

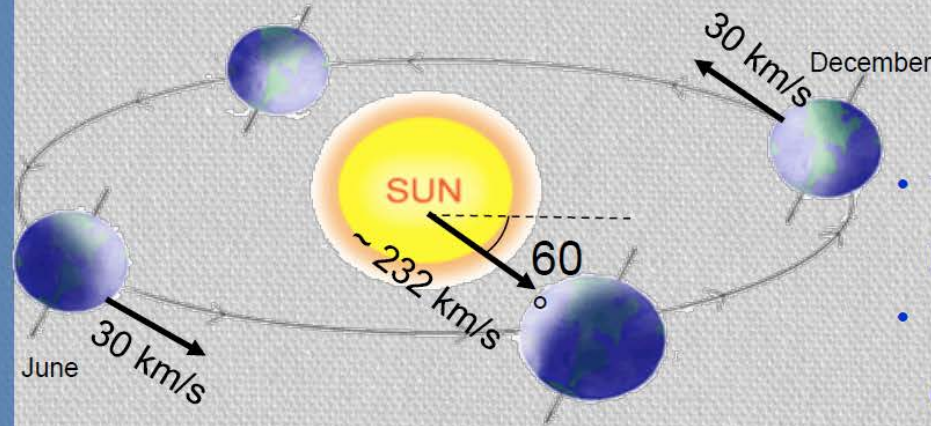
# The DM annual modulation: a model independent signature to investigate the DM particles component in the galactic halo

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.

## Requirements of the DM 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

Drukier, Freese, Spergel PRD86; Freese et al. PRD88



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

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

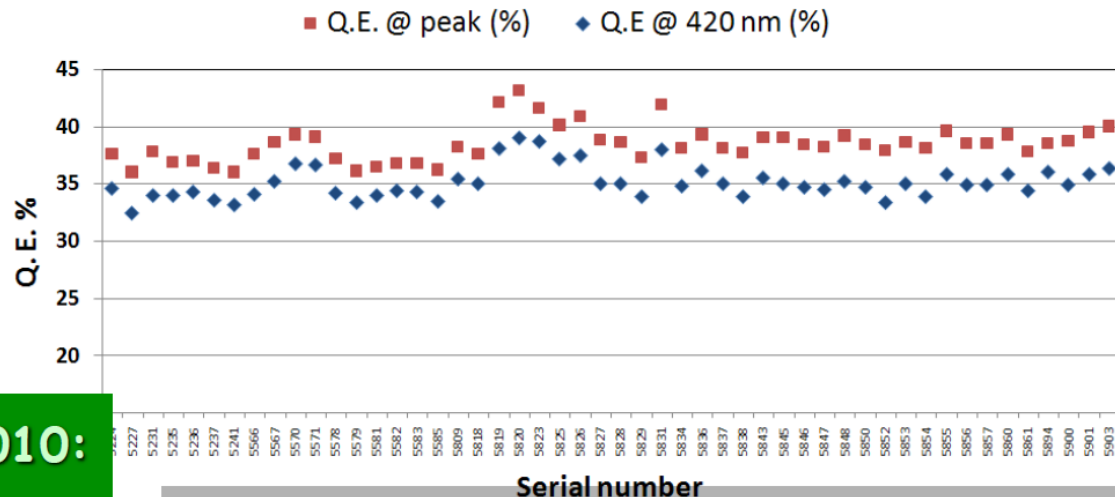
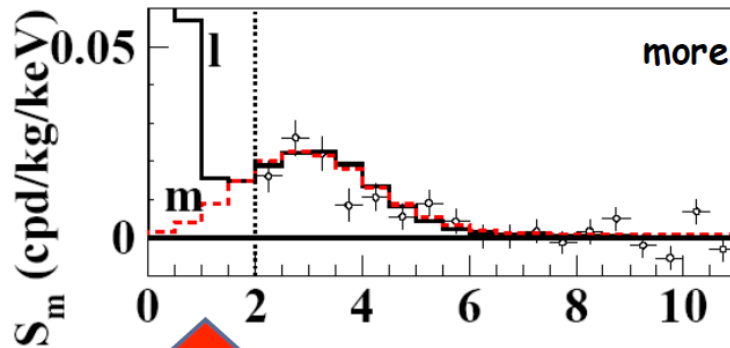
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \equiv S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

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

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

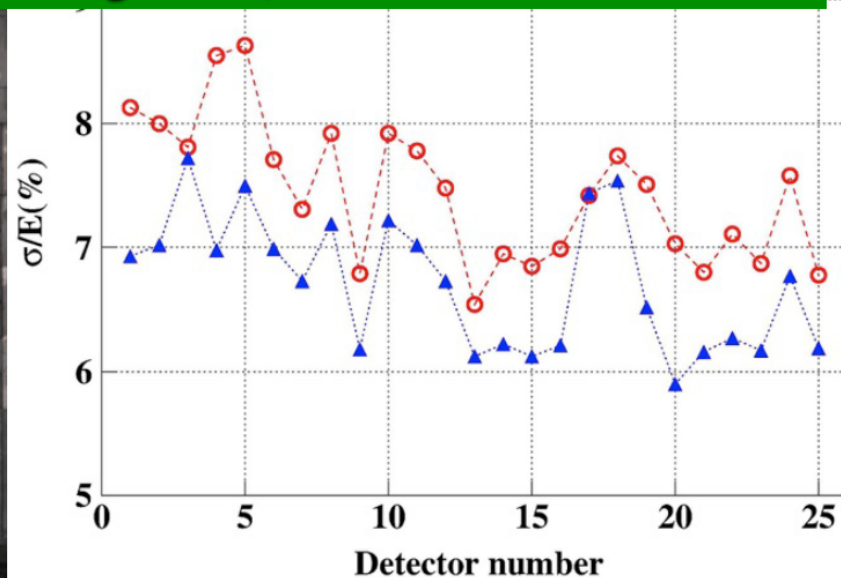


After a period of tests and optimizations in data taking in this new configuration



Second upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

typically  
 DAMA/LIBRA-phase1: 5.5-7.5 ph.e./keV  
 → DAMA/LIBRA-phase2: 6-10 ph.e./keV



<sup>234m</sup> Pa (Bq/kg)	<sup>235</sup> U (mBq/kg)	<sup>228</sup> Ra (Bq/kg)	<sup>228</sup> Th (mBq/kg)	<sup>40</sup> K (Bq/kg)	<sup>137</sup> Cs (mBq/kg)	<sup>60</sup> Co (mBq/kg)
-	47	0.12	83	0.54	-	-
-	10	0.02	17	0.16	-	-

- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes
- + R&D in progress towards more future phase3

# DAMA/LIBRA-phase2 data taking

Second upgrade at end of 2010:

JINST 7(2012)03009

all PMTs replaced with new ones of higher Q.E.

Energy resolution @ 60 keV mean value:

prev. PMTs 7.5% (0.6% RMS)

new HQE PMTs 6.7% (0.5% RMS)



- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 6 a.c.:  $\approx 1.3 \times 10^8$  events from sources
- ✓ Acceptance window eff. 6 a.c.:  $\approx 3.4 \times 10^6$  events ( $\approx 1.4 \times 10^5$  events/keV)

Annual Cycles	Period	Mass (kg)	Exposure	$(\alpha-\beta^2)$
I	Dec 23, 2010 - Sept. 9, 2011	commissioning		
II	Nov. 2, 2011 - Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 - Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 - Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 - Sept. 9, 2015	242.5	71180	0.486
VI	Sept. 10, 2015 - Aug. 24, 2016	242.5	67527	0.522
VII	Sept. 7, 2016 - Sept. 25, 2017	242.5	75135	0.480

Exposure first data release of DAMA/LIBRA-phase2:

**1.13 ton x yr**

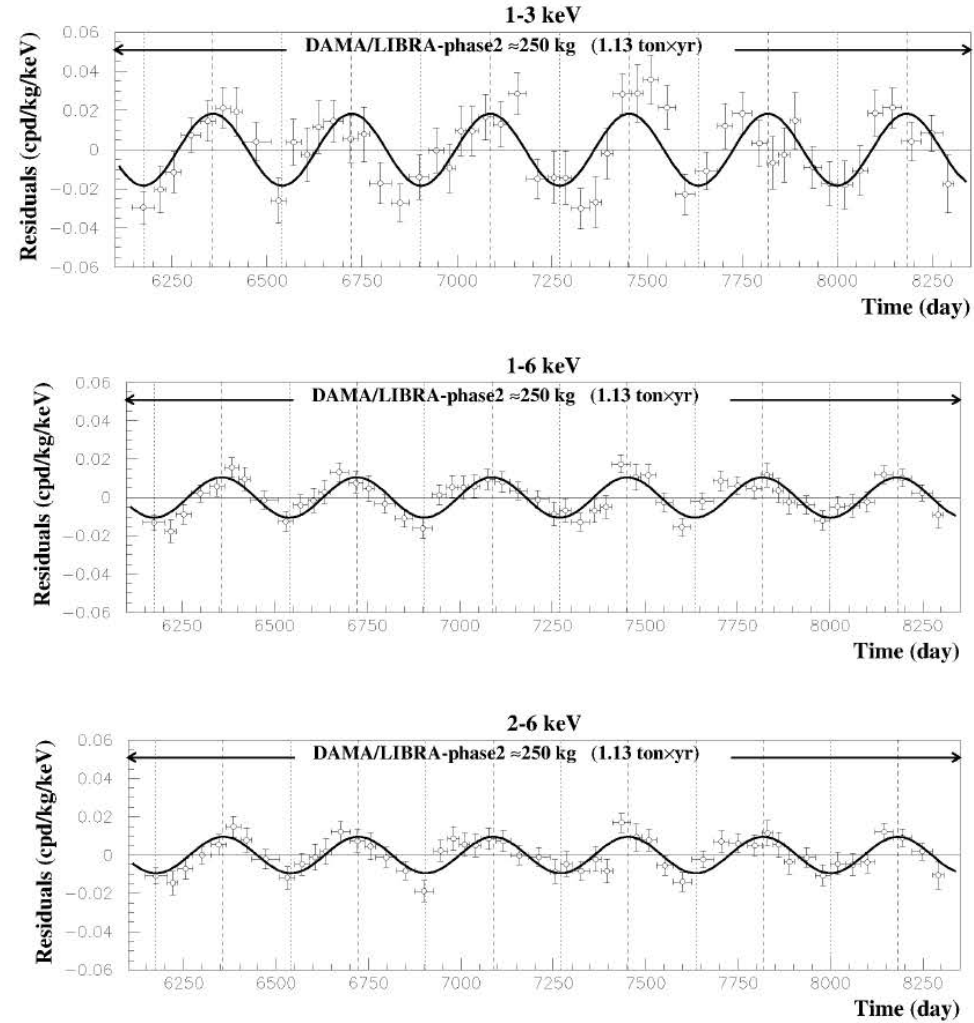
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2:

**2.46 ton x yr**



# DM Model Independent Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy  
DAMA/LIBRA-phase2 (1.13 ton × yr)



Absence of modulation? No

- 1-3 keV:  $\chi^2/\text{dof}=127/52 \Rightarrow P(A=0) = 3 \times 10^{-8}$
- 1-6 keV:  $\chi^2/\text{dof}=150/52 \Rightarrow P(A=0) = 2 \times 10^{-11}$
- 2-6 keV:  $\chi^2/\text{dof}=116/52 \Rightarrow P(A=0) = 8 \times 10^{-7}$

Fit on DAMA/LIBRA-phase2

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

**1-3 keV**

$A=(0.0184 \pm 0.0023) \text{ cpd/kg/keV}$   
 $\chi^2/\text{dof} = 61.3/51$  **8.0  $\sigma$  C.L.**

**1-6 keV**

$A=(0.0105 \pm 0.0011) \text{ cpd/kg/keV}$   
 $\chi^2/\text{dof} = 50.0/51$  **9.5  $\sigma$  C.L.**

**2-6 keV**

$A=(0.0095 \pm 0.0011) \text{ cpd/kg/keV}$   
 $\chi^2/\text{dof} = 42.5/51$  **8.6  $\sigma$  C.L.**

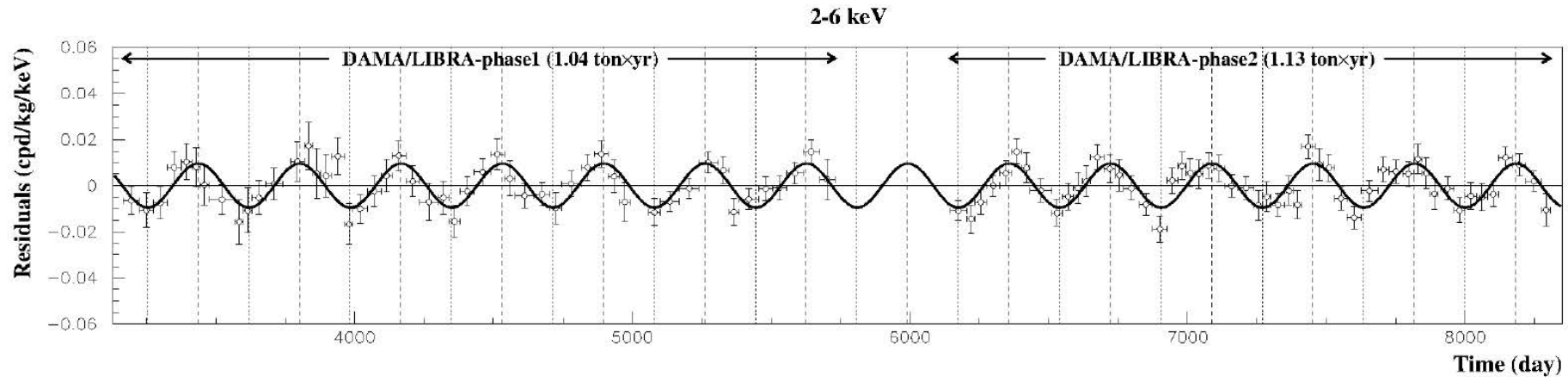
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 9.5 $\sigma$  C.L.



# Model Independent DM Annual Modulation Result

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

DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.17 ton × yr)



Absence of modulation? No

• 2-6 keV:  $\chi^2/\text{dof}=199.3/102 \Rightarrow P(A=0) = 2.9 \times 10^{-8}$

Fit on DAMA/LIBRA-phase1+  
DAMA/LIBRA-phase2

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

**2-6 keV**

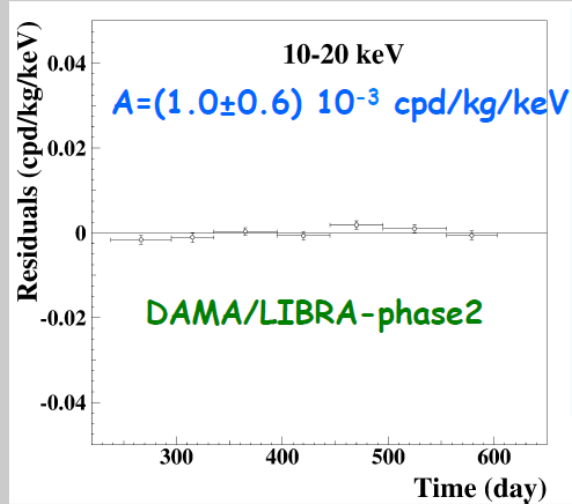
$A = (0.0095 \pm 0.0008) \text{ cpd/kg/keV}$

$\chi^2/\text{dof} = 71.8/101$  **11.9 $\sigma$  C.L.**

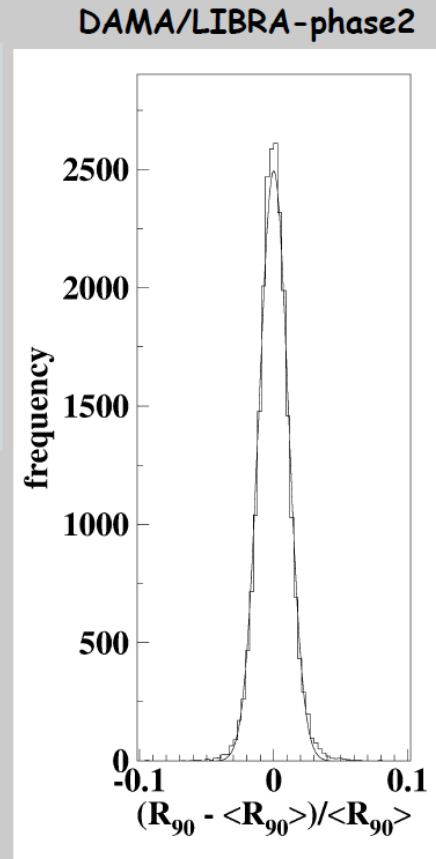
The data of DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.9  $\sigma$  C.L.

# Rate behaviour above 6 keV

## No Modulation above 6 keV



Mod. Ampl. (6-14 keV): cpd/kg/keV  
 (0.0032 ± 0.0017) DAMA/LIBRA-ph2\_2  
 (0.0016 ± 0.0017) DAMA/LIBRA-ph2\_3  
 (0.0024 ± 0.0015) DAMA/LIBRA-ph2\_4  
 -(0.0004 ± 0.0015) DAMA/LIBRA-ph2\_5  
 (0.0001 ± 0.0015) DAMA/LIBRA-ph2\_6  
 (0.0015 ± 0.0014) DAMA/LIBRA-ph2\_7  
 → statistically consistent with zero



$\sigma \approx 1\%$ , 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-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg

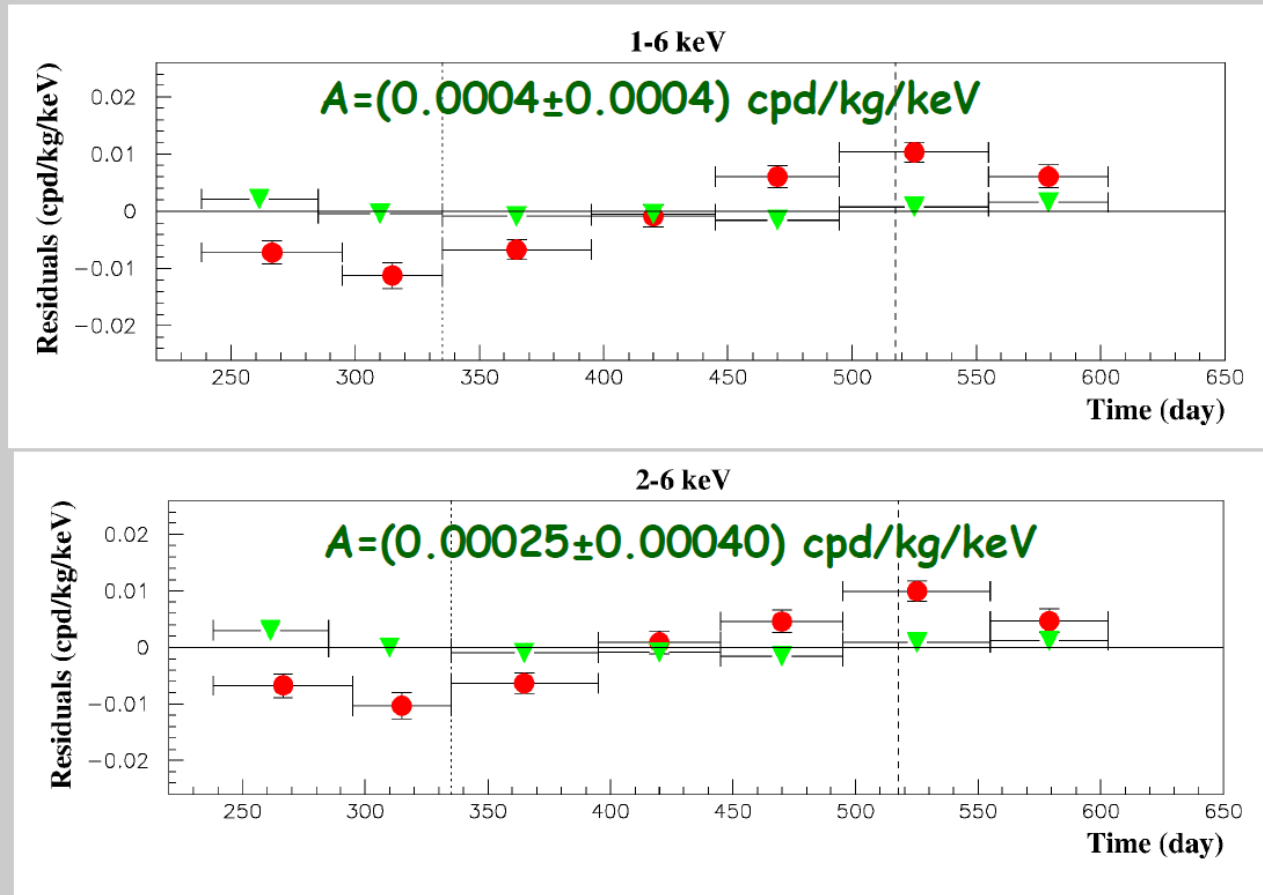
+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region →  $R_{90} \sim \text{tens cpd/kg} \rightarrow \sim 100 \sigma$  far away

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

# DM Model Independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.13 ton × yr)

Multiple hits events = Dark Matter particle “switched off”



Single hit residual rate (red) vs Multiple hit residual rate (green)

- Clear modulation in the single hit events;
- No modulation in the residual rate of the multiple hit events

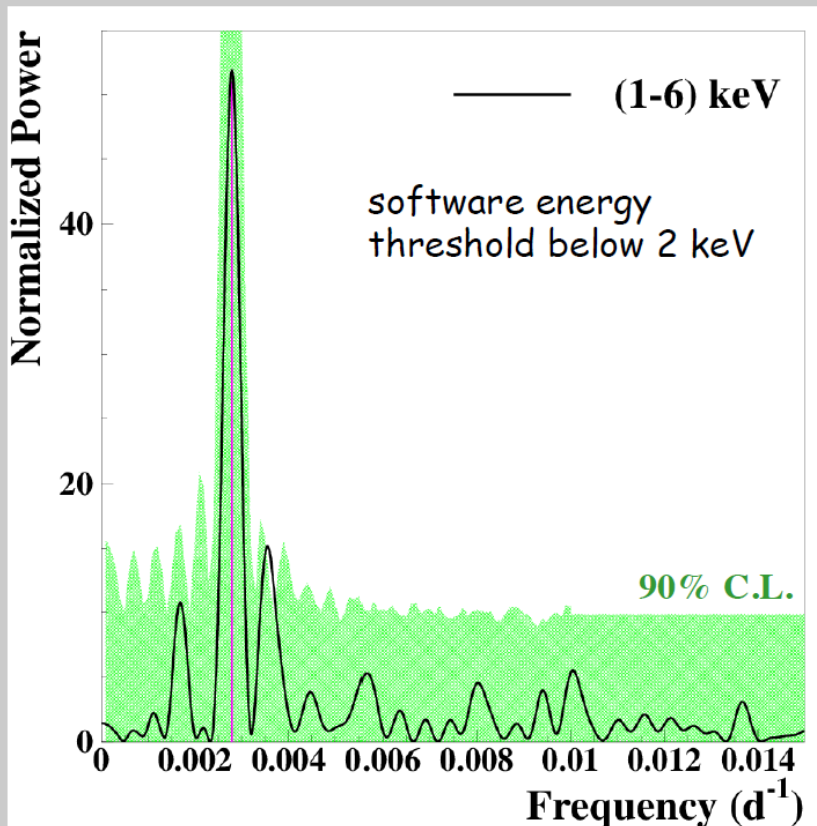
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background



# The analysis in frequency

(according to Phys. Rev. D 75 (2007) 013010)

To perform the Fourier analysis of the data in a wide region of frequency, the single-hit events have been grouped in 1 day bins



DAMA/LIBRA-phase2 (6 yr)  
total exposure: 1.13 ton $\times$ yr

Principal mode:  $2.79 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}$

Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

Clear annual modulation in (1-6) keV single-hit scintillation events



## Energy distribution of the modulation amplitudes

Max-likelihood analysis

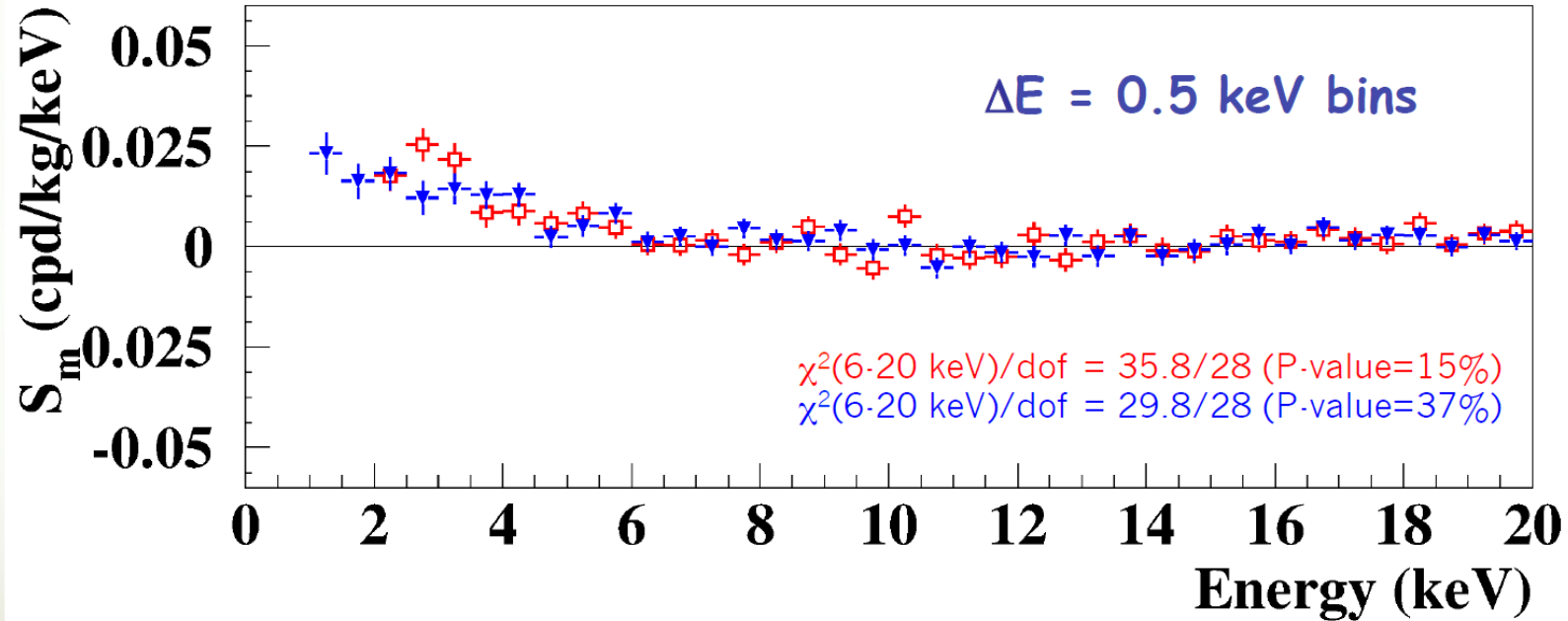
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$

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

DAMA/NaI + DAMA/LIBRA-phase1

vs

DAMA/LIBRA-phase2

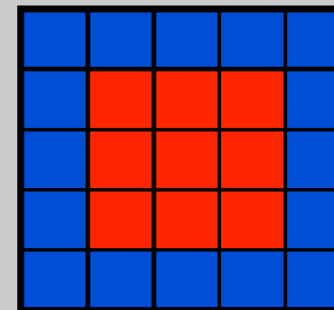
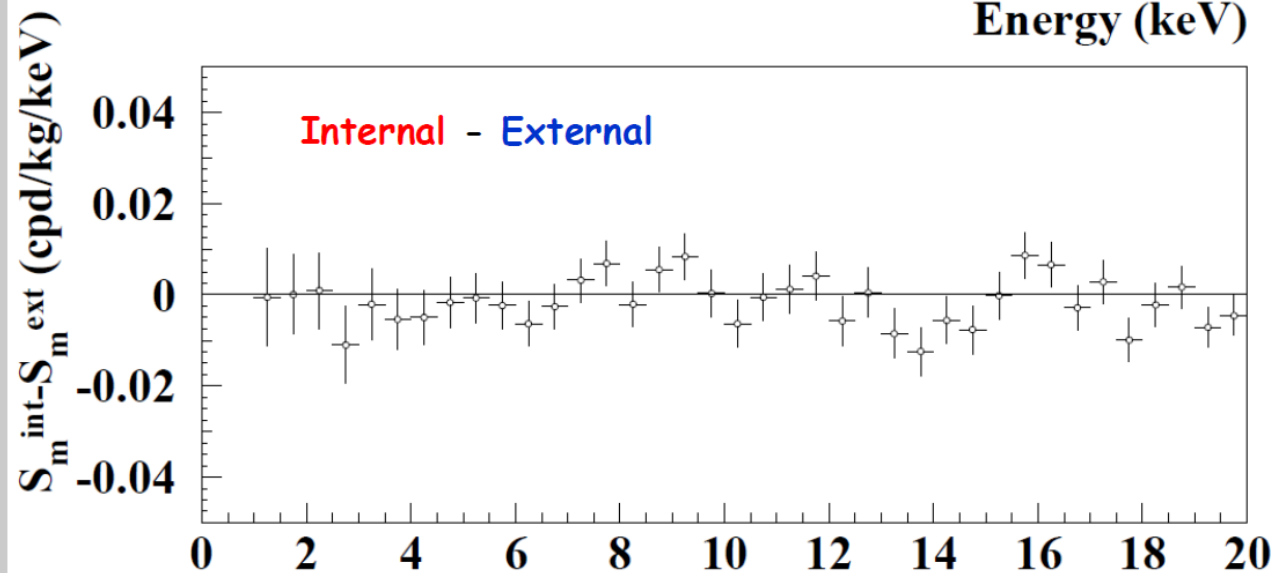
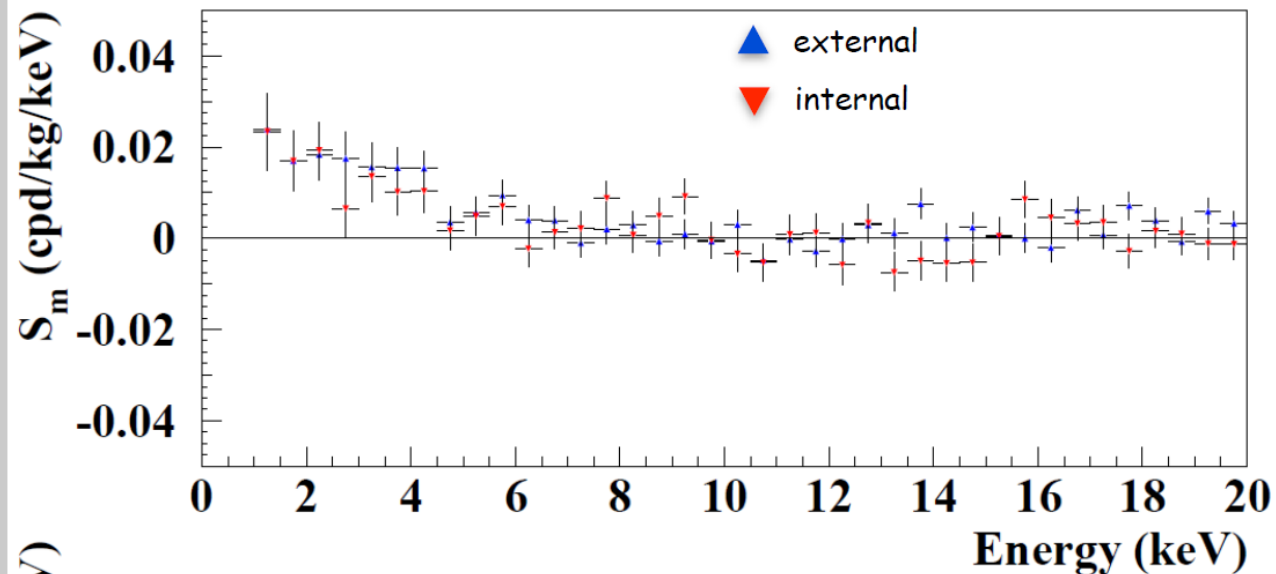


The  $S_m$  energy distributions obtained in DAMA/NaI+DAMA/LIBRA-ph1 and in DAMA/LIBRA-ph2 are consistent in the (2-20) keV energy interval:

$\chi^2 = \sum (r_1 - r_2)^2 / (\sigma_1^2 + \sigma_2^2)$	(2-20) keV	$\chi^2 / \text{d.o.f.} = 32.7/36$	(P=63%)
	(2-6) keV	$\chi^2 / \text{d.o.f.} = 10.7/8$	(P=22%)

# External vs internal detectors: DAMA/LIBRA-phase2

$\Delta E = 0.5$  keV



$\chi^2$ -Test

1-4 keV  $\chi^2/\text{dof} = 2.5/6$

1-10 keV  $\chi^2/\text{dof} = 12.1/8$

1-20 keV  $\chi^2/\text{dof} = 40.8/38$



## Stability parameters of DAMA/LIBRA-phase2

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 new running periods

	DAMA/LIBRA-phase2_2	DAMA/LIBRA-phase2_3	DAMA/LIBRA-phase2_4	DAMA/LIBRA-phase2_5	DAMA/LIBRA-phase2_6	DAMA/LIBRA-phase2_7
Temperature (°C)	$(0.0012 \pm 0.0051)$	$-(0.0002 \pm 0.0049)$	$-(0.0003 \pm 0.0031)$	$(0.0009 \pm 0.0050)$	$(0.0018 \pm 0.0036)$	$-(0.0006 \pm 0.0035)$
Flux N <sub>2</sub> (l/h)	$-(0.15 \pm 0.18)$	$-(0.02 \pm 0.22)$	$-(0.02 \pm 0.12)$	$-(0.02 \pm 0.14)$	$-(0.01 \pm 0.10)$	$-(0.01 \pm 0.16)$
Pressure (mbar)	$(1.1 \pm 0.9) \times 10^{-3}$	$(0.2 \pm 1.1) \times 10^{-3}$	$(2.4 \pm 5.4) \times 10^{-3}$	$(0.6 \pm 6.2) \times 10^{-3}$	$(1.5 \pm 6.3) \times 10^{-3}$	$(7.2 \pm 8.6) \times 10^{-3}$
Radon (Bq/m <sup>3</sup> )	$(0.015 \pm 0.034)$	$-(0.002 \pm 0.050)$	$-(0.009 \pm 0.028)$	$-(0.044 \pm 0.050)$	$(0.082 \pm 0.086)$	$(0.06 \pm 0.11)$
Hardware rate above single ph.e. (Hz)	$-(0.12 \pm 0.16) \times 10^{-2}$	$(0.00 \pm 0.12) \times 10^{-2}$	$-(0.14 \pm 0.22) \times 10^{-2}$	$-(0.05 \pm 0.22) \times 10^{-2}$	$-(0.06 \pm 0.16) \times 10^{-2}$	$-(0.08 \pm 0.17) \times 10^{-2}$

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)

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

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, EPJC74(2014)3196, IJMPA31(2017)issue31

Source	Main comment	Cautious upper limit (90%C.L.)
<b>RADON</b>	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5 \times 10^{-6}$ cpd/kg/keV
<b>TEMPERATURE</b>	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
<b>NOISE</b>	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
<b>ENERGY SCALE</b>	Routine + intrinsic calibrations	$<1-2 \times 10^{-4}$ cpd/kg/keV
<b>EFFICIENCIES</b>	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
<b>BACKGROUND</b>	No modulation above 6 keV; no modulation in the (2-6) keV <i>multiple-hits</i> events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
<b>SIDE REACTIONS</b>	Muon flux variation measured at LNGS	$<3 \times 10^{-5}$ cpd/kg/keV





# Final model independent result DAMA/NaI+DAMA/LIBRA-phase1+phase2

Presence of modulation **over 20 annual cycles at  $12.9 \sigma$  C.L.** with the proper distinctive features of the DM signature; all the features satisfied by the data over 20 independent experiments of 1 year each one

The total exposure by former DAMA/NaI, DAMA/LIBRA-phase1 and phase2 is **2.46 ton  $\times$  yr**

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  $(0.999 \pm 0.001)^*$  yr, well compatible with the 1 yr period, as expected for the DM signal

3)

Measured phase  $(145 \pm 5)^*$  days is well compatible with the roughly about 152.5 days as expected for the DM signal

4)

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

5)

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

6)

The measured modulation amplitude in NaI(Tl) of the *single-hit* events is:  $(0.0103 \pm 0.0008)^*$  cpd/kg/keV ( $12.9 \sigma$  C.L.).

\* Here 2–6 keV energy interval

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

... and well compatible with several candidates  
(in many possible astrophysical, nuclear and particle physics scenarios)