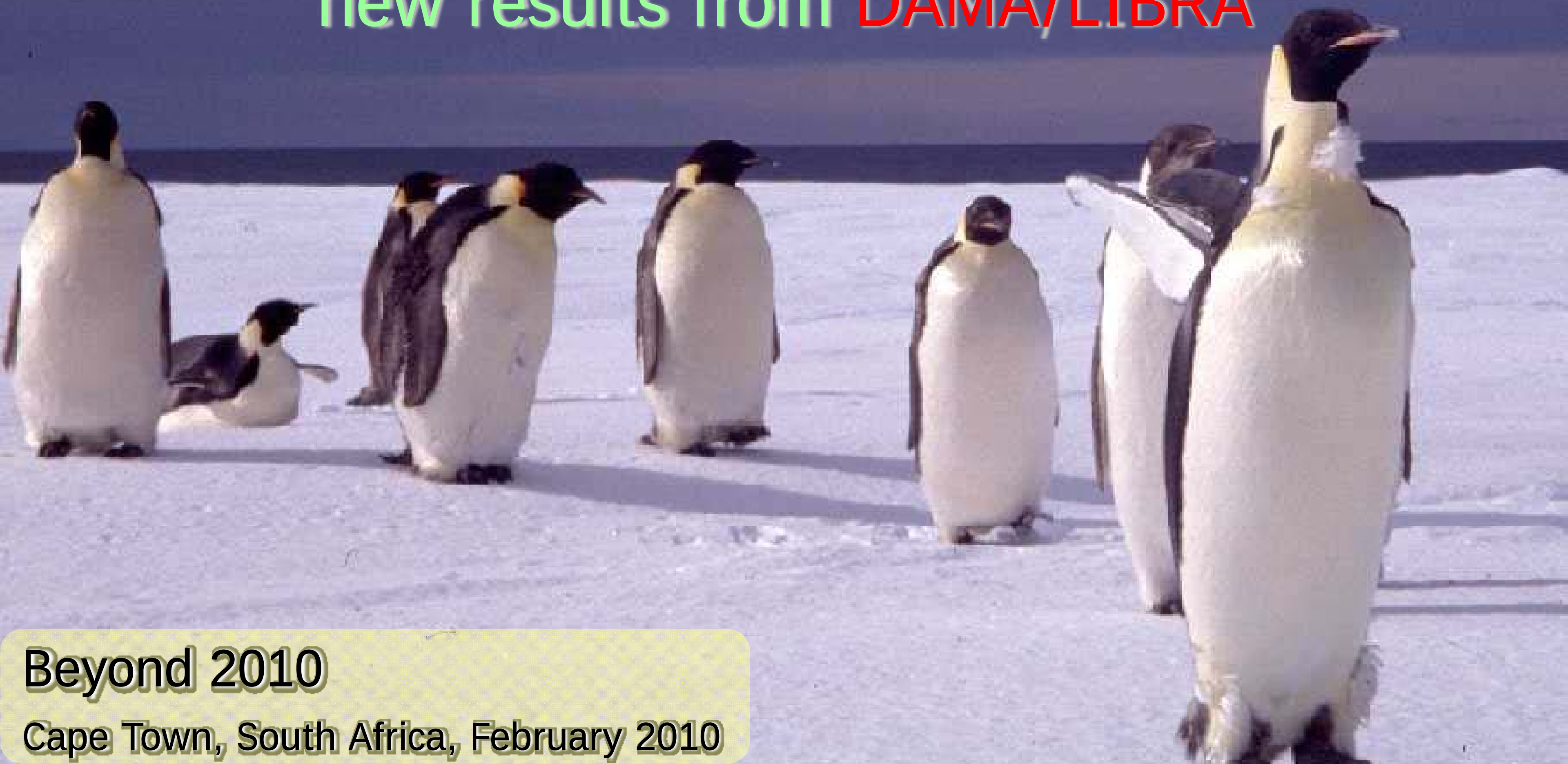
R. Bernabei
University and INFN Roma Tor Vergata

Signals from the Dark Universe: new results from DAMA/LIBRA



Beyond 2010

Cape Town, South Africa, February 2010

Relic DM particles from primordial Universe

SUSY (as neutralino or sneutrino In various scenarios)

the sneutrino in the Smith and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not yet foreseen by theories

axion-like (light pseudoscalar and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

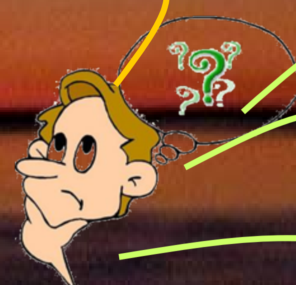
heavy exotic canditates, as "4th family atoms", ...

Elementary Black holes, Planckian objects, Daemons

etc…

(& invisible axions, ν's)

&



Right halo model and parameters?

- Composition? DM multicomponent also in the particle part?
- Right related nuclear and particle physics?

Non thermalized components?

Caustics?

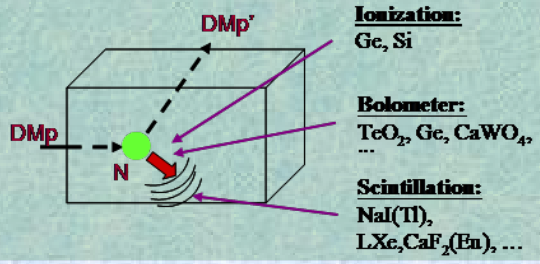
clumpiness?

etc… etc…

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

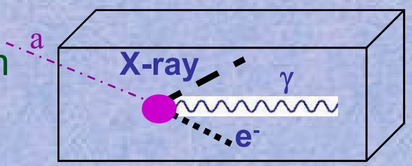
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

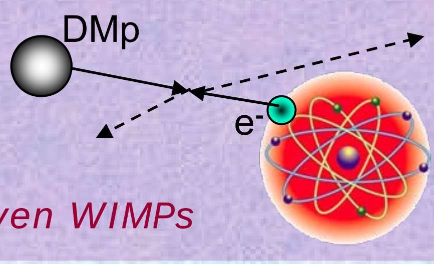
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

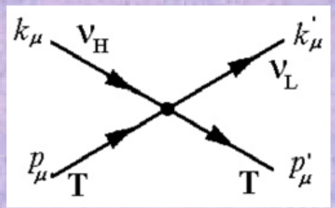


... even WIMPs

- 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**

accelerators can
prove the existence of some possible Dark Matter candidate particles

But accelerators cannot
credit that a certain particle is in the halo as the solution or the only solution for particle Dark Matter …

+ Dark Matter candidate particles and scenarios (even for neutralino candidate) exist which cannot be investigated at accelerators

→ Direct detection with a model independent approach

2 different questions:

- Are there Dark Matter particles in the galactic halo?

The exploitation of the annual modulation DM signature with highly radiopure NaI(Tl) as target material can permit to answer to this question by direct detection and in a way largely independent on the nature of the candidate and on the astrophysical, nuclear and particle Physics assumptions

DAMA/NaI and DAMA/LIBRA

- Which are exactly the nature of the Dark Matter particle(s) and the related astrophysical, nuclear and particle Physics scenarios?

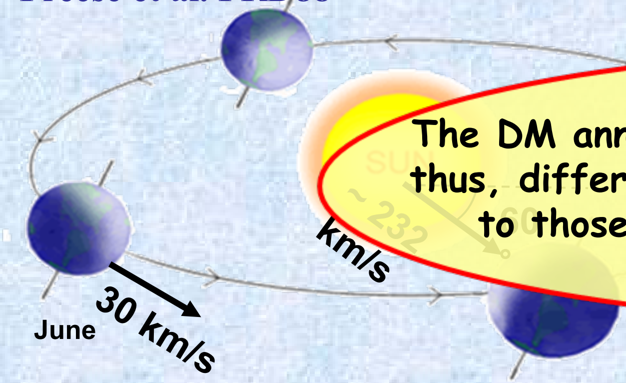
This requires subsequent model-dependent corollary analyses (see e.g. in recent DAMA – and other – literature;… and more)

N.B. It does not exist any approach to investigate the nature of the candidate in the direct and indirect DM searches, which can offer these latter information independently on assumed astrophysical, nuclear and particle Physics scenarios…

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

As a consequence of its annual revolution around the Sun, which is moving in the Galaxy, the Earth should be crossed by a larger flux of Dark Matter particles around 2 June (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around 2 December (when the two velocities are subtracted).

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
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

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

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

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

Expected rate in given energy bin changes because of the 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, systematics 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

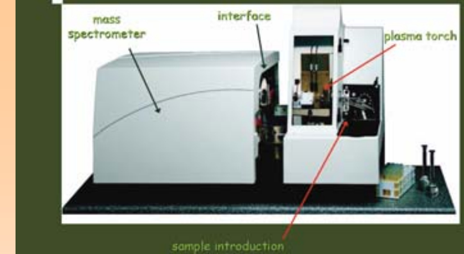
Competitiveness of ULB NaI(Tl) set-up

- 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

Development of highly radiopure scintillators by:



Powder samples selection – among those accessible to industry in that period - by

- low background Ge deep underground
- Mass and atomic absorption spectrometry
- Neutron activation

Study of standard and non-standard contami

This needs many years of long and difficult work, many specific experience and time. Similar developments and measurements are themselves difficult experiments, etc.

Chemical/physical purification of selected m

Selection of growing processes

Additives selection

Growing protocols

Handling protocols

Other materials selection (housing, optical grease, light guides,...)

Assembling, transport, storage protocols

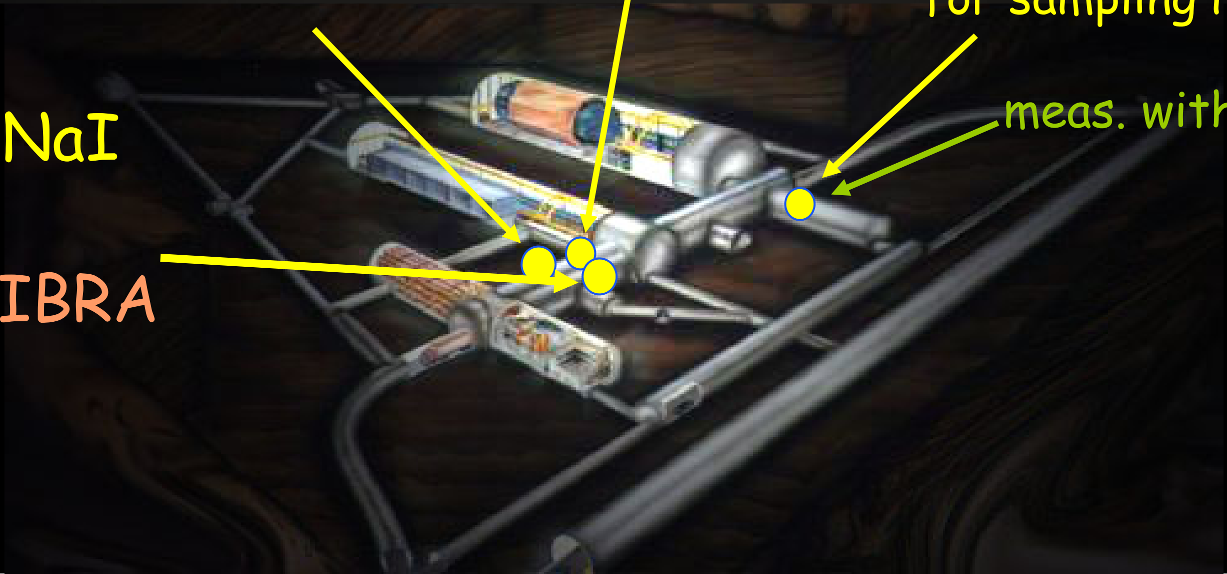
Prototypes tests

Physics and astrophysics with low background scintillators

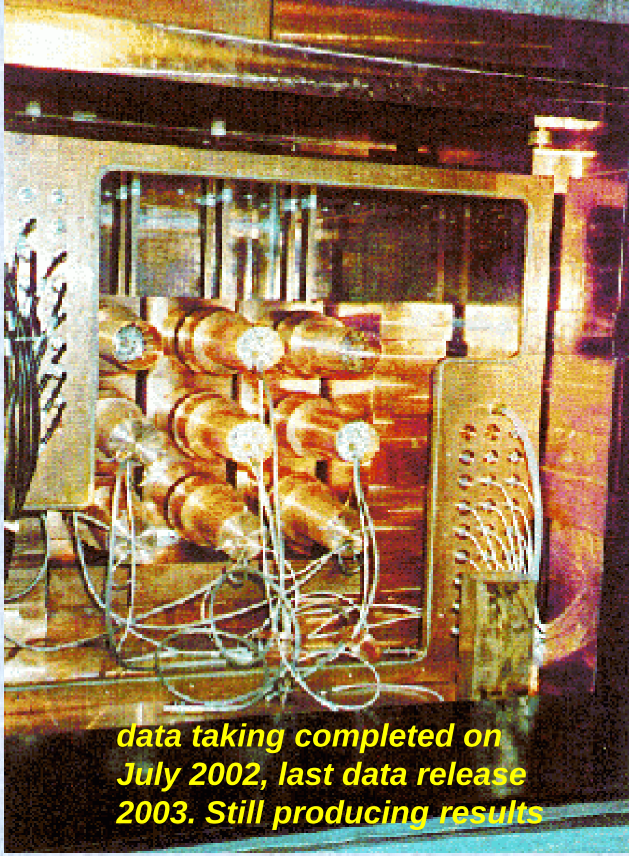
- INFN and Univ. Roma Tor Vergata
- INFN and Univ. Roma La Sapienza
- INFN-LNGS
- IHEP-Beijing

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

(+ other collaborations on by-products and small scale expts)



DAMA/NaI : ≈100 kg NaI(Tl)



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

Results on rare processes:

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

Results on DM particles:

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

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

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

total exposure (7 annual cycles) 0.29 ton x yr

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

Installing the DAMA/LIBRA set-up ~250 kg ULB NaI(Tl)

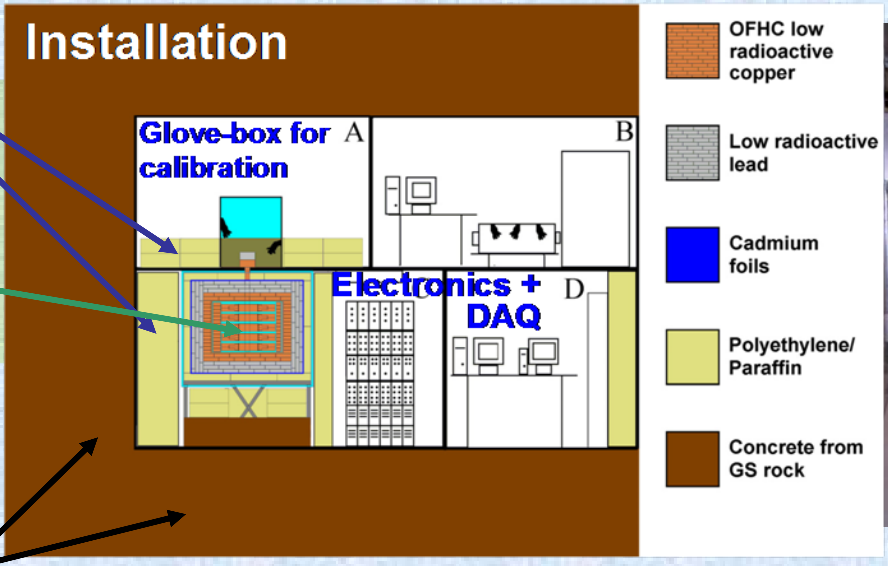
- ***Radiopurity,performances, procedures, etc.:*** NIMA592(2008)297
- ***Results on DM particles:*** *Annual Modulation Signature:* EPJC56(2008)333
- ***Results on rare processes:*** *Possible processes violating the Pauli exclusion principle in Na and I:* EPJC62(2009)327

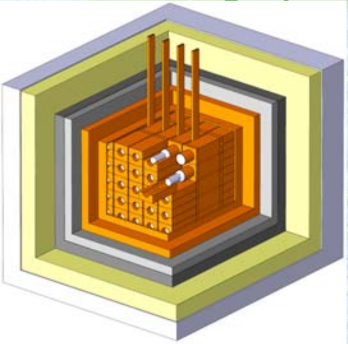
The DAMA/LIBRA set-up

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





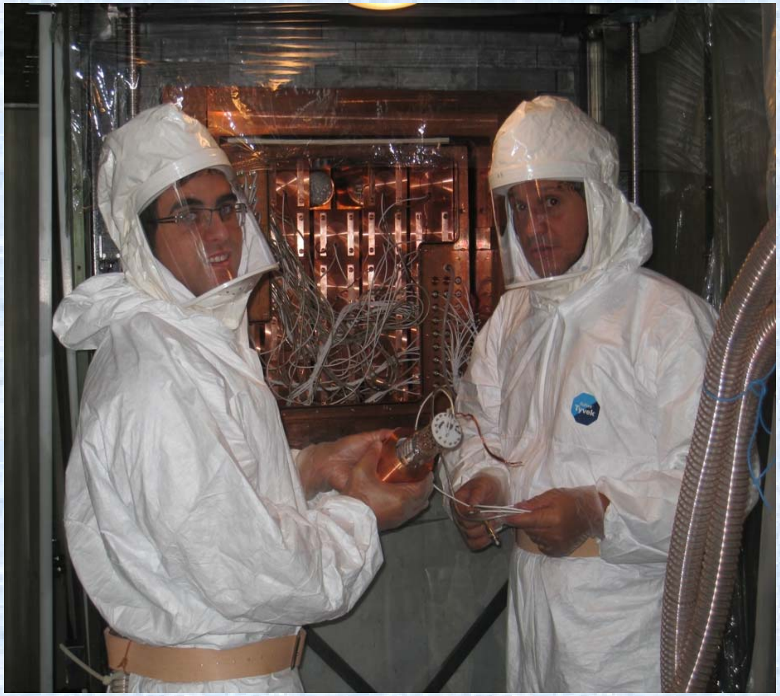
5.5-7.5 phe/keV

~ 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

The first upgrade in fall 2008

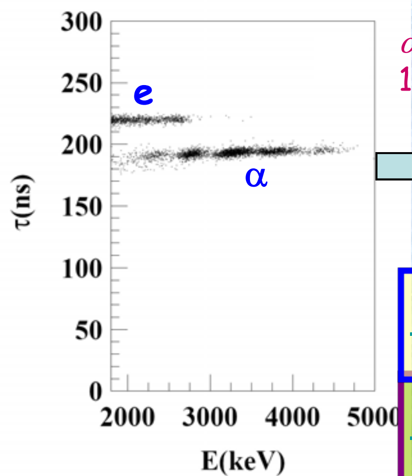
- Opening of the shield of DAMA/LIBRA set-up in HP N_2 atmosphere
- Replacement of some PMT in HP N_2 atmosphere
- Restore 1 detector to operation



- Dismounting of the Tektronix TDs and mounting of the new U1063A Acqiris 1GS/s 8-bit High-Speed cPCI DC270 Digirizers and of the new DAQ system with optical read-out

Since Oct. 2008 again in data taking

Some on residual contaminants in new ULB NaI(Tl) detectors



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

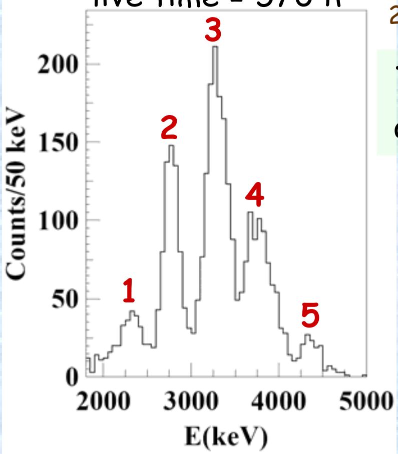
The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/day

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

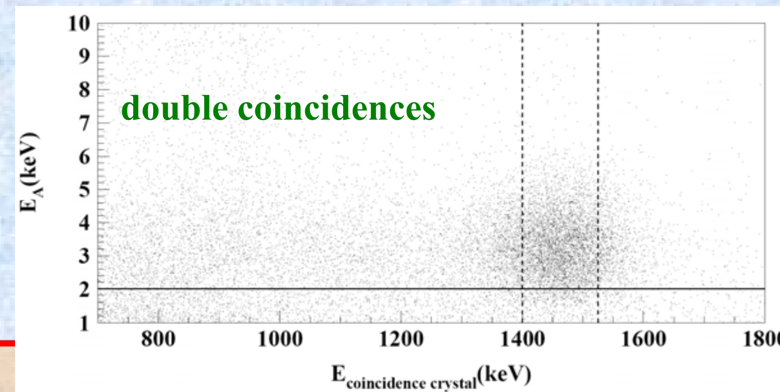
live time = 570 h

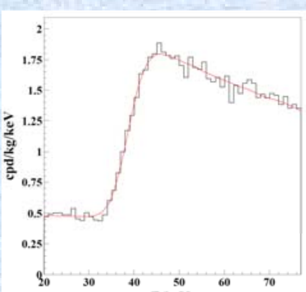


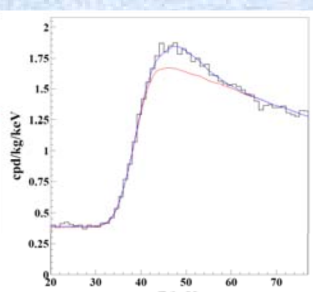
^{238}U chain splitted into 5 subchains: ^{238}U $\rightarrow$ ^{234}U $\rightarrow$ ^{230}Th $\rightarrow$ ^{226}Ra $\rightarrow$ ^{210}Pb $\rightarrow$ ^{206}Pb

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 ≈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

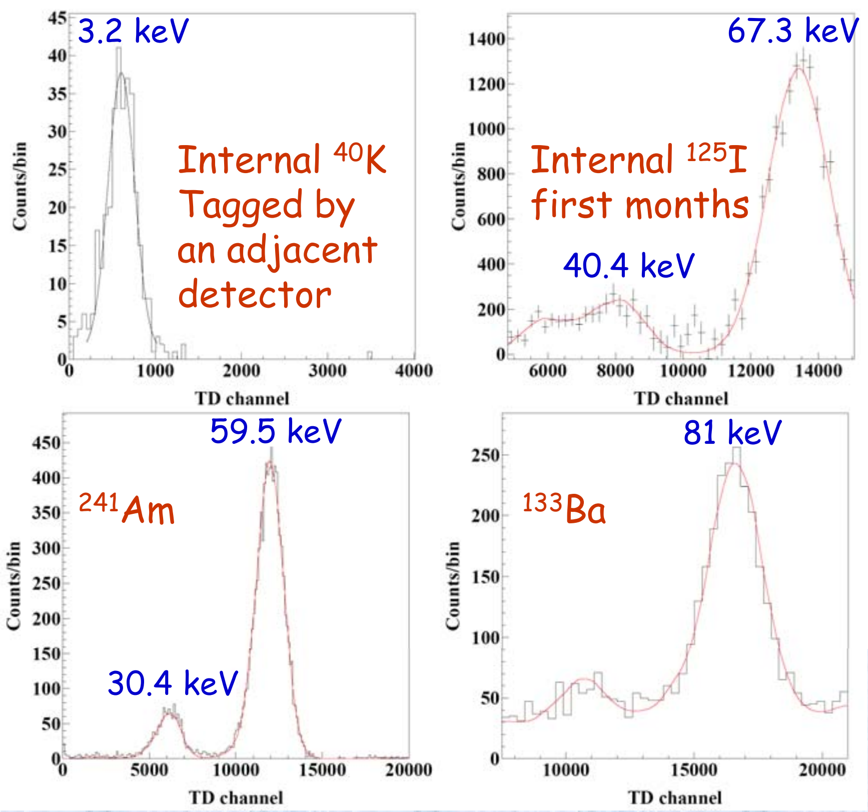
... more on NIMA592(2008)297

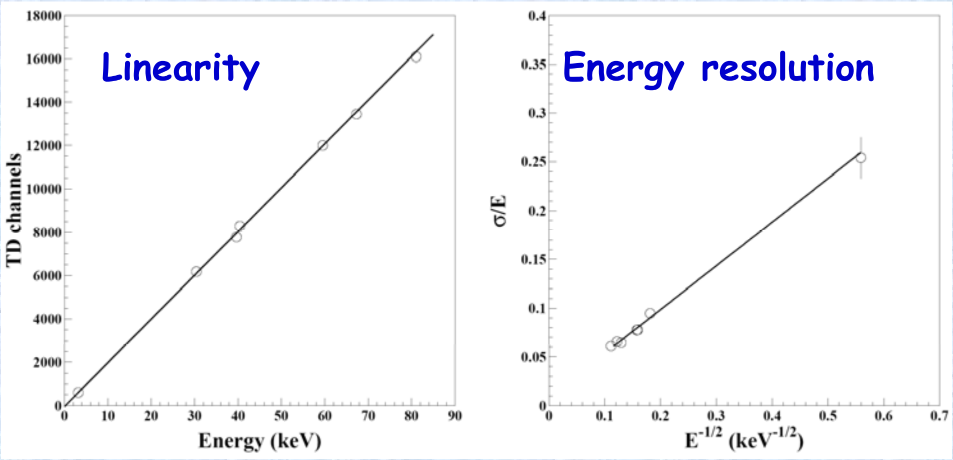
DAMA/LIBRA: calibrations at low energy

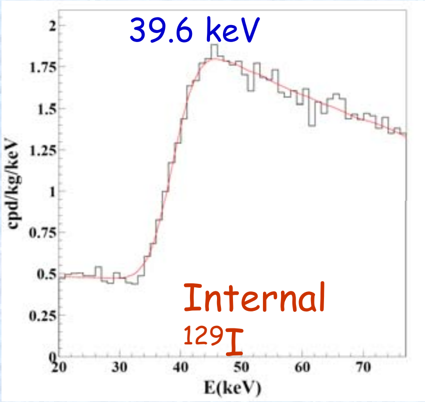
Studied by using various external gamma sources (^{241}Am, ^{133}Ba) and internal X-rays or gamma's (^{40}K, ^{125}I, ^{129}I)

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

- **Internal ^{40}K:** 3.2 keV due to X-rays/Auger electrons (tagged by 1461 keV γ in an adiacent detector).
- **Internal ^{125}I:** 67.3 keV peak (EC from K shell + 35.5 keV γ) and composite peak at 40.4 keV (EC from L,M,.. shells + 35.5 keV γ).
- **External ^{241}Am source:** 59.5 keV γ peak and 30.4 keV composite peak.
- **External ^{133}Ba source:** 81.0 keV γ peak.
- **Internal ^{129}I:** 39.6 keV structure (39.6 keV γ + β spectrum).





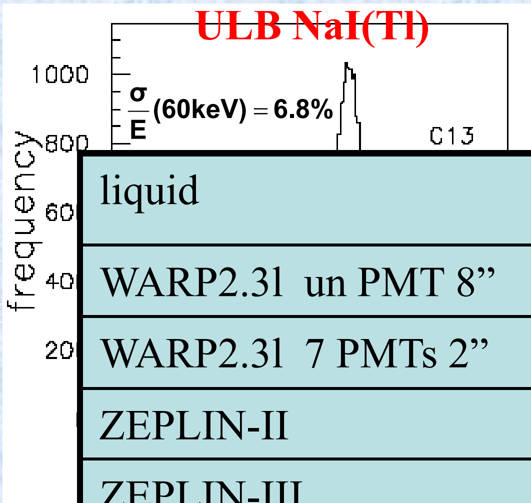


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

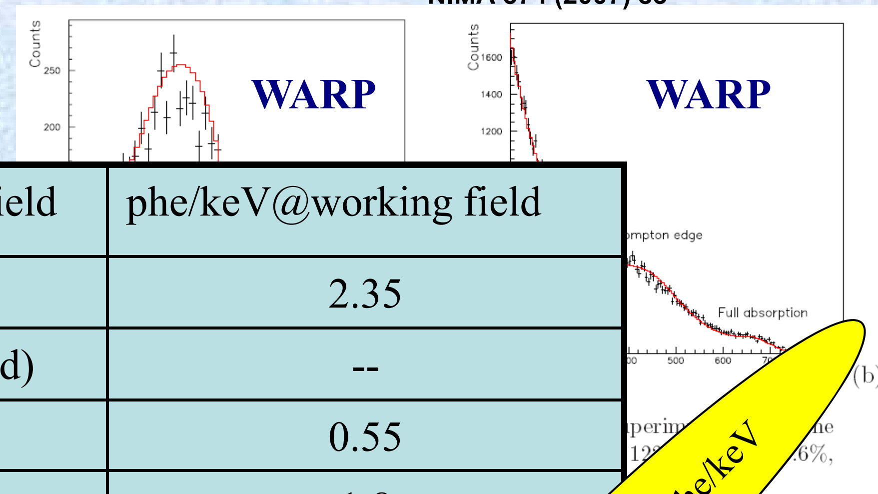
Routine calibrations with ^{241}Am

Examples of energy resolutions

DAMA/LIBRA
ULB NaI(Tl)



NIMA 574 (2007) 83



liquid	phe/keV@zero field	phe/keV@working field
WARP2.31 un PMT 8"	--	2.35
WARP2.31 7 PMTs 2"	0.5-1 (deduced)	--
ZEPLIN-II	1.1	0.55
ZEPLIN-III		1.8
XENON10	--	2.2 (^{137}Cs), 3.1 (^{57}C
XENON100	2.7	--
Neon	0.93	field not f

DAMA/LIBRA : 5.5 – 7.5 phe/keV

AP 28 (2007) 287

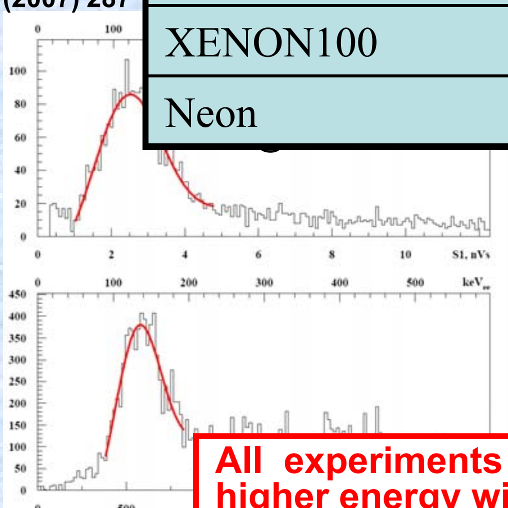
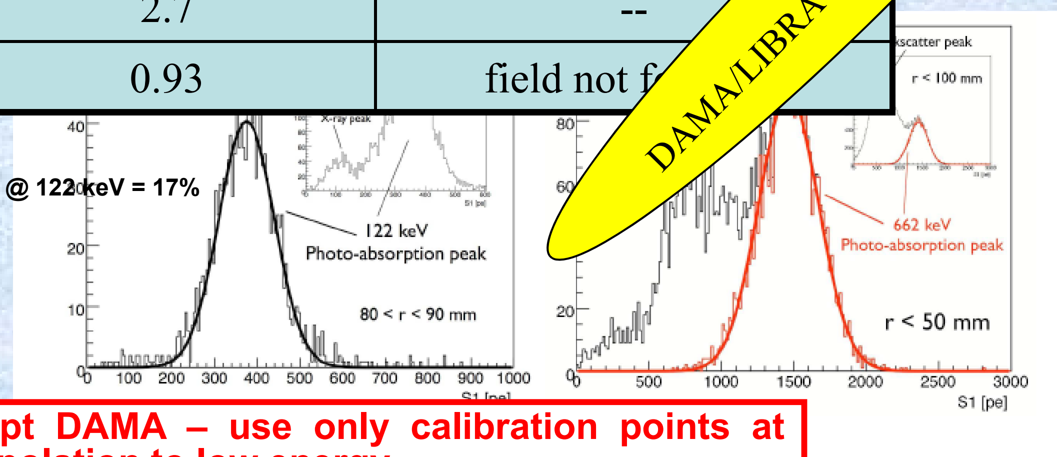


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.



...ght yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

All experiments – except DAMA – use only calibration points at higher energy with extrapolation to low energy

JoP: Conf. Ser. 65 (2007) 012015

Infos about DAMA/LIBRA data taking

- **First upgrade in Sept 2008**
- **New upgrade foreseen on fall 2010**

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

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**

NEW

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

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

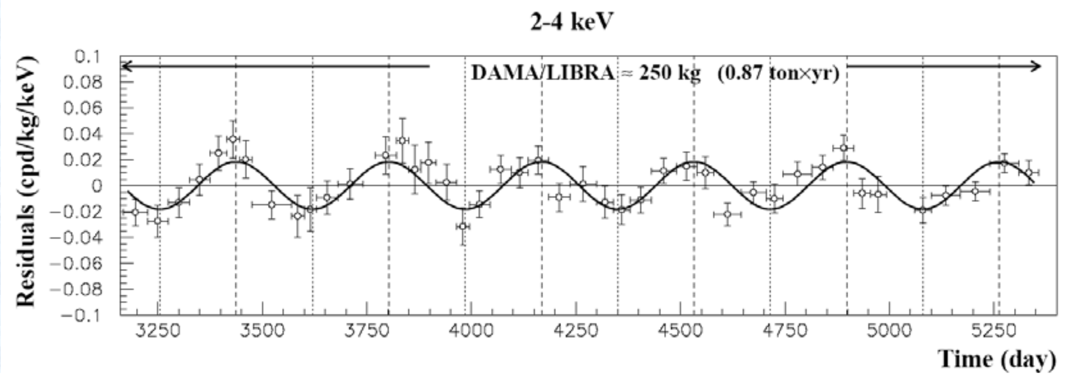
Continuously running

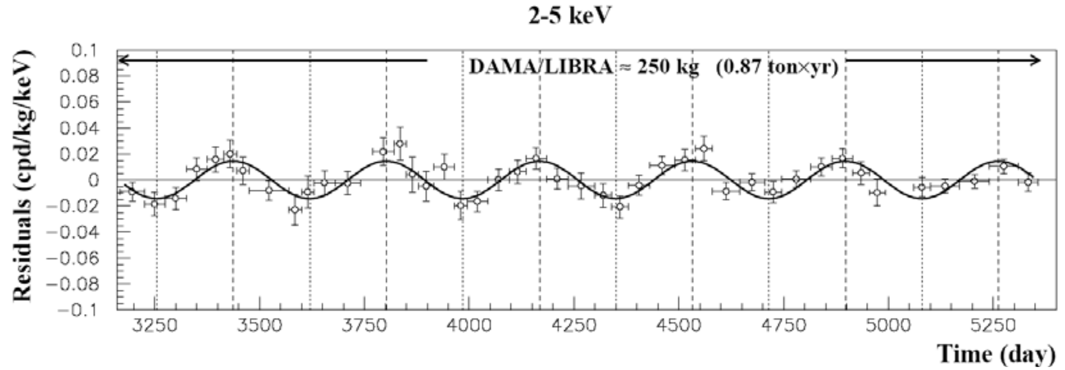
DAMA/LIBRA-1 to 6 Model Independent Annual Modulation Result

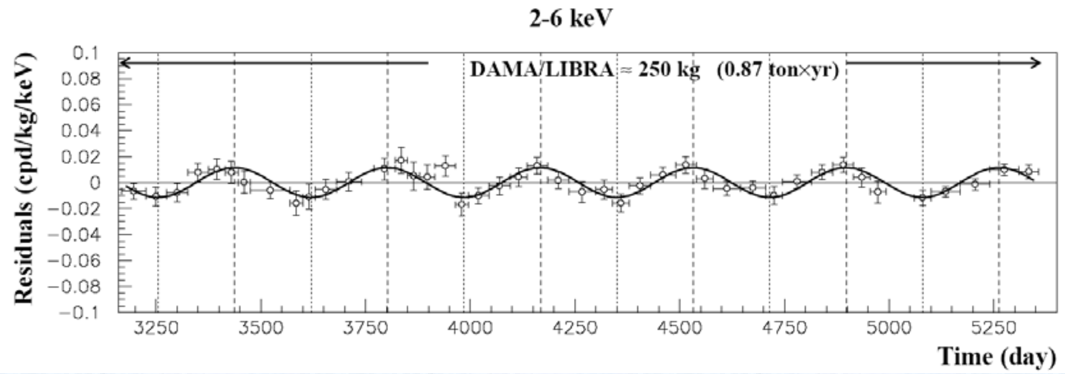
experimental single-hit residuals rate vs time and energy

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

Experimental values of the modulation parameters

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

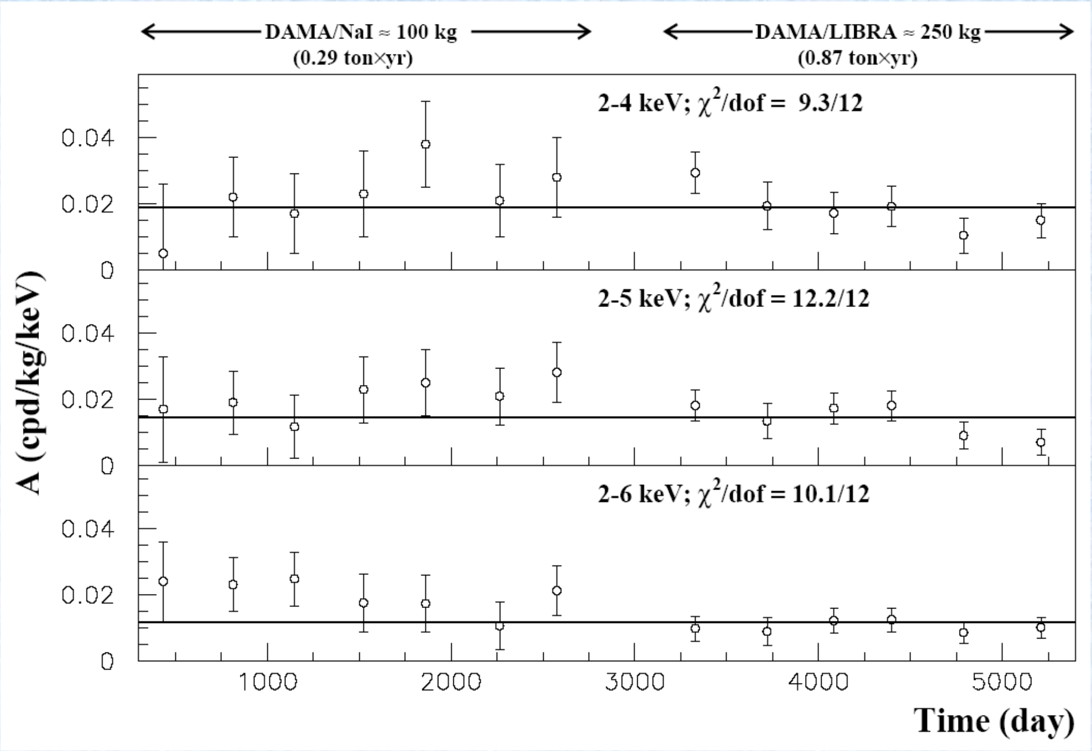
	A (cpd/kg/keV)	T= 2π/ω (yr)	t_0 (day)	C.L.
DAMA/NaI (7 years)				
(2÷4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2÷5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2÷6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA (6 years)				
(2÷4) keV	0.0180 ± 0.0025	0.996 ± 0.002	135 ± 8	7.2σ
(2÷5) 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

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

- The difference in the (2 – 6) keV modulation amplitudes between DAMA/NaI and DAMA/LIBRA mainly depends on the rate in the (5 – 6) keV energy bin.

- 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
  (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

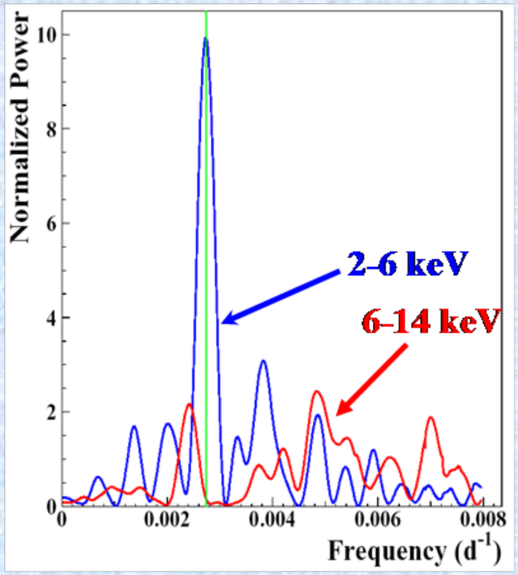
Power spectrum of single-hit residuals

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

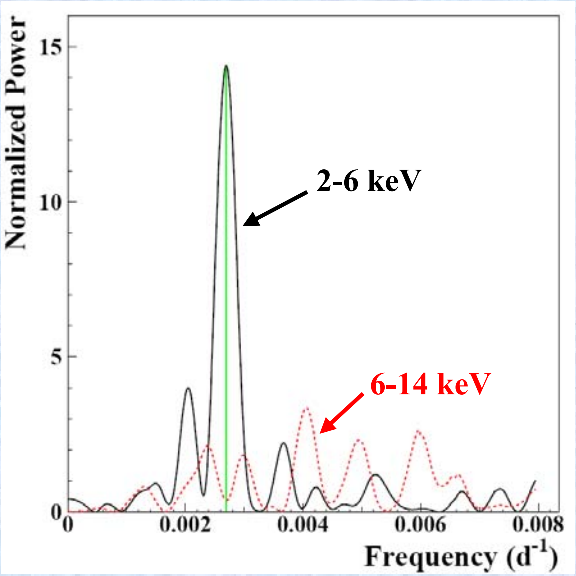
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

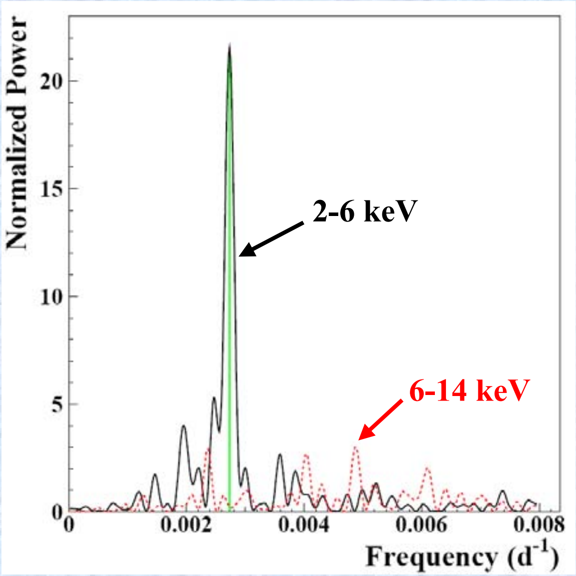
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



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
$2.737 \cdot 10^{-3}$ $d^{-1} \approx 1$ y^{-1}	2.697×10^{-3} $d^{-1} \approx 1$ yr^{-1}	2.735×10^{-3} $d^{-1} \approx 1$ yr^{-1}

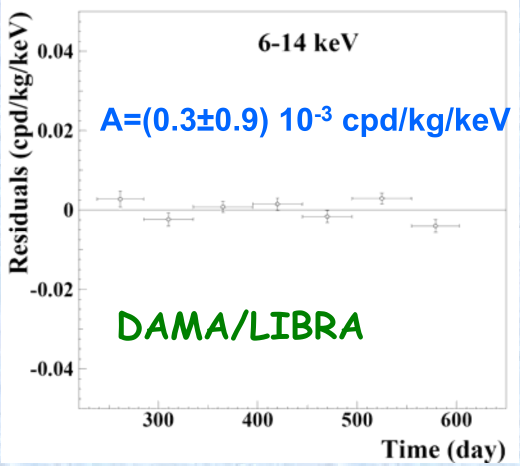
+

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

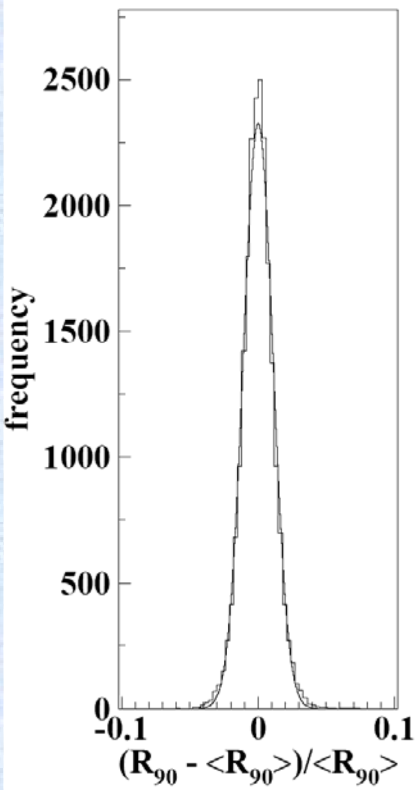
- **No Modulation above 6 keV**



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:

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

consistent with zero

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

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

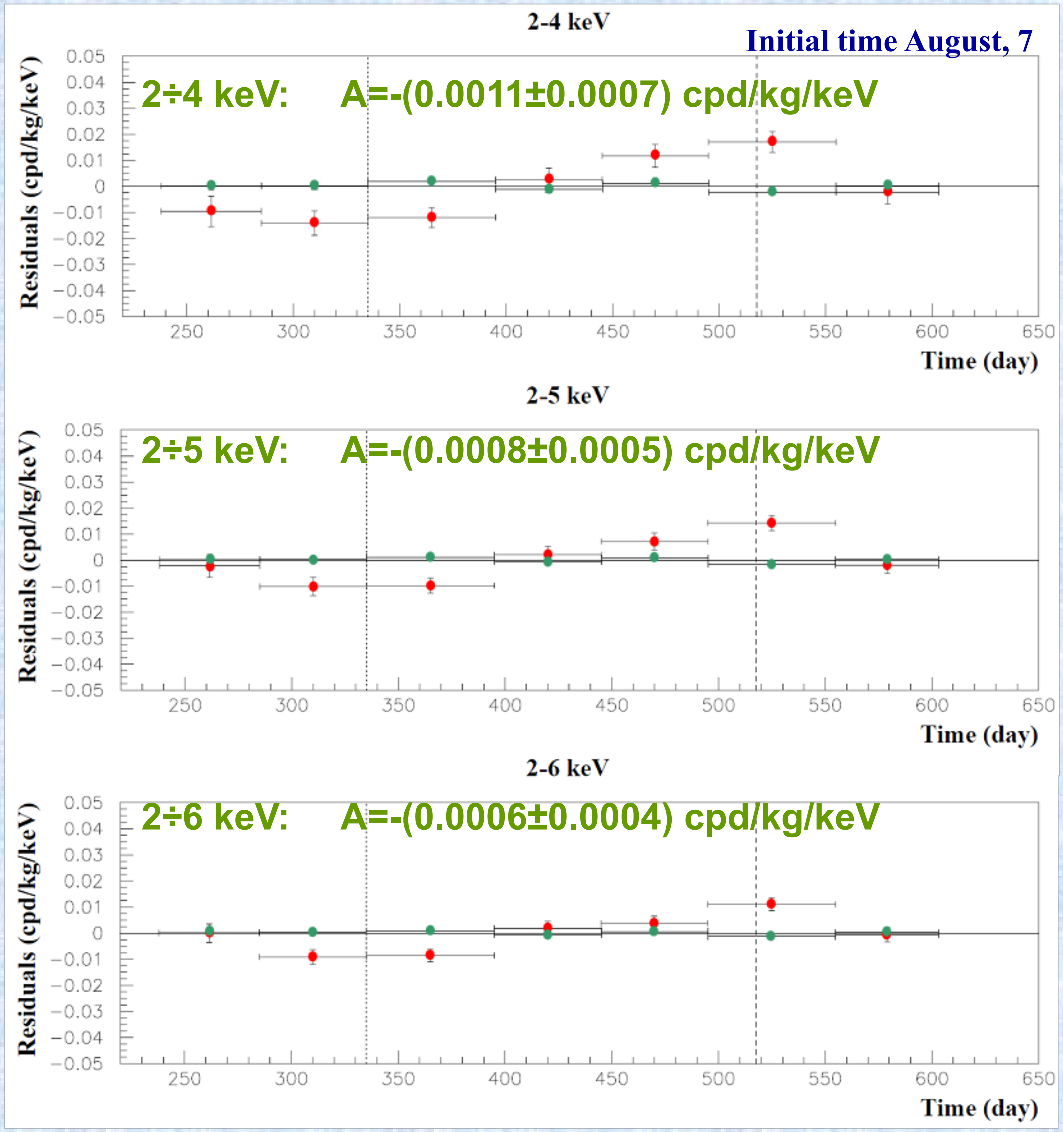
Multiple-hits events in the region of the signal - DAMA/LIBRA 1-6

- 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

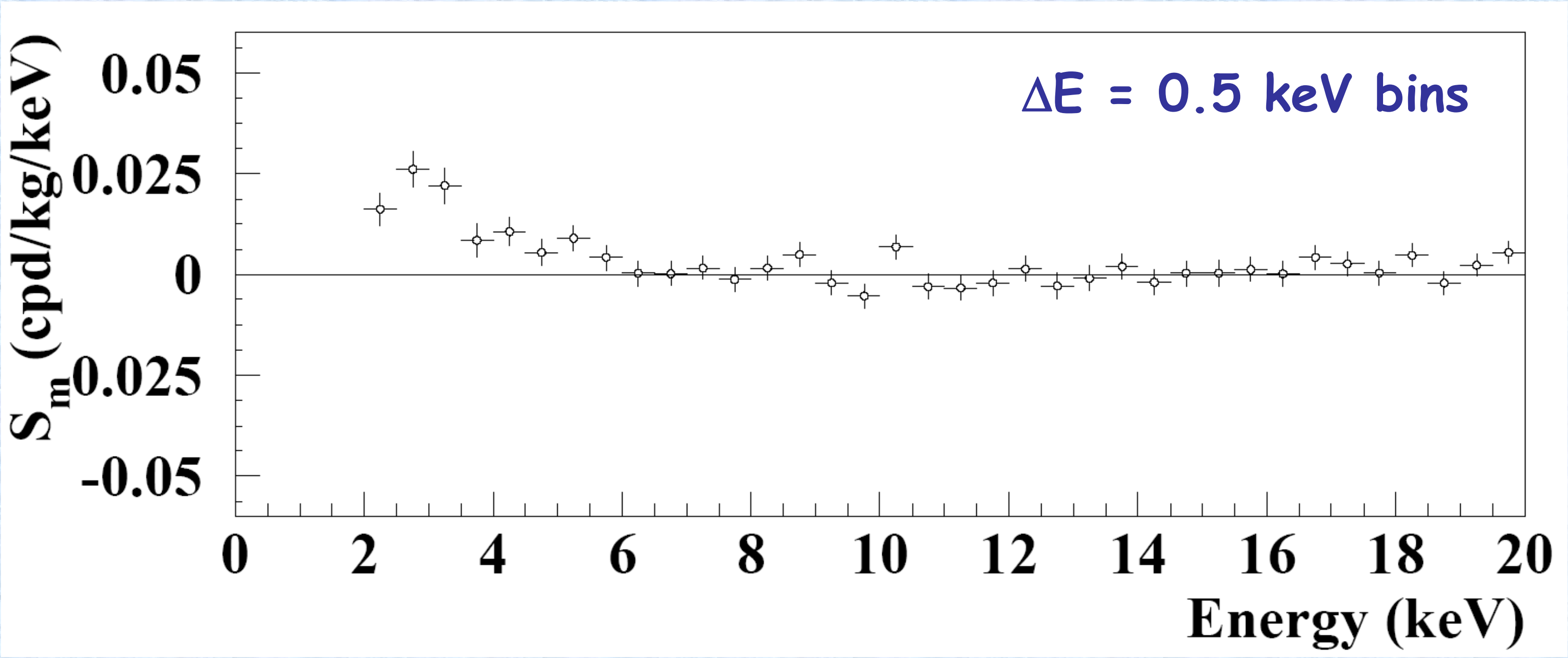
Energy distribution of the modulation amplitudes

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

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)

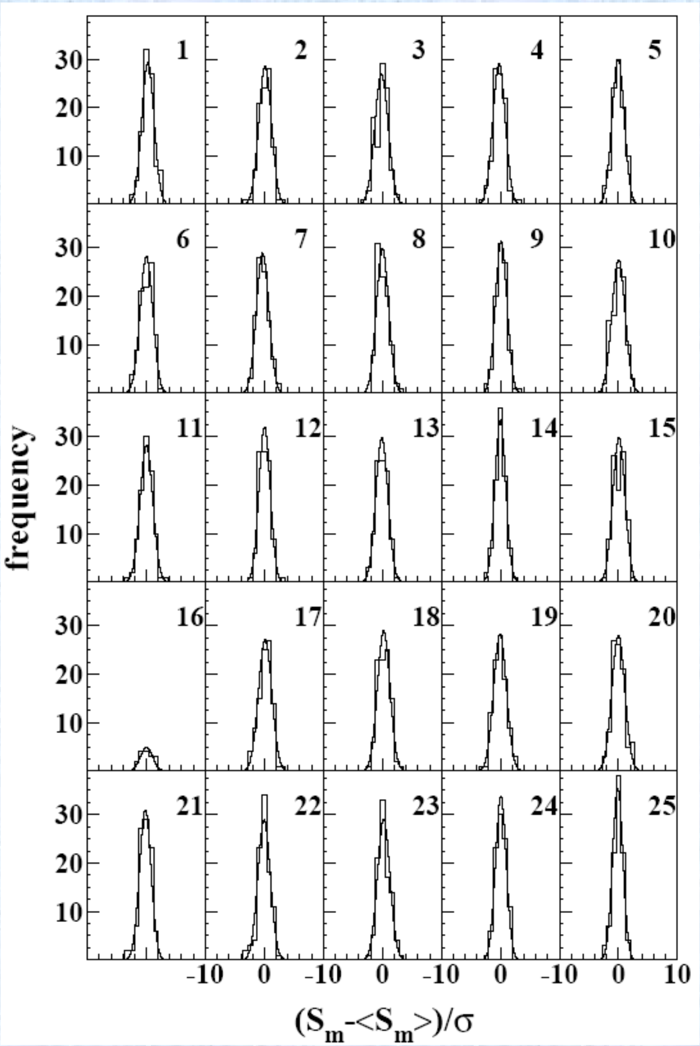
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

b) $\langle S_m \rangle$ = 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)

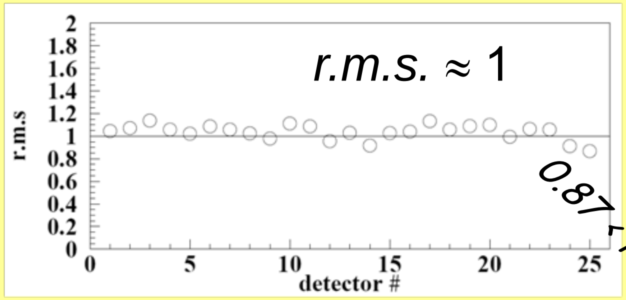


2-6 keV

Standard deviations of the variable

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

for the DAMA/LIBRA detectors



$0.87 < r.m.s. < 1.14$

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

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

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

S_m statistically well distributed in all the detectors and annual cycles

Statistical analyses about modulation amplitudes (S_m)

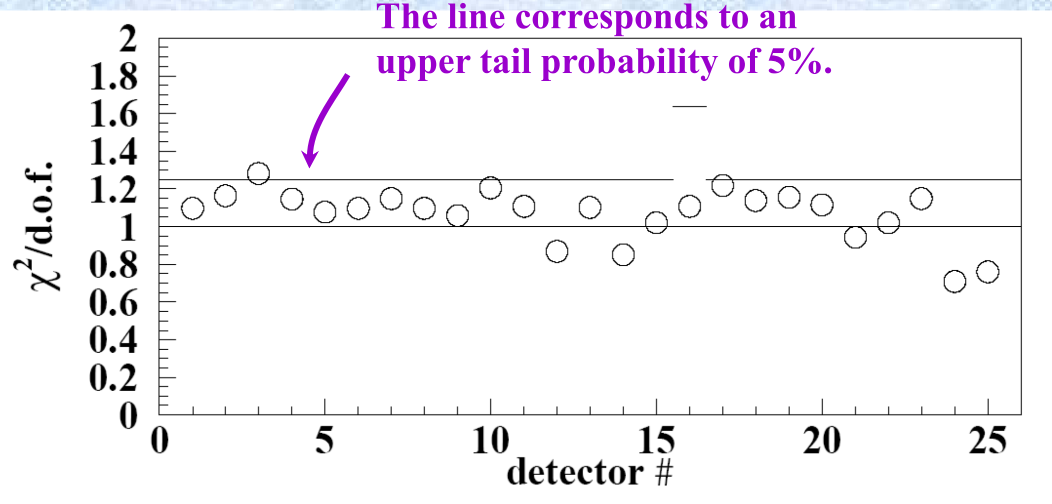
$x=(S_m-\langle S_m\rangle)/\sigma$,

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

$\chi^2/d.o.f.$ 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.

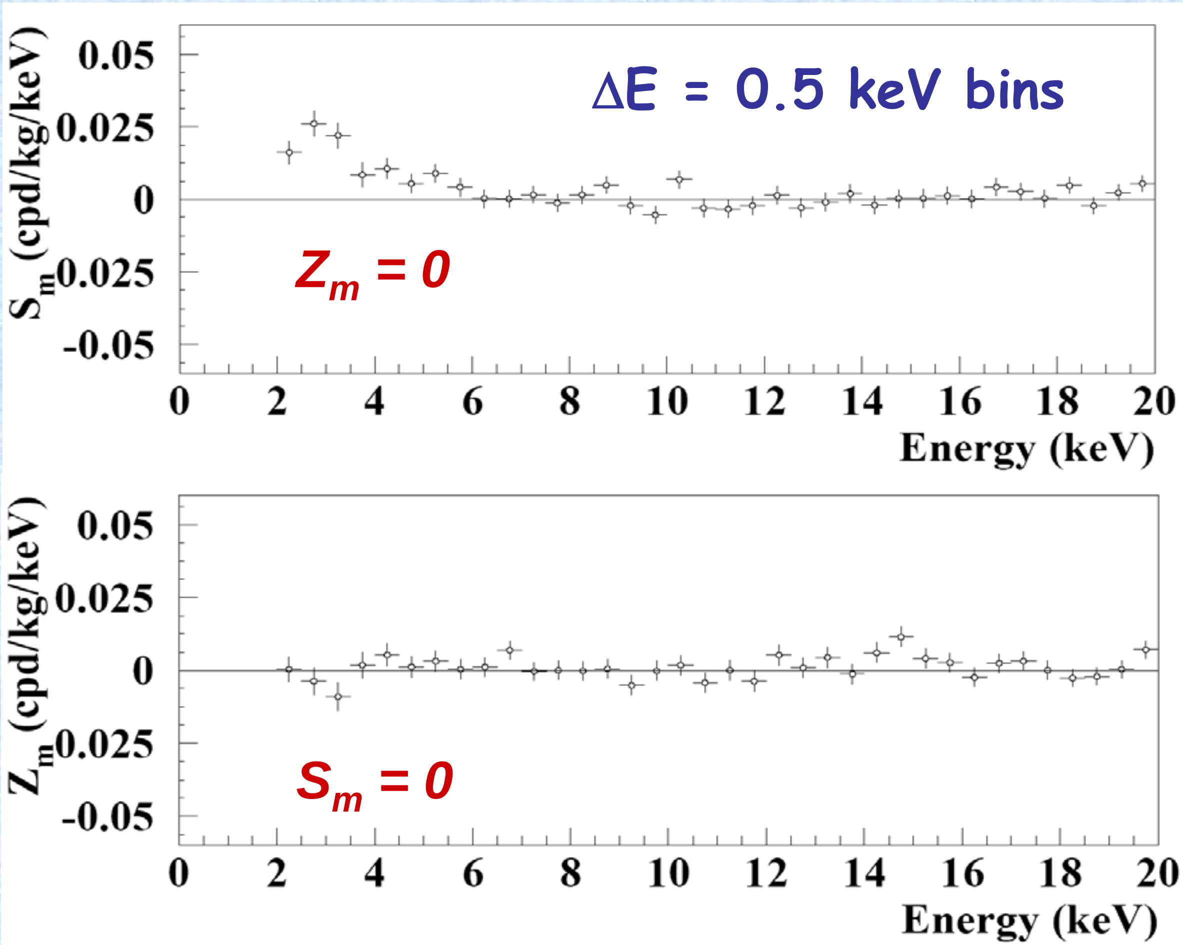
- The mean value of the twenty-five points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 4 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, 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)

phase at **2° June**

as for DM particles

phase 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)

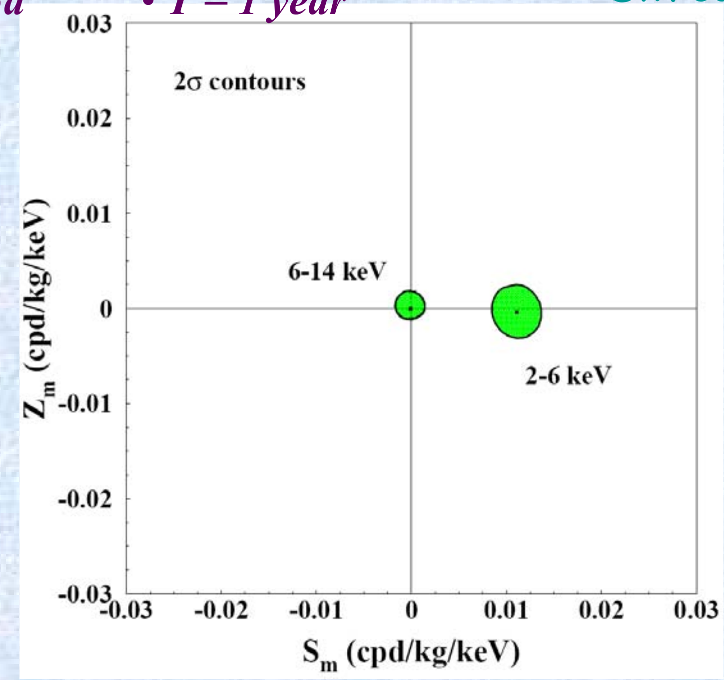
total exposure: 425428 kg×day = 1.17 ton×yr

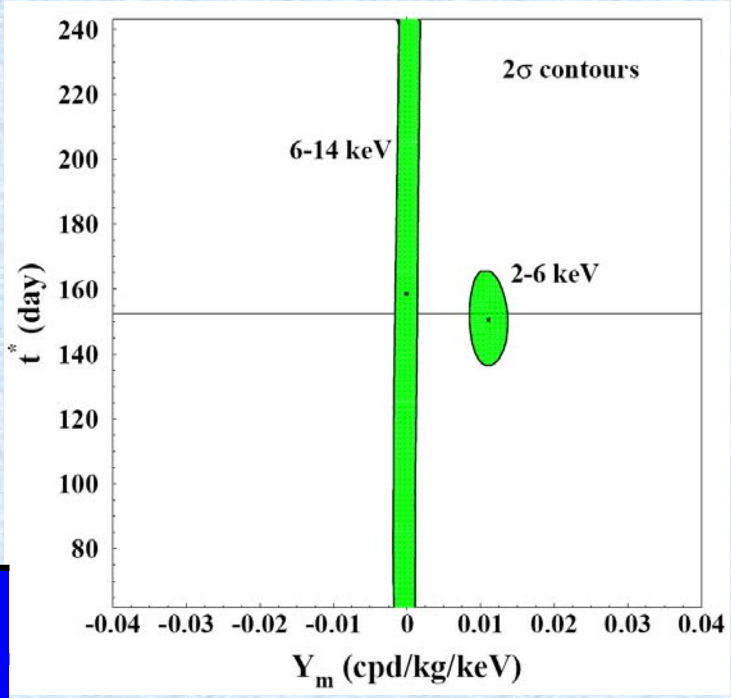
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

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)

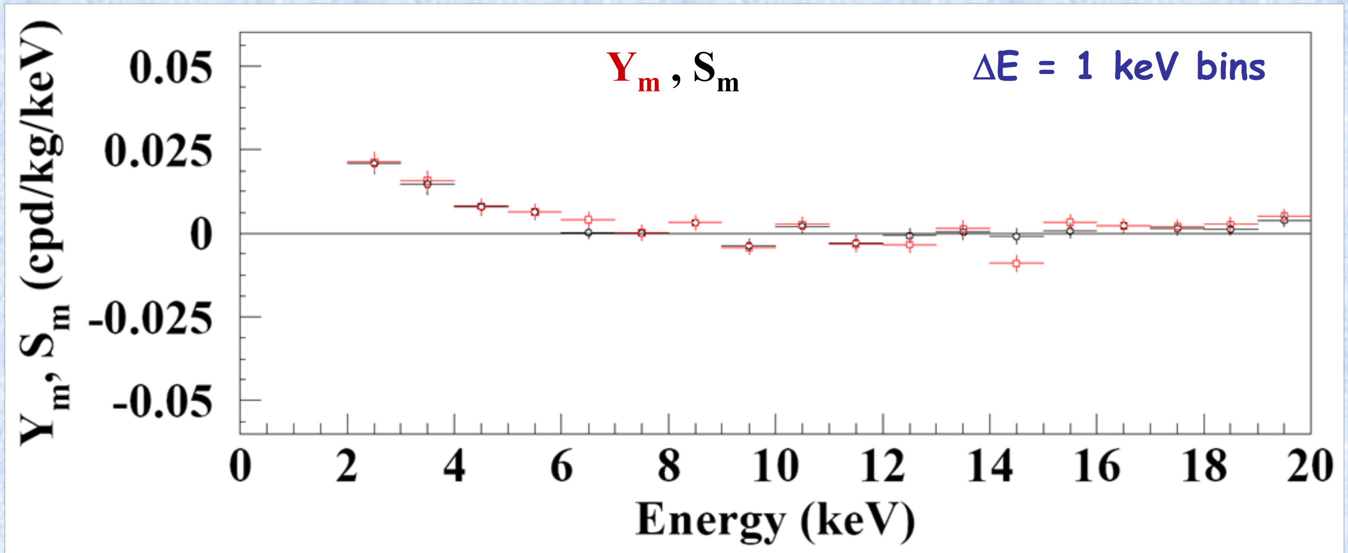
total exposure: 425428 kg×day = 1.17 ton×yr

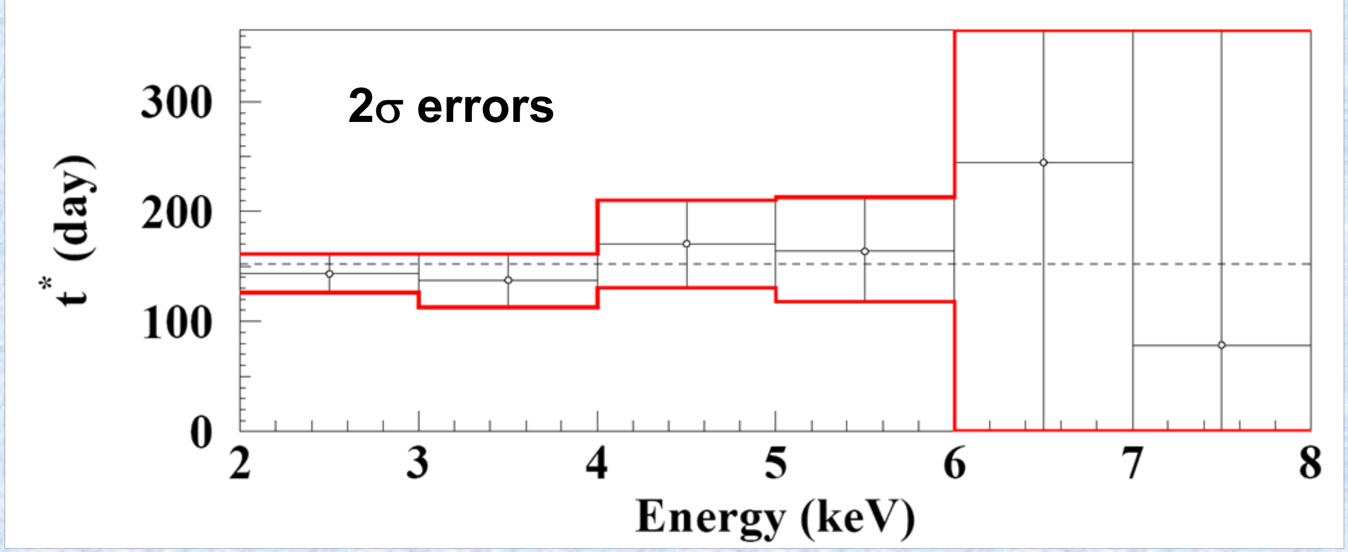
For Dark Matter signals:

$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

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





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

Stability parameters

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

Running conditions stable at a level better than 1% also in the two new running periods

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4	DAMA/LIBRA-5	DAMA/LIBRA-6
Temperature	$-(0.0001 \pm 0.0061)$ °C	(0.0026 ± 0.0086) °C	(0.001 ± 0.015) °C	(0.0004 ± 0.0047) °C	(0.0001 ± 0.0036) °C	(0.0007 ± 0.0059) °C
Flux N_2	(0.13 ± 0.22) l/h	(0.10 ± 0.25) l/h	$-(0.07 \pm 0.18)$ l/h	$-(0.05 \pm 0.24)$ l/h	$-(0.01 \pm 0.21)$ l/h	$-(0.01 \pm 0.15)$ l/h
Pressure	(0.015 ± 0.030) mbar	$-(0.013 \pm 0.025)$ mbar	(0.022 ± 0.027) mbar	(0.0018 ± 0.0074) mbar	$-(0.08 \pm 0.12) \times 10^{-2}$ mbar	$(0.07 \pm 0.13) \times 10^{-2}$ mbar
Radon	$-(0.029 \pm 0.029)$ Bq/m^3	$-(0.030 \pm 0.027)$ Bq/m^3	(0.015 ± 0.029) Bq/m^3	$-(0.052 \pm 0.039)$ Bq/m^3	(0.021 ± 0.037) Bq/m^3	$-(0.028 \pm 0.036)$ Bq/m^3
Hardware rate above single photoelectron	$-(0.20 \pm 0.18) \times 10^{-2}$ Hz	$(0.09 \pm 0.17) \times 10^{-2}$ Hz	$-(0.03 \pm 0.20) \times 10^{-2}$ Hz	$(0.15 \pm 0.15) \times 10^{-2}$ Hz	$(0.03 \pm 0.14) \times 10^{-2}$ Hz	$(0.08 \pm 0.11) \times 10^{-2}$ Hz

All the measured amplitudes well compatible with zero

+ none can account for the observed effect

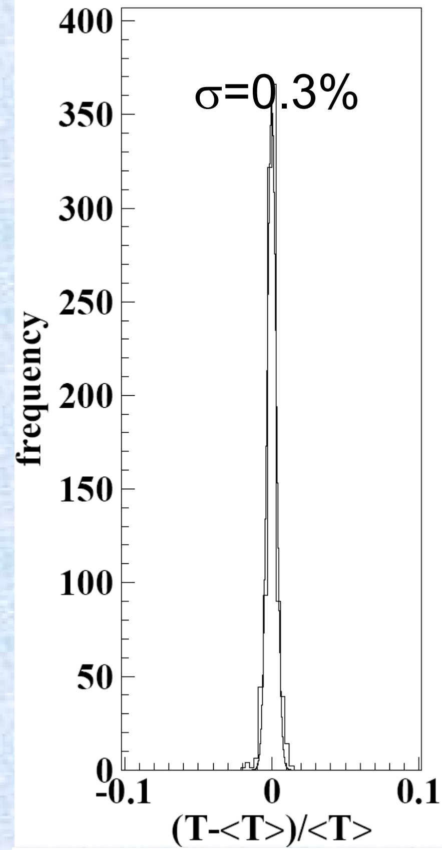
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

Temperature

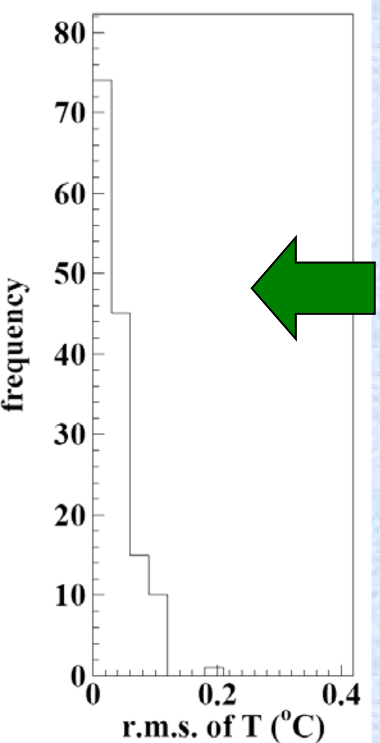
- **Detectors in Cu housings directly in contact with multi-ton shield →huge heat capacity (≈10^6 cal/^{0}C)**
- **Experimental installation continuosly air conditioned (2 independent systems for redundancy)**
- **Operating T of the detectors continuously controlled**

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

	T (°C)
DAMA/LIBRA-1	-(0.0001 ± 0.0061)
DAMA/LIBRA-2	(0.0026 ± 0.0086)
DAMA/LIBRA-3	(0.001 ± 0.015)
DAMA/LIBRA-4	(0.0004 ± 0.0047)
DAMA/LIBRA-5	(0.0001 ± 0.0036)
DAMA/LIBRA-6	(0.0007 ± 0.0059)



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



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

mean value ≈ 0.04°C

Considering the slope of the light output ≈ -0.2%/ °C: relative light output variation < 10^{-4} :

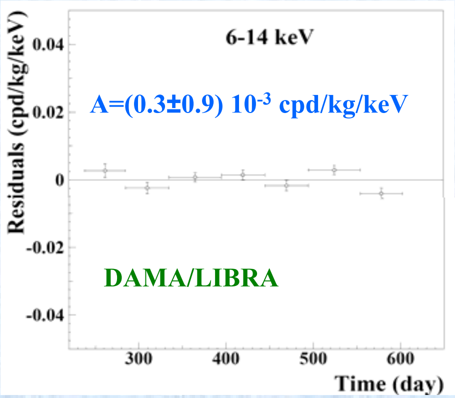
<10^{-4} cpd/kg/keV (< 0.5% $S_m^{observed}$)

An effect from temperature can be excluded

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

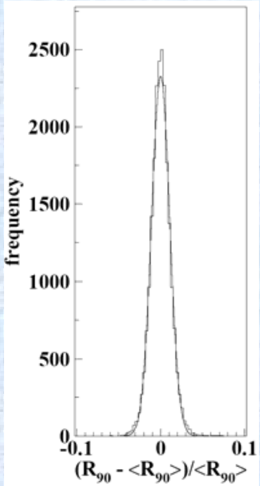
Summarizing on
a hypothetical background modulation in DAMA/LIBRA 1-6

- **No Modulation above 6 keV**



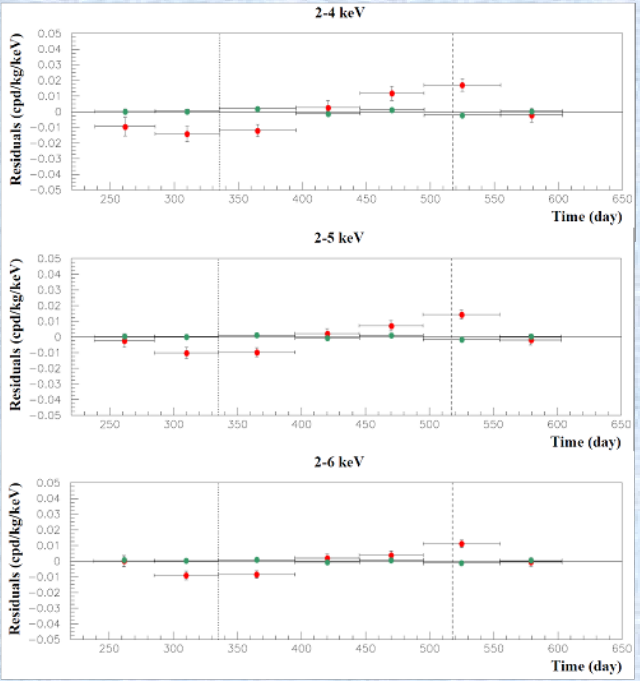
- **No modulation in the whole energy spectrum**

$\sigma \approx 1\%$



+ 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**



multiple-hits residual rate (green points) vs single-hit residual rate (red points)

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

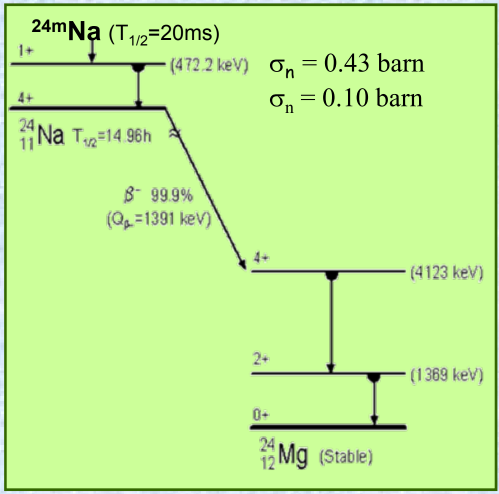
Nevertheless, additional investigations performed ...

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:

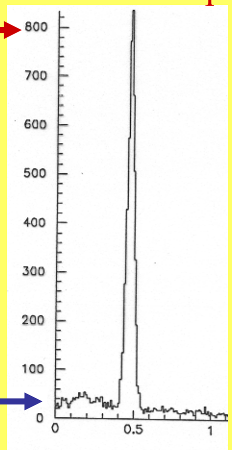
$S_m^{(thermal\ n)} < 0.8 \times 10^{-6}$ cpd/kg/keV (< 0.01% $S_m^{observed}$)

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 $\approx 10^{-3}$ 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}

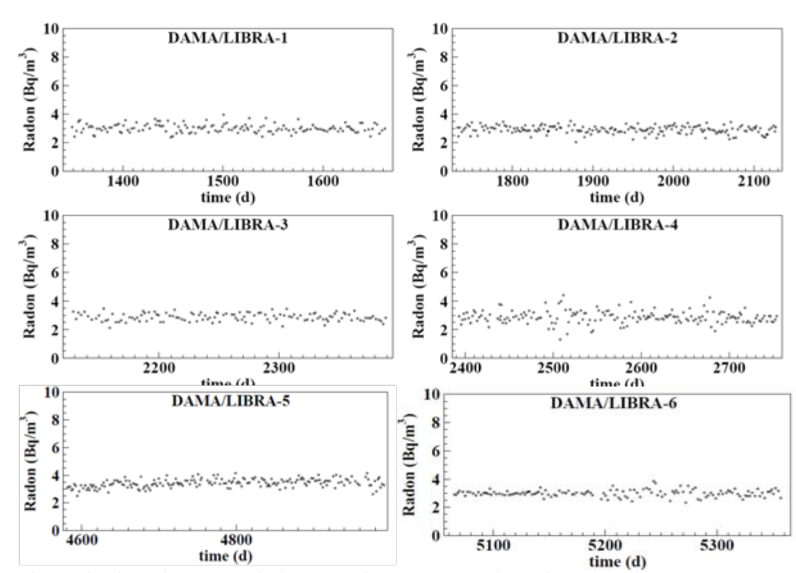
- a modulation amplitude for multiple-hit events different from zero

  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

Radon

- Three-level system to exclude Radon from the detectors:
- Walls and floor of the inner installation sealed in Supronyl (2×10^{-11} cm^2/s permeability).
- Whole shield in plexiglas box maintained in HP Nitrogen atmosphere in slight overpressure with respect to environment
- Detectors in the inner Cu box in HP Nitrogen atmosphere in slight overpressure with respect to environment continuously since several years



Time behaviours of the environmental radon in the installation (i.e. after the Supronyl), from which in addition the detectors are excluded by other two levels of sealing!

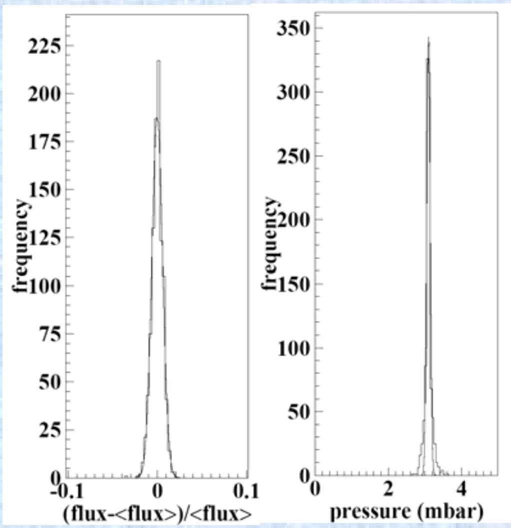
measured values at level of sensitivity of the used radonmeter

Amplitudes for annual modulation of Radon external to the shield:

	Radon (Bq/m^3)
DAMA/LIBRA-1	$-(0.029 \pm 0.029)$
DAMA/LIBRA-2	$-(0.030 \pm 0.027)$
DAMA/LIBRA-3	(0.015 ± 0.029)
DAMA/LIBRA-4	$-(0.052 \pm 0.039)$
DAMA/LIBRA-5	(0.021 ± 0.037)
DAMA/LIBRA-6	$-(0.028 \pm 0.036)$

<flux> ≈ 320 l/h

Over pressure ≈ 3.1 mbar



NO DM-like modulation amplitude in the time behaviour of external Radon (from which the detectors are excluded), of HP Nitrogen flux and of Cu box pressure

Investigation in the HP Nitrogen atmosphere of the Cu-box

- Study of the double coincidences of γ's (609 & 1120 keV) from ^{214}Bi Radon daughter
- Rn concentration in Cu-box atmosphere $<5.8 \cdot 10^{-2}$ Bq/m^3 (90% C.L.)
- By MC: $<2.5 \cdot 10^{-5}$ cpd/kg/keV @ low energy for *single-hit* events(enlarged matrix of detectors and better filling of Cu box with respect to DAMA/NaI)
- An hypothetical 10% modulation of possible Rn in Cu-box:

$<2.5 \times 10^{-6}$ cpd/kg/keV ($<0.01\%$ $S_m^{observed}$)

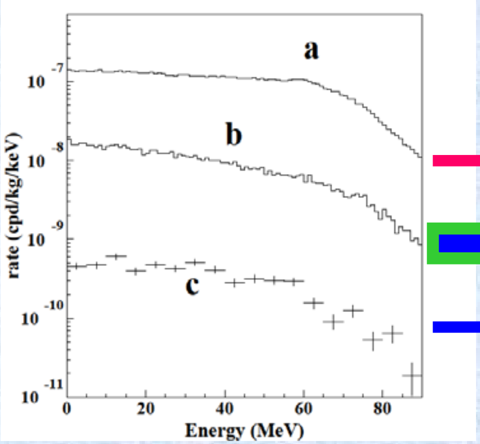
An effect from Radon can be excluded

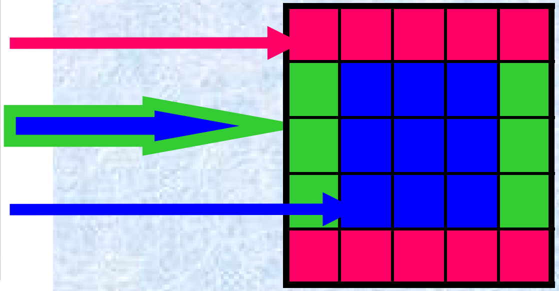
+ any possible modulation due to Radon would always fail some of the peculiarities of the signature and would affect also other energy regions

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; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)
Knowing that: $M_{setup} \approx 250$ kg and ΔE=4keV

→ **$S_m^{(\mu)} < (0.4÷3) \times 10^{-5}$ 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 sizeable 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

NO

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

(+ see above)

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

The new annual cycles DAMA/LIBRA-5,6 have further confirmed a peculiar annual modulation of the *single-hit* events in the (2-6) keV energy region which satisfies the many requests of the DM annual modulation signature.

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 it *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

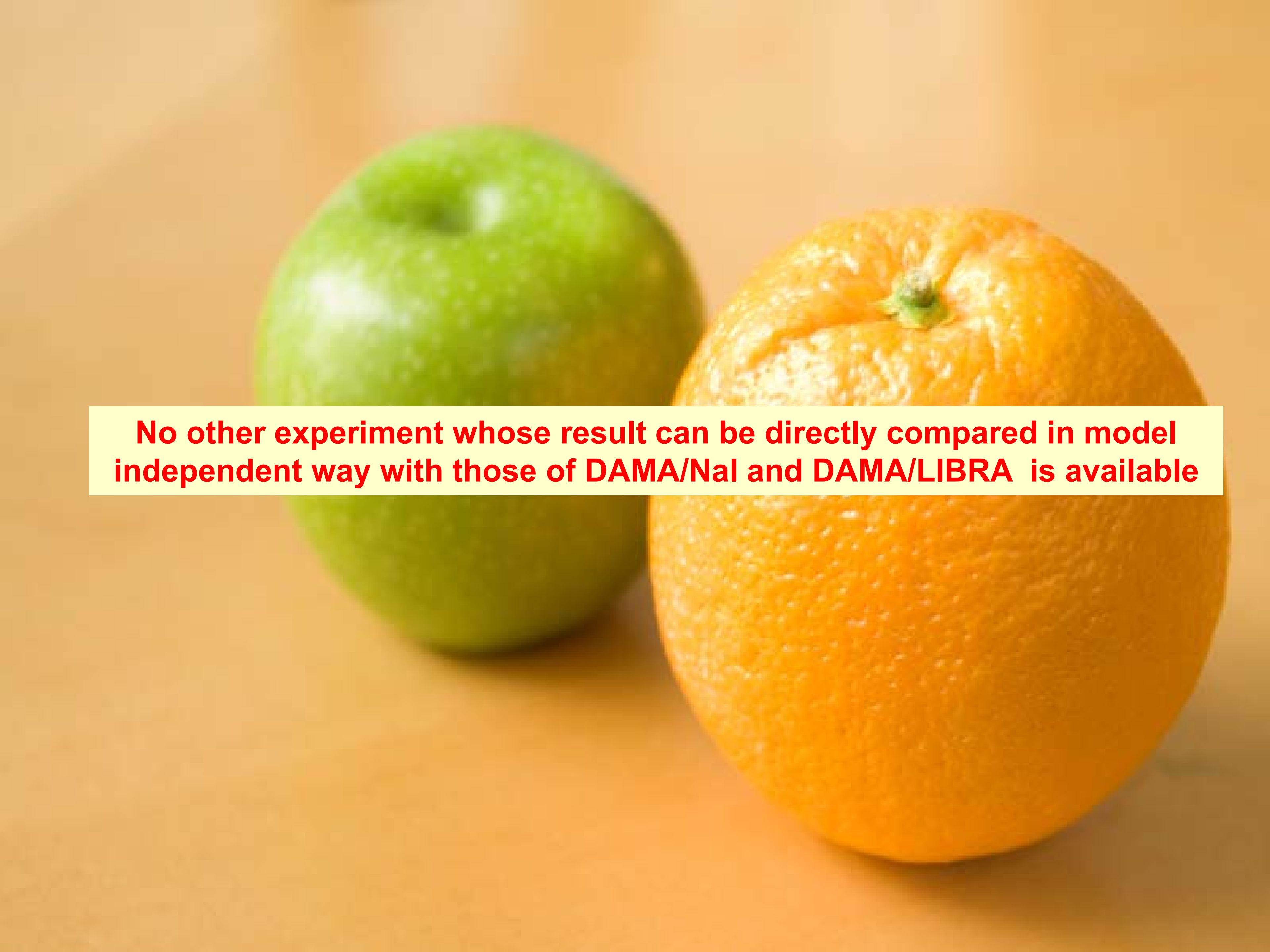
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

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

- Neutralino as LSP in various SUSY theories
- Various kinds of WIMP candidates with several different kind of interactions Pure SI, pure SD, mixed + Migdal effect +channeling,… (from low to high mass)
- a heavy ν of the 4-th family
- Pseudoscalar, scalar or mixed light bosons with axion-like interactions
- WIMP with preferred inelastic scattering
- Mirror Dark Matter
- Light Dark Matter
- Self interacting Dark Matter
- Dark Matter (including some scenarios for WIMP) electron-interacting
- Sterile neutrino
- heavy exotic canditates, as "4th family atoms", ...
- Elementary Black holes such as the Daemons
- Kaluza Klein particles
- … and more

Possible model dependent positive hints from indirect searches (but interpretation, evidence itself, derived m… and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc. e… **not in conflict with DAMA results**

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



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

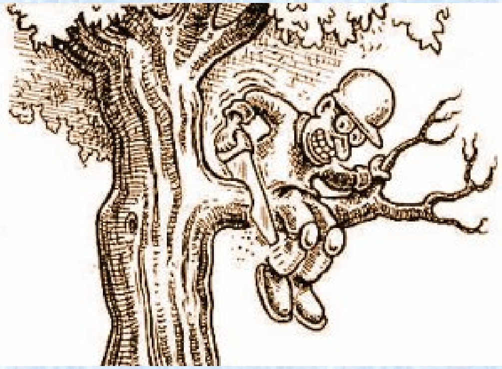
About model dependent exclusion plots

Selecting just one semplified model framework, making lots of assumptions, fixing large numbers of parameters … but…

- *which particle?*
- *which couplings? which model for the coupling?*
- *which form factors for each target material and related parameters?*
- *which nuclear model framework for each target material?*
- *Which spin factor for each case?*
- *which scaling laws?*
- *which halo profile?*
- *which halo parameters?*
- *which velocity distribution?*
- *which parameters for velocity distribution?*
- *which v_0?*
- *which v_{esc}?*
- *…etc. etc.*

and experimental aspects ,,,

- *marginal and "selected" exposures*
- *Threshold, energy scale and energy resolution when calibration in other energy region (& few phe/keV)? Stability? Too few calibration procedures and often not in the same running conditions*
- *Selections of detectors and of data*
- *handling of (many) "subtraction" procedures and stability in time of all the cut 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*
- *etc., etc.?*



+ no uncertainties accounted for

no sensitivity to DM annual modulation signature

Different target materials

DAMA implications generally not correctly presented

Exclusion plots have no "universal validity" and cannot disproof a model independent result in any given general model framework (they depend on the cooking) + often overestimated + methodological robustness (see R. Hudson, Found. Phys. 39 (2009) 174)

On the other hand, possible positive hints (above an estimated background) should be interpreted. Large space for compatibility.

- In progress updated/new model dependent analyses by applying maximum likelihood analysis in time and energy accounting for at least some of the many existing uncertainties in the field (as done in 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), to improve the investigations and to enlarge them to other scenarios

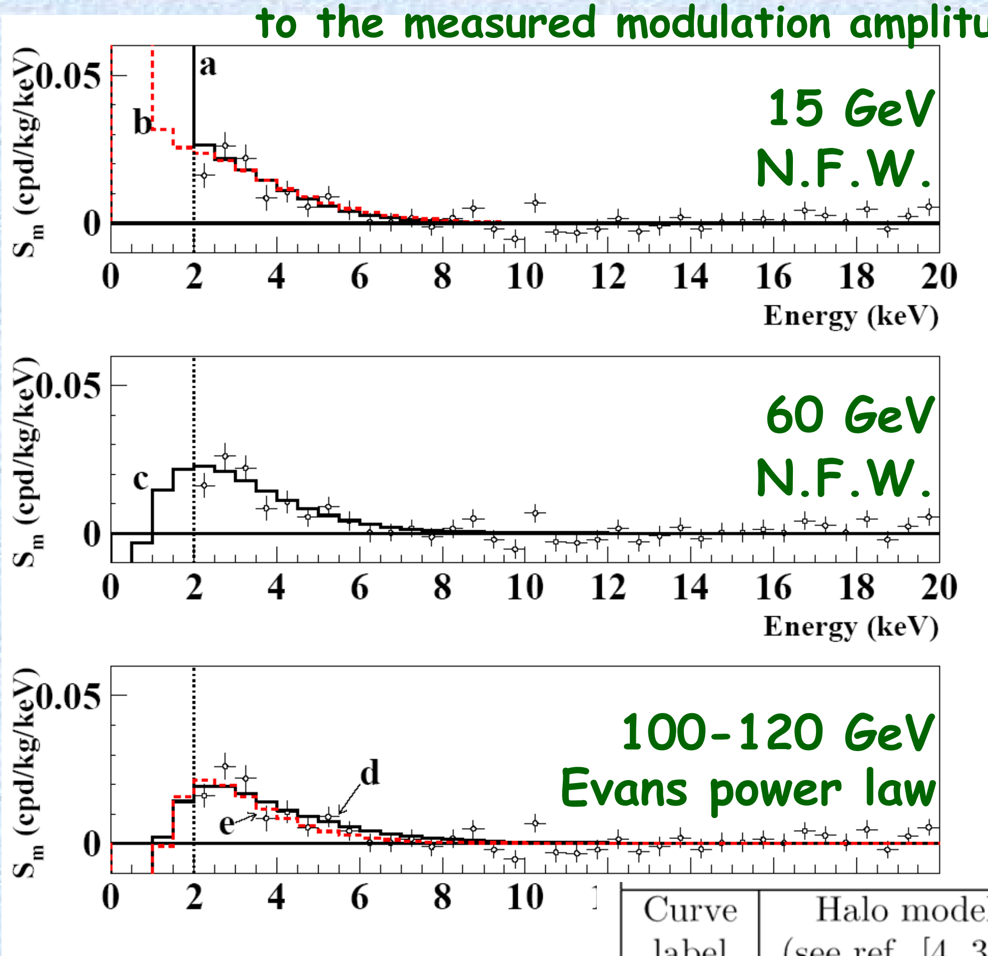
- Just to offer some naive feeling on the complexity of the argument:

experimental S_m values vs expected behaviours

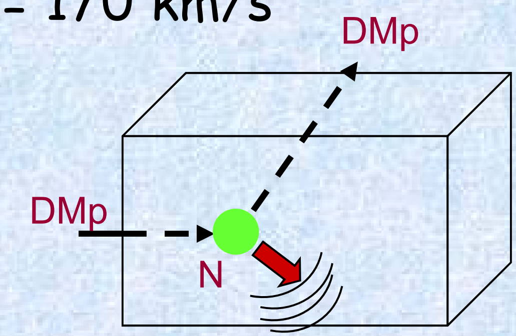
for some DM candidates in few of the many possible astrophysical, nuclear and particle physics scenarios and parameters values

↓

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



WIMP DM candidate as in [4]
considering elastic scattering on nuclei
SI dominant coupling
v_0 = 170 km/s



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

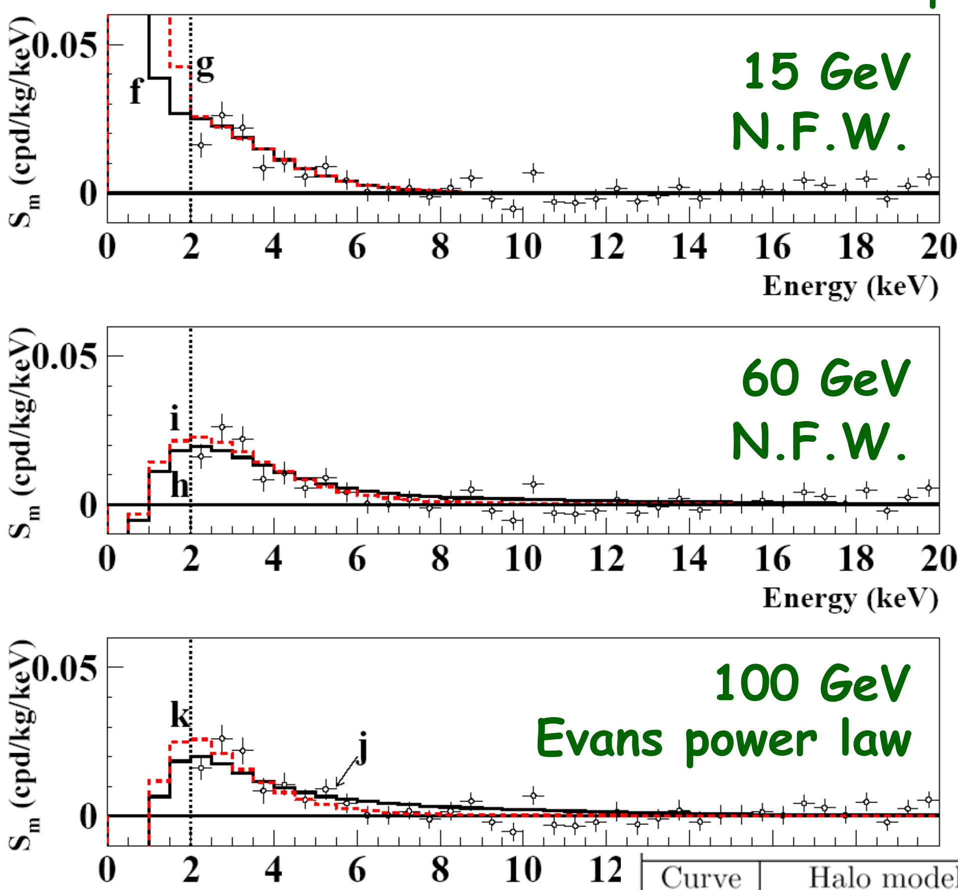
…scaling from NaI

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}

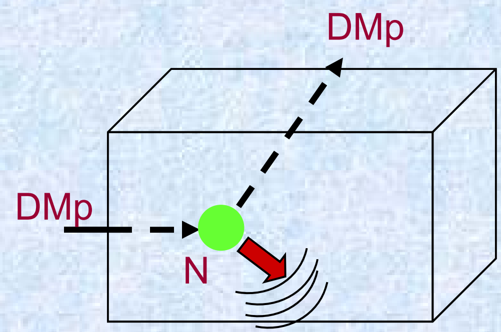
channeling contribution as in EPJC53(2008)205 considered for curve *b*

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

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



WIMP DM candidate as in [4]
Elastic scattering on nuclei
SI & SD mixed coupling
v_0 = 170 km/s



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

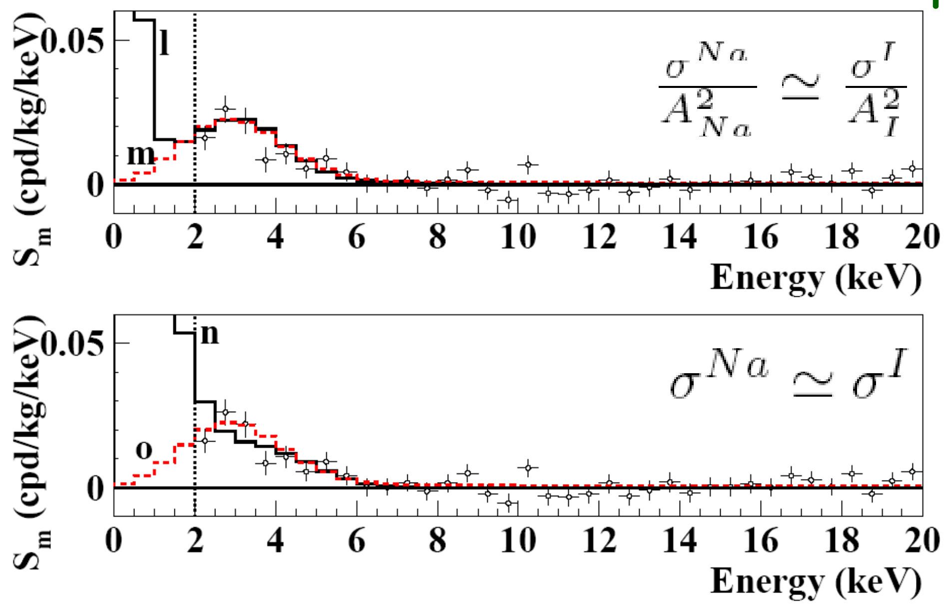
…scaling from NaI

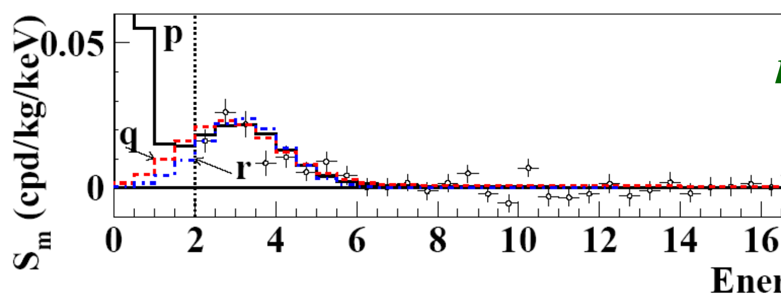
$\theta = 2.435$

Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)	$\xi\sigma_{SD}$ (pb)
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 $S_{m,k}$

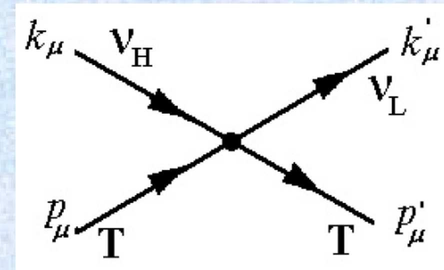




$m_L=0$

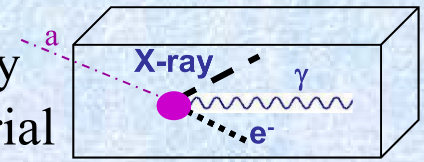
LDM candidate

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



Light bosonic candidate

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



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

(NFW) halo model as in [4, 34], local density = 0.17 GeV/cm^3, 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}

Conclusions

- The positive evidence for the presence of DM particles in the galactic halo is now supported at 8.9 σ C.L. by the cumulative 1.17 ton $\times$ yr exposure collected over 13 annual cycles by the former DAMA/NaI and the present DAMA/LIBRA
- The modulation parameters are now determined with better precision
- 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 disantangle among at least some of the possible scenarios
- Collect a suitable exposure in the new running conditions
- Investigate second order effects

… and …