

# First model-independent results by DAMA/LIBRA-phase2



CSLNGS  
March 26, 2018

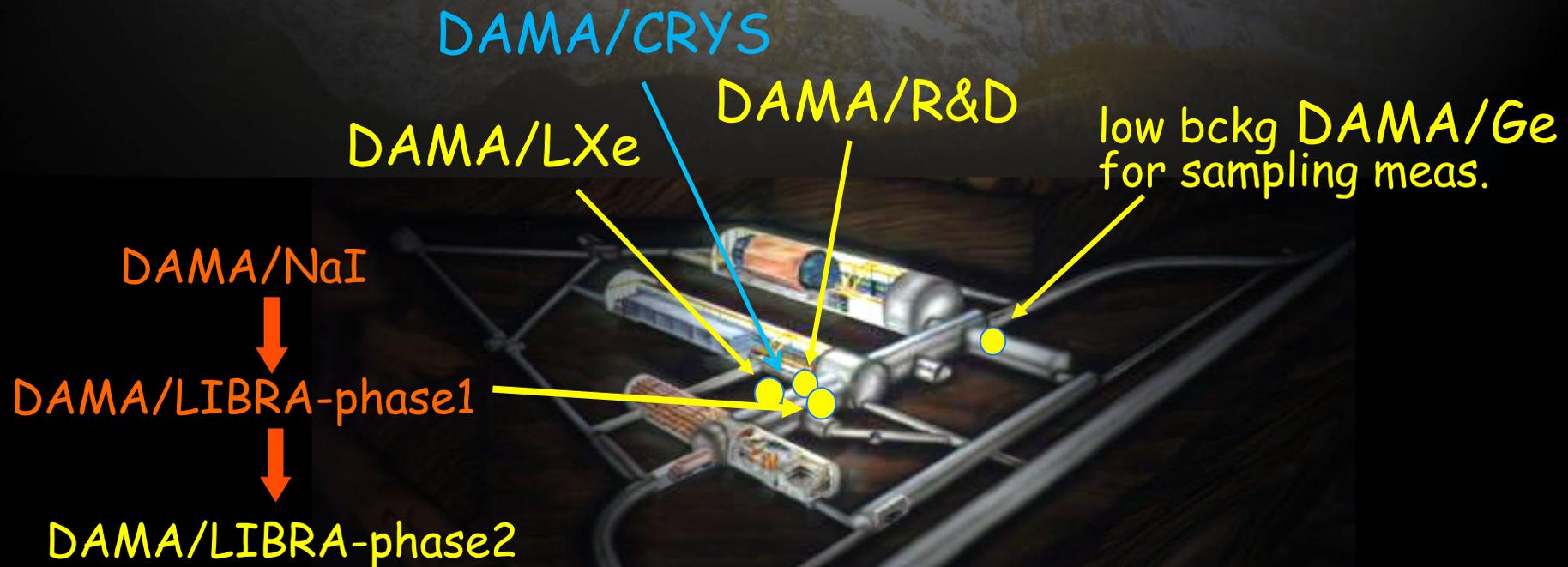
R. Bernabei  
University & INFN Roma Tor Vergata

# Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

- + by-products and small scale expts.: INR-Kiev + others
- + neutron meas.: ENEA-Frascati, ENEA-CASACCIA
- & in some studies on  $\beta\beta$  decays (DST-MAE project):  
IIT Kharagpur/Ropar, India



## DAMA: an observatory for rare processes @LNGS



# Relic DM particles from primordial Universe

What accelerators can do:  
to demonstrate the existence of  
some of the DM candidates

What accelerators cannot do:  
to credit that a certain particle  
is a DM solution or the "only"  
DM particle solution...

+ DM candidates and scenarios  
exist (even for neutralino  
candidate) on which accelerators  
cannot give any information



Nuclear recoils and/or e.m. radiation

MULTI-MESSENGER?

ONLY FOR SOME PARTICULAR CASES

DM multicomponent also  
in the particle part?

Right related nuclear and  
particle physics?

etc

Right halo model and parameters?

Non thermalized  
components?

Caustics?

clumpiness?



# The relevance of ULB NaI(Tl) as target-material

- 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, ...)
- $\lambda$  of the NaI(Tl) scintillation light well directly match PMTs sensitivity
- Uniform response in the realized detectors
- High light response (5.5 - 7.5 ph.e./keV phase1 and typically 6-10 phe/keV in phase2)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold ( $\tau$  of NaI(Tl) pulses hundreds ns, while  $\tau$  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 and to candidates also inducing e.m. radiation
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up
- etc.



ULB NaI(Tl) also allows the study of several rare processes

High benefits/cost



To develop ULB NaI(Tl): many years of work, specific experience in the specific detector, suitable raw materials availability/selections, developments of purification strategies, additives, growing/handling protocols, selective cuts, abrasives, etc. etc. → long dedicated time and efforts.

The developments themselves are difficult and uncertain experiments.



ULB NaI(Tl) - as whatever ULB detector - cannot be simply bought or made by another researcher for you ...

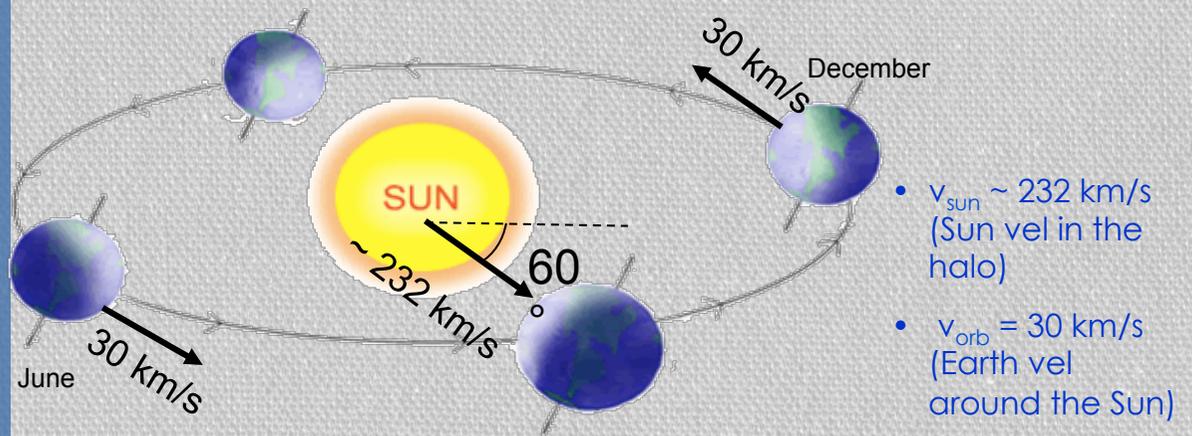
# The DM annual modulation: a model independent signature to investigate the DM particles component in the galactic halo

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



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

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

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

**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

# The pioneer DAMA/NaI: $\approx 100$ kg highly radiopure NaI(Tl)

## Performances:

### Results on rare processes:

- Possible Pauli exclusion principle violation
- CNC processes
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
- Search for solar axions.
- Exotic Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

### Results on DM particles:

- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- Annual Modulation Signature

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

PLB408(1997)439  
PRC60(1999)065501

PLB460(1999)235  
PLB515(2001)6  
EPJdirect C14(2002)1  
EPJA23(2005)7  
EPJA24(2005)51

PLB389(1996)757  
N.Cim.A112(1999)1541  
PRL83(1999)4918

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.



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

model independent evidence of a particle DM component in the galactic halo at  $6.3\sigma$  C.L.  
total exposure (7 annual cycles)  $0.29 \text{ ton} \times \text{yr}$

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PLB408(1997)439  
PRC60(1999)065501

## Results on DM particles:

- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- Annual Modulation Signature

model independent evidence  
total exposure (C)

## The DAMA/LIBRA set-up $\sim 250$ kg NaI(Tl) (Large sodium Iodide Bulk for RARE processes)

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

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

DAMA/LIBRA-phase1 (exposure 1.04 ton x yr over 7 annual cycles)  
confirms the positive model independent signal

- Radiopurity performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles: Ann. Mod. Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648
- related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC75 (2015) 239, EPJC75(2015)400, IJMPA31dedicated full issue31 (2016), EPJC77(2017)83
- Results on rare processes: PEP violation in Na, I: EPJC62(2009).327, CNC in I: EPJC72(2012)1920  
IPP in  $^{241}\text{Am}$ : EPJA49(2013)64, Noncommutative Spacetimes and Violations of PEP.arXiv:1712.08082

# The DAMA/LIBRA-phase2 set-up

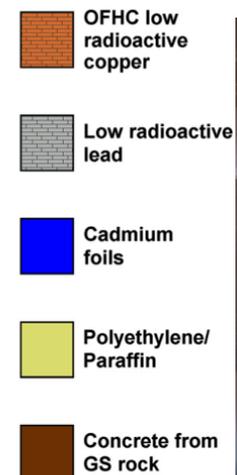
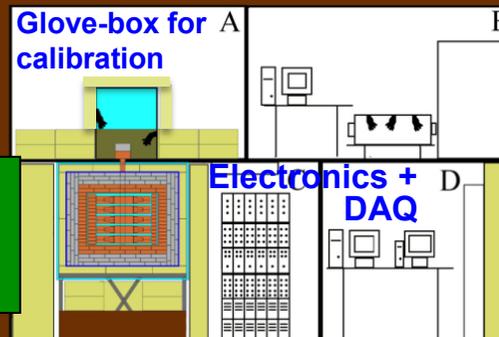
For details, radiopurity, performances, procedures, etc.

NIMA592(2008)297, JINST 7(2012)03009, IJMPA31(2017)issue31

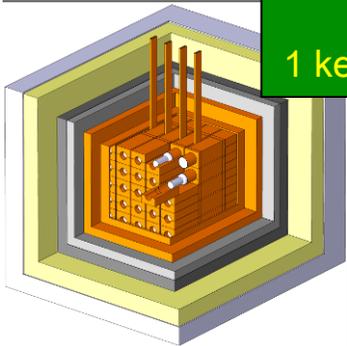


- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two new high Q.E. PMTs working in coincidence at the single ph. el. threshold

## Installation



Typical DAMA/LIBRA-phase2:  
6-10 phe/keV;  
1 keV software energy threshold



- Whole setup decoupled from ground
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- Dismounting/Installing protocol in HPN<sub>2</sub>
- All the materials selected for low radioactivity
- **Multiton-multicomponent passive shield** (>10 cm of OFHC Cu, 15 cm of boliden 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
- Never neutron source in DAMA installations
- **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 both for single-hit and multiple-hit events
- Data collected from low energy **up to MeV region**, despite the hardware optimization was done for the low energy
- DAQ with optical readout
- Some new electronic modules



# DAMA/LIBRA - phase2

JINST 7(2012)03009

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

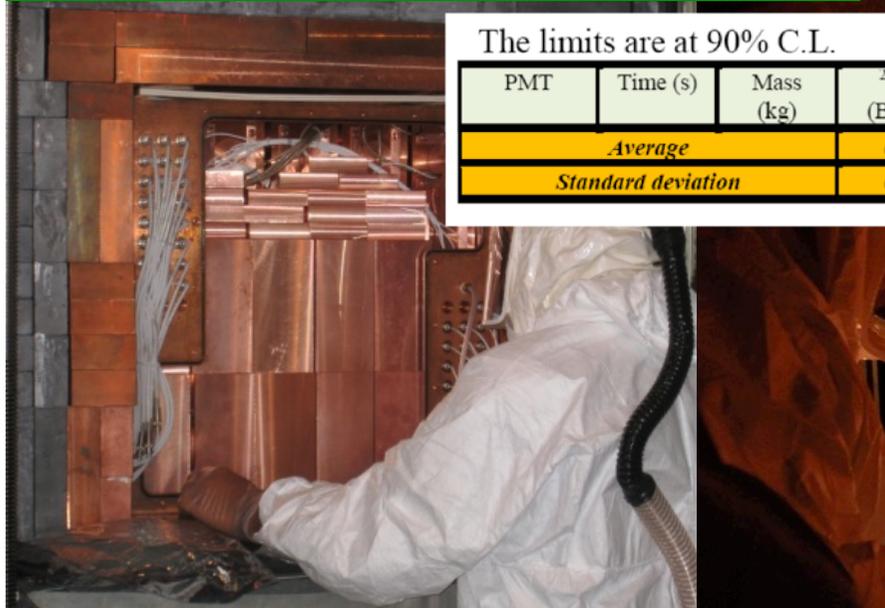


Second upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

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

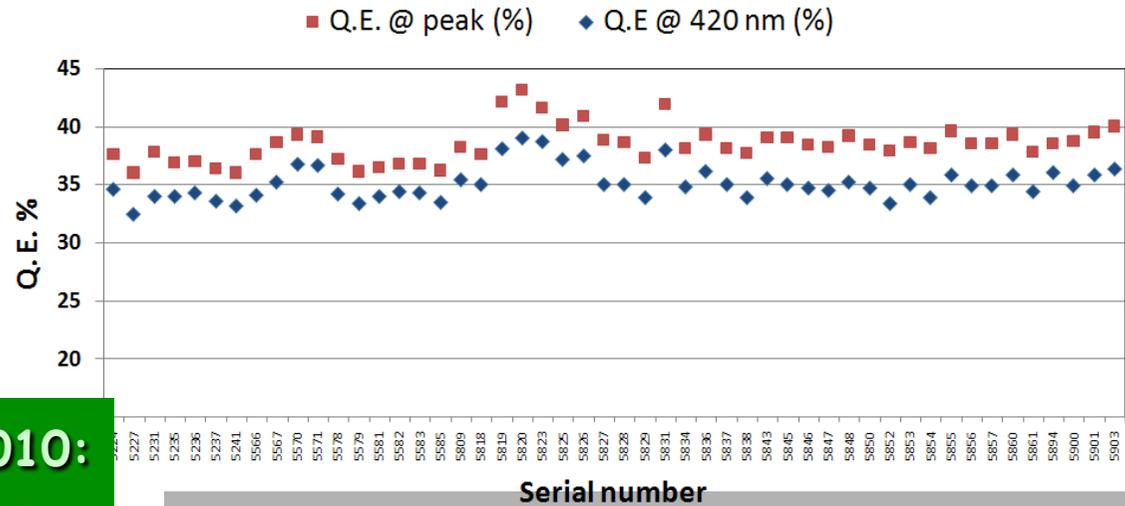
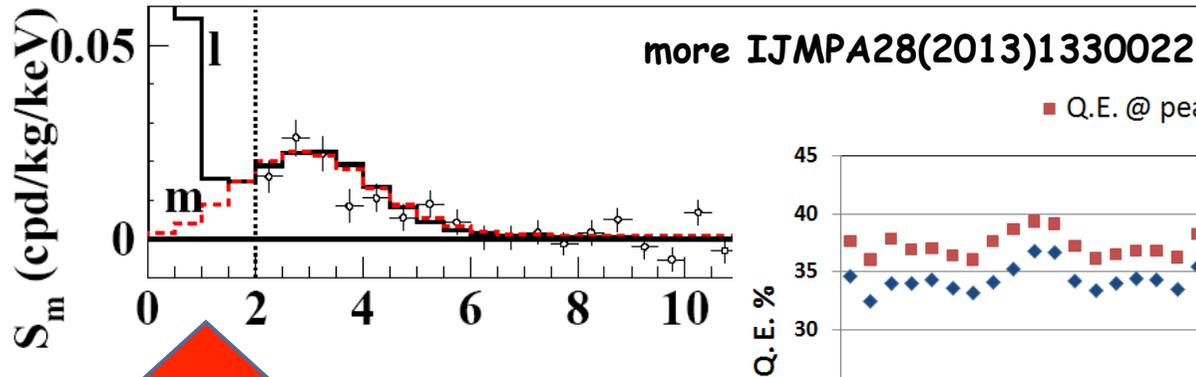
The limits are at 90% C.L.

PMT	Time (s)	Mass (kg)	<sup>226</sup> Ra (Bq/kg)	<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)
<i>Average</i>			0.43	-	47	0.12	83	0.54	-	-
<i>Standard deviation</i>			0.06	-	10	0.02	17	0.16	-	-



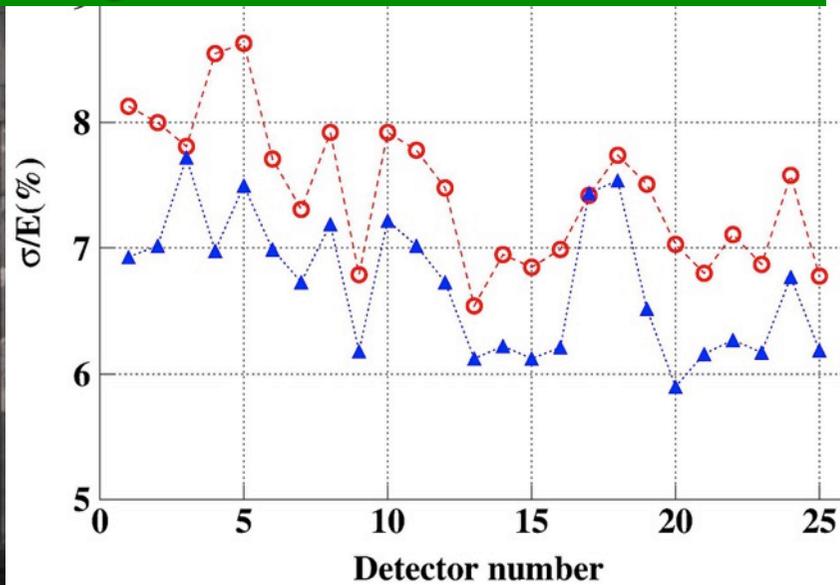
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes
- + R&D in progress towards more future phase3

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



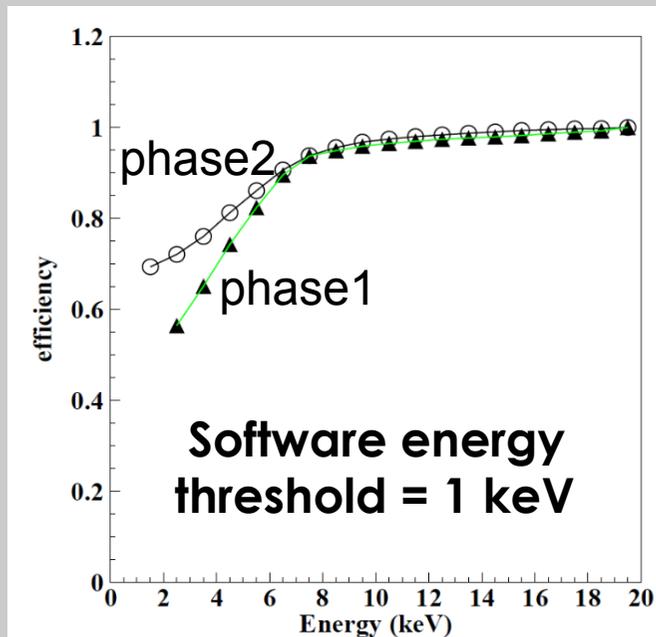
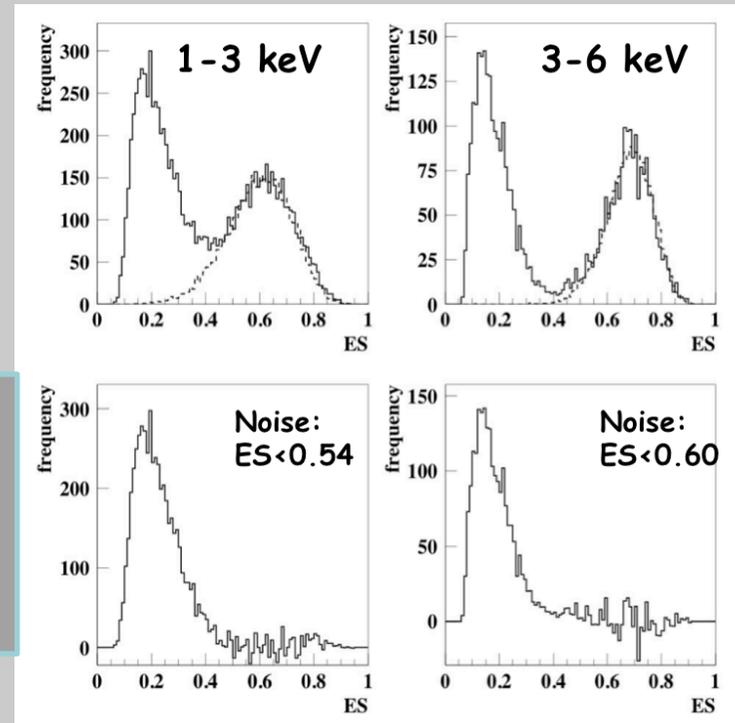
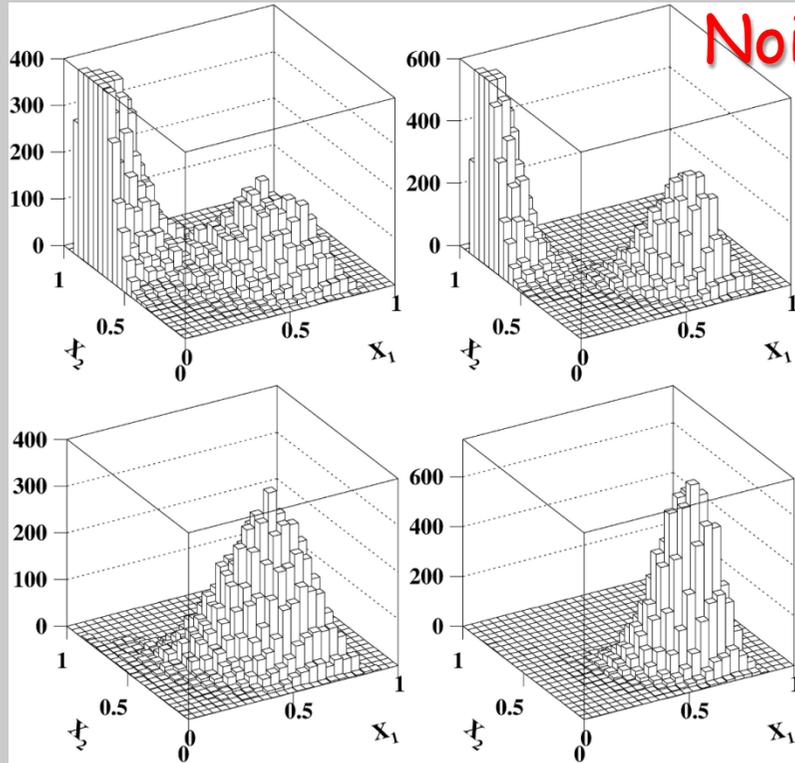
<sup>234m</sup> Pa (Bq/kg)	<sup>235</sup> U (mBq/kg)	<sup>228</sup> Ra (Bq/kg)	<sup>228</sup> Th (mBq/kg)	<sup>40</sup> K (Bq/kg)	<sup>137</sup> Cs (mBq/kg)	<sup>60</sup> Co (mBq/kg)
-	47	0.12	83	0.54	-	-
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- To study the nature of the particles and 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

# Noise rejection in phase2

- Comparison of the noise and the scintillation pulses distributions in 1-3 keV and 3-6 keV
- production data vs  $\gamma$  source
- scintillation events well separated from noise

$X_1 = \text{Area}(\text{from } 100 \text{ to } 600 \text{ ns}) / \text{Area}(\text{from } 0 \text{ to } 600 \text{ ns})$   
 $X_2 = \text{Area}(\text{from } 0 \text{ to } 50 \text{ ns}) / \text{Area}(\text{from } 0 \text{ to } 600 \text{ ns})$



Residual noise events:  
 $(15 \pm 62) (<120)$   
 $-(18 \pm 41) (<51)$

→ possible noise contamination,  $f$ , in the selected events  $<3\%$  @ software energy threshold

# DAMA/LIBRA-phase2 data taking

Second upgrade at end of 2010:

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

JINST 7(2012)03009



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**

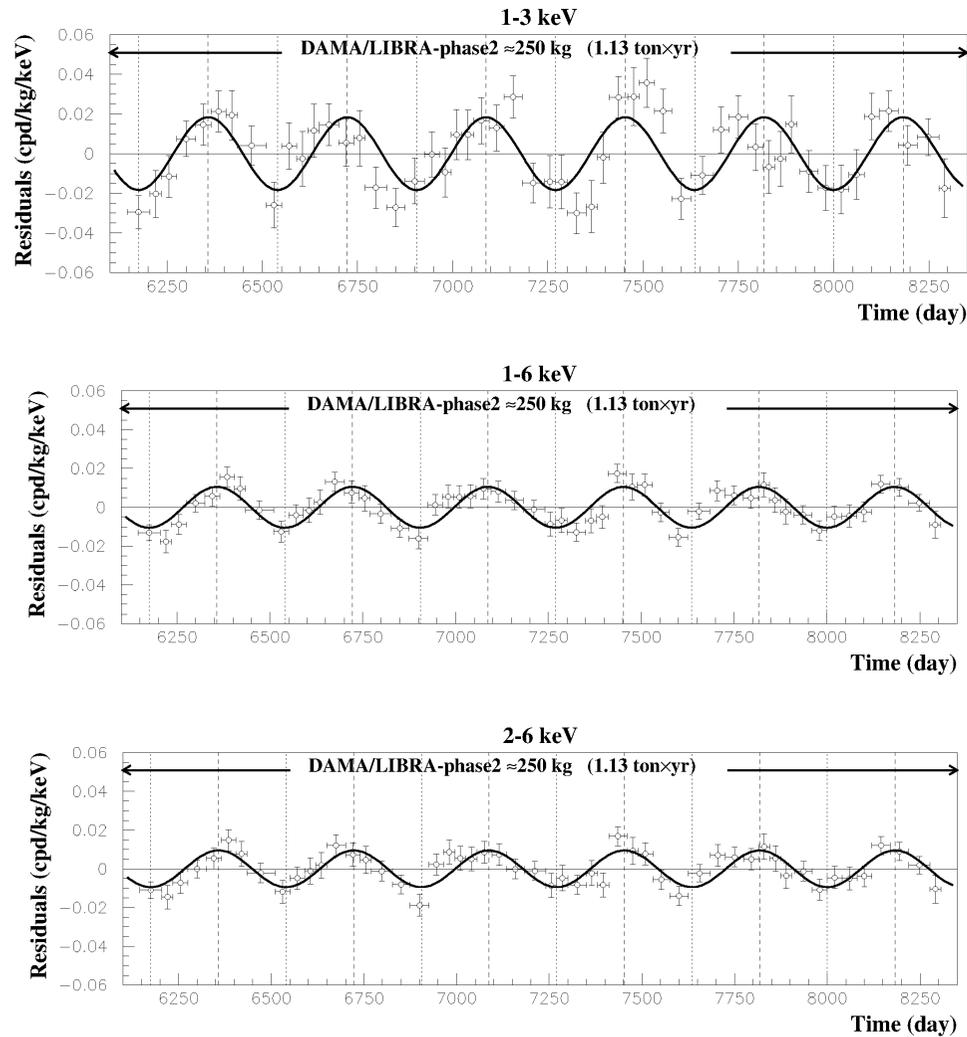
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2:

**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**

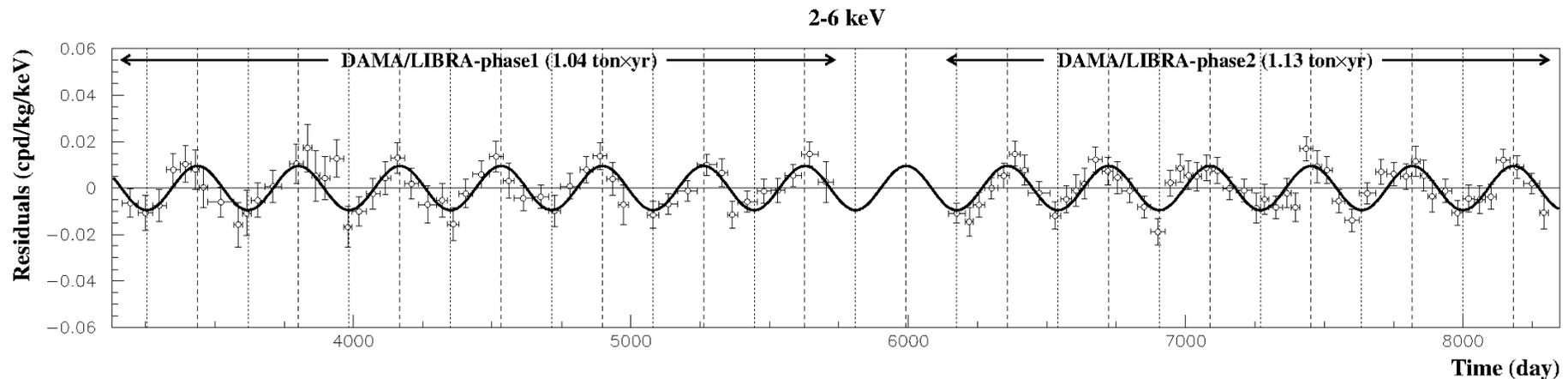
$A=(0.0095 \pm 0.0011) \text{ cpd/kg/keV}$   
 $\chi^2/\text{dof} = 42.5/51$  **8.6  $\sigma$  C.L.**

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

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

continuous lines:  $t_0 = 152.5$  d,  $T = 1.00$  y

**2-6 keV**

$A = (0.0095 \pm 0.0008)$  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.

## Releasing period (T) and phase ( $t_0$ ) in the fit

	$\Delta E$	$A(\text{cpd/kg/keV})$	$T=2\pi/\omega$ (yr)	$t_0$ (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	$0.0184 \pm 0.0023$	$1.0000 \pm 0.0010$	$153 \pm 7$	$8.0\sigma$
	(1-6) keV	$0.0106 \pm 0.0011$	$0.9993 \pm 0.0008$	$148 \pm 6$	$9.6\sigma$
	(2-6) keV	$0.0096 \pm 0.0011$	$0.9989 \pm 0.0010$	$145 \pm 7$	$8.7\sigma$
DAMA/LIBRA-ph1 + color: blue;">DAMA/LIBRA-ph2	(2-6) keV	$0.0096 \pm 0.0008$	$0.9987 \pm 0.0008$	$145 \pm 5$	$12.0\sigma$
DAMA/NaI + color: red;">DAMA/LIBRA-ph1 + color: blue;">DAMA/LIBRA-ph2	(2-6) keV	$0.0103 \pm 0.0008$	$0.9987 \pm 0.0008$	$145 \pm 5$	$12.9\sigma$

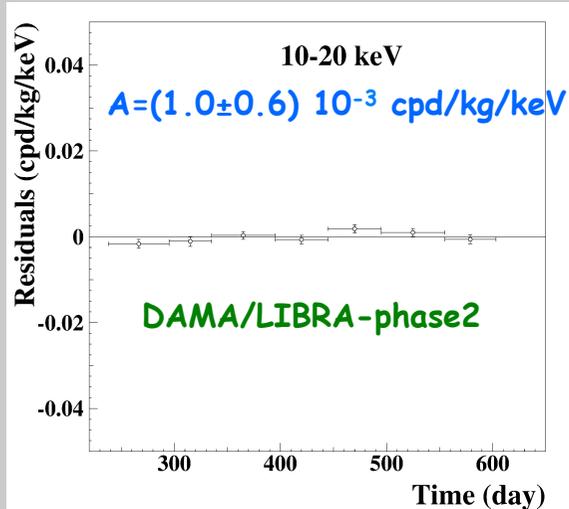
$$A \cos[\omega(t-t_0)]$$

DAMA/NaI (0.29 ton x yr) +  
 color: red;">DAMA/LIBRA-ph1 (1.04 ton x yr) +  
 color: blue;">DAMA/LIBRA-ph2 (1.13 ton x yr)

total exposure = 2.46 ton x yr

## Rate behaviour above 6 keV

- **No Modulation above 6 keV**

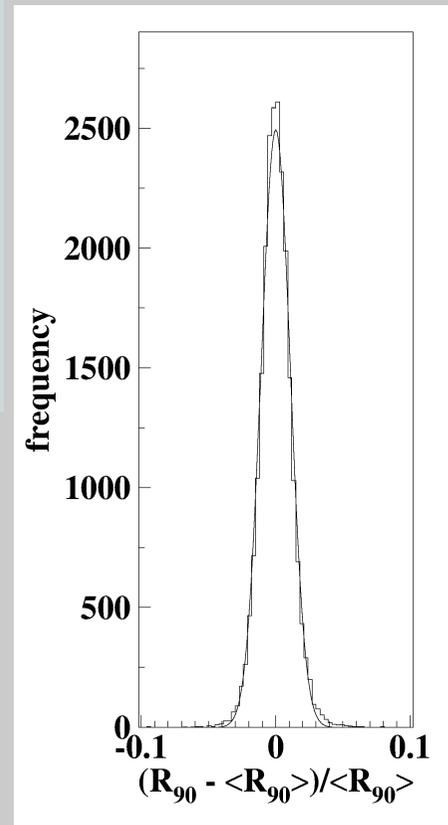


Mod. Ampl. (6-14 keV): cpd/kg/keV

- (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

DAMA/LIBRA-phase2



$\sigma \approx 1\%$ , 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

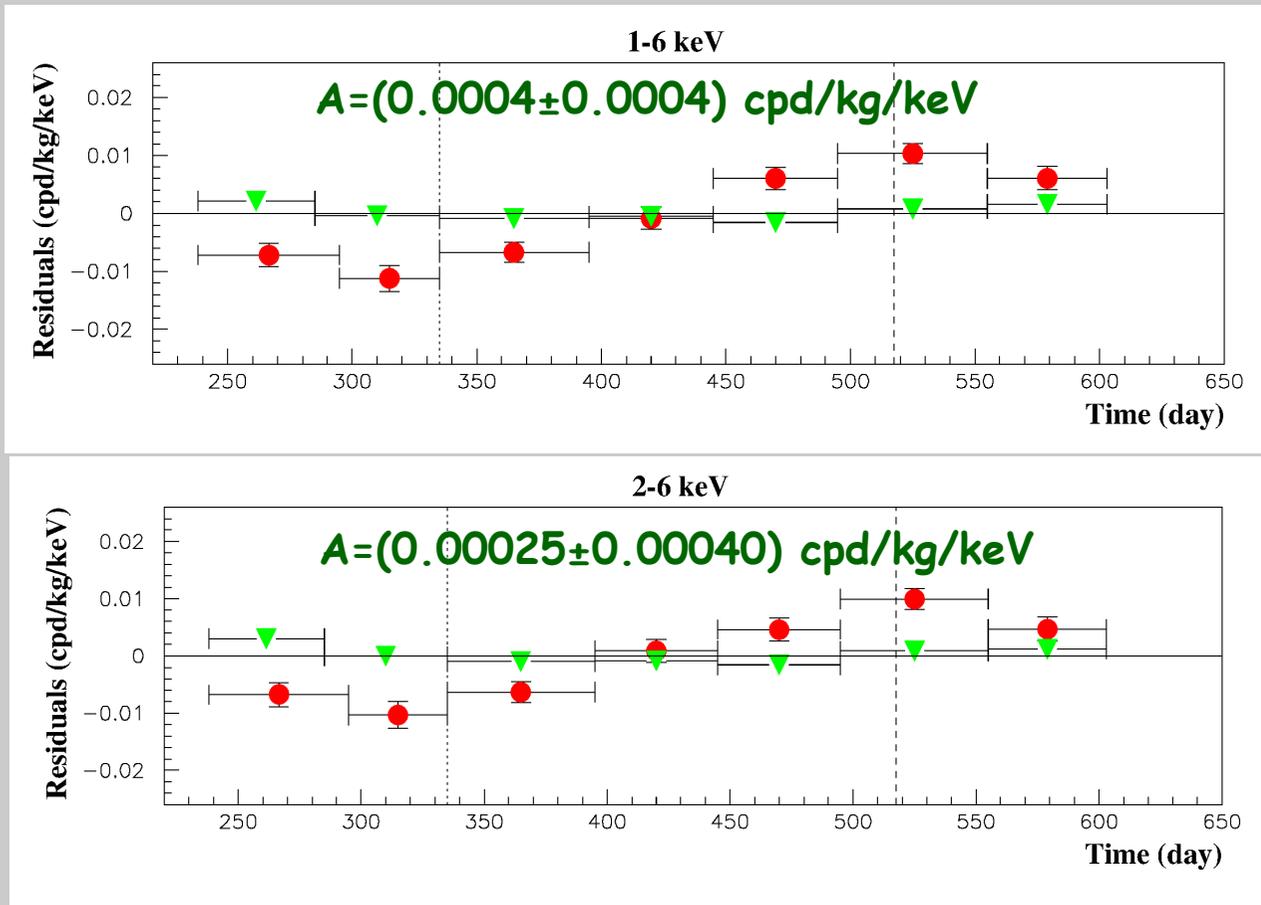
No modulation above 6 keV

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

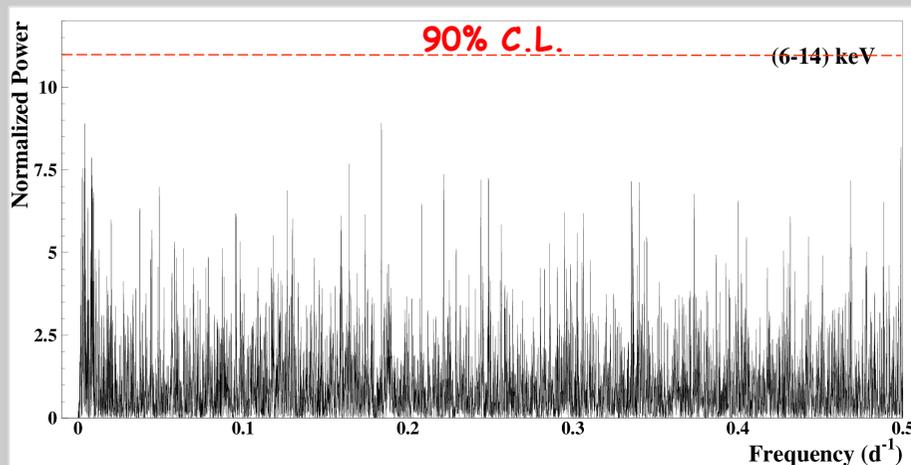
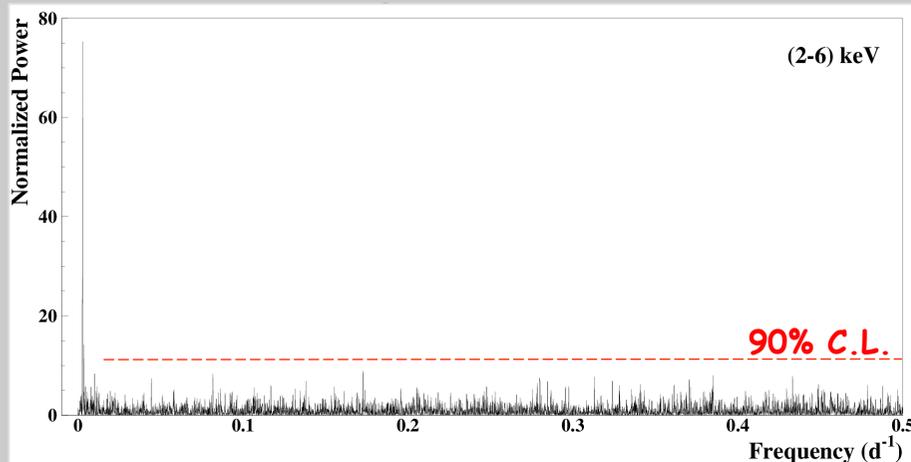
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

# The analysis in frequency

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

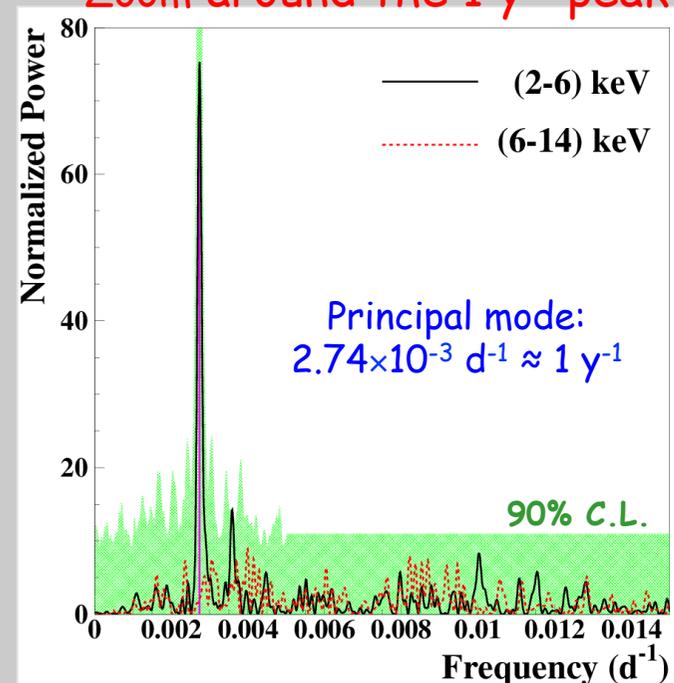
To perform the Fourier analysis of the data in a wide region of frequency, the single-hit scintillation events have been grouped in 1 day bins

The whole power spectra up to the Nyquist



DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (20 yr)  
total exposure: 2.46 ton $\times$ yr

Zoom around the  $1 y^{-1}$  peak



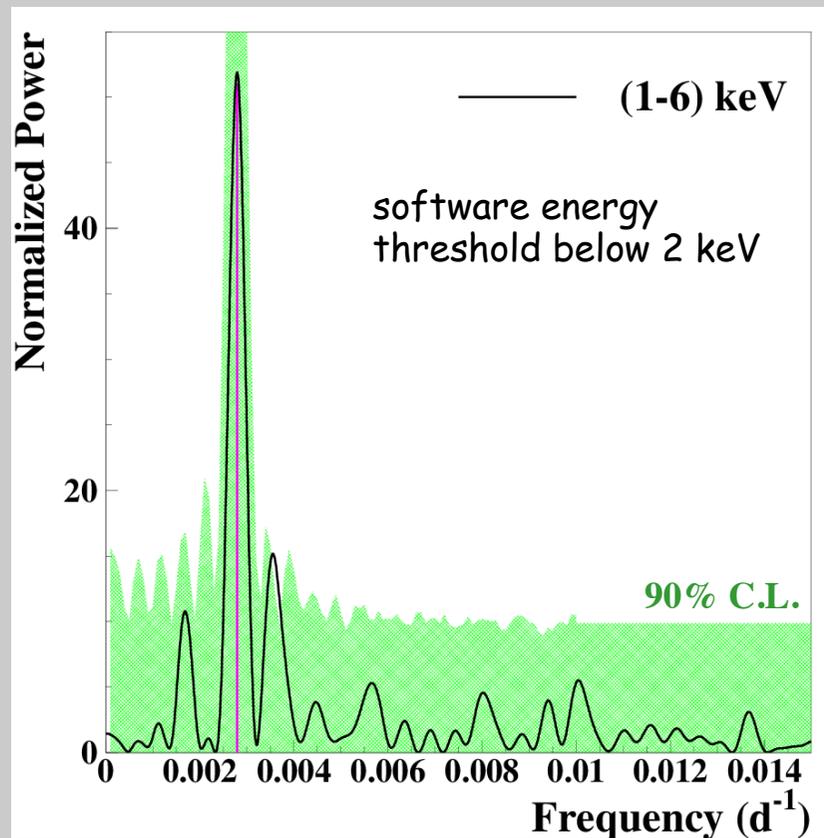
Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region

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

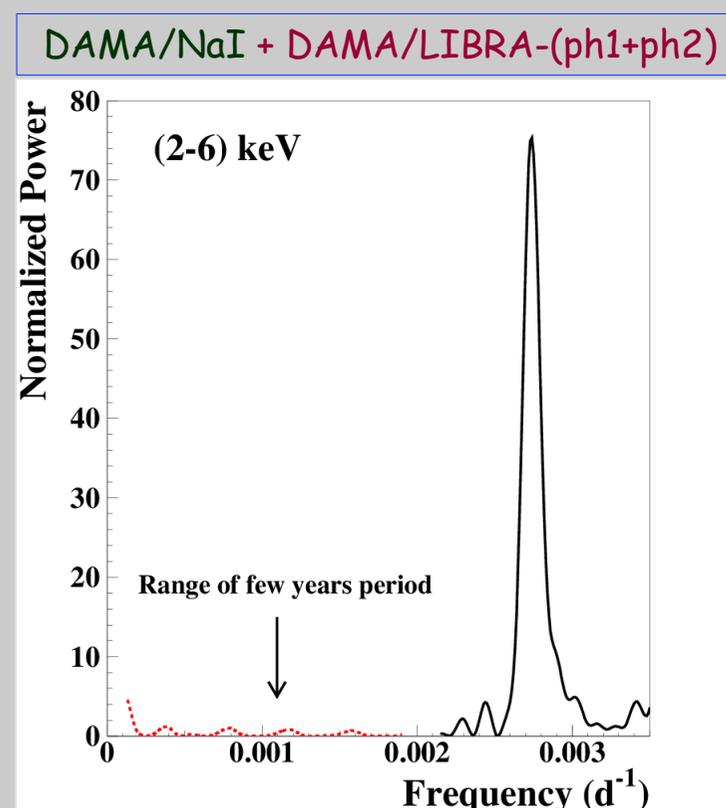
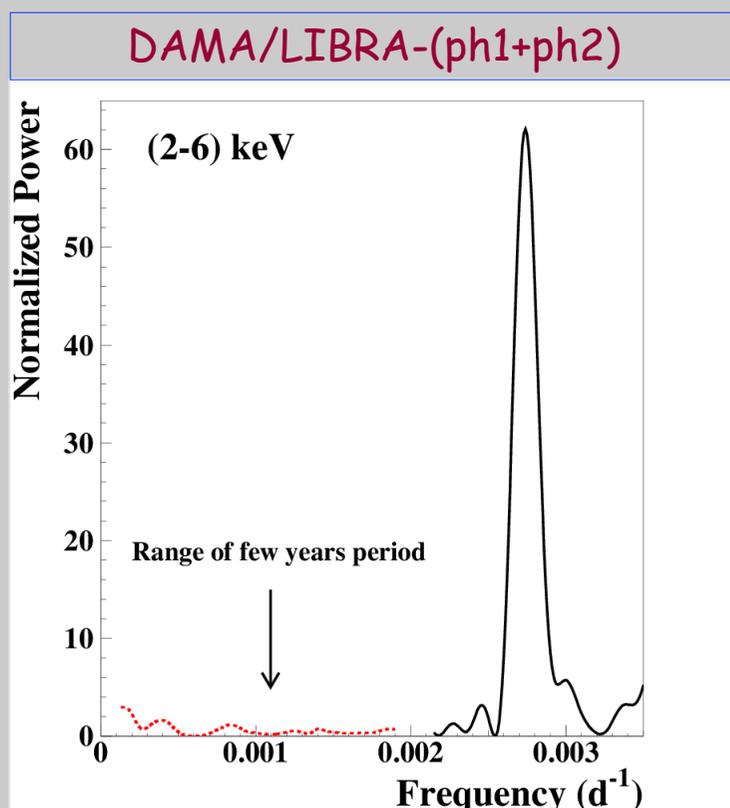
Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

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

## Investigating the possible presence of long term modulation in the counting rate

We calculated annual baseline counting rates - that is the averages on all the detectors ( $j$  index) of  $flat_j$  (i.e. the single-hit scintillation rate of the  $j$ -th detector averaged over the annual cycle)

For comparison the power spectra for the measured single-hit residuals in (2-6) keV are also shown: **Principal modes @  $2.74 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}$**



No statistically significant peak at lower frequency

## Energy distribution of the modulation amplitudes

Max-likelihood analysis

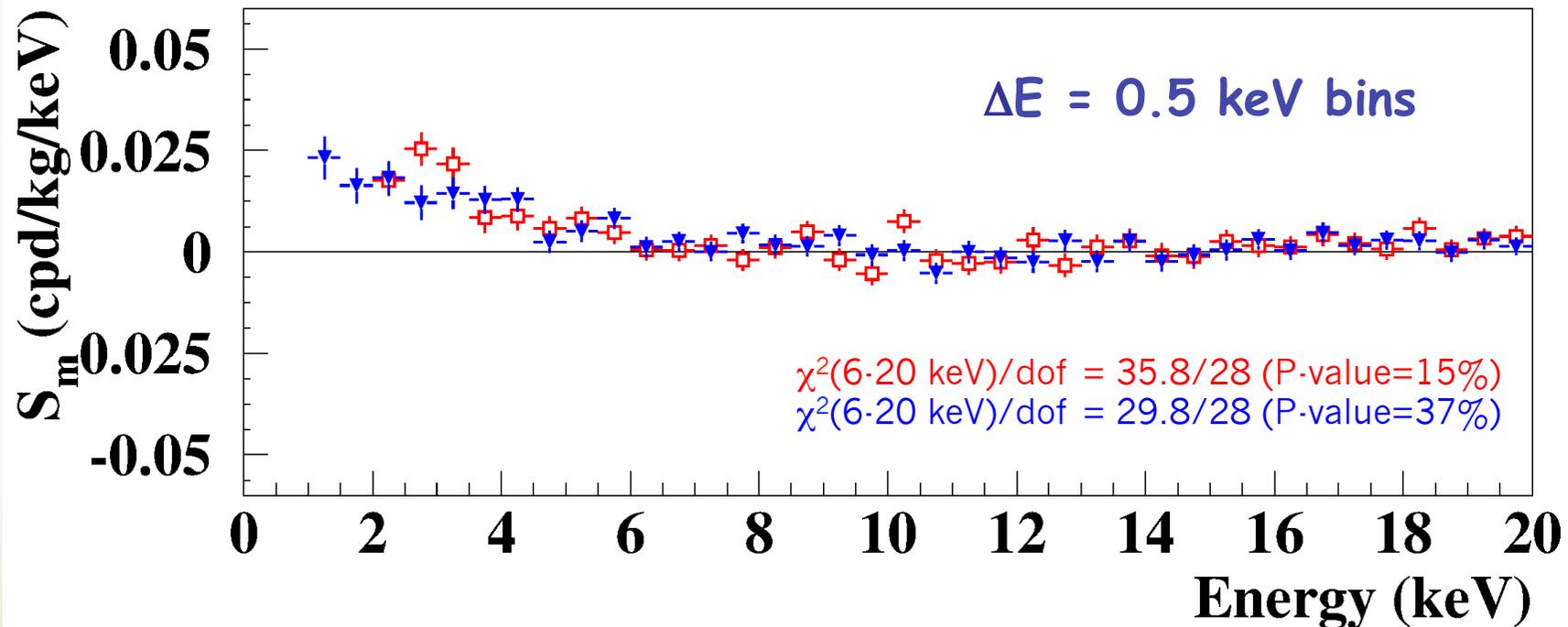
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$

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	$\chi^2$ /d.o.f.=32.7/36	(P=63%)
	(2-6) keV	$\chi^2$ /d.o.f.=10.7/8	(P=22%)

## Energy distribution of the modulation amplitudes

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

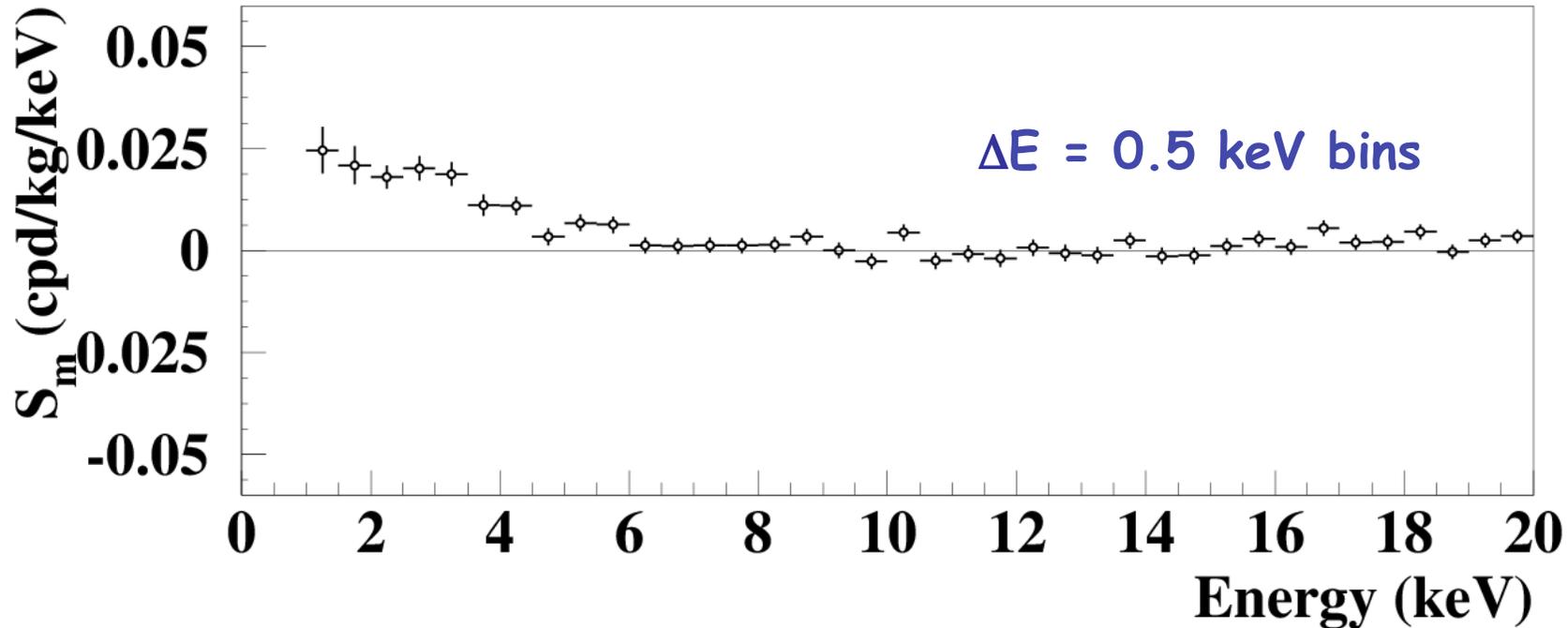
here  $T=2\pi/\omega=1$  yr and  $t_0=152.5$  day

DAMA/NaI

+ DAMA/LIBRA-phase1

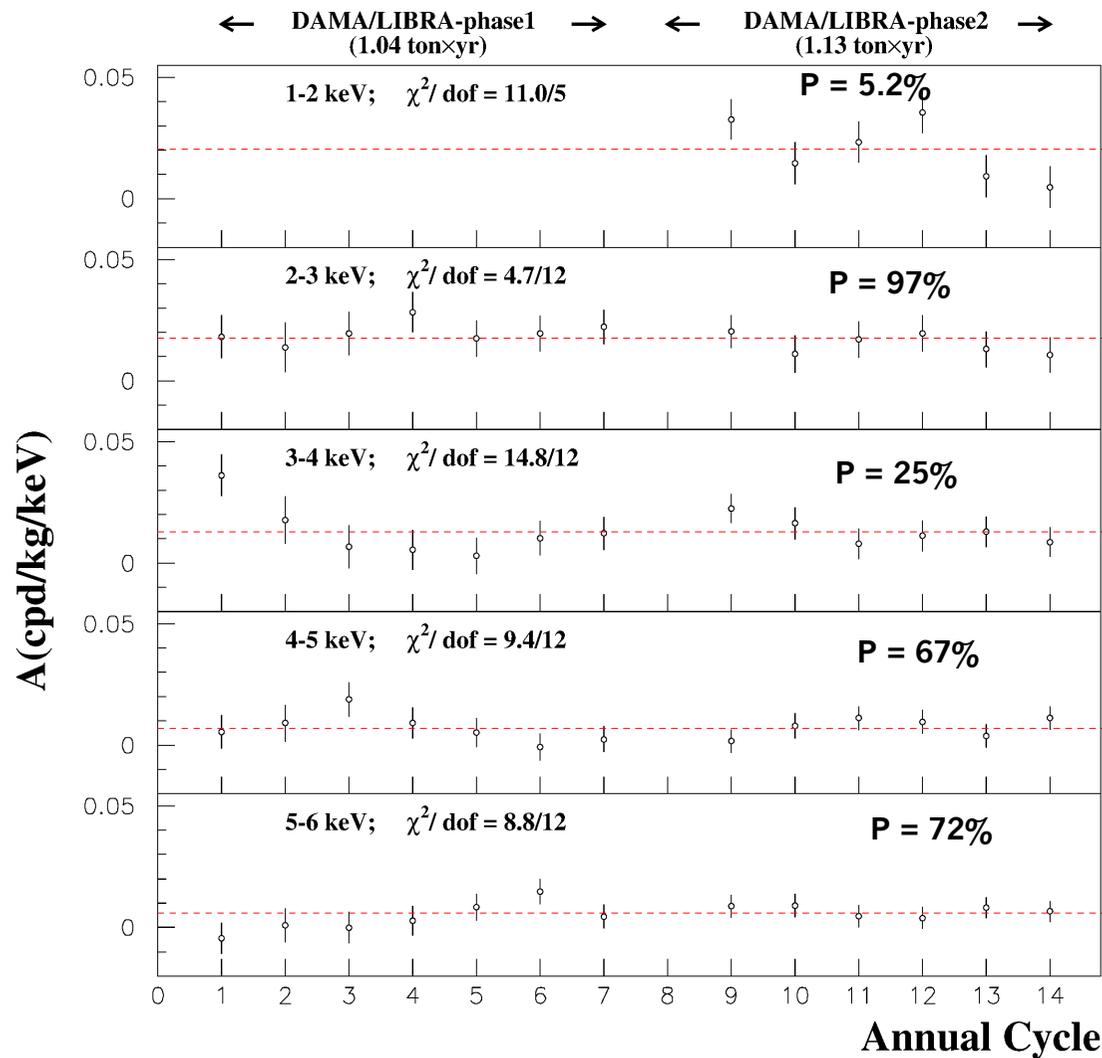
+ DAMA/LIBRA-phase2

total exposure:  $\approx 2.46$  ton $\times$ yr



- A clear modulation is present in the (1-6) keV energy interval, while  $S_m$  values compatible with zero are present just above
- The  $S_m$  values in the (6-14) keV energy interval have random fluctuations around zero with  $\chi^2$  equal to 19.0 for 16 degrees of freedom (upper tail probability 27%)
- The  $S_m$  values in the (6-20) keV energy interval have random fluctuations around zero with  $\chi^2$  equal to 42.6 for 28 degrees of freedom (upper tail probability 4%). The obtained  $\chi^2$  value is rather large due mainly to two data points, whose centroids are at 16.75 and 18.25 keV, far away from the (1-6) keV energy interval. The P-values obtained by excluding only the first and either the points are 11% and 25%.

# $S_m$ values for each annual cycle



**DAMA/LIBRA-phase1 +**  
**DAMA/LIBRA-phase2**  
 total exposure: **2.46 ton×yr**

Energy Bin (keV)	run test probability	
	Lower	Upper
1-2	70%	70%
2-3	50%	73%
3-4	85%	35%
4-5	88%	30%
5-6	88%	30%

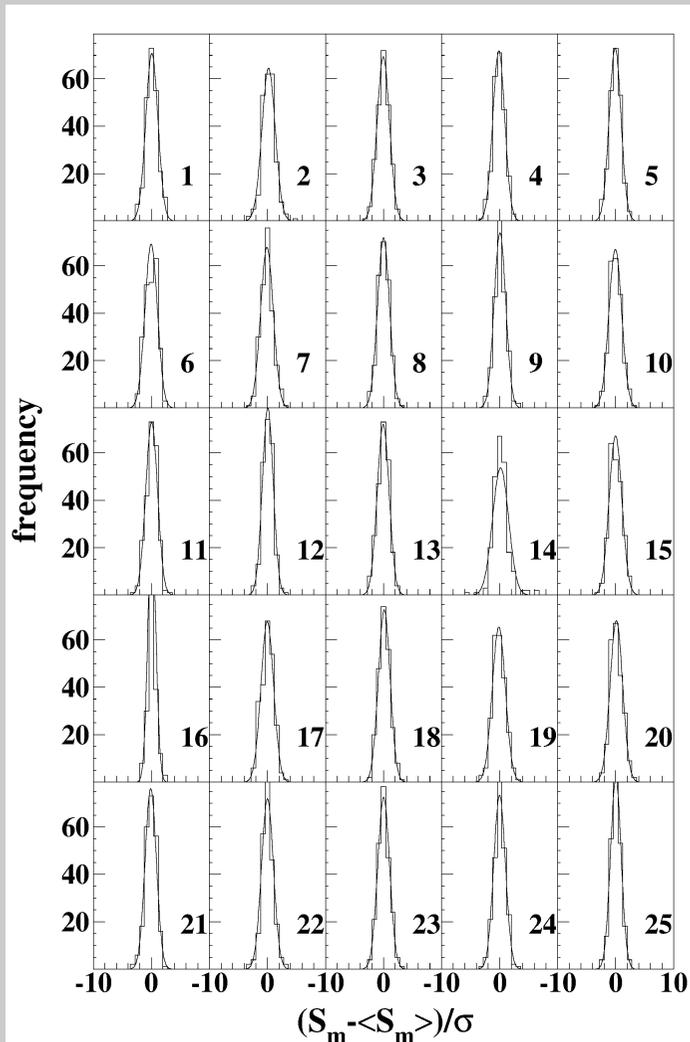
The signal is well distributed over all the annual cycles in each energy bin

# 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;  $\sigma$  = error on  $S_m$

**DAMA/LIBRA-phase1 +  
 DAMA/LIBRA-phase2 (13 years)**  
**total exposure: 2.17 ton×yr**

Each panel refers to each detector separately; 232 entries (the 16 energy bins in the (2-6) keV energy interval of the 7 DAMA/LIBRA-phase1 annual cycles and the 20 energy bins in the (1-6) keV energy interval of the 6 DAMA/LIBRA-phase2 annual cycles), but 152 for the 16th detector (only 2 annual cycles of DAMA/LIBRA-phase1)



2-6 keV phase1 + 1-6 keV phase2

$$x = (S_m - \langle S_m \rangle) / \sigma, \quad \chi^2 = \sum x^2$$

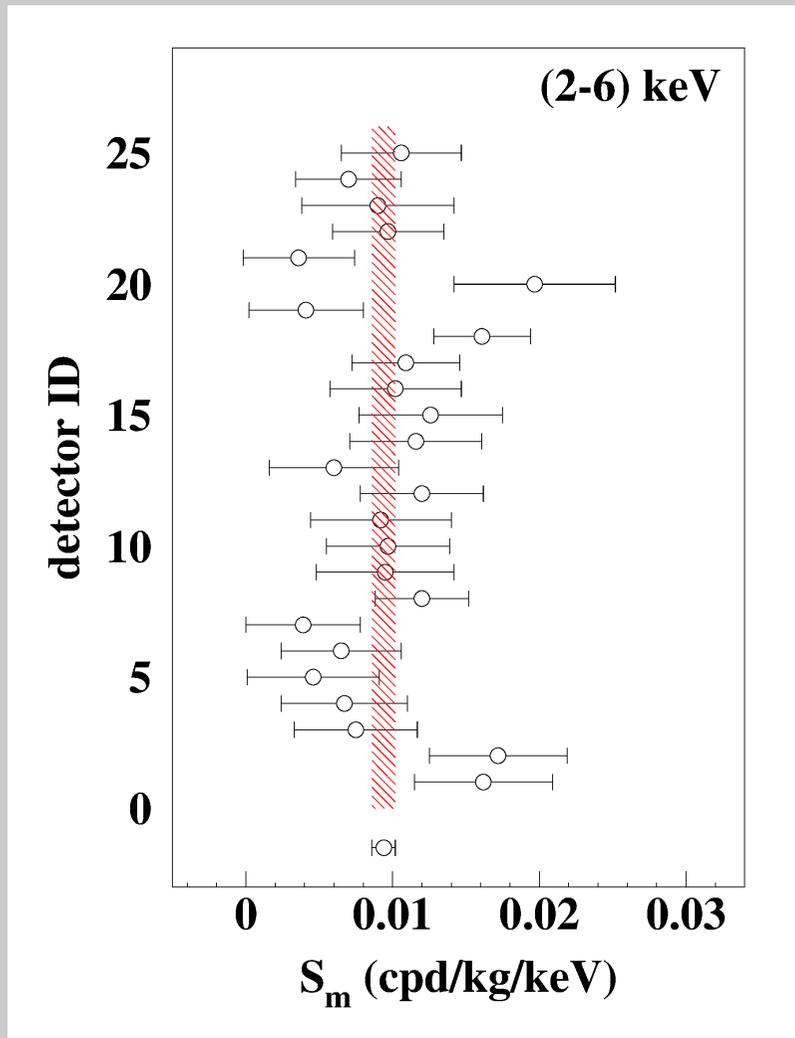
Individual  $S_m$  values follow a normal distribution since  $(S_m - \langle S_m \rangle) / \sigma$  is distributed as a Gaussian with a unitary standard deviation (r.m.s.)

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

The  $\chi^2/d.o.f.$  values range from 0.69 to 1.95 for all the 25 detectors

- The mean value of the 25  $\chi^2$  is 1.07, 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  $\leq 2.1 \times 10^{-4}$  cpd/kg/keV, if quadratically combined, or  $\leq 3 \times 10^{-5}$  cpd/kg/keV, if linearly combined, to the modulation amplitude below 6 keV.
- This possible additional error ( $\leq 2\%$  or  $\leq 0.3\%$ , respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

## $S_m$ values for each detector



DAMA/LIBRA-phase1 +  
DAMA/LIBRA-phase2  
total exposure: 2.17 ton $\times$ yr

$S_m$  integrated in the range (2 - 6) keV for each of the 25 detectors ( $1\sigma$  error)

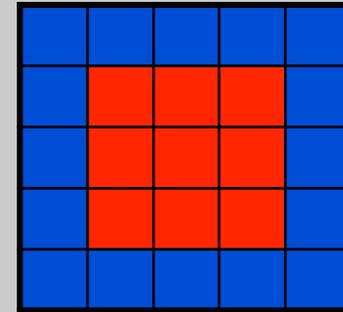
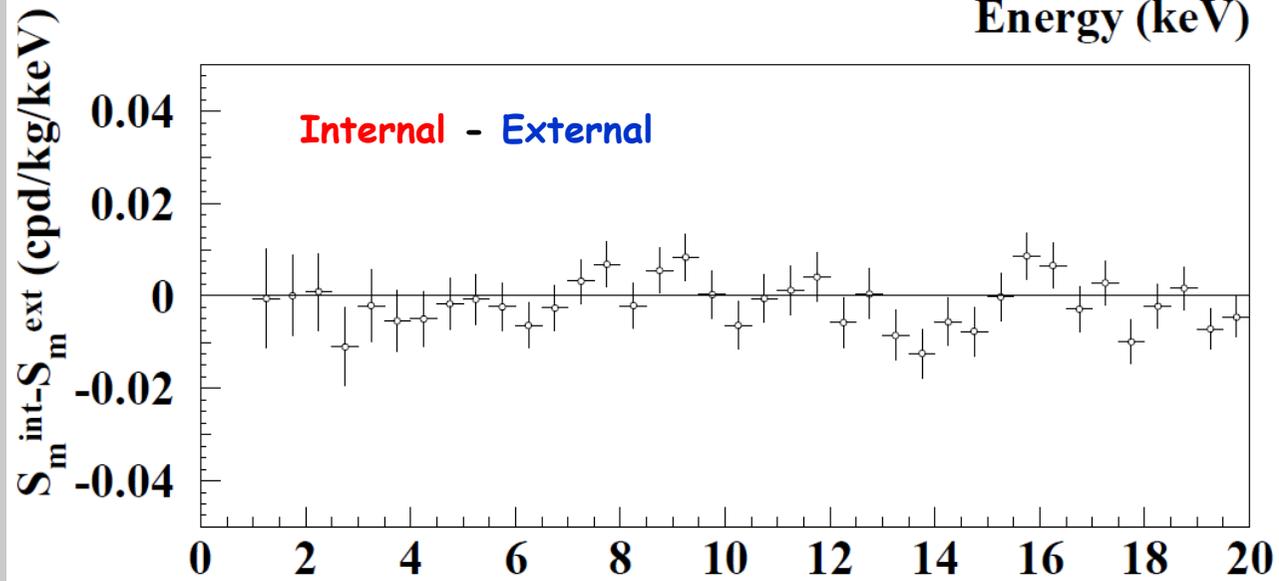
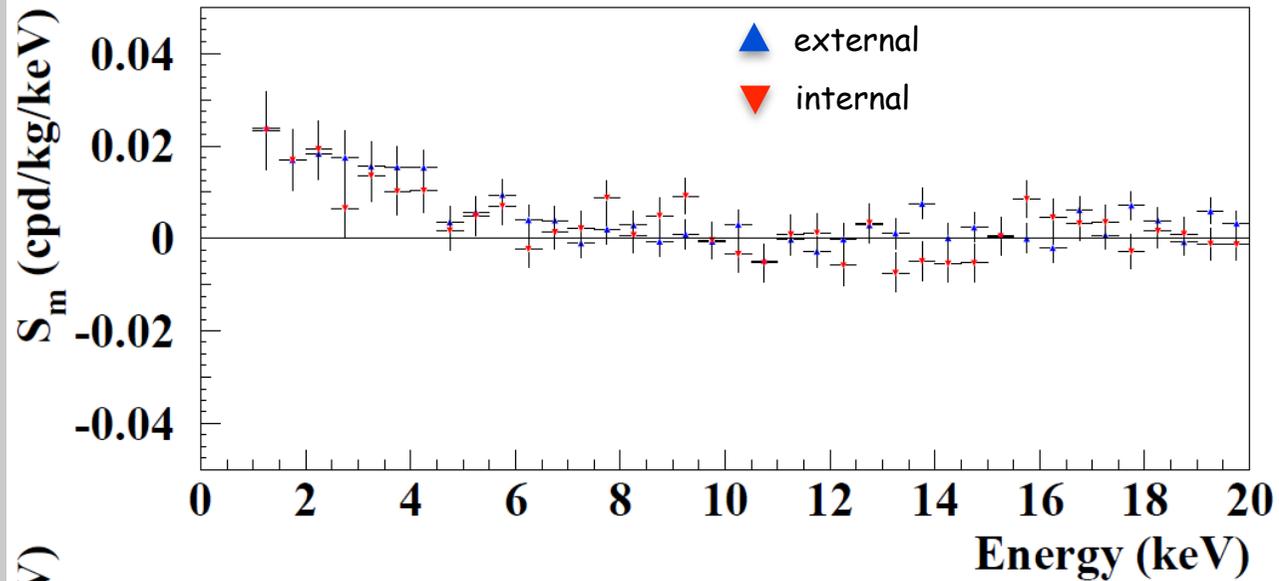
Shaded band = weighted averaged  $S_m$  value  $\pm 1\sigma$

$\chi^2/\text{dof} = 23.9/24$  d.o.f.

The signal is well distributed over all the 25 detectors.

# 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  $\chi^2/\text{dof} = 40.8/38$

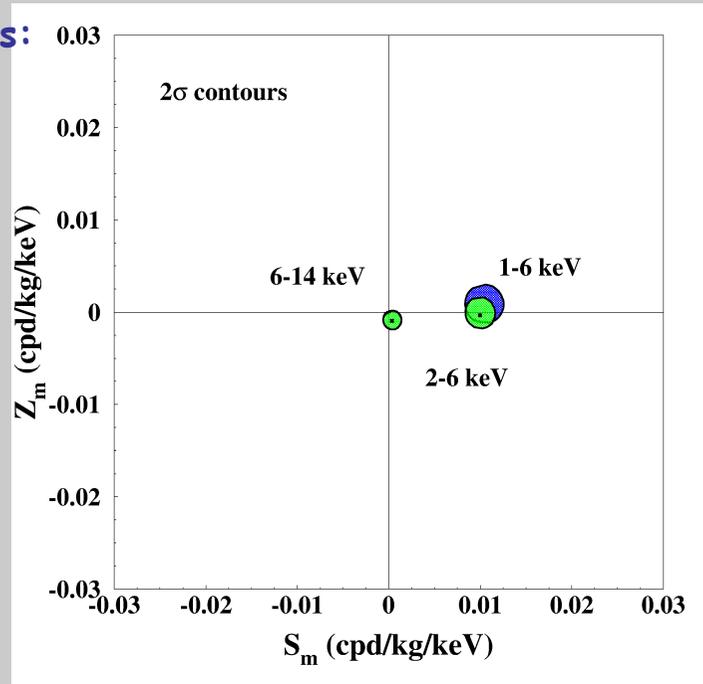
# Is there a sinusoidal contribution in the signal? Phase $\neq 152.5$ day?

DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 [total exposure: 2.46 ton  $\times$  yr]

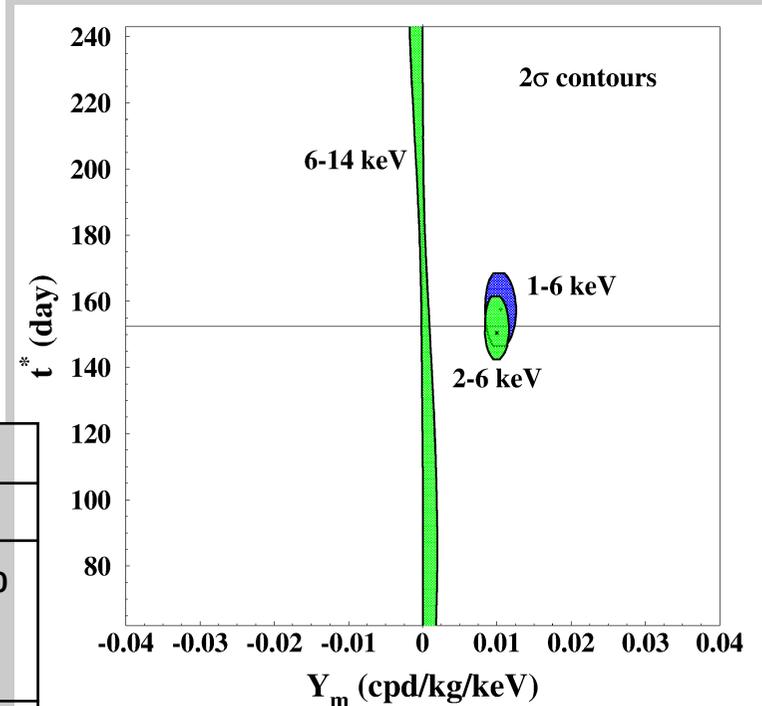
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

For Dark Matter signals:

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



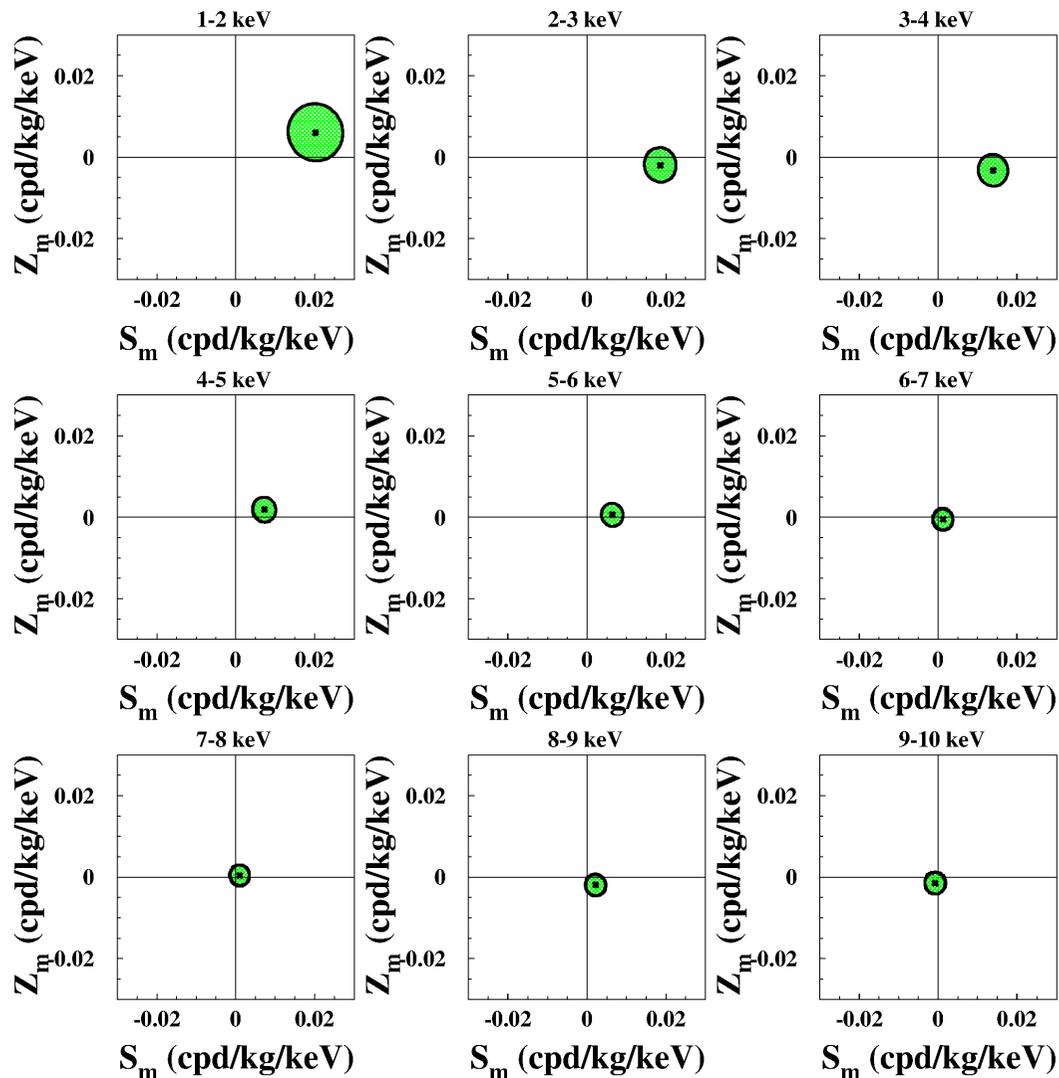
Slight differences from 2<sup>nd</sup> June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)



E (keV)	$S_m$ (cpd/kg/keV)	$Z_m$ (cpd/kg/keV)	$Y_m$ (cpd/kg/keV)	$t^*$ (day)
<b>DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2</b>				
2-6	$0.0100 \pm 0.0008$	$-0.0003 \pm 0.0008$	$0.0100 \pm 0.0008$	$150.5 \pm 5.0$
6-14	$0.0003 \pm 0.0005$	$-0.0009 \pm 0.0006$	$0.0010 \pm 0.0013$	undefined
<b>DAMA/LIBRA-ph2</b>				
1-6	$0.0105 \pm 0.0011$	$0.0009 \pm 0.0010$	$0.0105 \pm 0.0011$	$157.5 \pm 5.0$

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

## 2 $\sigma$ contours



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

total exposure: 2.46 ton  $\times$  yr

For Dark Matter induced  
signals:

$$|Z_m| \ll |Y_m| \approx |S_m|$$

$$t^* \approx t_0 = 152.5d$$

$$\omega = 2\pi/T$$

$$T = 1 \text{ year}$$

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

# Phase vs energy

DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2  
 total exposure: 2.46 ton × yr

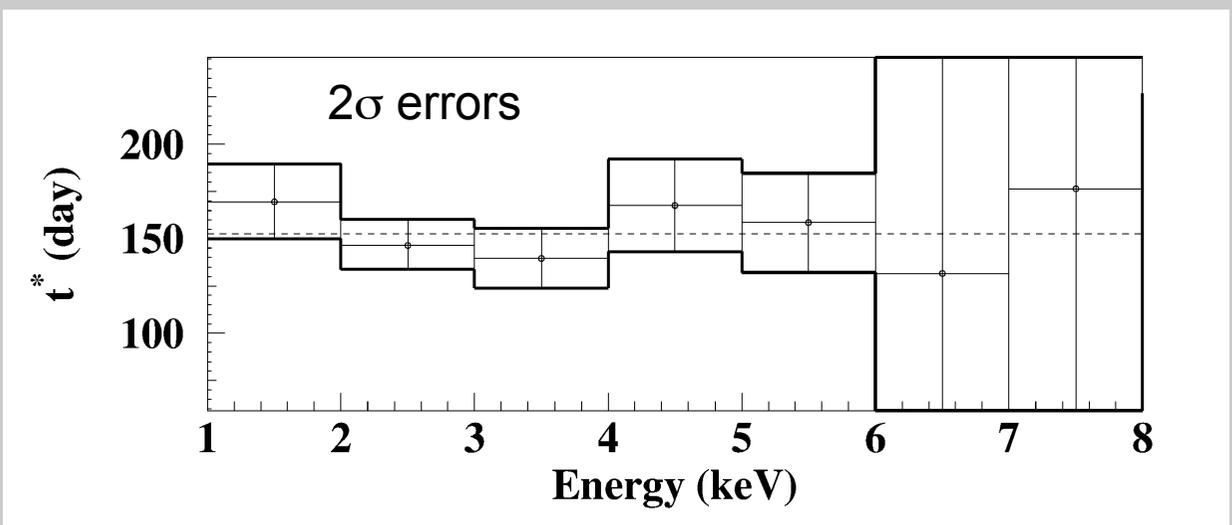
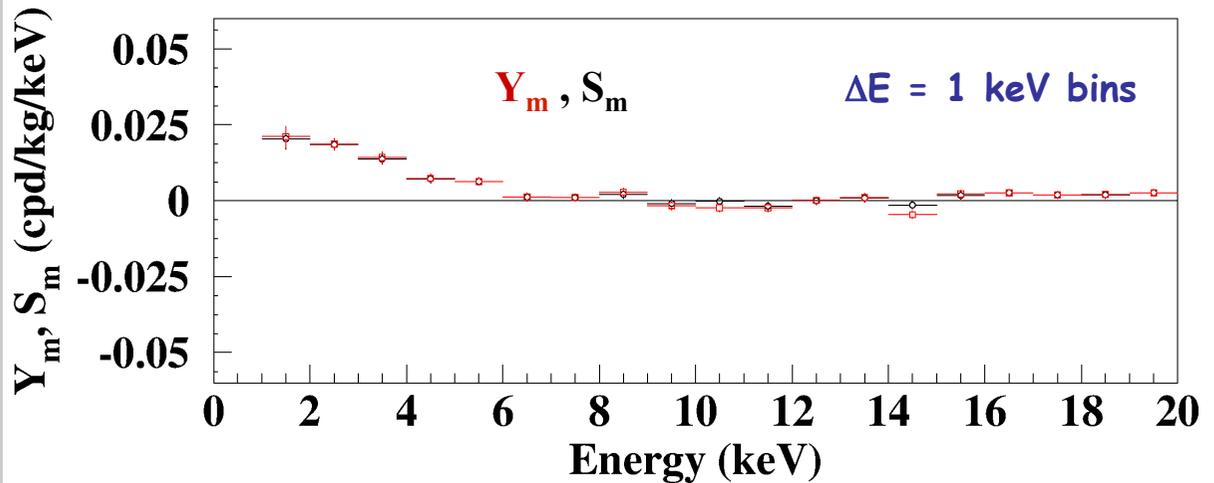
$$R(t) = S_0 + Y_m \cos\left[\omega(t - t^*)\right]$$

For DM signals:

$$|Y_m| \approx |S_m|$$

$$t^* \approx t_0 = 152.5d$$

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



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

## 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)	$-(0.12 \pm 0.16) \times 10^{-2}$	$(0.00 \pm 0.12) \times 10^{-2}$	$-(0.14 \pm 0.22) \times 10^{-2}$	$-(0.05 \pm 0.22) \times 10^{-2}$	$-(0.06 \pm 0.16) \times 10^{-2}$	$-(0.08 \pm 0.17) \times 10^{-2}$

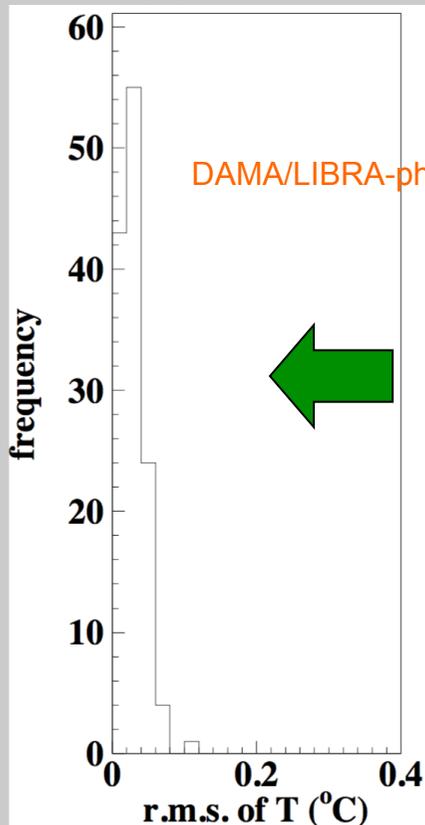
All the measured amplitudes well compatible with zero  
 + none can account for the observed effect

(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)

# Temperature

- Detectors in Cu housings directly in contact with multi-ton shield  
→ huge heat capacity ( $\approx 10^6$  cal/ $^{\circ}$ C)
- Experimental installation continuously 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**



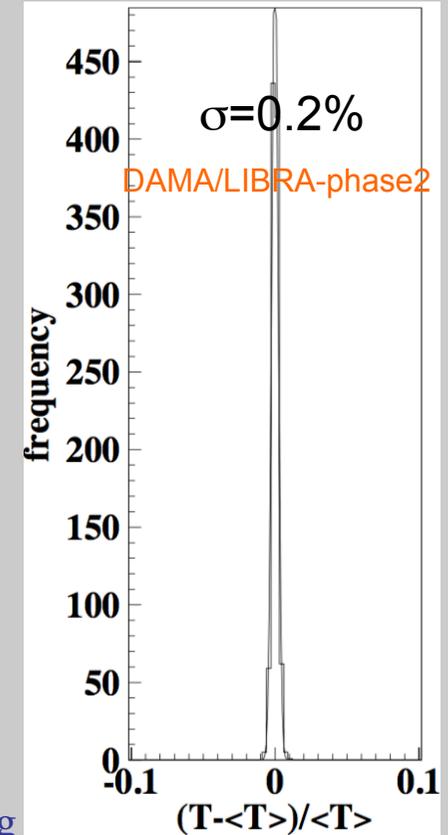
	T ( $^{\circ}$ C)
DAMA/LIBRA-ph2_2	$(0.0012 \pm 0.0051)$
DAMA/LIBRA-ph2_3	$-(0.0002 \pm 0.0049)$
DAMA/LIBRA-ph2_4	$-(0.0003 \pm 0.0031)$
DAMA/LIBRA-ph2_5	$(0.0009 \pm 0.0050)$
DAMA/LIBRA-ph2_6	$(0.0018 \pm 0.0036)$
DAMA/LIBRA-ph2_7	$-(0.0006 \pm 0.0035)$

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

mean value  $\approx 0.03^{\circ}$ C

Considering the slope of the light output  $\approx -0.2\%/^{\circ}$ C:  
relative light output variation  $< 10^{-4}$ :

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



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

**An effect from temperature can be excluded**

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

# Radon

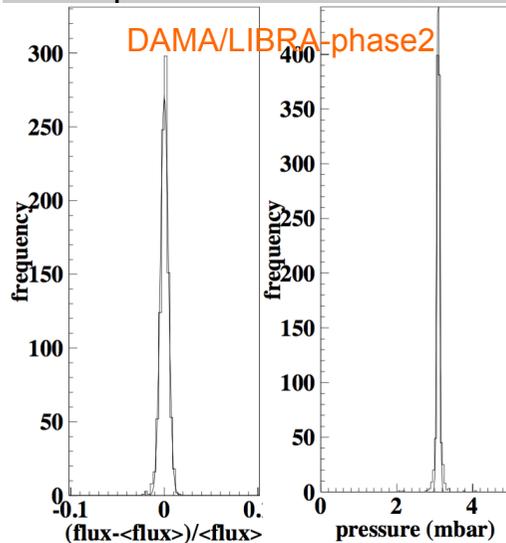
- Three-level system to exclude Radon from the detectors:
- Walls and floor of the inner installation sealed in Supronyl ( $2 \times 10^{-11} \text{ cm}^2/\text{s}$  permeability).
- Whole shield in plexiglas box maintained in HP Nitrogen atmosphere in slight overpressure with respect to environment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

measured values at level of sensitivity of the used radonmeter

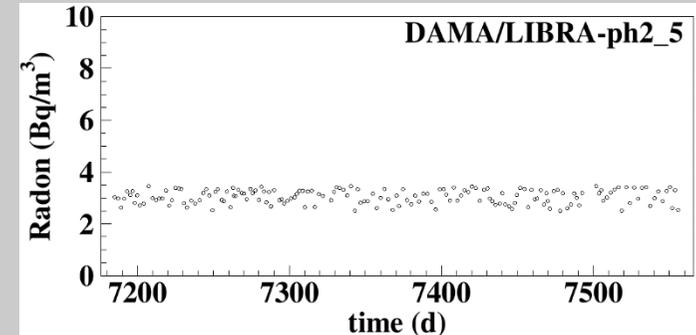
Amplitudes for annual modulation of Radon external to the shield:

$\langle \text{flux} \rangle \approx 320 \text{ l/h}$

Over pressure  $\approx 3.1 \text{ mbar}$



	Radon (Bq/m <sup>3</sup> )
DAMA/LIBRA-ph2_2	(0.015 ± 0.034)
DAMA/LIBRA-ph2_3	-(0.002 ± 0.050)
DAMA/LIBRA-ph2_4	-(0.009 ± 0.028)
DAMA/LIBRA-ph2_5	-(0.044 ± 0.050)
DAMA/LIBRA-ph2_6	(0.082 ± 0.086)
DAMA/LIBRA-ph2_7	(0.06 ± 0.11)



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!

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  $\gamma$ 's (609 & 1120 keV) from  $^{214}\text{Bi}$  Radon daughter
- Rn concentration in Cu-box atmosphere  $< 5.8 \cdot 10^{-2} \text{ Bq/m}^3$  (90% C.L.)
- By MC:  $< 2.5 \cdot 10^{-5} \text{ cpd/kg/keV}$  @ 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:

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

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

- Contributions to the total **neutron flux** at LNGS; →
- **Counting rate** in DAMA/LIBRA for *single-hit* events, in the (2 - 6) keV energy region induced by:

- neutrons,
- muons,
- solar neutrinos.

(See e.g. also EPJC 56 (2008) 333, EPJC 72(2012) 2064, IJMPA 28 (2013) 1330022)

$$\Phi_k = \Phi_{0,k} (1 + \eta_k \cos \omega (t - t_k))$$

$$R_k = R_{0,k} (1 + \eta_k \cos \omega (t - t_k))$$

EPJC74(2014)3196

Modulation amplitudes

Source	$\Phi_{0,k}^{(n)}$ (neutrons $\text{cm}^{-2} \text{s}^{-1}$ )	$\eta_k$	$t_k$	$R_{0,k}$ (cpd/kg/keV)	$A_k = R_{0,k} \eta_k$ (cpd/kg/keV)	$A_k / S_m^{\text{exp}}$	
SLOW neutrons	thermal n ( $10^{-2} - 10^{-1}$ eV)	$1.08 \times 10^{-6}$ [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	-	$< 8 \times 10^{-6}$ [2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	$2 \times 10^{-6}$ [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	-	$< 3 \times 10^{-3}$ [2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, ( $\alpha, n$ ) $\rightarrow$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	-	$< 6 \times 10^{-4}$ [2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \rightarrow n$ from rock ( $> 10$ MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$ (see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \rightarrow n$ from Pb shield ( $> 10$ MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$ (see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
$\nu \rightarrow n$ (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$ (see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$	
direct $\mu$	$\Phi_0^{(\mu)} \simeq 20 \mu \text{ m}^{-2} \text{d}^{-1}$ [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$ [2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$	
direct $\nu$	$\Phi_0^{(\nu)} \simeq 6 \times 10^{10} \nu \text{ cm}^{-2} \text{s}^{-1}$ [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$ [31]	$3 \times 10^{-7}$	$3 \times 10^{-5}$	

\* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

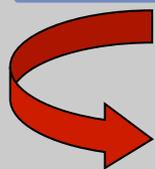
All are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude.

+ In no case neutrons (of whatever origin), muon or muon induced events, solar  $\nu$  can mimic the DM annual modulation signature since some of the peculiar requirements of the signature would fail (and - in addition - quantitatively negligible amplitude with respect to the measured effect).

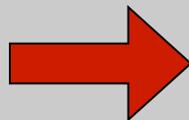
# Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA

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



+ 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+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.).

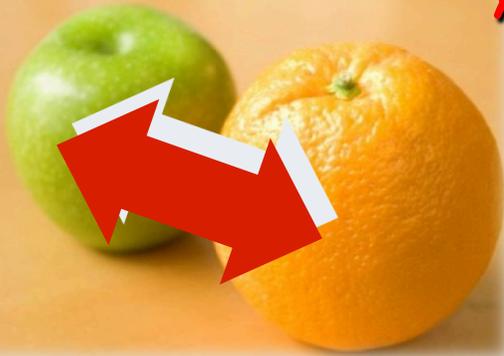
\* Here 2-6 keV energy interval

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)

# About interpretation and comparisons

See e.g.: Riv.N.Cim.26 ono.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022



## ...models...

- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- 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?
- ...

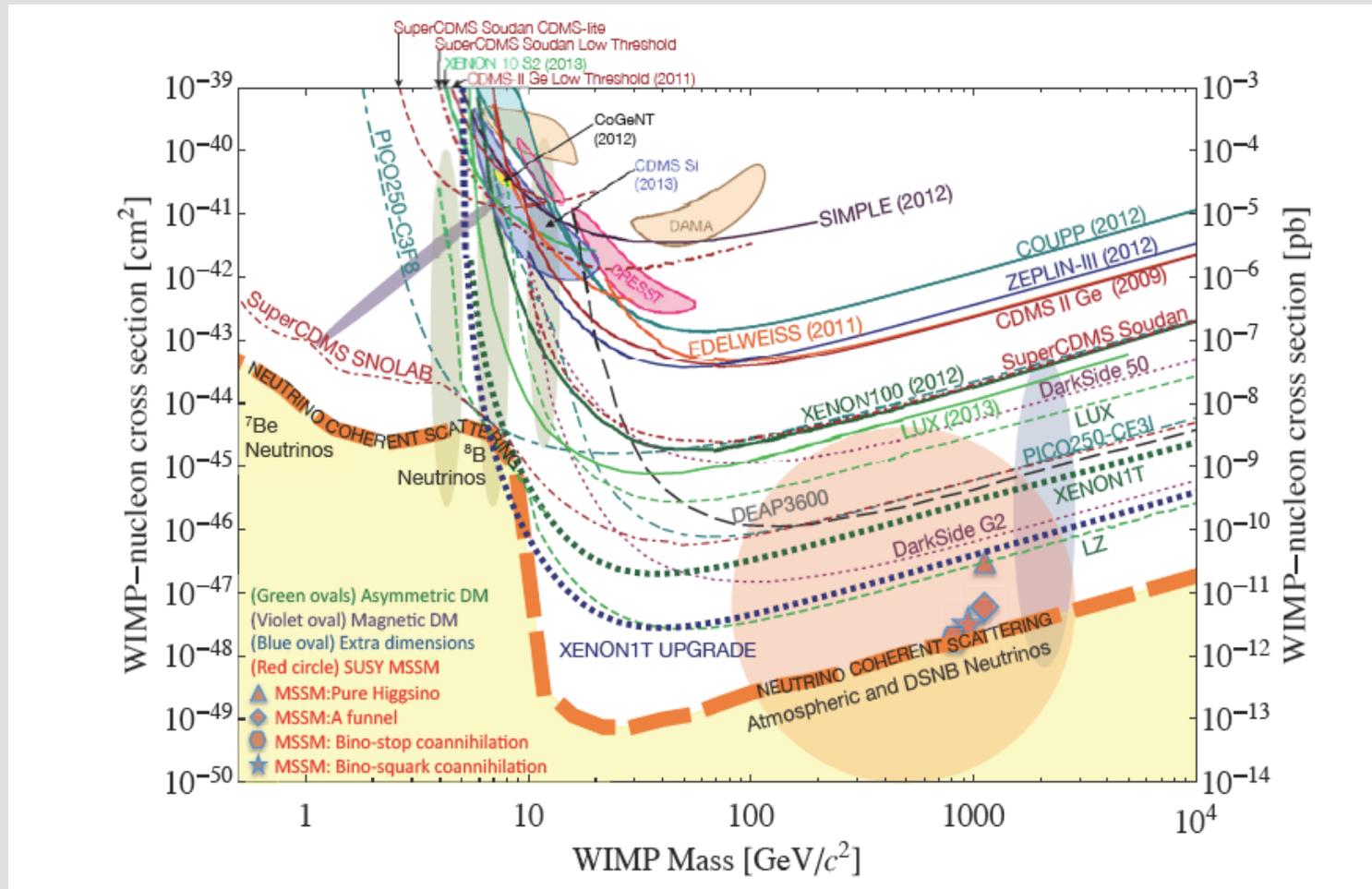
## ...and experimental aspects...

- 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 - at least in principle - be directly compared in a model independent way with DAMA so far

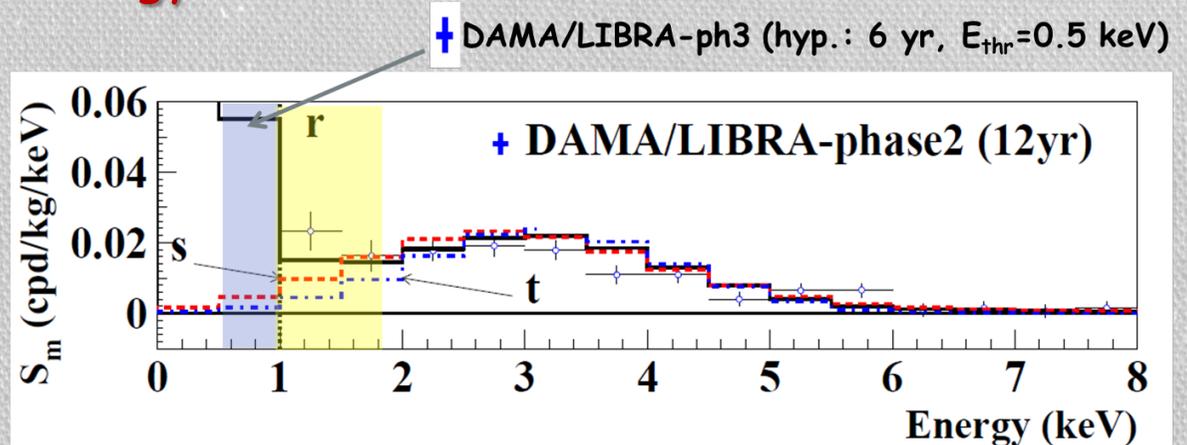
Is it an “universal” and “correct” way to approach the problem of DM and comparisons?



No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

## Running phase2 and towards future DAMA/LIBRA-phase3 with software energy threshold below 1 keV

Enhancing sensitivities for DM  
corollary aspects, other DM  
features, second order effects  
and other rare processes:



- R&D towards possible DAMA/LIBRA-phase3 continuing: i) new protocols for possible modifications of the detectors; ii) alternative strategies under investigation; moreover, 4 new PMT prototypes from a dedicated R&D with HAMAMATSU already at hand.
- Improving the light collection of the detectors (and accordingly the light yields and the energy thresholds). Improving the electronics.
- **Other possible option:** new ULB crystal scintillators (e.g.  $ZnWO_4$ ) placed in between the DAMA/LIBRA detectors to add also a high sensitivity directionality meas.

The presently-reached metallic PMTs features:

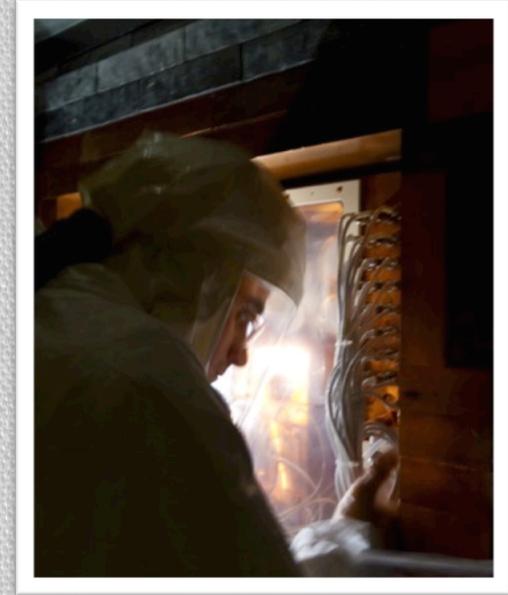
- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- Radiopurity at level of 5 mBq/PMT ( $^{40}K$ ), 3-4 mBq/PMT ( $^{232}Th$ ), 3-4 mBq/PMT ( $^{238}U$ ), 1 mBq/PMT ( $^{226}Ra$ ), 2 mBq/PMT ( $^{60}Co$ ).

4 prototypes at hand



# Conclusions

- Model-independent positive evidence for the presence of DM particles in the galactic halo at  $12.9\sigma$  C.L. (20 independent annual cycles with 3 different set-ups: 2.46 ton  $\times$  yr)
- Modulation parameters determined with increasing precision
- New investigations on different peculiarities of the DM signal exploited in progress
- Full sensitivity to many kinds of DM candidates and interactions types (both inducing recoils and/or e.m. radiation), **full sensitivity to low and high mass candidates**



- DAMA/LIBRA-phase2 continuing data taking
- **DAMA/LIBRA - phase3 R&D in progress**
- R&D for a possible DAMA/1ton - full sensitive mass - set-up, proposed to INFN by DAMA since 1996, **continuing at some extent** as well as **some other R&Ds**
- New corollary analyses in progress
- Continuing investigations of rare processes other than DM