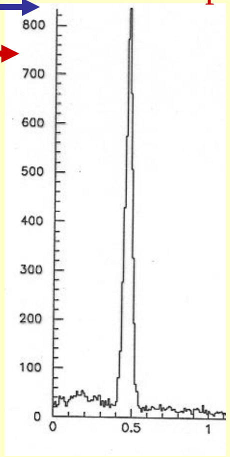
$S_m^{(\text{thermal n})} < 0.8 \times 10^{-6}$ cpd/kg/keV (< 0.01% S_m^{observed})

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:

$S_m^{(\text{fast n})} < 10^{-4}$ 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):
  $\Phi_n < 2.2 \times 10^{-7}$ n cm^{-2} s^{-1} (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 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.	**<2.5×10^{-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 + instrinsic calibrations	**<1-2 ×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 *multiple-hits* events; this limit includes all possible sources of background	**<10^{-4} cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**<3×10^{-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, as expected for the DM signal

2)

Measured period is equal to (0.999±0.002) yr, well compatible with the 1 yr period, as expected for the DM signal

3)

Measured phase (146±7) days is well compatible with the roughly about 152.5 days as expected for the DM signal

4)

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

5)

The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal

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

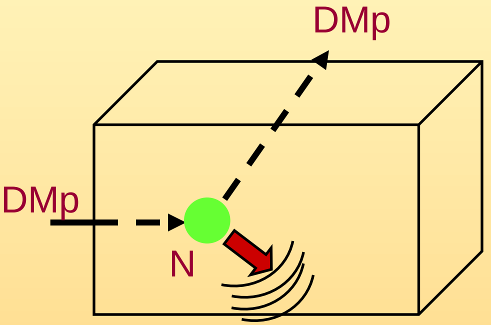
Available results from direct searches using different target materials and approaches do not give any robust conflict

Possible model dependent positive hints from indirect searches not in conflict with DAMA; but interpretation and the evidence itself in indirect searches 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, whatever hints from other direct searches must be interpreted; in any case large room of compatibility with DAMA is present

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 km/s

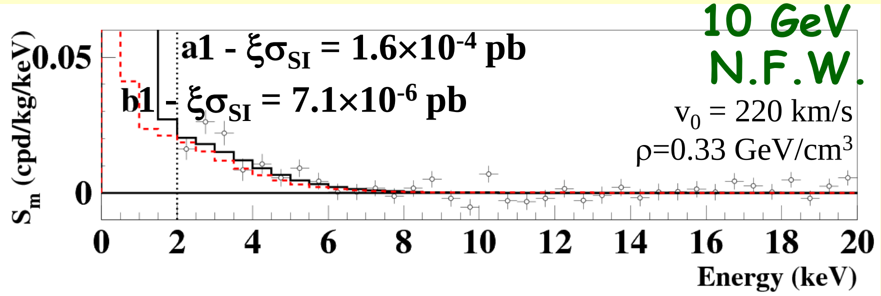


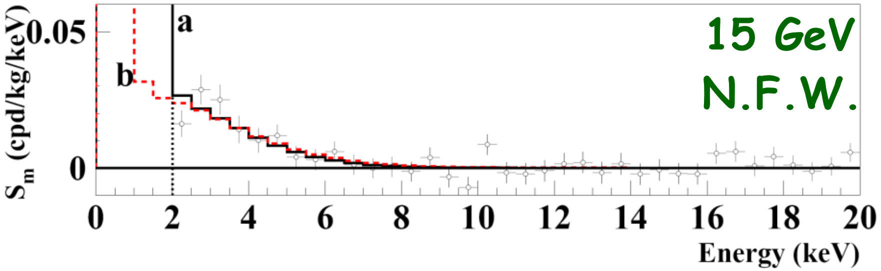
About the same C.L.

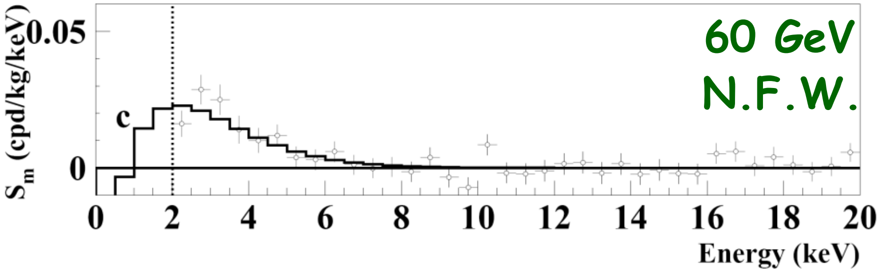
...scaling from NaI

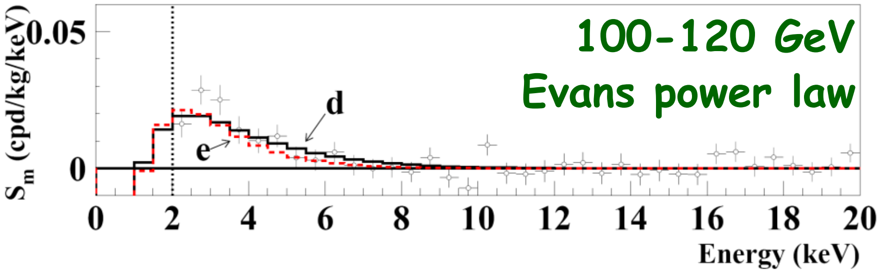
Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)
a	A5 (NFW)	0.2	A	15 GeV	3.1×10^{-4}
b	A5 (NFW)	0.2	A	15 GeV	1.3×10^{-5}
c	A5 (NFW)	0.2	B	60 GeV	5.5×10^{-6}
d	B3 (Evans power law)	0.17	B	100 GeV	6.5×10^{-6}
e	B3 (Evans power law)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

[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503



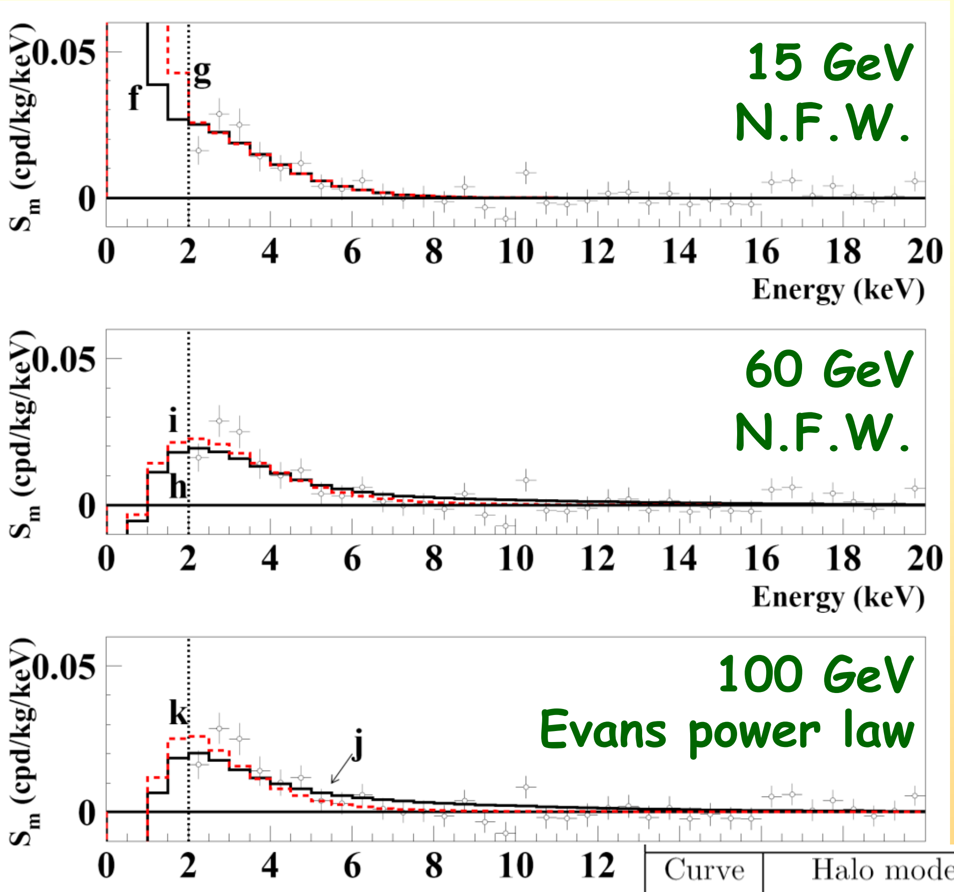






channeling contribution as in EPJC53(2008)205 considered for curve *b*

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

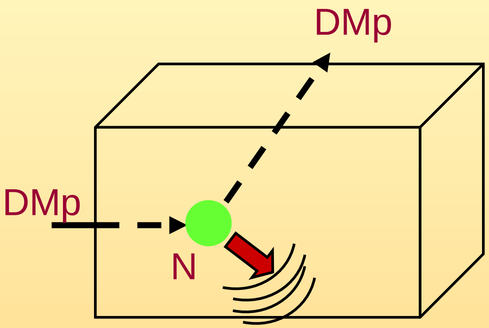


WIMP DM candidate (as in [4])

Elastic scattering on nuclei

SI & SD mixed coupling

v_0 = 170 km/s



About the same C.L.

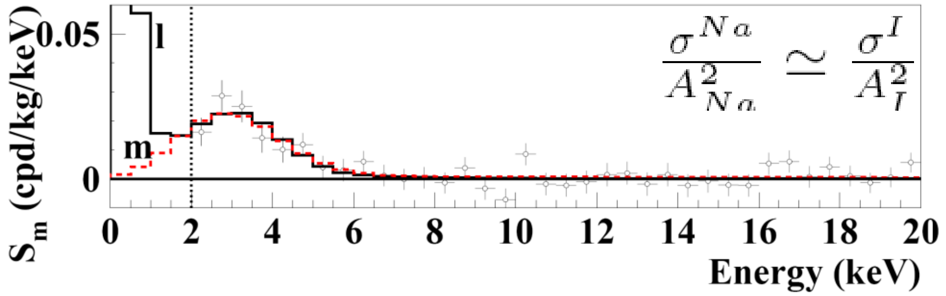
...scaling from NaI

$\theta = 2.435$

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)
f	A5 (NFW)	0.2	A	15 GeV	10^{-7}	2.6
g	A5 (NFW)	0.2	A	15 GeV	1.4×10^{-4}	1.4
h	A5 (NFW)	0.2	B	60 GeV	10^{-7}	1.4
i	A5 (NFW)	0.2	B	60 GeV	8.7×10^{-6}	8.7×10^{-2}
j	B3 (Evans power law)	0.17	A	100 GeV	10^{-7}	1.7
k	B3 (Evans power law)	0.17	A	100 GeV	1.1×10^{-5}	0.11

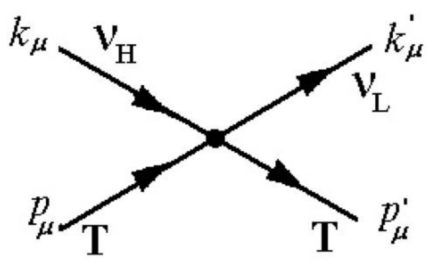
[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

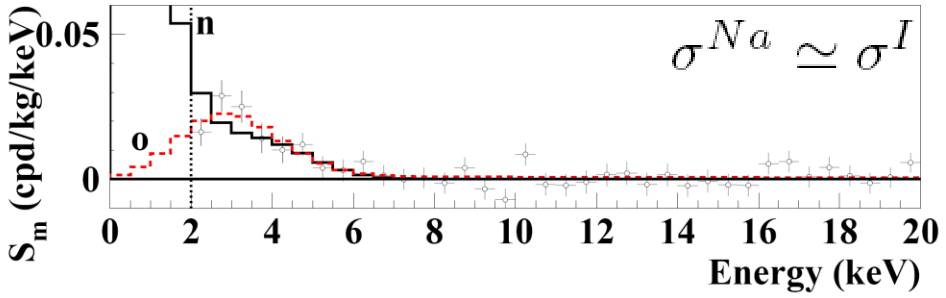
Examples for few of the many possible scenarios superimposed to the measured modulation amplitues $S_{m,k}$



LDM candidate

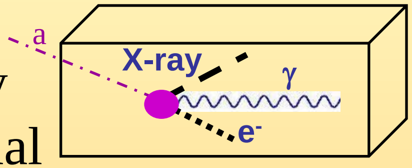
(as in arXiv:0802.4336): inelastic interaction with electron or nucleus targets



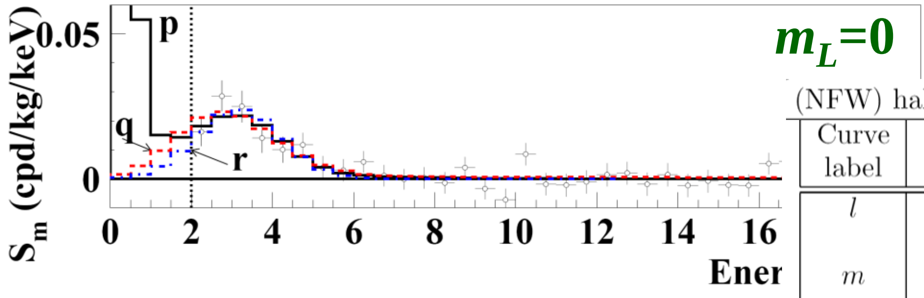


Light bosonic candidate

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



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)
l	LDM	coherent on nuclei	A	30 MeV	18 MeV	$\xi\sigma_m^{coh} = 1.8 \times 10^{-6}$
m	LDM	coherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{coh} = 2.8 \times 10^{-6}$
n	LDM	incoherent on nuclei	A	30 MeV	3 MeV	$\xi\sigma_m^{inc} = 2.2 \times 10^{-2}$
o	LDM	incoherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{inc} = 4.6 \times 10^{-2}$
p	LDM	coherent on nuclei	A	28 MeV	28 MeV	$\xi\sigma_m^{coh} = 1.6 \times 10^{-6}$
q	LDM	incoherent on nuclei	A	88 MeV	88 MeV	$\xi\sigma_m^{inc} = 4.1 \times 10^{-2}$
r	LDM	on electrons	–	60 keV	60 keV	$\xi\sigma_m^{e} = 0.3 \times 10^{-6}$

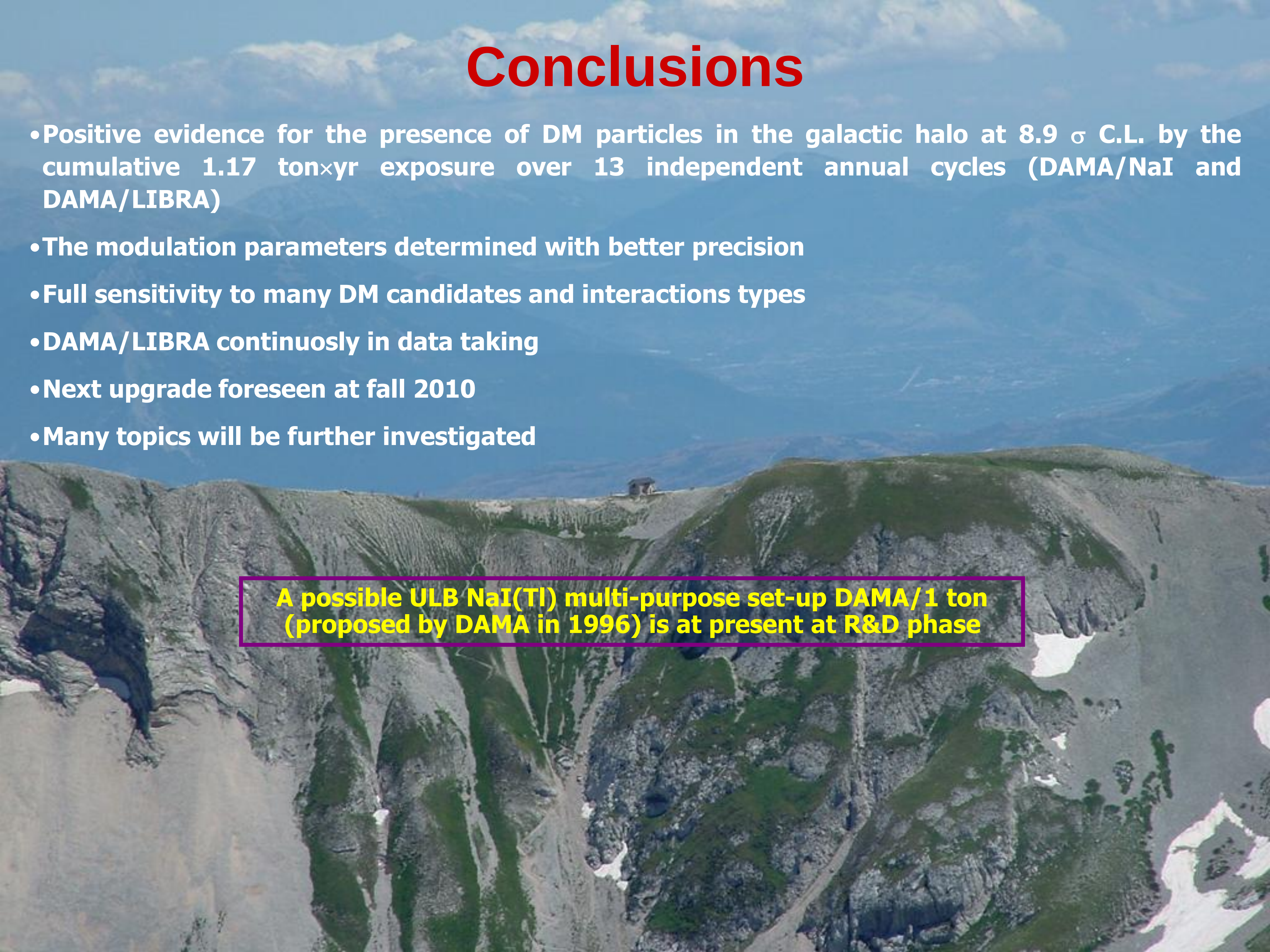
curve *r*: also pseudoscalar axion-like candidates (e.g. majoron) m_a=3.2 keV g_{aee}= 3.9 10^{-11}

[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

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



Conclusions

- Positive evidence for the presence of DM particles in the galactic halo at 8.9 σ C.L. by the cumulative 1.17 ton×yr exposure over 13 independent annual cycles (DAMA/NaI and DAMA/LIBRA)
- The modulation parameters determined with better precision
- Full sensitivity to many DM candidates and interactions types
- DAMA/LIBRA continuosly in data taking
- Next upgrade foreseen at fall 2010
- Many topics will be further investigated

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