New results and perspectives of DAMA/LIBRA

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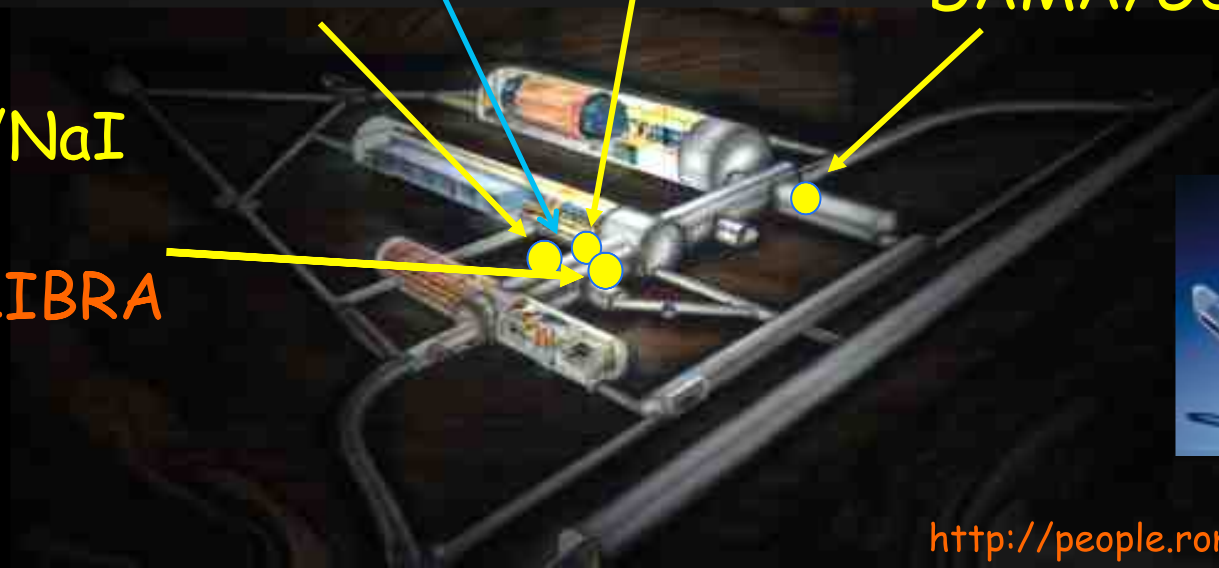
P. Belli

INFN-Roma Tor Vergata

Roma2,Roma1,LNGS,IHEP/Beijing

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

DAMA: an observatory for rare processes @LNGS

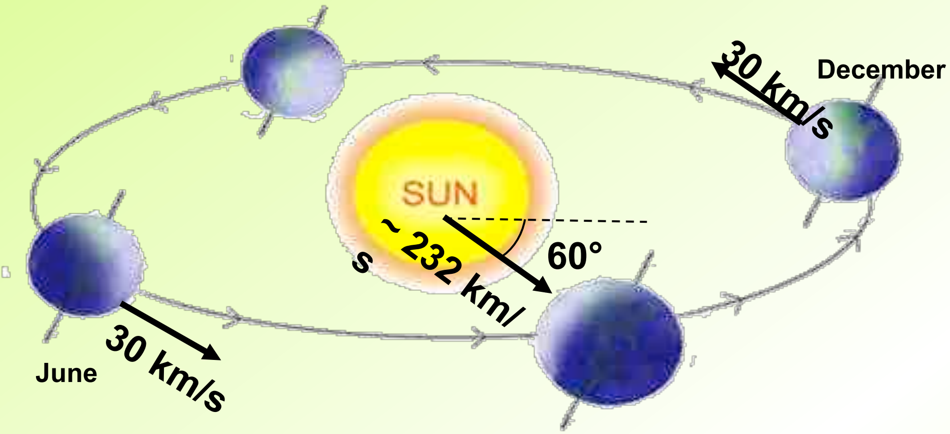


http://people.roma2.infn.it/dama

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

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

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



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

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

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

Expected rate in given energy bin changes because the revolution motion of the Earth around the Sun, which is moving in the Galaxy

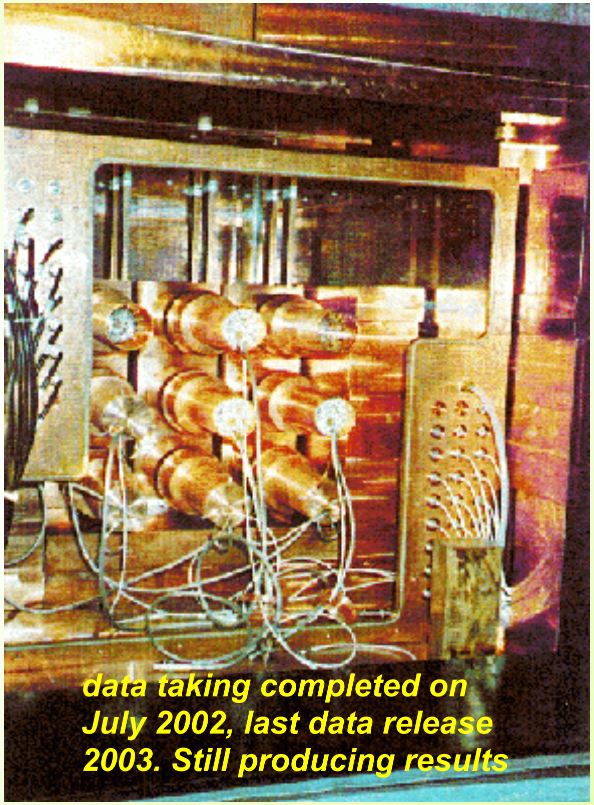
Requirements of the annual modulation

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

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

The DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

The pioneer DAMA/NaI: ≈100 kg highly radiopure 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×yr

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

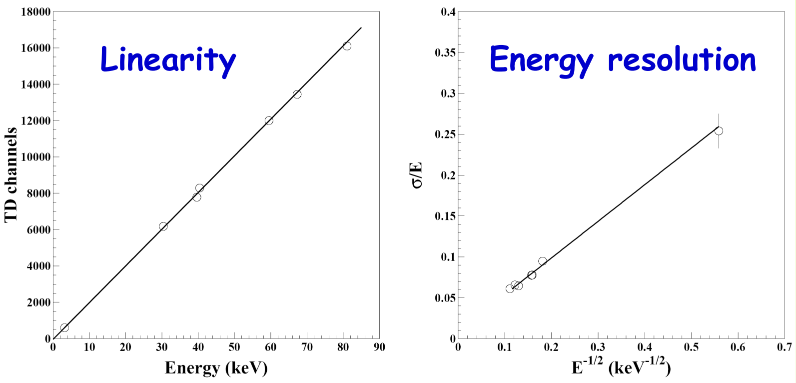
As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors:
^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

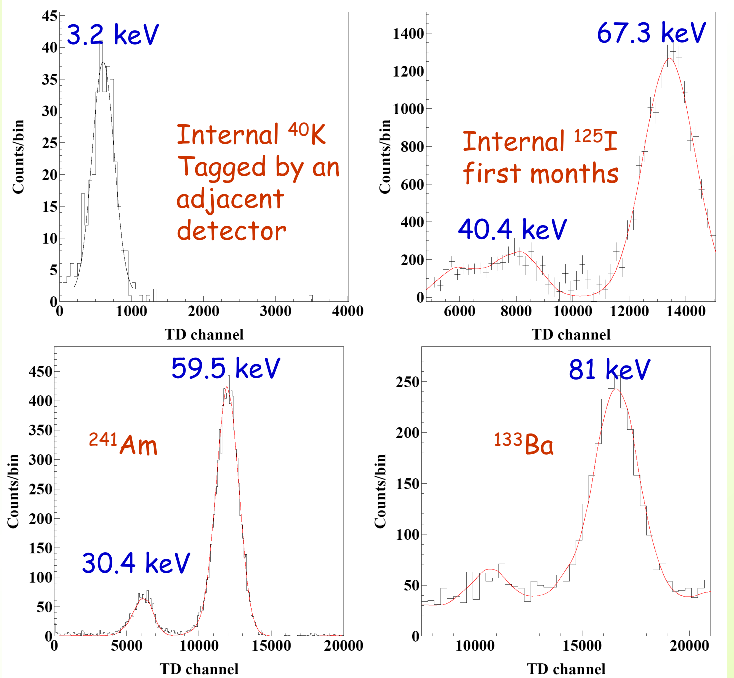
- **Radiopurity,performances, procedures, etc.:** NIMA592(2008)297, JINST 7 (2012) 03009
- **Results on DM particles:** *Annual Modulation Signature:* EPJC56(2008)333, EPJC67(2010)39, arXiv:1308.5109. *Related results:* PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022
- **Results on rare processes:** *PEP violation in Na, I:* EPJC62(2009)327, *CNC in I:* EPJC72(2012)1920, *IPP in ^{241}Am decay:* EPJA49(2013)64

DAMA/LIBRA calibrations

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

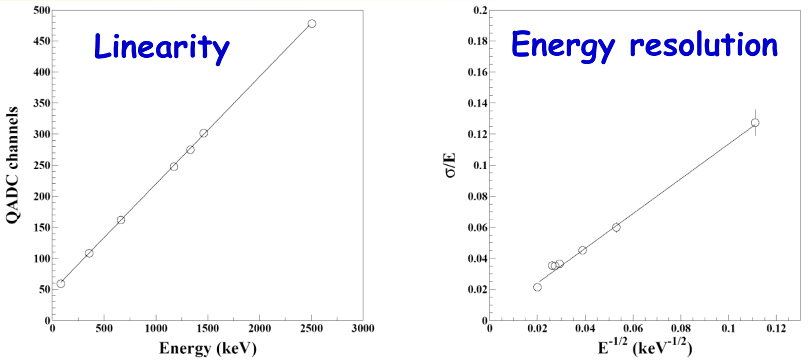


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

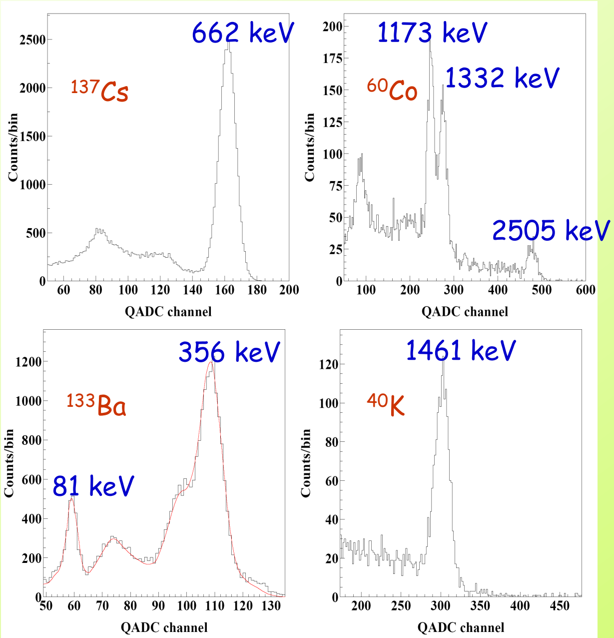


The curves superimposed to the experimental data have been obtained by simulations

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



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



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

Thus, here and hereafter keV means keV electron equivalent

Complete DAMA/LIBRA-phase1

	Period	Mass (kg)	Exposure (kg×day)	$(\alpha - \beta^2)$
DAMA/LIBRA-1	Sept. 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 - Sept. 1, 2009	242.5	58768	0.519
DAMA/LIBRA-7	Sep. 1, 2009 - Sept. 8, 2010	242.5	62098	0.515
DAMA/LIBRA-phase1	Sept. 9, 2003 - Sept. 8, 2010		379795 ≃ 1.04 ton×yr	0.518
DAMA/NaI + DAMA/LIBRA-phase1:			1.33 ton×yr	

a ton × yr experiment? done

- EPJC56(2008)333
- EPJC67(2010)39
- arXiv:1308.5109 (ROM2F/2013/13)

- calibrations: ≈96 M events from sources
- acceptance window eff: 95 M events (≈3.5 M events/keV)

- **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

START of DAMA/LIBRA – phase 2

- **Second upgrade on Oct./Nov. 2010**

✧ Replacement of all the PMTs with higher Q.E. ones from dedicated developments

✧ Goal: lowering the software energy threshold

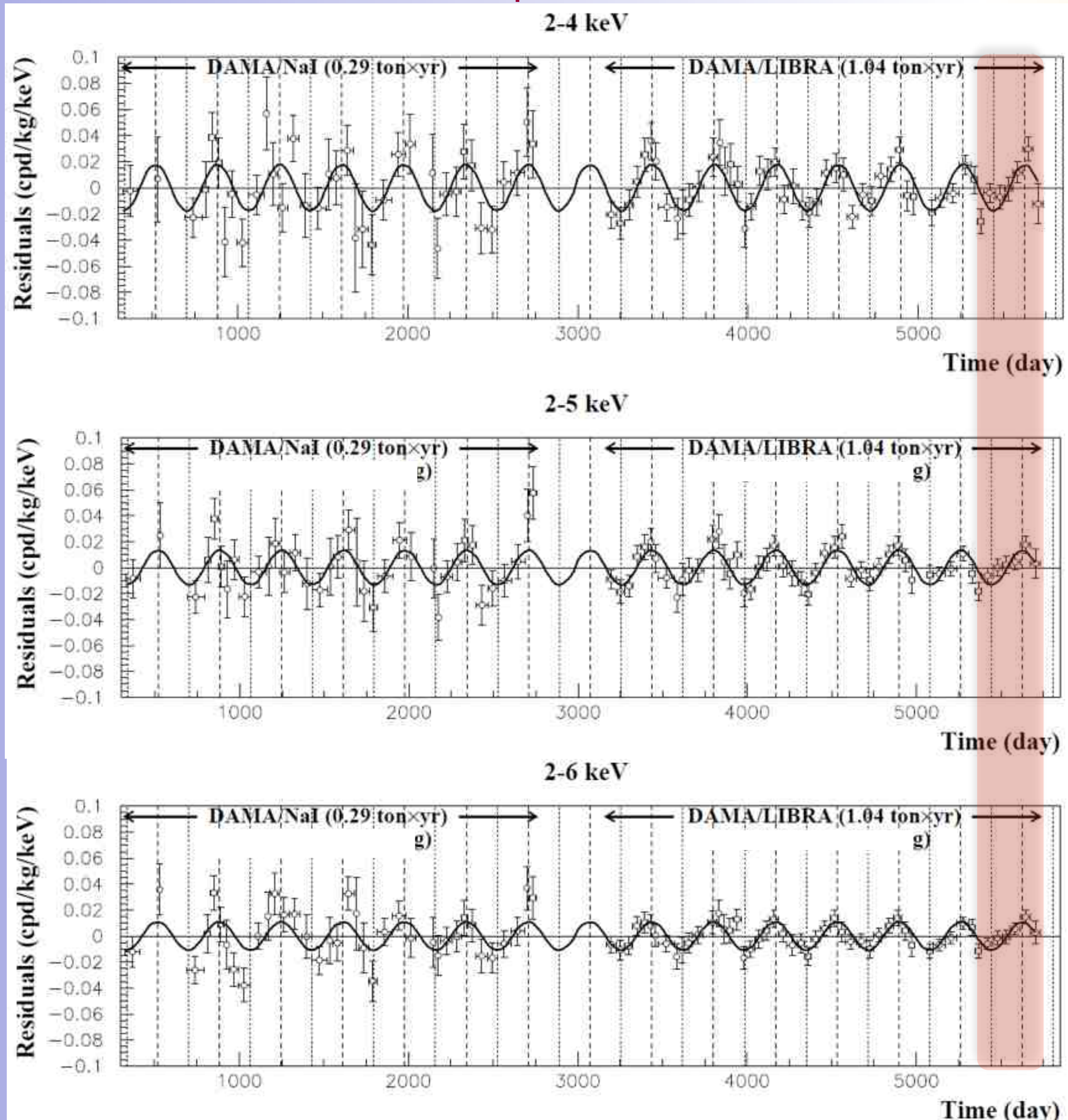
Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

... continuously running

Model Independent DM Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = 1.33 ton×yr



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

2-4 keV

A=(0.0179±0.0020) cpd/kg/keV

χ^2/dof = 87.1/86 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=169/87 ⇒ P(A=0) = 3.7×10^{-7}

2-5 keV

A=(0.0135±0.0015) cpd/kg/keV

χ^2/dof = 68.2/86 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=152/87 ⇒ P(A=0) = 2.2×10^{-5}

2-6 keV

A=(0.0110±0.0012) cpd/kg/keV

χ^2/dof = 70.4/86 **9.2 σ C.L.**

Absence of modulation? No

χ^2/dof=154/87 ⇒ P(A=0) = 1.3×10^{-5}

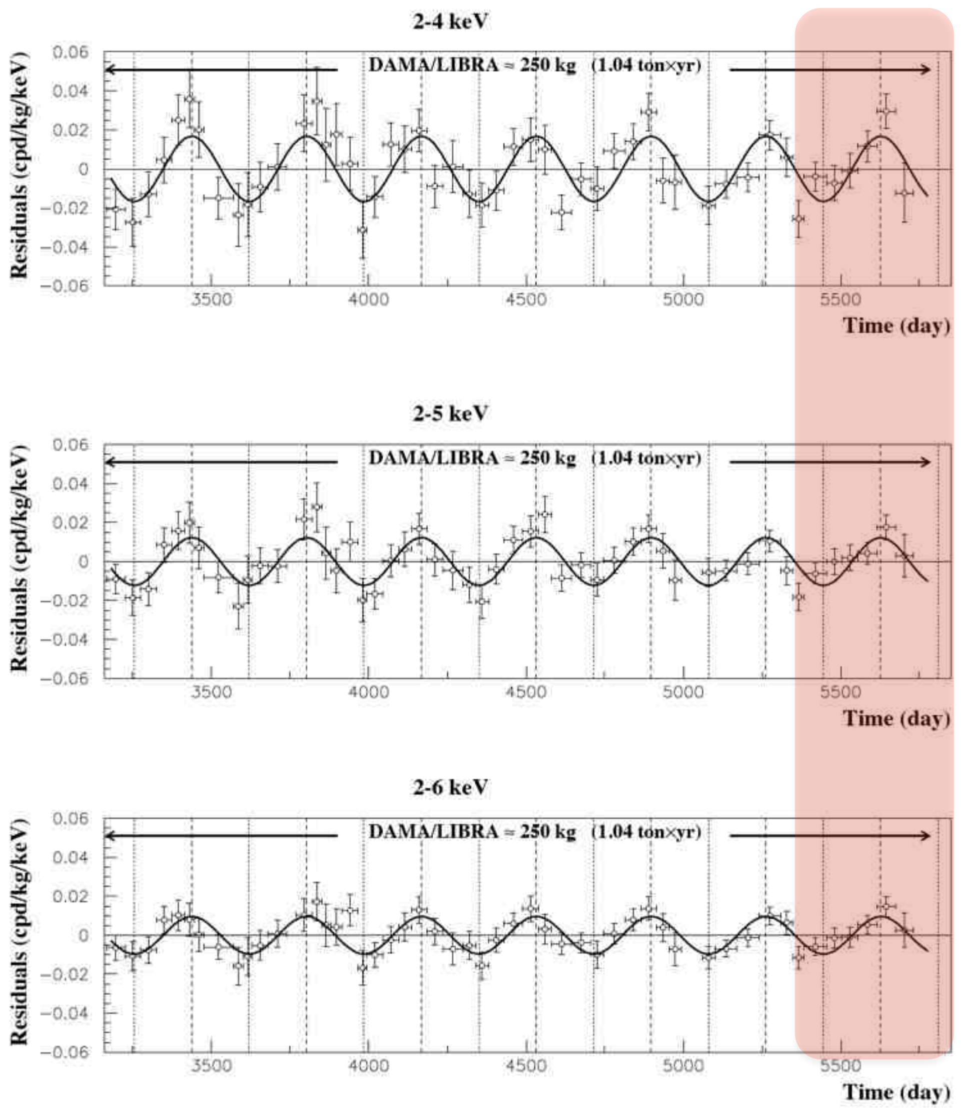
The data favor the presence of a modulated behavior with proper features at 9.2σ C.L.

Model Independent DM Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/LIBRA-phase1

Fit on DAMA/LIBRA-phase1(1.04 ton × yr)



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

2-4 keV

A=(0.0167±0.0022) cpd/kg/keV

χ^2/dof = 52.3/49 **7.6 σ C.L.**

Absence of modulation? No

χ^2/dof=111.2/50 ⇒ P(A=0) =1.5×10^{-6}

2-5 keV

A=(0.0122±0.0016) cpd/kg/keV

χ^2/dof = 41.4/49 **7.6 σ C.L.**

Absence of modulation? No

χ^2/dof=98.5/50 ⇒ P(A=0) = 5.2×10^{-5}

2-6 keV

A=(0.0096±0.0013) cpd/kg/keV

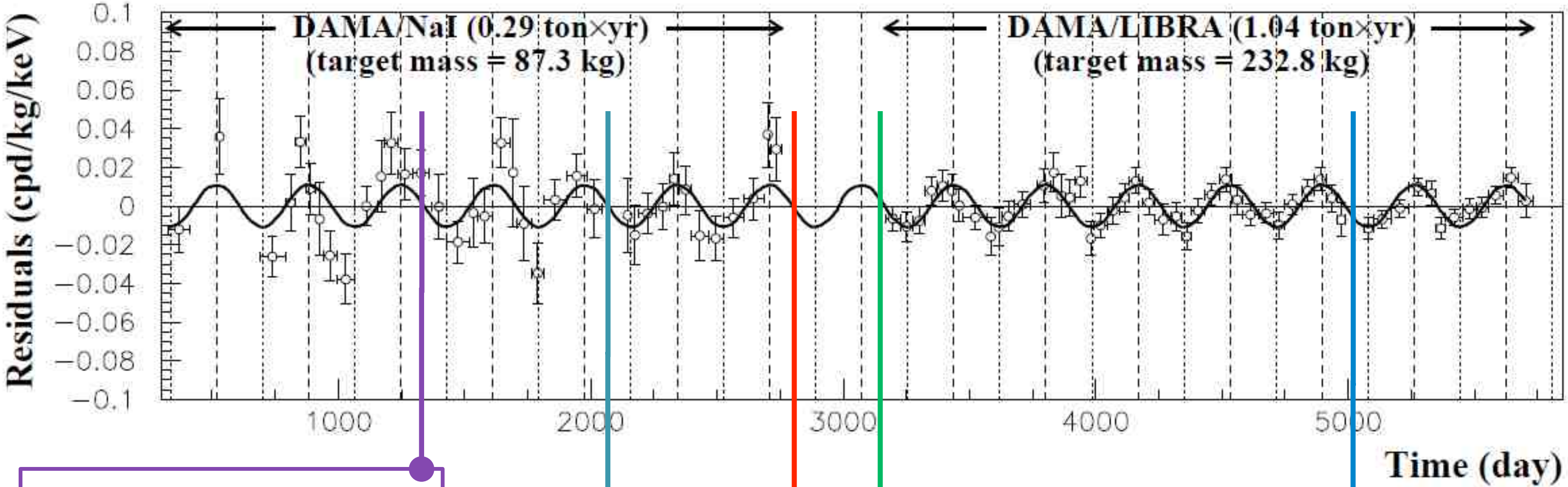
χ^2/dof = 29.3/49 **7.4 σ C.L.**

Absence of modulation? No

χ^2/dof=83.1/50 ⇒ P(A=0) = 2.2×10^{-3}

The data of DAMA/NaI + DAMA/LIBRA-phase1 favor the presence of a modulated behavior with proper features at 9.2σ C.L.

DAMA/NaI & DAMA/LIBRA experiments main upgrades and improvements



PHASE2

Minimal upgrade in Fall

July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector):

(i) TD VXI Tektronix;
(ii) Digital Unix DAQ system;
(iii) GPIB-CAMAC.

July 2002 DAMA/NaI data taking completed

On 2003 DAMA/LIBRA has begun first operations

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:

① one detector recovered by replacing a broken PMT
② a new optimization of some PMTs and HVs performed
③ all the TD replaced with new ones (U1063A Acqiris 8-bit 1GS/s DC270 High-Speed cPCI Digitizers)
④ a new DAQ with optical read-out installed.

The second DAMA/LIBRA upgrade in Fall 2010:
Replacement of all the PMTs with higher Q.E. ones from dedicated developments
(+new preamp in Fall 2012 and other developments in progress)

DAMA/LIBRA-phase2 *in data taking*

Modulation amplitudes (A), period (T) and phase (t_0) measured in DAMA/NaI and DAMA/LIBRA-phase1

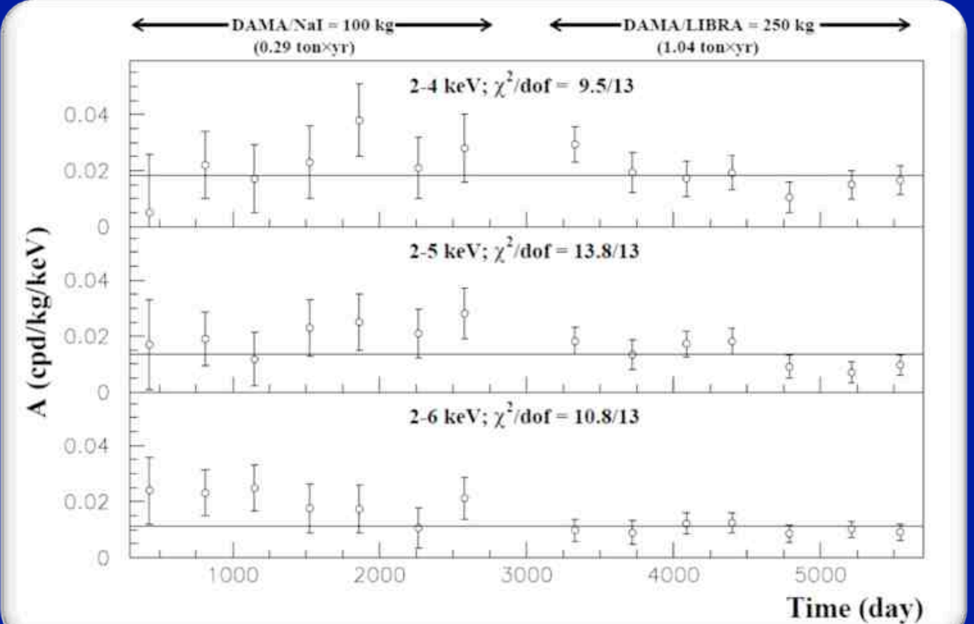
DAMA/NaI (0.29 ton x yr) + DAMA/LIBRA-phase1 (1.04 ton x yr)

total exposure: 487526 kg×day = 1.33 ton×yr

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

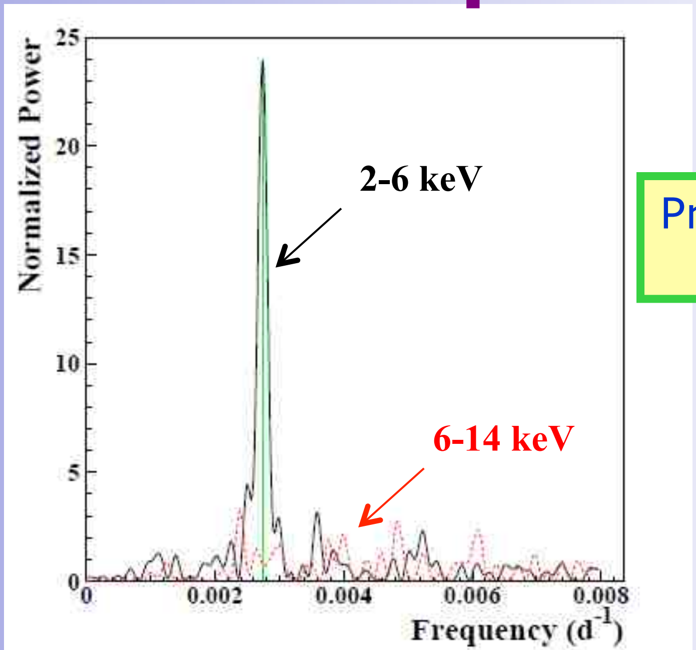
	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	0.0190 ±0.0020	0.996 ±0.0002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.0002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.0002	144 ± 7	9.3σ

χ^2 test (χ^2 = 9.5, 13.8 and 10.8 over 13 *d.o.f.* for the three energy intervals, respectively; upper tail probability 73%, 39%, 63%) and *run test* (lower tail probabilities of 41%, 29% and 23% 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



DAMA/NaI (7 years) + DAMA/LIBRA-phase1 (7 years)
total exposure: 1.33 ton×yr

Principal mode in the 2-6 keV region:
2.737×10^{-3} d^{-1} ≈ 1 yr^{-1}

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

The Lomb-Scargle periodogram, as reported in DAMA papers, always according to Ap.J. 263 (1982) 835, Ap.J. 338 (1989) 277 with the treatment of the experimental errors and of the time binning:

Given a set of data values r_i, $i = 1, \ldots N$ at respective observation times t_i, the Lomb-Scargle periodogram is:

$$P_N(\omega) = \frac{1}{2\sigma^2}\left\{ \frac{\left[\sum_i (r_i - \bar{r})\cos\omega(t_i-\tau)\right]^2}{\sum_i \cos^2\omega(t_i-\tau)} + \frac{\left[\sum_i (r_i - \bar{r})\sin\omega(t_i-\tau)\right]^2}{\sum_i \sin^2\omega(t_i-\tau)} \right\}$$

where: $\bar{r} = \frac{1}{N}\sum_1^N r_i$ $\quad \sigma^2 = \frac{1}{N-1}\sum_1^N (r_i - \bar{r})^2$

and, for each angular frequency $\omega = 2\pi f > 0$ of interest, the time-offset τ is:

$$\tan(2\omega\tau) = \frac{\sum_i \sin(2\omega t_i)}{\sum_i \cos(2\omega t_i)}$$

In order to take into account the different time binning and the residuals' errors we have to rewrite the previous formulae replacing:

$$\sum_i \;\rightarrow\; \sum_i \frac{\frac{N}{\Delta r_i^2}}{\sum_j \frac{1}{\Delta r_j^2}} = \frac{N}{\sum_j \frac{1}{\Delta r_j^2}} \cdot \sum_i \frac{1}{\Delta r_i^2}$$

$$\sin\omega t_i \;\rightarrow\; \frac{1}{2\Delta t_i}\int_{t_i-\Delta t_i}^{t_i+\Delta t_i} \sin\omega t \, dt$$

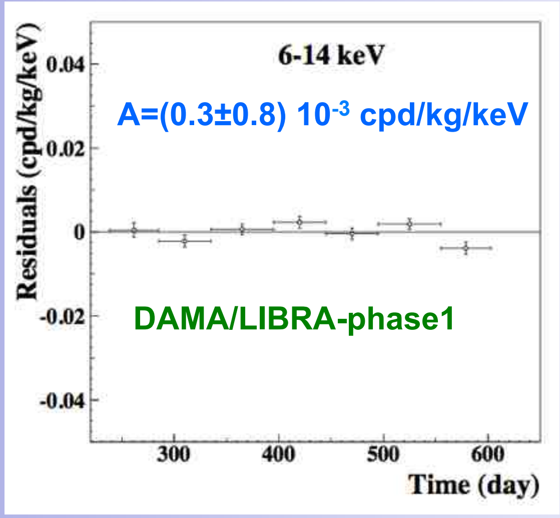
$$\cos\omega t_i \;\rightarrow\; \frac{1}{2\Delta t_i}\int_{t_i-\Delta t_i}^{t_i+\Delta t_i} \cos\omega t \, dt$$

The Nyquist frequency is ≈3 y^{-1} (≈0.008 d^{-1}); meaningless higher frequencies, washed off by the integration over the time binning.

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

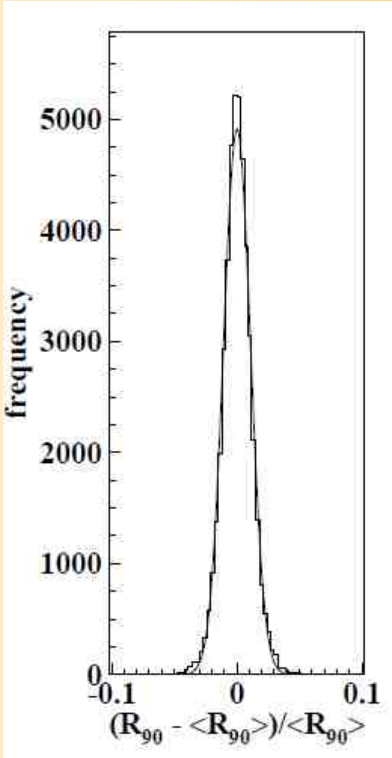
Rate behaviour above 6 keV

- **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
-(0.0023 ± 0.0024) DAMA/LIBRA-7
→ statistically consistent with zero

DAMA/LIBRA-phase1



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

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

consistent with zero

Period	Mod. Ampl.
DAMA/LIBRA-1	-(0.05±0.19) cpd/kg
DAMA/LIBRA-2	-(0.12±0.19) cpd/kg
DAMA/LIBRA-3	-(0.13±0.18) cpd/kg
DAMA/LIBRA-4	(0.15±0.17) cpd/kg
DAMA/LIBRA-5	(0.20±0.18) cpd/kg
DAMA/LIBRA-6	-(0.20±0.16) cpd/kg
DAMA/LIBRA-7	-(0.28±0.18) cpd/kg

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

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

Multiple-hits events in the region of the signa

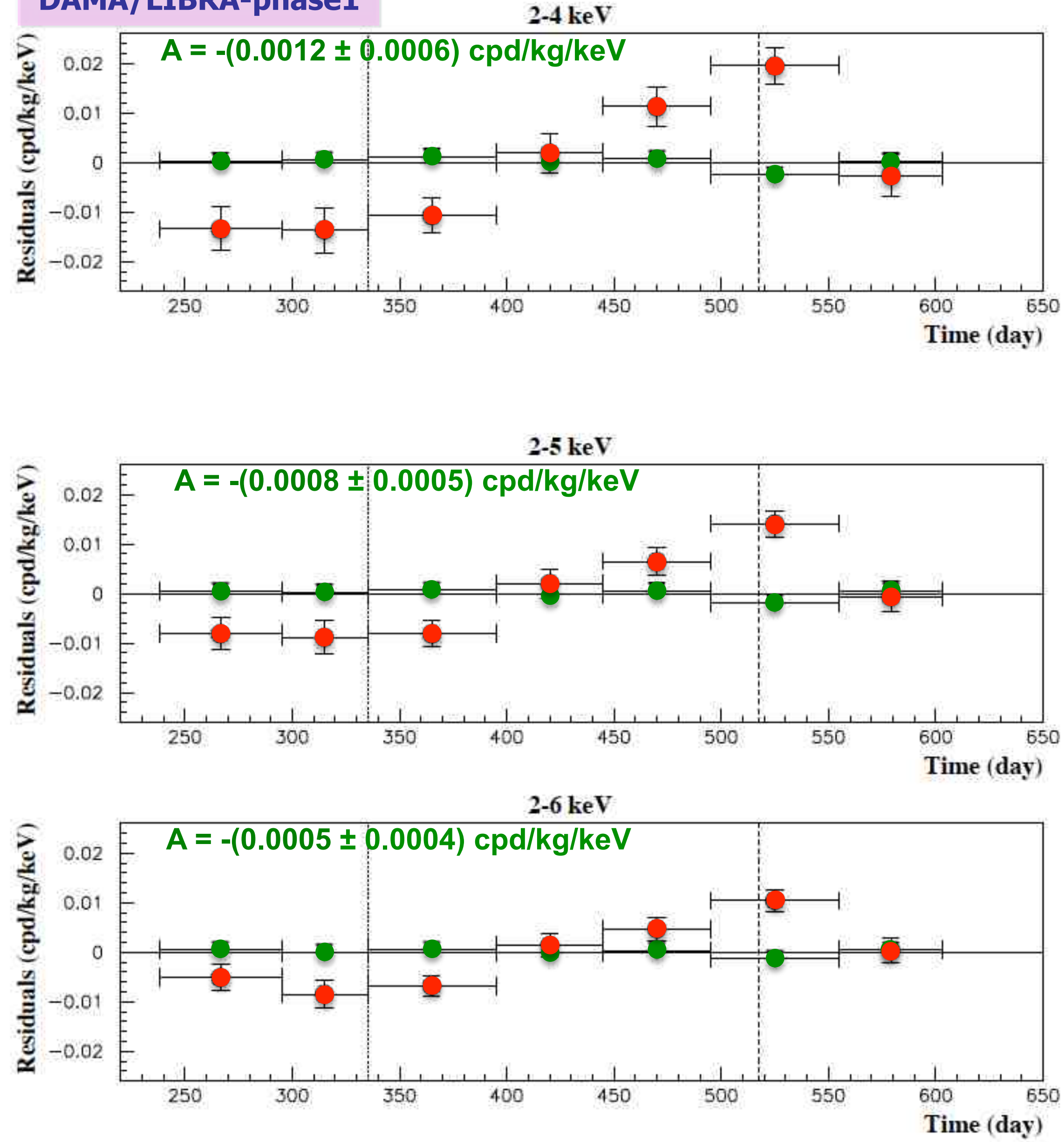
- Each detector has its own TDs read-out → pulse profiles of *multiple-hits* events (multiplicity > 1) acquired (exposure: 1.04 ton×yr).
- The same hardware and software procedures as those followed for *single-hit* events

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:
- present in the ***single-hit*** residuals
- absent in the ***multiple-hits*** residual

DAMA/LIBRA-phase1



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

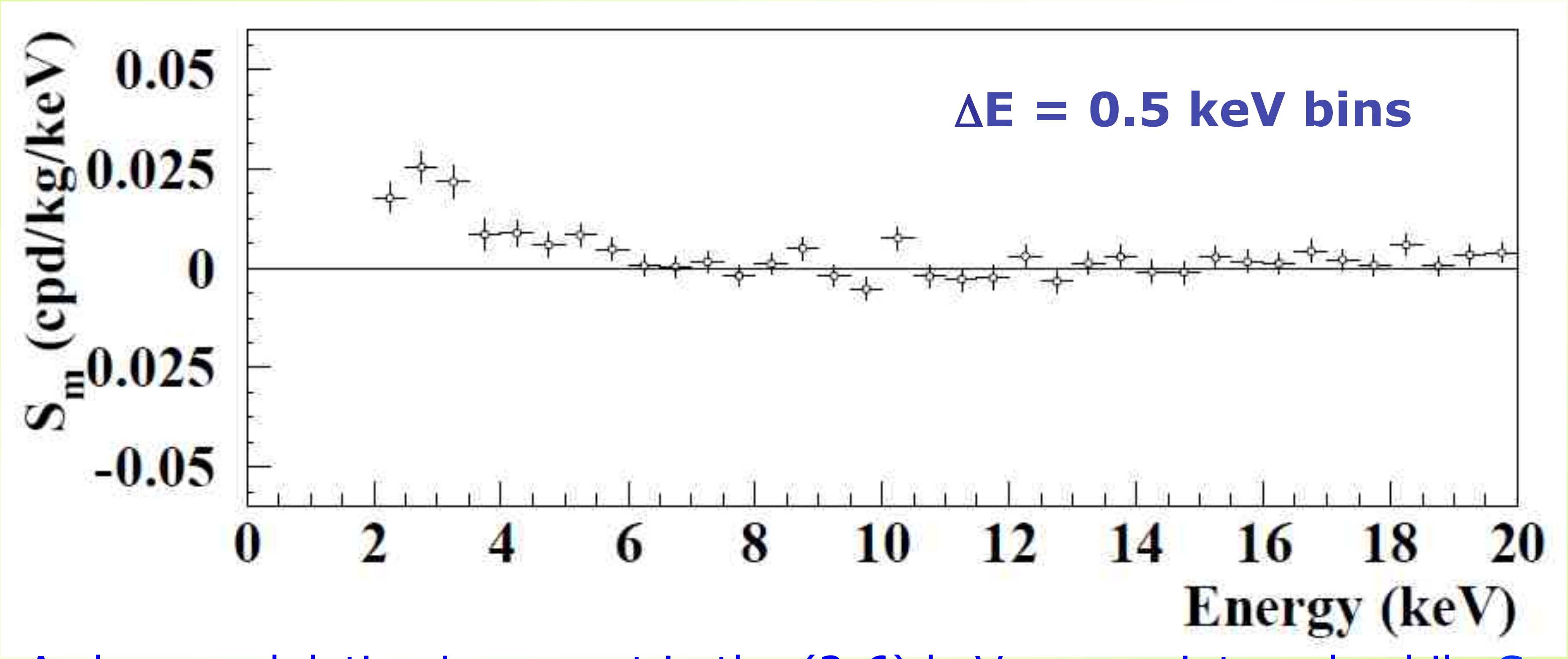
Energy distribution of the modulation amplitudes

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

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

DAMA/NaI **+ DAMA/LIBRA-phase1**

total exposure: 487526 kg×day ≈**1.33 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 35.8 for 28 degrees of freedom (upper tail probability 15%)

Statistical distributions of the modulation amplitudes (S_m)

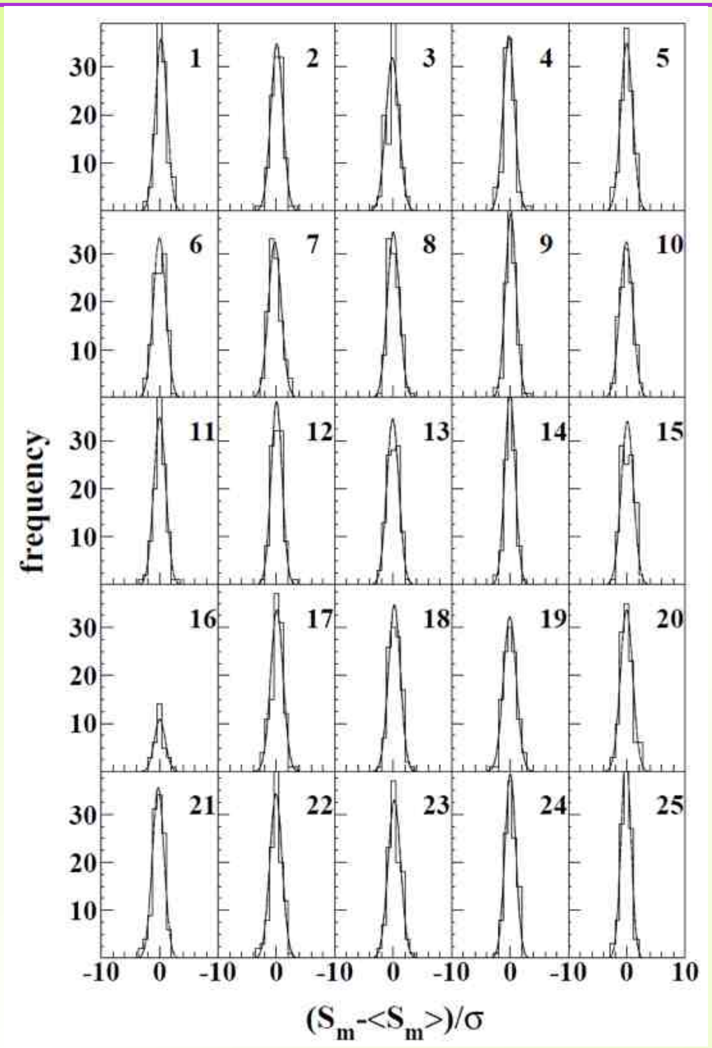
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

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

DAMA/LIBRA-phase1 (7 years)

total exposure: 1.04 ton×yr

Each panel refers to each detector separately; 112 entries = 16 energy bins in 2-6 keV energy interval × 7 DAMA/LIBRA-phase1 annual cycles (for crys 16, 2 annual cycle, 32 entries)



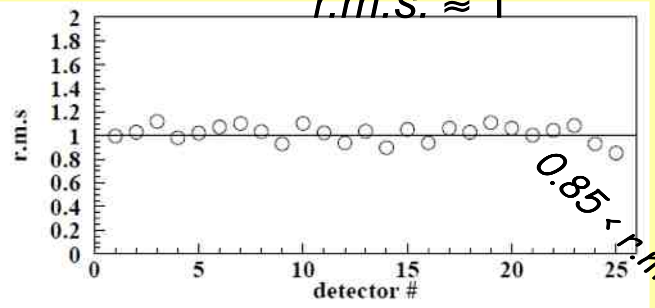
2-6 keV

Standard deviations of

$\mathbf{(S_m-\langle S_m\rangle)/\sigma}$

for each detectors

r.m.s. ≈ 1



0.85 < r.m.s. < 1.12

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

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

Individual S_m values follow a normal distribution since $\mathbf{(S_m-<S_m>)/\sigma}$ is distributed as a Gaussian with a unitary standard deviation (r.m.s.)

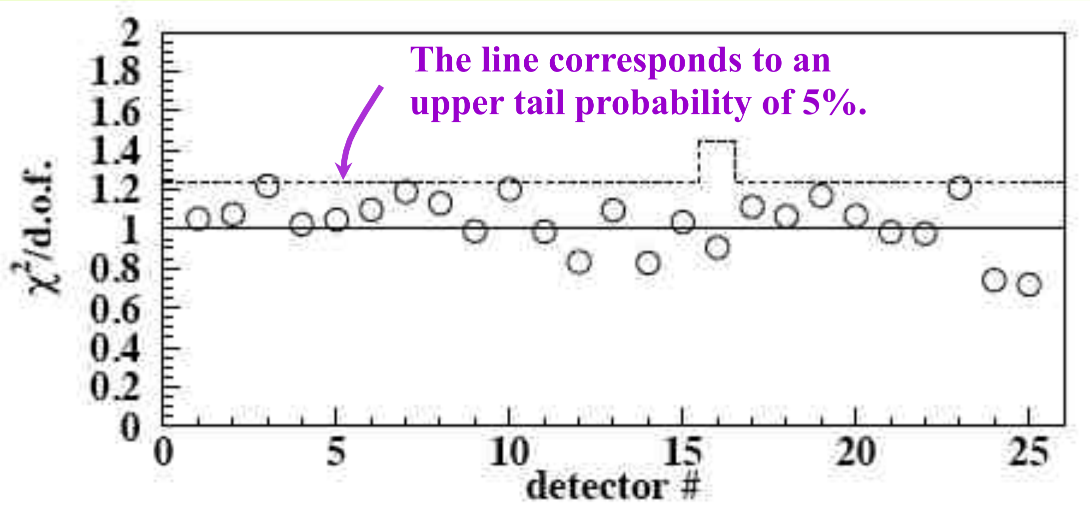
→ **S_m** statistically well distributed in all the detectors, energy bin and annual cycles

Statistical analyses about modulation amplitudes (S_m)

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

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

$\chi^2/d.o.f.$ values of S_m distributions for each DAMA/LIBRA-phase1 detector in the (2–6) keV energy interval for the seven annual cycles.



DAMA/LIBRA-phase1 (7 years)

total exposure: 1.04 ton × yr

The $\chi^2/d.o.f.$ values range from 0.72 to 1.22 for all 25 detectors ⇒ at 95% C.L. the observed annual modulation effect is well distributed in all the detectors.

- The mean value of the twenty-five points is 1.030, 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 $\leq 3 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 2\times10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (**≤ 3 %** or **≤ 0.2%**, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

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

DAMA/NaI (7 years) + **DAMA/LIBRA-phase1 (7 years)**

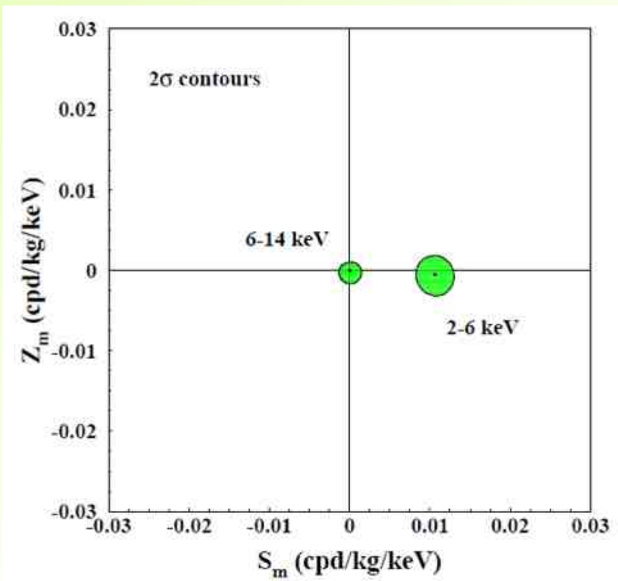
total exposure: 487526 kg×day **= 1.33 ton × yr**

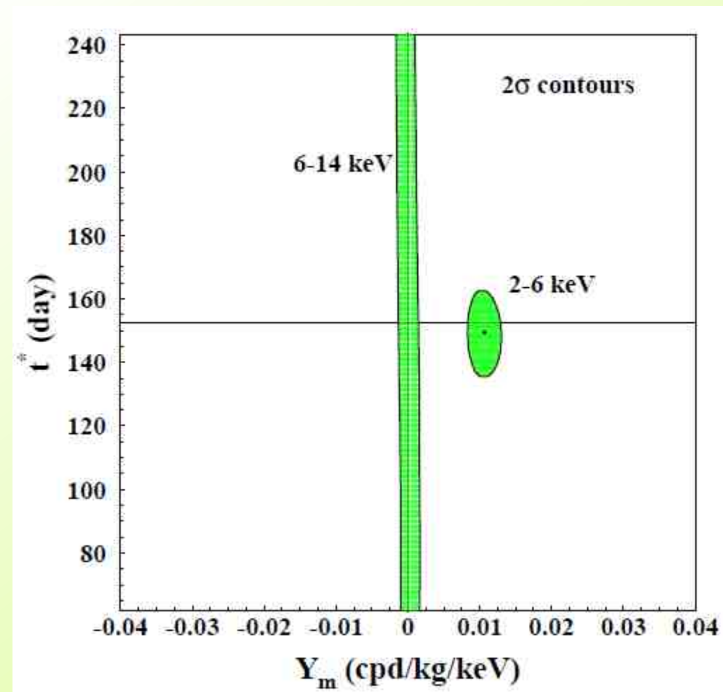
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

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	0.0106 ± 0.0012	-0.0006 ± 0.0012	0.0107 ± 0.0012	149.5 ± 7.0
6-14	0.0001 ± 0.0007	0.0000 ± 0.0005	0.0001 ± 0.0008	--

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

Additional investigations on the stability parameters

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

Running conditions stable at a level better than 1% 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	DAMA/LIBRA-7
Temperature (°C)	-(0.0001 ± 0.0061)	(0.0026 ± 0.0086)	(0.001 ± 0.015)	(0.0004 ± 0.0047)	(0.0001 ± 0.0036)	(0.0007 ± 0.0059)	(0.0000 ± 0.0054)
Flux N_2 (l/h)	(0.13 ± 0.22)	(0.10 ± 0.25)	-(0.07 ± 0.18)	-(0.05 ± 0.24)	-(0.01 ± 0.21)	-(0.01 ± 0.15)	-(0.00 ± 0.14)
Pressure (mbar)	(0.015 ± 0.030)	-(0.013 ± 0.025)	(0.022 ± 0.027)	(0.0018 ± 0.0074)	-(0.08 ± 0.12) $\times 10^{-2}$	(0.07 ± 0.13) $\times 10^{-2}$	-(0.26 ± 0.55) $\times 10^{-2}$
Radon (Bq/m^3)	-(0.029 ± 0.029)	-(0.030 ± 0.027)	(0.015 ± 0.029)	-(0.052 ± 0.039)	(0.021 ± 0.037)	-(0.028 ± 0.036)	(0.012 ± 0.047)
Hardware rate above single ph.e. (Hz)	-(0.20 ± 0.18) $\times 10^{-2}$	(0.09 ± 0.17) $\times 10^{-2}$	-(0.03 ± 0.20) $\times 10^{-2}$	(0.15 ± 0.15) $\times 10^{-2}$	(0.03 ± 0.14) $\times 10^{-2}$	(0.08 ± 0.11) $\times 10^{-2}$	(0.06 ± 0.10) $\times 10^{-2}$

All the measured amplitudes well compatible with zero

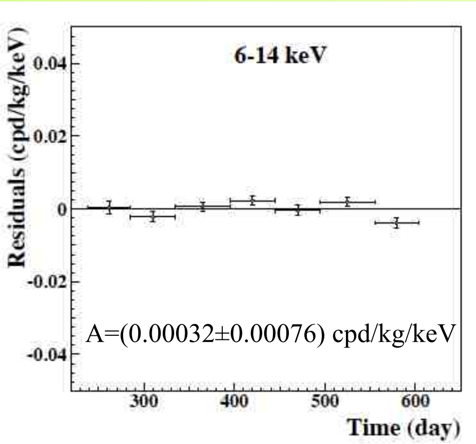
\+ none can account for the observed effect

(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)

Summarizing on a hypothetical background modulation

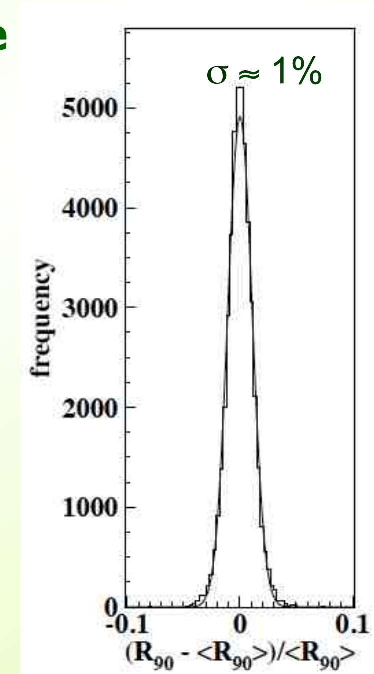
DAMA/LIBRA-phase1

- **No Modulation above 6 keV**

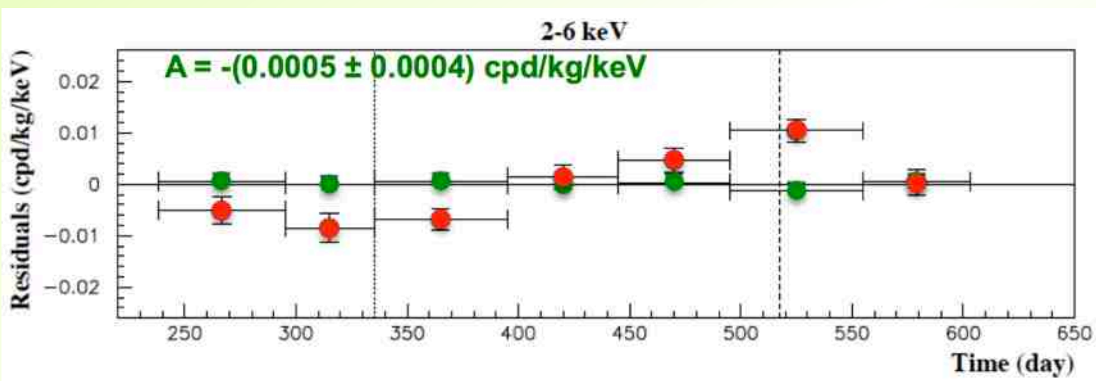


- **No modulation in the whole energy spectrum**

+ 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**



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

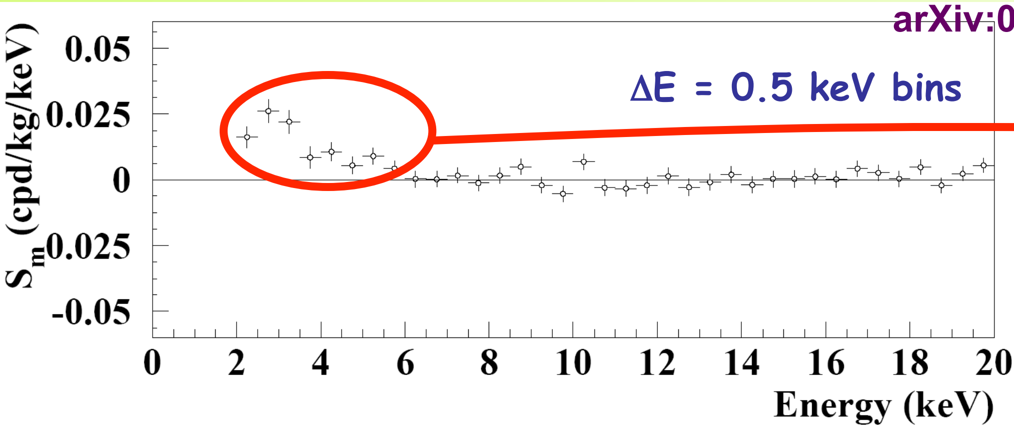
No background modulation (and cannot mimic the signature):
all this accounts for the all possible sources of bckg

Nevertheless, additional investigations performed ...

See DAMA literature

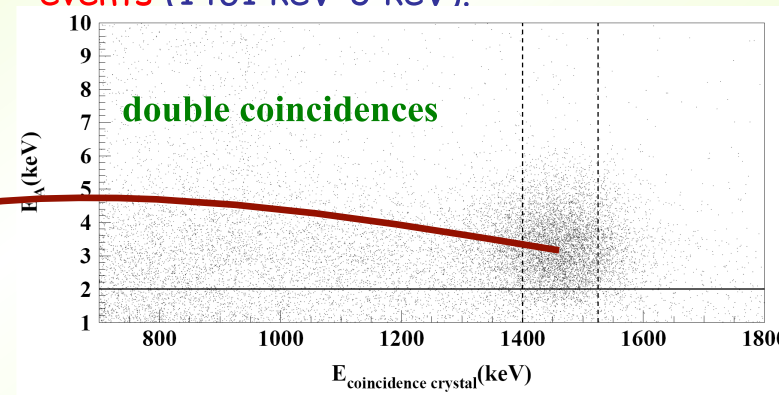
No role for ^{40}K in the experimental S_m

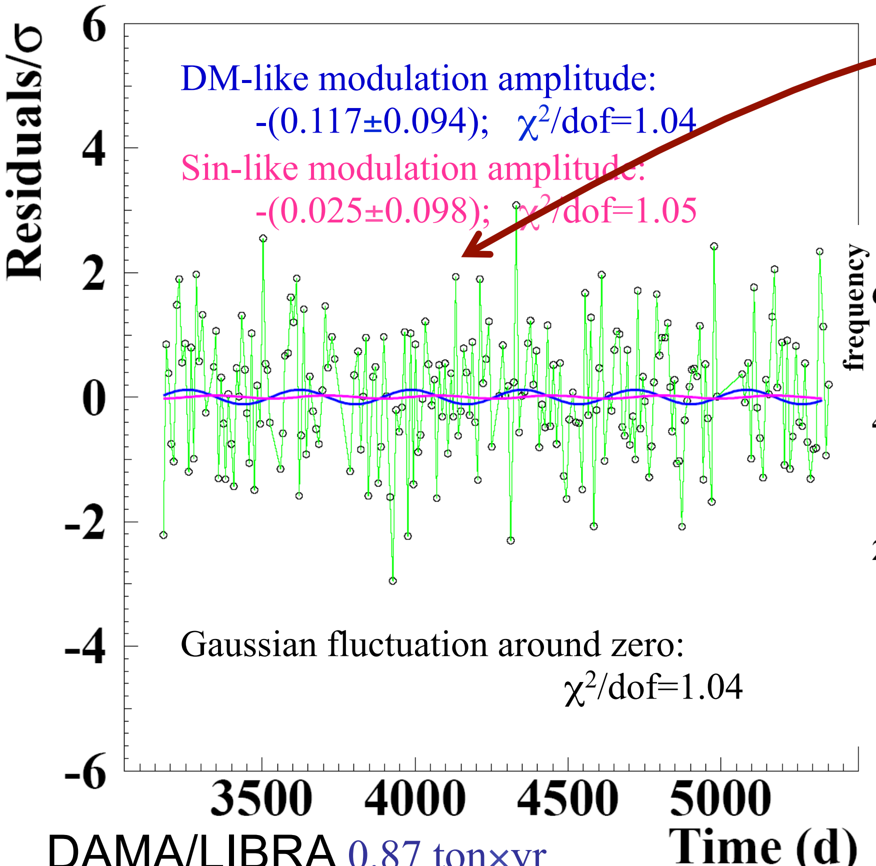
arXiv:0912.0660, IJMPA28(2013)1330022 and refs therein

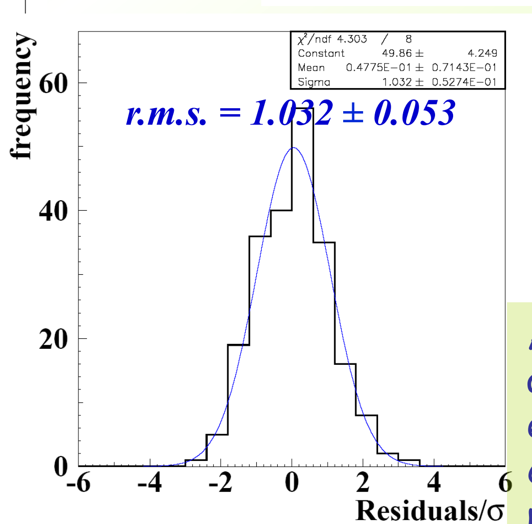


The experimental S_m cannot be due to ^{40}K for many reasons.

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







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

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

No role for μ in DAMA annual modulation result

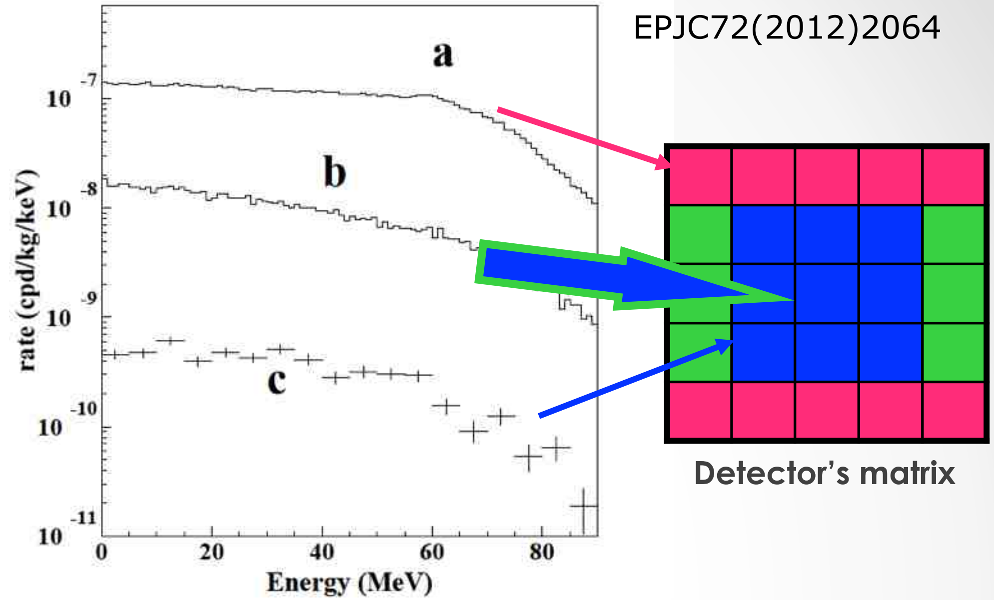
✓ **Direct μ interaction in DAMA/LIBRA set-up:**

DAMA/LIBRA surface ≈0.13 m^2
μ flux @ DAMA/LIBRA ≈2.5 μ/day

MonteCarlo simulation:
- muon intensity distribution
- Gran Sasso rock overburden map
- Single hit events

It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.

EPJC72(2012)2064



Detector's matrix

✓ **Rate, R_n, of fast neutrons produced by μ:**

$$R_n = \text{(fast n by } \mu)/\text{(time unit)} = \Phi_\mu \, Y \, M_{eff}$$

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Measured neutron Yield @ LNGS:

$$Y = 1 \div 7 \; 10^{-4} \; n/\mu/(g/cm^2)$$

Annual modulation amplitude at low energy due to μ **modulation**:

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

g = geometrical factor;
ε = detection eff. by elastic scattering
f_{DE} = 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

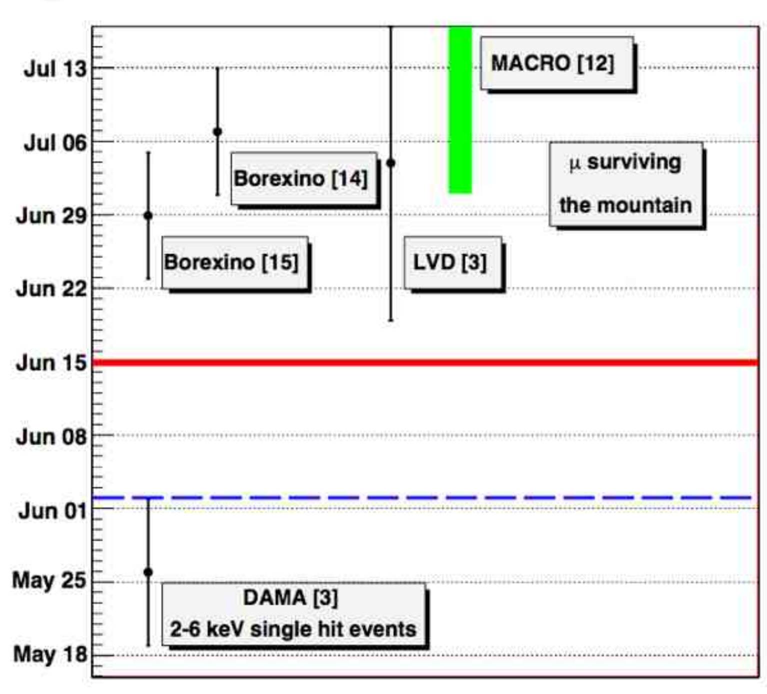
$$S_m^{(m)} < (0.3\text{-}2.4) \times 10^{-5} \text{ cpd/kg/keV}$$

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 by R_{90}, by *multi-hits* analysis + different phase, etc.

Inconsistency of the phase between DAMA signal and μ modulation

For many others arguments EPJC72(2012)2064



μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈$3 \cdot 10^{-4}$ $m^{-2}s^{-1}$; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)

but

- the muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a "mean" of the muon phase of each year
- The DAMA: modulation amplitude 10^{-2} cpd/kg/keV, in 2-6 keV energy range for single hit events; phase:
  May 26 ± 7 days (stable over 13 years)

considering the seasonal weather al LNGS, quite impossible that the max. temperature of the outer atmosphere (on which μ flux variation is dependent) is observed e.g. in June 15 which is 3 σ from DAMA

The DAMA phase is 5.7σ far from the LVD/BOREXINO phases of muons (7.1 σ far from MACRO measured phase)

Similar for the whole DAMA/LIBRA-phase1

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
- pulses with time structure as scintillation light

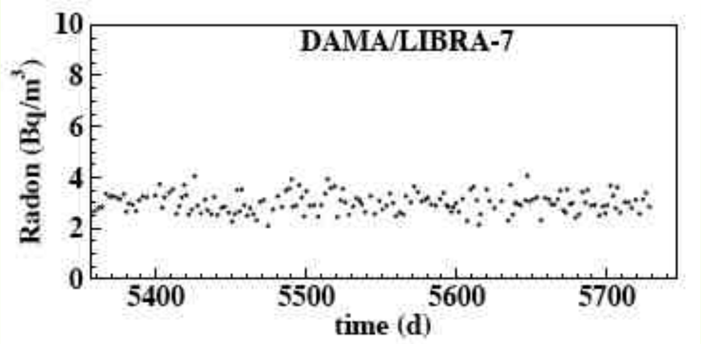
But, its phase should be (much) larger than μ phase, t_μ :

- 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: different phase

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

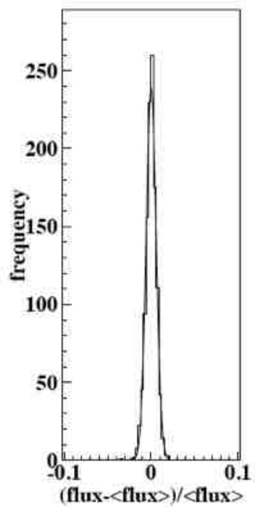
Amplitudes for annual modulation of Radon external to the shield:

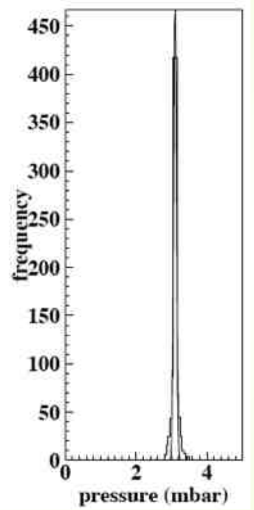
	Radon (Bq/m^3)
DAMA/LIBRA-1	-(0.029 ± 0.029)
DAMA/LIBRA-2	-(0.030 ± 0.027)
DAMA/LIBRA-3	(0.015 ± 0.029)
DAMA/LIBRA-4	-(0.052 ± 0.039)
DAMA/LIBRA-5	(0.021 ± 0.037)
DAMA/LIBRA-6	-(0.028 ± 0.036)
DAMA/LIBRA-7	(0.012 ± 0.047)

<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

Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

(NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022)

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 $\times10^{-4}$ 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	**<3×10^{-5} cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

Final model independent result DAMA/NaI + DAMA/LIBRA-phase1

- Presence of modulation for 14 annual cycles at 9.3σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 14 independent experiments of 1 year each one
- The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.33 ton × yr (14 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 (0.998±0.002) yr, well compatible with the 1 yr period, as expected for the DM signal

3. Measured phase (144±7) days is well compatible with 152.5 days, as expected for the DM signal

4. The modulation is present only in the low energy (2-6) keV 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-hits*, as expected for the DM signal

6. The measured modulation amplitude in NaI(Tl) of the *single-hit* events in (2-6) keV is: (0.0112 ± 0.0012) cpd/kg/keV (9.3σ 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 possible astrophysical, nuclear and particle physics scenarios)

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

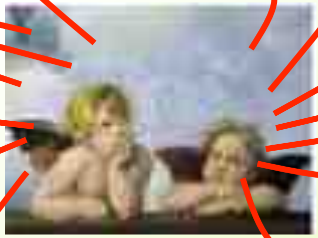
Self interacting Dark Matter

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



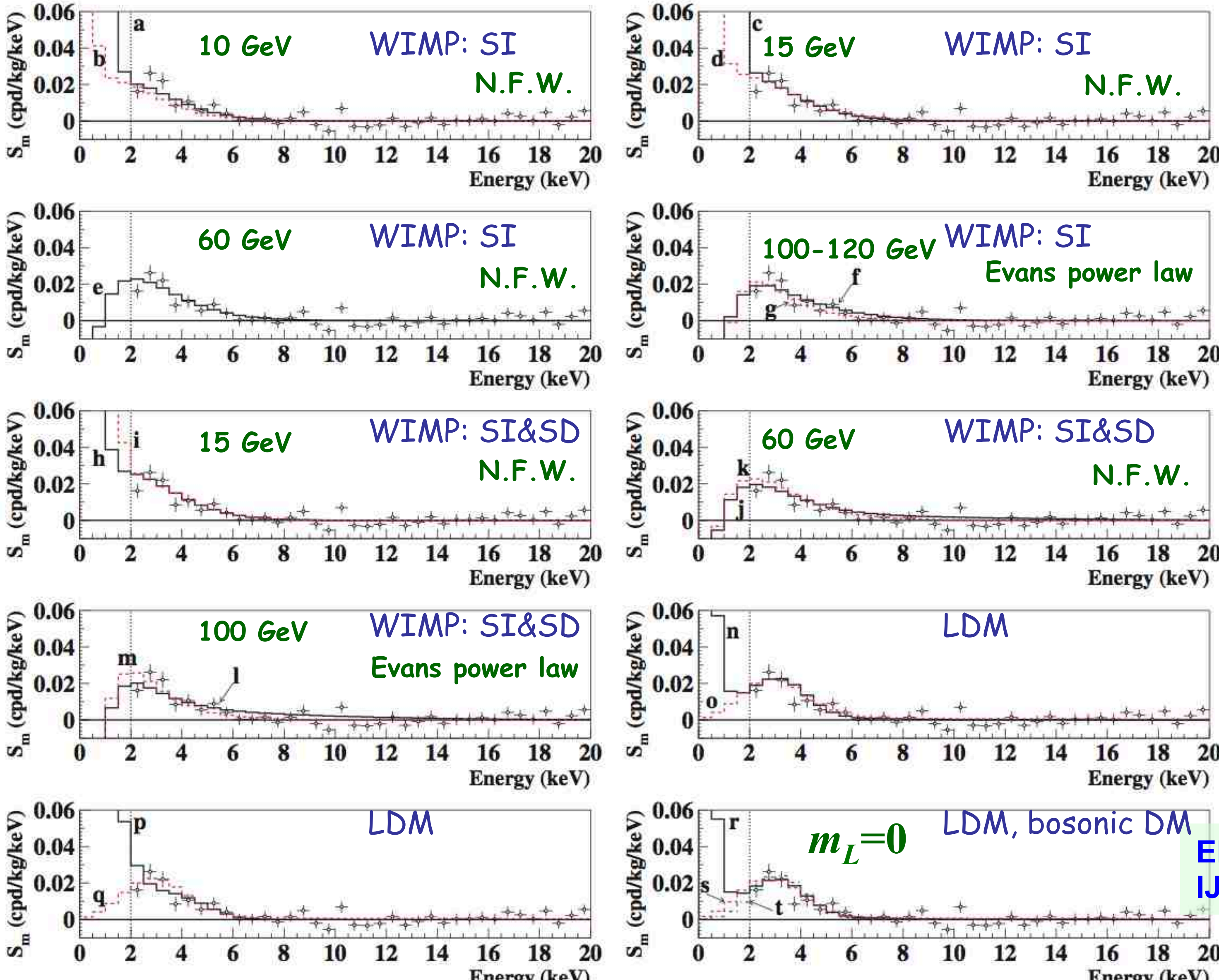
Kaluza Klein particles

… and more

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

Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with positive excesses

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

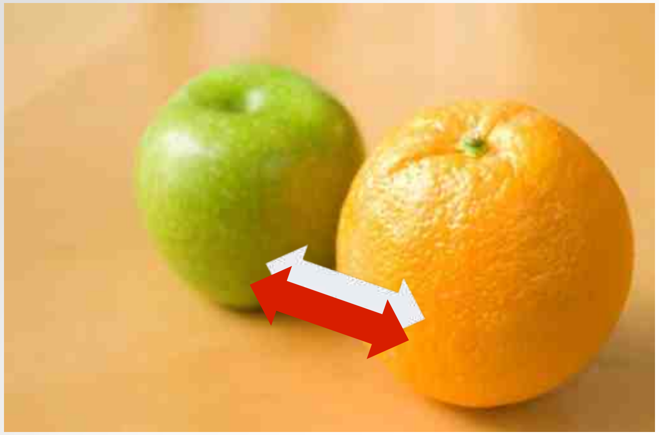


- Not best fit
- About the same C.L.

$\theta = 2.435$

EPJC56(2008)333
IJMPA28(2013)1330022

Compatibility with several candidates; other ones are open



About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28 (2013)1330022

…models…

- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- …

…and experimental aspects…

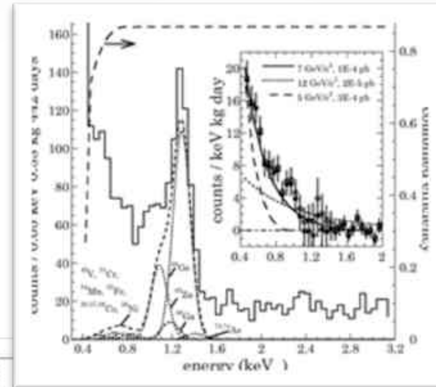
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling, …
- …

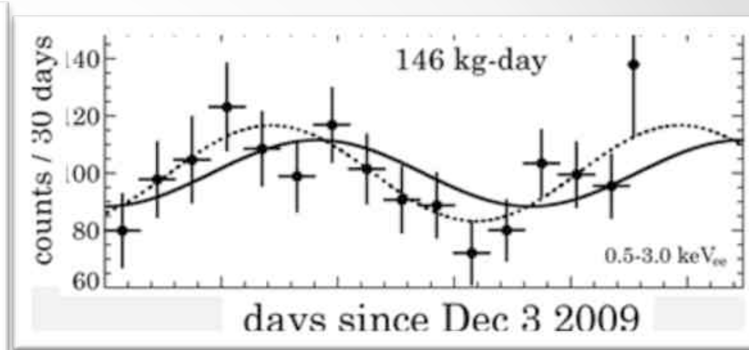
Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

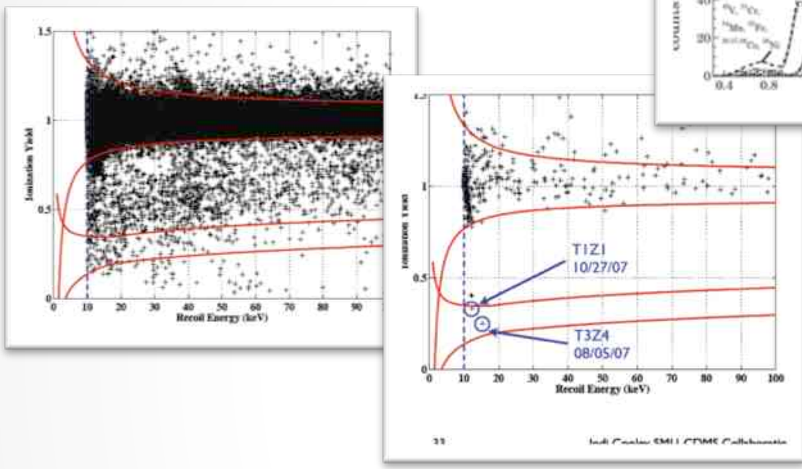
No experiment can be directly compared in model independent way with DAMA

DAMA vs possible positive hints 2010 - 2013

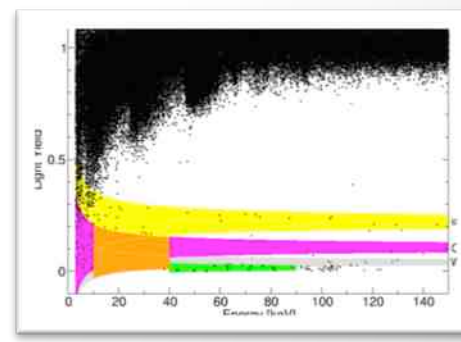
CoGeNT:
low-energy rise in the spectrum ("irreducible" by the applied background reduction procedures) + annual modulation



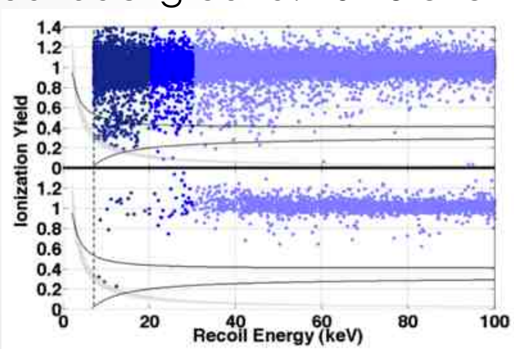




CDMS-Ge:
after many data selections and cuts, 2 Ge recoil-like candidates survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)



CRESST: after many data selections and cuts, 67 recoil-like candidates in the O/Ca bands survive in an exposure of 730 kg x day (expected residual background: 40-45 events, depending on minimization)

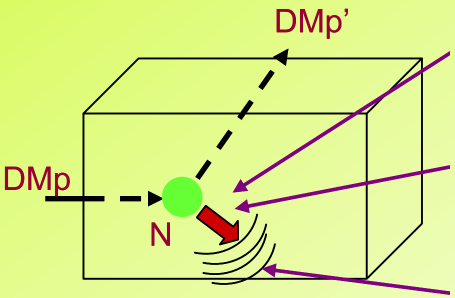


CDMS-Si:
after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

All those recoil-like excesses with respect to an estimated bckg surviving cuts as well as the CoGeNT result are compatible with the DAMA 9.3 σ C.L. annual modulation result in various scenarios

... an example in literature...

Case of DM particles inducing elastic scatterings on target-nuclei, SI case



Regions in the nucleon cross section vs DM particle mass plane

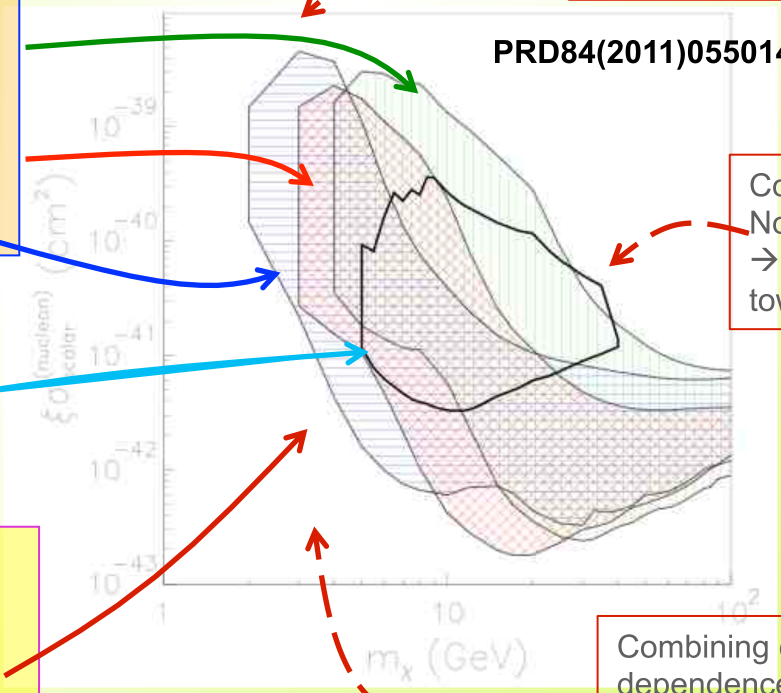
- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

Including the Migdal effect
→Towards lower mass/higher σ

PRD84(2011)055014, IJMPA28(2013)1330022

DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent Quenching Factors (red);

7.5 σ C.L.



Co-rotating halo,
Non thermalized component
→ Enlarge allowed region towards larger mass

CoGeNT; qf at fixed assumed value

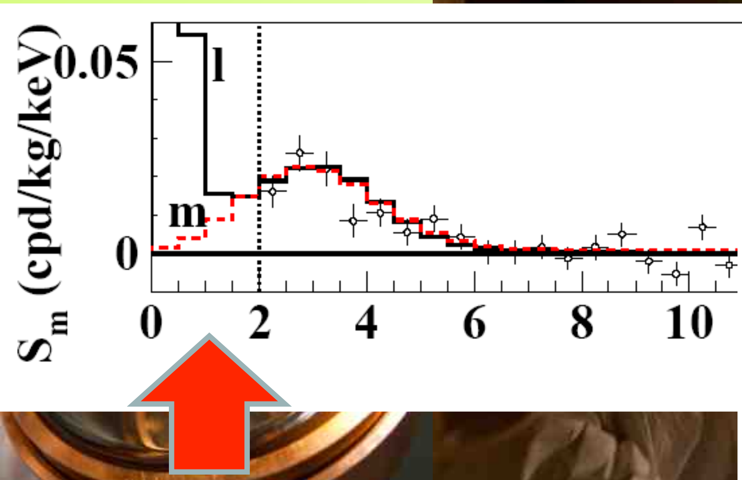
1.64 σ C.L.

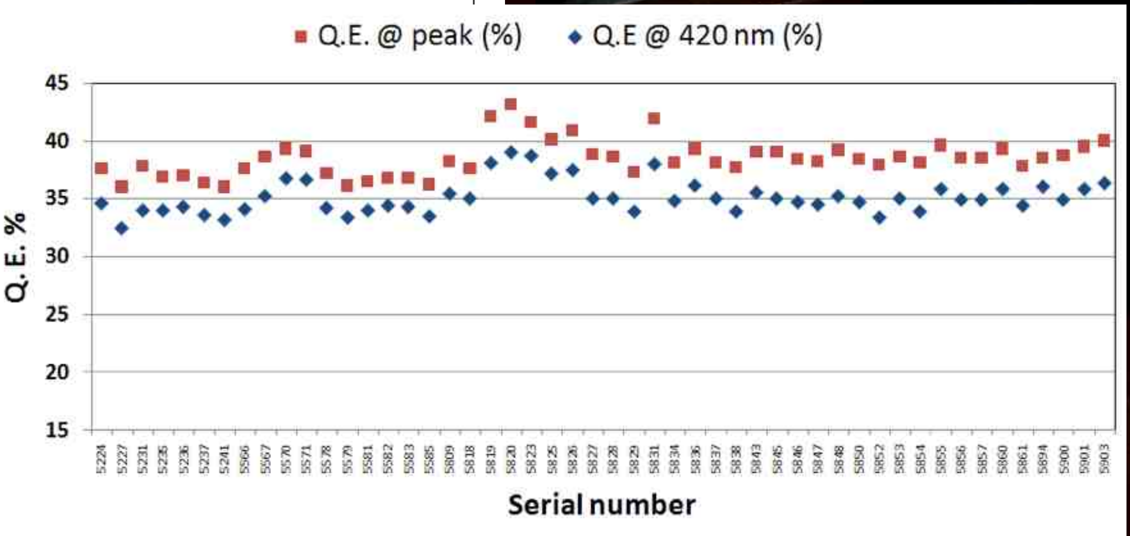
Compatibility also with CRESST and CDMS, if the two CDMS-Ge, the three CDMS-Si and the CRESST recoil-like events are interpreted as relic DM interactions

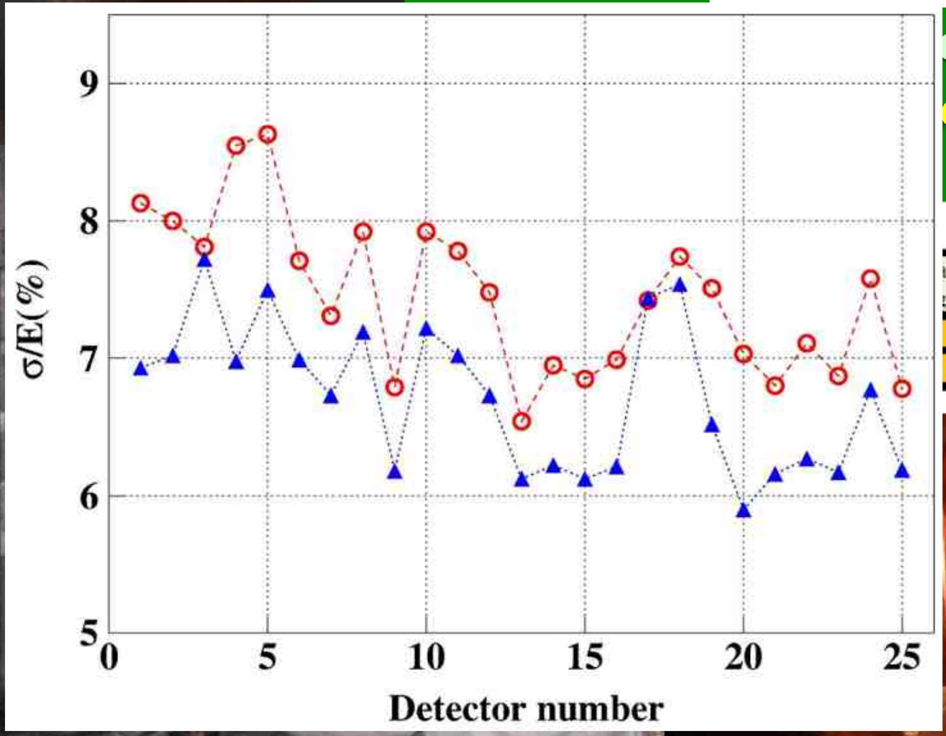
Combining channeling and energy dependence of q.f. (AstrPhys33 (2010) 40)
→Towards lower σ

DAMA/LIBRA – stage 2

JINST 7(2012)03009



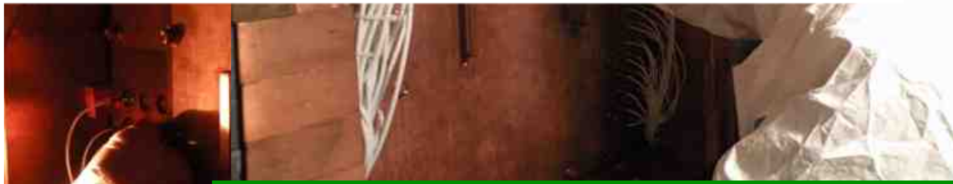




ov/Dec

ed with new

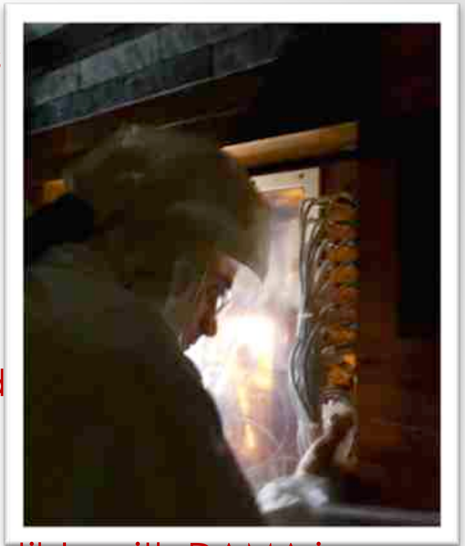
)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
	47	0.12	83	0.54	-	-
	10	0,02	17	0.16	-	-



Since Dec 2010 data taking and optimizations in this new configuration started

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo supported at 9.3σ C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: 1.33 ton × yr)
- The modulation parameters determined with better precision
- Full sensitivity to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation.



- Possible positive hints in direct searches are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties. Indirect model dependent searches not in conflict

- New PMTs with higher Q.E.

DAMA/LIBRA – phase2 perspectives

- ***Continuing data taking*** in the new configuration with lower software energy threshold (below 2 keV).
- New preamplifiers (installed in Fall 2012), trigger modules and other developments realized to further implement low energy studies.
- Suitable exposure planned in the new configuration to deeper study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects.
- Investigation on dark matter peculiarities and second order effect
- Special data taking for other rare processes.