

# Final model independent result of DAMA/LIBRA–phase1

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**Abstract** The results obtained with the total exposure of  $1.04 \text{ ton} \times \text{yr}$  collected by DAMA/LIBRA–phase1 deep underground at the Gran Sasso National Laboratory (LNGS) of the I.N.F.N. during 7 annual cycles (i.e. adding a further  $0.17 \text{ ton} \times \text{yr}$  exposure) are presented. The DAMA/LIBRA–phase1 data give evidence for the presence of Dark Matter (DM) particles in the galactic halo, on the basis of the exploited model independent DM annual modulation signature by using highly radio-pure NaI(Tl) target, at  $7.5\sigma$  C.L. Including also the first generation DAMA/NaI experiment (cumulative exposure  $1.33 \text{ ton} \times \text{yr}$ , corresponding to 14 annual cycles), the C.L. is  $9.3\sigma$  and the modulation amplitude of the *single-hit* events in the (2–6) keV energy interval is:  $(0.0112 \pm 0.0012) \text{ cpd/kg/keV}$ ; the measured phase is  $(144 \pm 7) \text{ days}$  and the measured period is  $(0.998 \pm 0.002) \text{ yr}$ , values well in agreement with those expected for DM particles. No systematic or side reaction able to mimic the exploited DM signature has been found or suggested by anyone over more than a decade.

## 1 Introduction

The present DAMA/LIBRA [1–10] experiment, as the former DAMA/NaI [11–40], has the main aim to investigate the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature (originally suggested in Refs. [41, 42]). Moreover, the

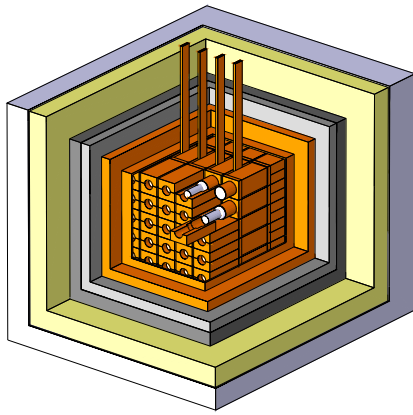
developed highly radio-pure NaI(Tl) target-detectors [1] assure sensitivity to a wide range of DM candidates, interaction types and astrophysical scenarios.

As a consequence of the Earth’s revolution around the Sun, which is moving in the Galaxy with respect to the Local Standard of Rest towards the star Vega near the constellation of Hercules, the Earth should be crossed by a larger flux of DM particles around  $\simeq 2$  June and by a smaller one around  $\simeq 2$  December.<sup>1</sup> In the former case the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy, while in the latter the two velocities are subtracted. The DM annual modulation signature is very distinctive since the effect induced by DM particles must simultaneously satisfy all the following requirements: the rate must contain a component modulated according to a cosine function (1) with one year period (2) and a phase that peaks roughly  $\simeq 2$  June (3); this modulation must only be found in a well-defined low energy range, where DM particle induced events can be present (4); it must apply only to those events in which just one detector of many actually “fires” (*single-hit* events), since the DM particle multi-interaction probability is negligible (5); the modulation amplitude in the region of maximal sensitivity must be  $\simeq 7 \%$  for usually adopted halo distributions (6), but it can be larger in case of some possible scenarios such as e.g. those in Refs. [43–47] (even up to  $\simeq 30 \%$ ). Thus this signature is model indepen-

<sup>1</sup>Thus, the DM annual modulation signature has a different origin and peculiarities than the seasons on the Earth and than effects correlated with seasons (consider the expected value of the phase as well as the other requirements listed below).

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**Fig. 1** Schematic view of the DAMA/LIBRA apparatus. The 25 highly radiopure NaI(Tl) crystal scintillators (5-rows by 5-columns matrix), housed in the sealed copper box continuously maintained in High Purity Nitrogen atmosphere, within low-radioactive passive shield are visible. Mostly outside the installation, the DAMA/LIBRA apparatus is also almost fully surrounded by about 1 m concrete made of the Gran Sasso rock. The copper guides of the calibration system are also shown. For details see Ref. [1]

dent, very effective and, in addition, it allows to test a large interval of cross sections and of halo densities.

This DM signature might be mimicked only by systematic effects or side reactions able to account for the whole observed modulation amplitude and to simultaneously satisfy all the requirements given above. No one is available [1–3, 6, 7, 21–23].

The full description of the DAMA/LIBRA set-up during the phase1 and other related arguments have been discussed in details in Refs. [1–3, 7] and references therein. Here we just remind—as can be seen in Fig. 1—that the sensitive part of this set-up is made of 25 highly radiopure NaI(Tl) crystal scintillators (5-rows by 5-columns matrix) having 9.70 kg mass each one. In each detector two 10 cm long UV light guides (made of Suprasil B quartz) act also as optical windows on the two end faces of the crystal, and are coupled to two low background photomultipliers (PMTs) working in coincidence at single photoelectron level. The low background 9265-B53/FL and 9302-A/FL PMTs, developed by EMI-Electron Tubes with dedicated R&Ds, were used in the phase1; for details see Refs. [1, 20, 22] and references therein. The detectors are housed in a sealed low-radioactive copper box installed in the center of a low-radioactive Cu/Pb/Cd-foils/polyethylene/paraffin shield; moreover, about 1 m concrete (made from the Gran Sasso rock material) almost fully surrounds (mostly outside the barrack) this passive shield, acting as a further neutron moderator. A threefold-levels sealing system prevents the detectors to be in contact with the environmental air of the underground laboratory [1]. The light response of the detectors during phase1 typically ranges from 5.5 to 7.5 photoelectrons/keV, depending on the detector. The

hardware threshold of each PMT is at single photoelectron, while a software energy threshold of 2 keV electron equivalent (hereafter keV) is used [1, 20]. Energy calibration with X-rays/ $\gamma$  sources are regularly carried out in the same running condition down to few keV [1]; in particular, double coincidences due to internal X-rays from  $^{40}\text{K}$  (which is at ppt levels in the crystals) provide (when summing the data over long periods) a calibration point at 3.2 keV close to the software energy threshold (for details see Ref. [1]). The DAQ system records both *single-hit* events (where just one of the detectors fires) and *multiple-hit* events (where more than one detector fires) up to the MeV region despite the optimization is performed for the lowest one. The radiopurity, the procedures and details are discussed in Refs. [1–3, 7] and references therein.

The data of the former DAMA/NaI setup (0.29 ton  $\times$  yr) and, later, those of the first 6 annual cycles of DAMA/LIBRA (0.87 ton  $\times$  yr) have already given positive model independent evidence for the presence of DM particles in the galactic halo with high confidence level on the basis of the exploited DM annual modulation signature [2, 3, 7, 22].

In this paper the final model independent result of DAMA/LIBRA–phase1, obtained by including in the analysis also the data collected during the last seventh annual cycle of operation, is presented. The total exposure of DAMA/LIBRA–phase1 is: 1.04 ton  $\times$  yr; when including also that of the first generation DAMA/NaI experiment it is 1.33 ton  $\times$  yr, corresponding to 14 annual cycles.

## 2 The results

Table 1 summarizes the information about the seven annual cycles of DAMA/LIBRA–phase1; the cumulative exposure, considering also the former DAMA/NaI, is also given.

The total number of events collected for the energy calibrations during the entire DAMA/LIBRA–phase1 is about  $9.6 \times 10^7$ , while about  $3.5 \times 10^6$  events/keV have been collected for the evaluation of the acceptance window efficiency for noise rejection near energy threshold [1].

As it can be inferred from Table 1, the duty cycle of the experiment is high; the routine calibrations and, in particular, those related with the acceptance windows efficiency mainly affect it. The further improvement of the duty cycle in the last two annual cycles is mainly due to the improved performances of the new transient digitizers and DAQ system installed at fall 2008 before the start of the sixth annual cycle [3].

The same procedures previously adopted [1–3, 7] have been exploited also in the analysis of the data of the seventh annual cycle and several analyses on the model-independent investigation of the DM annual modulation signature have been performed.

**Table 1** Exposures of the 7 annual cycles of DAMA/LIBRA–phase1. Here  $\alpha = \langle \cos^2 \omega(t - t_0) \rangle$  is the mean value of the squared cosine, and  $\beta = \langle \cos \omega(t - t_0) \rangle$  is the mean value of the cosine (the averages are taken over the live time of the data taking and  $t_0 = 152.5$

	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 $\simeq$ 1.04 ton × yr	0.518
DAMA/NaI + DAMA/LIBRA–phase1:			1.33 ton × yr	

**Table 2**  $\chi^2$  test of absence of modulation in the entire DAMA/LIBRA–phase1 data. The P-values are also shown. A null modulation amplitude is discarded

Energy interval (keV)	DAMA/LIBRA–phase1 (7 annual cycles)
2–4	$\chi^2/\text{d.o.f.} = 111.2/50 \rightarrow P = 1.5 \times 10^{-6}$
2–5	$\chi^2/\text{d.o.f.} = 98.5/50 \rightarrow P = 5.2 \times 10^{-5}$
2–6	$\chi^2/\text{d.o.f.} = 83.1/50 \rightarrow P = 2.2 \times 10^{-3}$

Figure 2 shows the time behaviour of the experimental residual rates of the *single-hit* scintillation events in the (2–4), (2–5) and (2–6) keV energy intervals for the complete DAMA/LIBRA–phase1. The residuals of the DAMA/NaI data (0.29 ton × yr) are given in Refs. [2, 7, 22, 23]. We remind that these residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part:  $\langle r_{ijk} - flat_{jk} \rangle_{jk}$ . Here  $r_{ijk}$  is the rate in the considered  $i$ th time interval for the  $j$ th detector in the  $k$ th energy bin, while  $flat_{jk}$  is the rate of the  $j$ th detector in the  $k$ th energy bin averaged over the cycles. The average is made on all the detectors ( $j$  index) and on all the energy bins ( $k$  index) which constitute the considered energy interval. The weighted mean of the residuals must obviously be zero over one cycle.

The  $\chi^2$  test excludes the hypothesis of absence of modulation in the data as shown in Table 2.

The *single-hit* residual rate of the entire DAMA/LIBRA–phase1 (Fig. 2) has been fitted with the function:  $A \cos \omega(t - t_0)$ , considering a period  $T = \frac{2\pi}{\omega} = 1$  yr and a phase  $t_0 = 152.5$  day (June 2nd) as expected by the DM annual modulation signature; this can be repeated including the former DAMA/NaI data [22] for the cumulative exposure: 1.33 ton × yr. The results of the best fits in the two conditions are summarized in Table 3.

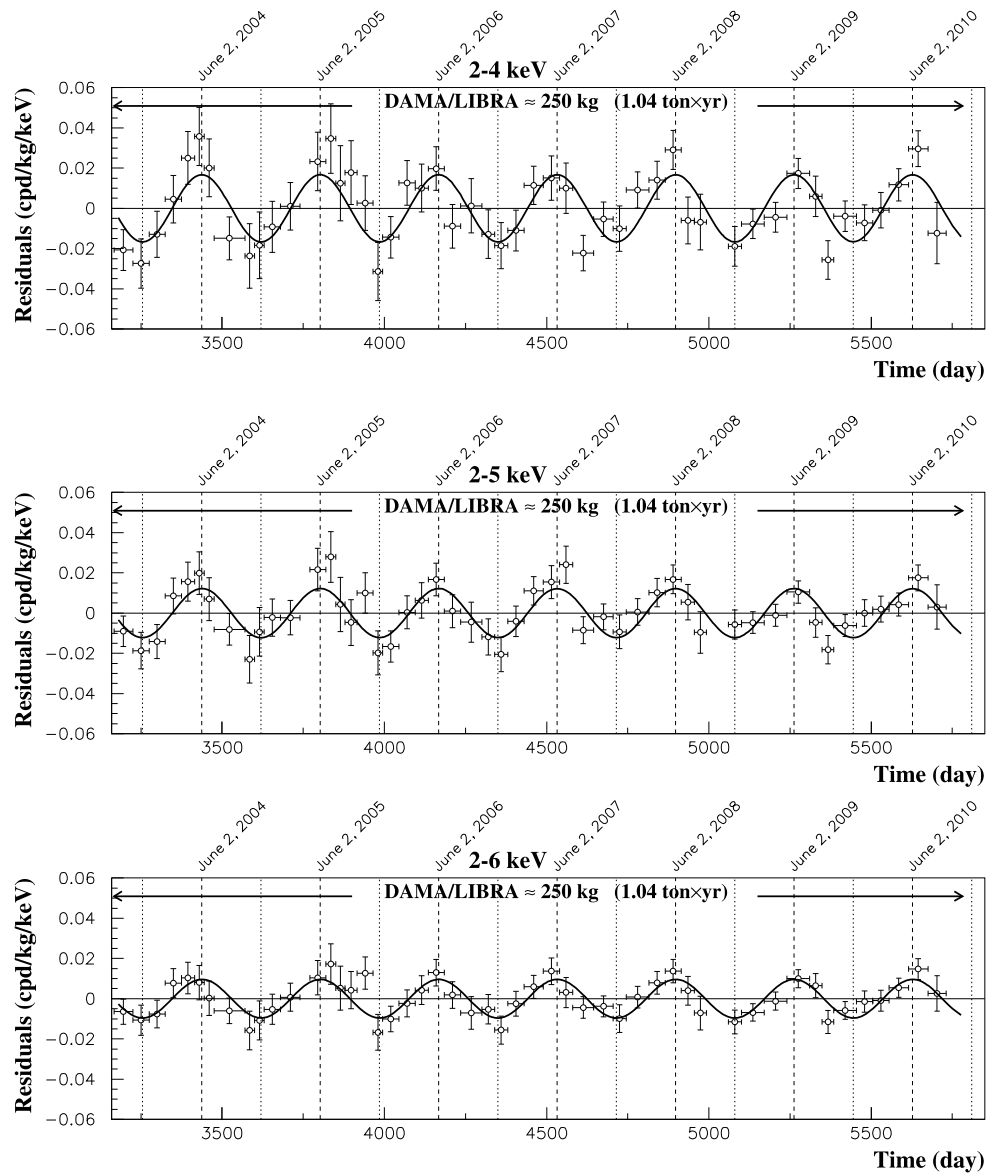
day, i.e. June 2nd); thus,  $(\alpha - \beta^2)$  indicates the variance of the cosine (i.e. it is 0.5 for a detector being operational evenly throughout the year). During the first five annual cycles a detector was out of trigger; it was recovered in the 2008 upgrade [3]

Table 4 shows the results obtained for the entire DAMA/LIBRA–phase1 and including also DAMA/NaI when the period, and the phase are kept free in the fitting procedure. The period and the phase are well compatible with expectations for a DM annual modulation signal. In particular, the phase is consistent with about June 2nd and is fully consistent with the value independently determined by Maximum Likelihood analysis (see later). For completeness, we recall that a slight energy dependence of the phase could be expected in case of possible contributions of non-thermalized DM components to the galactic halo, such as e.g. the SagDEG stream [25, 46, 48–51] and the caustics [52].

In Fig. 3 the modulation amplitudes singularly calculated for each annual cycle of DAMA/NaI and DAMA/LIBRA–phase1 are shown. To test the hypothesis that the amplitudes are compatible and normally fluctuating around their mean values the  $\chi^2$  test and the *run test* have been performed. The mean values in the (2–4) keV, (2–5) keV and (2–6) keV are:  $(0.0185 \pm 0.0020)$  cpd/kg/keV,  $(0.0138 \pm 0.0015)$  cpd/kg/keV and  $(0.0114 \pm 0.0012)$  cpd/kg/keV, respectively. The  $\chi^2$  values obtained in the (2–4) keV, (2–5) keV and (2–6) keV are 9.5, 13.8, 10.8, respectively over 13 d.o.f. corresponding to an upper tail probability of 73 %, 39 % and 63 % for the three energy intervals. We have also performed the *run test* obtaining a lower tail probabilities of 41 %, 29 % and 23 % for the three energy intervals, respectively. This analysis confirms that the data collected in all the annual cycles with DAMA/NaI and DAMA/LIBRA–phase1 are statistically compatible and can be considered together, on the contrary of the statements in Ref. [53].

The DAMA/LIBRA–phase1 *single-hit* residuals of Fig. 2 and those of DAMA/NaI have also been investigated by a Fourier analysis. The data analysis procedure has been described in details in Ref. [7]. A clear peak corresponding to a period of 1 year (see Fig. 4) is evident for the (2–6) keV

**Fig. 2** Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–4), (2–5) and (2–6) keV energy intervals as a function of the time. The time scale is maintained the same of the previous DAMA papers for coherence. The data points present the experimental errors as *vertical bars* and the associated time bin width as *horizontal bars*. The superimposed curves are the cosinusoidal functions behaviours  $A \cos \omega(t - t_0)$  with a period  $T = \frac{2\pi}{\omega} = 1$  yr, a phase  $t_0 = 152.5$  day (June 2nd) and modulation amplitudes,  $A$ , equal to the central values obtained by best fit on the data points of the entire DAMA/LIBRA–phase1. The *dashed vertical lines* correspond to the maximum expected for the DM signal (June 2nd), while the *dotted vertical lines* correspond to the minimum



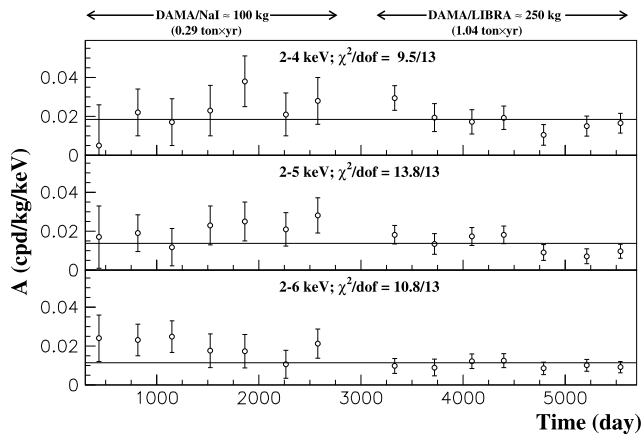
**Table 3** Modulation amplitude,  $A$ , obtained by fitting the *single-hit* residual rate of the entire DAMA/LIBRA–phase1 (Fig. 2), and including also the former DAMA/NaI data [22] for a total cumulative exposure of 1.33 ton × yr. It was obtained by fitting the data with

the formula:  $A \cos \omega(t - t_0)$  with  $T = \frac{2\pi}{\omega} = 1$  yr and  $t_0 = 152.5$  day (June 2nd) as expected by the DM annual modulation signature. The corresponding  $\chi^2$  value of each fit and the confidence level (C.L.) are also reported

Energy interval (keV)	DAMA/LIBRA–phase1 (cpd/kg/keV)	DAMA/NaI & DAMA/LIBRA–phase1 (cpd/kg/keV)
2–4	$A = (0.0167 \pm 0.0022) \rightarrow 7.6\sigma$ C.L. $\chi^2/\text{d.o.f.} = 52.3/49$	$A = (0.0179 \pm 0.0020) \rightarrow 9.0\sigma$ C.L. $\chi^2/\text{d.o.f.} = 87.1/86$
2–5	$A = (0.0122 \pm 0.0016) \rightarrow 7.6\sigma$ C.L. $\chi^2/\text{d.o.f.} = 41.4/49$	$A = (0.0135 \pm 0.0015) \rightarrow 9.0\sigma$ C.L. $\chi^2/\text{d.o.f.} = 68.2/86$
2–6	$A = (0.0096 \pm 0.0013) \rightarrow 7.4\sigma$ C.L. $\chi^2/\text{d.o.f.} = 29.3/49$	$A = (0.0110 \pm 0.0012) \rightarrow 9.2\sigma$ C.L. $\chi^2/\text{d.o.f.} = 70.4/86$

**Table 4** Modulation amplitude ( $A$ ), period ( $T = \frac{2\pi}{\omega}$ ) and phase ( $t_0$ ), obtained by fitting, with the formula:  $A \cos \omega(t - t_0)$ , the *single-hit* residual rate of the entire DAMA/LIBRA–phase1, and including also the former DAMA/NaI data. The results are well compatible with expectations for a signal in the DM annual modulation signature

	$A$ (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	$t_0$ (days)	C.L.
DAMA/LIBRA–phase1				
2–4 keV	$(0.0178 \pm 0.0022)$	$(0.996 \pm 0.002)$	$134 \pm 7$	$8.1\sigma$
2–5 keV	$(0.0127 \pm 0.0016)$	$(0.996 \pm 0.002)$	$137 \pm 8$	$7.9\sigma$
2–6 keV	$(0.0097 \pm 0.0013)$	$(0.998 \pm 0.002)$	$144 \pm 8$	$7.5\sigma$
DAMA/NaI & DAMA/LIBRA–phase1				
2–4 keV	$(0.0190 \pm 0.0020)$	$(0.996 \pm 0.002)$	$134 \pm 6$	$9.5\sigma$
2–5 keV	$(0.0140 \pm 0.0015)$	$(0.996 \pm 0.002)$	$140 \pm 6$	$9.3\sigma$
2–6 keV	$(0.0112 \pm 0.0012)$	$(0.998 \pm 0.002)$	$144 \pm 7$	$9.3\sigma$



**Fig. 3** The data points are the modulation amplitudes of each single annual cycle of DAMA/NaI and DAMA/LIBRA–phase1 experiments. The error bars are the  $1\sigma$  errors. The same time scale and the same energy intervals as in Fig. 2 are adopted. The *solid horizontal lines* shows the central values obtained by best fit over the whole data set. The  $\chi^2$  test and the *run test* accept the hypothesis at 90 % C.L. that the modulation amplitudes are normally fluctuating around the best fit values. See text

energy interval; the same analysis in the (6–14) keV energy region shows instead only aliasing peaks. Neither other structure at different frequencies has been observed (see also Ref. [7]).

Absence of any significant background modulation in the energy spectrum has been verified in energy regions not of interest for DM.<sup>2</sup> As an example, the measured rate integrated above 90 keV,  $R_{90}$ , as a function of the time has been analysed. Figure 5 shows the distribution of the percentage variations of  $R_{90}$  with respect to the mean values for all the detectors in the entire DAMA/LIBRA–phase1 data. It shows a cumulative Gaussian behaviour with  $\sigma \simeq 1\%$ , well

<sup>2</sup>In fact, the background in the lowest energy region is essentially due to “Compton” electrons, X-rays and/or Auger electrons, muon induced events, etc., which are strictly correlated with the events in the higher energy region of the spectrum. Thus, if a modulation detected in the lowest energy region were due to a modulation of the background (rather than to a signal), an equal or larger modulation in the higher energy regions should be present.

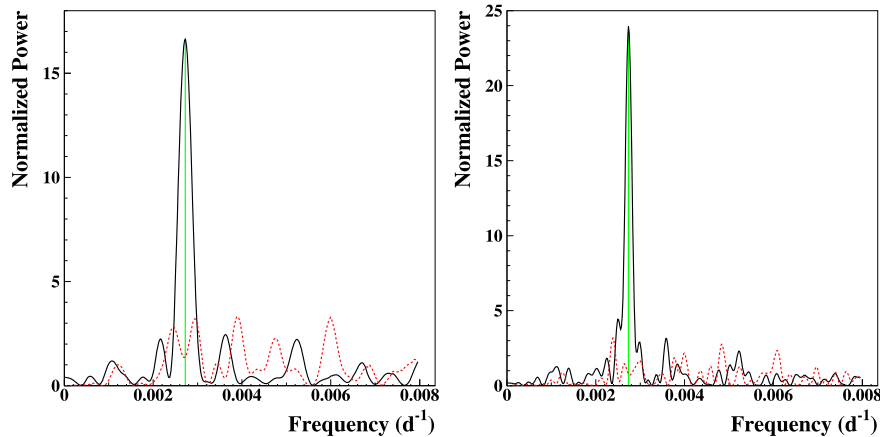
accounted by the statistical spread expected from the used sampling time. Moreover, fitting the time behaviour of  $R_{90}$  including a term with phase and period as for DM particles, a modulation amplitude compatible with zero has also been found for all the annual cycles (see Table 5). This also excludes the presence of any background modulation in the whole energy spectrum at a level much lower than the effect found in the lowest energy region for the *single-hit* events. In fact, otherwise—considering the  $R_{90}$  mean values—a modulation amplitude of order of tens cpd/kg would be present for each annual cycle, that is  $\simeq 100\sigma$  far away from the measured values. Similar result is obtained when comparing the *single-hit* residuals in the (2–6) keV with those in other energy intervals; for example Fig. 6 shows the *single-hit* residuals in the (2–6) keV and in the (6–14) keV energy regions for the entire DAMA/LIBRA–phase1 data as if they were collected in a single annual cycle (i.e. binning in the variable time from the Jan 1st of each annual cycle). It is worth noting that the obtained results account of whatever kind of background and, in addition, no background process able to mimic the DM annual modulation signature (that is able to simultaneously satisfy all the peculiarities of the signature and to account for the measured modulation amplitude) is available (see also discussions e.g. in Refs. [1–3, 6, 7, 54–60]).

Also in the entire DAMA/LIBRA–phase1 a further relevant investigation has been performed by applying the same hardware and software procedures, used to acquire and to analyse the *single-hit* residual rate, to the *multiple-hit* one. In fact, since the probability that a DM particle interacts in more than one detector is negligible, a DM signal can be present just in the *single-hit* residual rate. Thus, the comparison of the results of the *single-hit* events with those of the *multiple-hit* ones corresponds practically to compare between them the cases of DM particles beam-on and beam-off. This procedure also allows an additional test of the background behaviour in the same energy interval where the positive effect is observed. In particular, in Fig. 7 the residual rates of the *single-hit* events measured over the whole DAMA/LIBRA–phase1 annual cycles are reported, as collected in a single cycle, together with the residual rates of

**Table 5** Modulation amplitudes obtained by fitting the time behaviour of  $R_{90}$  for the seven annual cycles of DAMA/LIBRA–phase1, including a term with a cosine function having phase and period as expected

Period	$A_{R_{90}}$ (cpd/kg)	Period	$A_{R_{90}}$ (cpd/kg)
DAMA/LIBRA-1	$-(0.05 \pm 0.19)$	DAMA/LIBRA-5	$(0.20 \pm 0.18)$
DAMA/LIBRA-2	$-(0.12 \pm 0.19)$	DAMA/LIBRA-6	$-(0.20 \pm 0.16)$
DAMA/LIBRA-3	$-(0.13 \pm 0.18)$	DAMA/LIBRA-7	$-(0.28 \pm 0.18)$
DAMA/LIBRA-4	$(0.15 \pm 0.17)$		

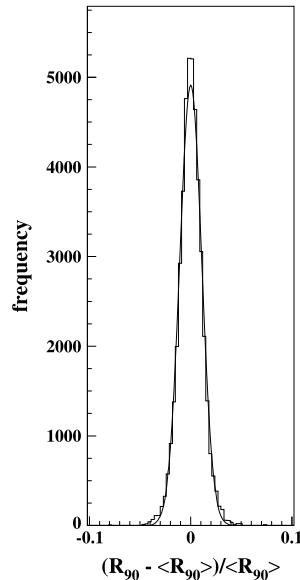
for a DM signal. The obtained amplitudes are compatible with zero, and absolutely incompatible ( $\simeq 100\sigma$ ) with modulation amplitudes of tens cpd/kg (see text)



**Fig. 4** Power spectrum of the measured *single-hit* residuals in the (2–6) keV (solid lines) and (6–14) keV (dotted lines) energy intervals calculated according to Ref. [7], including also—as usual in DAMA analyses—the treatment of the experimental errors and of the time binning. The data refer to: (a) DAMA/LIBRA–phase1 (left); (b) DAMA/NaI and DAMA/LIBRA–phase1 (right). As it can be seen,

the principal mode present in the (2–6) keV energy interval corresponds to a frequency of  $2.722 \times 10^{-3} \text{ d}^{-1}$  and  $2.737 \times 10^{-3} \text{ d}^{-1}$  (vertical lines), respectively, in the (a) and (b) case. They correspond to a period of  $\simeq 1$  year. A similar peak is not present in the (6–14) keV energy interval

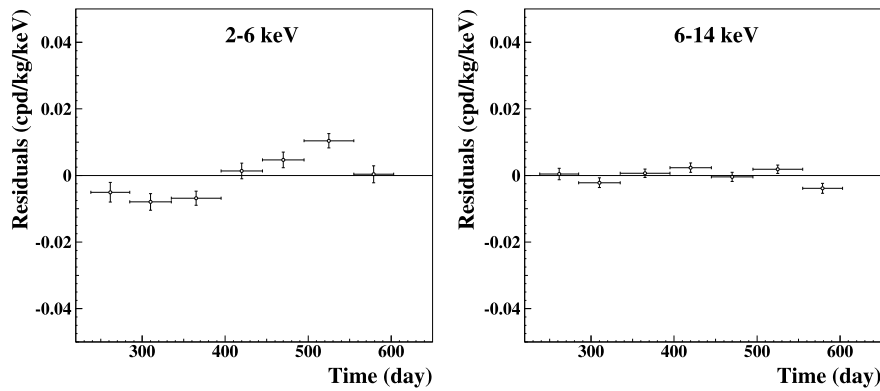
**Fig. 5** Distribution of the percentage variations of  $R_{90}$  with respect to the mean values for all the detectors in the DAMA/LIBRA–phase1 (histogram); the superimposed curve is a Gaussian fit. See text



the *multiple-hit* events, in the considered energy intervals. While, as already observed, a clear modulation, satisfying all the peculiarities of the DM annual modulation signature,

is present in the *single-hit* events, the fitted modulation amplitudes for the *multiple-hit* residual rate are well compatible with zero:  $-(0.0012 \pm 0.0006)$  cpd/kg/keV,  $-(0.0008 \pm 0.0005)$  cpd/kg/keV, and  $-(0.0005 \pm 0.0004)$  cpd/kg/keV in the energy regions (2–4), (2–5) and (2–6) keV, respectively. Thus, again evidence of annual modulation with proper features as required by the DM annual modulation signature is present in the *single-hit* residuals (events class to which the DM particle induced events belong), while it is absent in the *multiple-hit* residual rate (event class to which only background events belong). Similar results were also obtained for the last two annual cycles of the DAMA/NaI experiment [23]. Since the same identical hardware and the same identical software procedures have been used to analyse the two classes of events, the obtained result offers an additional strong support for the presence of a DM particle component in the galactic halo.

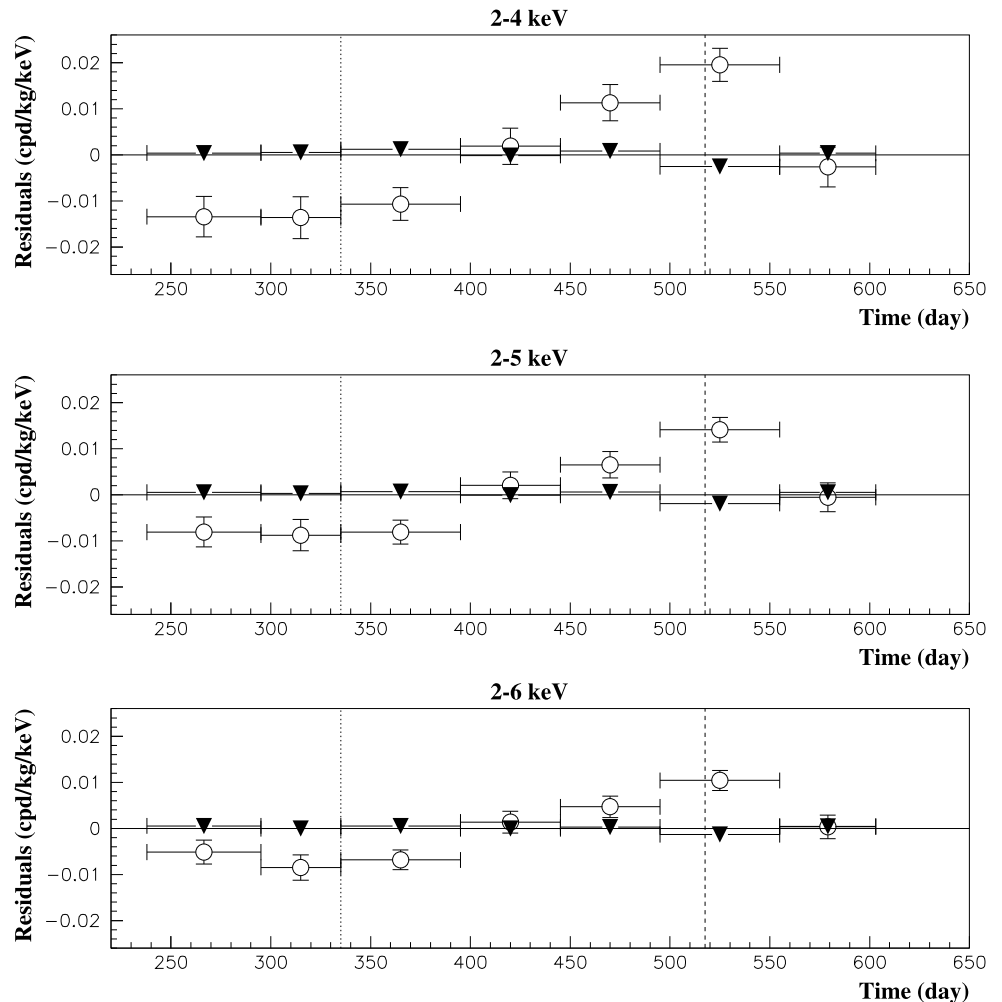
As in Refs. [2, 3, 7], the annual modulation present at low energy can also be pointed out by depicting—as a function of the energy—the modulation amplitude,  $S_{m,k}$ , obtained by maximum likelihood method over the data considering  $T = 1 \text{ yr}$  and  $t_0 = 152.5 \text{ day}$ . For such purpose the like-



**Fig. 6** Experimental *single-hit* residuals in the (2–6) keV and in the (6–14) keV energy regions for the entire DAMA/LIBRA–phase1 data as if they were collected in a single annual cycle (i.e. binning in the variable time from the Jan 1st of each annual cycle). The data points present the experimental errors as *vertical bars* and the associated time

bin width as *horizontal bars*. The initial time of the figures is taken at August 7th. A clear modulation satisfying all the peculiarities of the DM annual modulation signature is present in the lowest energy interval with  $A = (0.0088 \pm 0.0013)$  cpd/kg/keV, while it is absent just above:  $A = (0.00032 \pm 0.00076)$  cpd/kg/keV

**Fig. 7** Experimental residual rates over the entire DAMA/LIBRA–phase1 *single-hit* events (*open circles*), class of events to which DM events belong, and for *multiple-hit* events (*filled triangles*), class of events to which DM events do not belong. They have been obtained by considering for each class of events the data as collected in a single annual cycle and by using in both cases the same identical hardware and the same identical software procedures. The initial time of the figure is taken on August 7th. The experimental points present the errors as *vertical bars* and the associated time bin width as *horizontal bars*. Analogous results were obtained for the DAMA/NaI data [23]



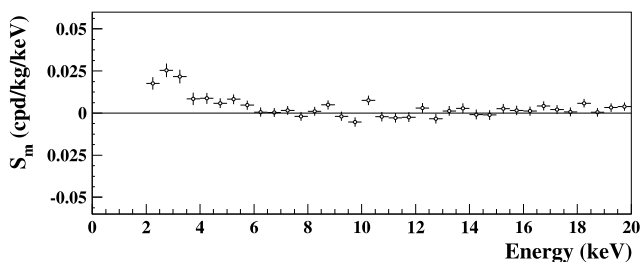
likelihood function of the *single-hit* experimental data in the  $k$ th energy bin is defined as:  $\mathbf{L}_k = \prod_{ij} e^{-\mu_{ijk}} (\mu_{ijk}^{N_{ijk}} / N_{ijk}!)$ , where  $N_{ijk}$  is the number of events collected in the  $i$ th time interval (hereafter 1 day), by the  $j$ th detector and in the  $k$ th

energy bin.  $N_{ijk}$  follows a Poisson’s distribution with expectation value  $\mu_{ijk} = [b_{jk} + S_{ik}]M_j \Delta t_i \Delta E \epsilon_{jk}$ . The  $b_{jk}$  are the background contributions,  $M_j$  is the mass of the  $j$ th detector,  $\Delta t_i$  is the detector running time during the

$i$ th time interval,  $\Delta E$  is the chosen energy bin,  $\epsilon_{jk}$  is the overall efficiency. Moreover, the signal can be written as  $S_{ik} = S_{0,k} + S_{m,k} \cdot \cos \omega(t_i - t_0)$ , where  $S_{0,k}$  is the constant part of the signal and  $S_{m,k}$  is the modulation amplitude. The usual procedure is to minimize the function  $y_k = -2 \ln(\mathbf{L}_k) - \text{const}$  for each energy bin; the free parameters of the fit are the  $(b_{jk} + S_{0,k})$  contributions and the  $S_{m,k}$  parameter. Hereafter, the index  $k$  is omitted for simplicity.

In Fig. 8 the obtained  $S_m$  are shown in each considered energy bin (there  $\Delta E = 0.5$  keV) when the data of DAMA/NaI and DAMA/LIBRA–phase1 are considered. It can be inferred that positive signal is present in the (2–6) keV energy interval, while  $S_m$  values compatible with zero are present just above. In fact, the  $S_m$  values in the (6–20) keV energy interval have random fluctuations around zero with  $\chi^2$  equal to 35.8 for 28 degrees of freedom (upper tail probability of 15 %). All this confirms the previous analyses. As previously done for the other data releases [2, 3, 7], the method also allows the extraction of the  $S_m$  values for each detector, for each annual cycle and for each energy bin. The  $S_m$  are expected to follow a normal distribution in absence of any systematic effects. Therefore, the variable  $x = \frac{S_m - \langle S_m \rangle}{\sigma}$  has been considered to verify that the  $S_m$  are statistically well distributed in all the seven DAMA/LIBRA–phase1 annual cycles, in all the sixteen energy bins ( $\Delta E = 0.25$  keV in the (2–6) keV energy interval) and in each detector. Here,  $\sigma$  are the errors associated to  $S_m$  and  $\langle S_m \rangle$  are the mean values of the  $S_m$  averaged over the detectors and the annual cycles for each considered energy bin. The distributions and their Gaussian fits obtained for the detectors are depicted in Fig. 9.

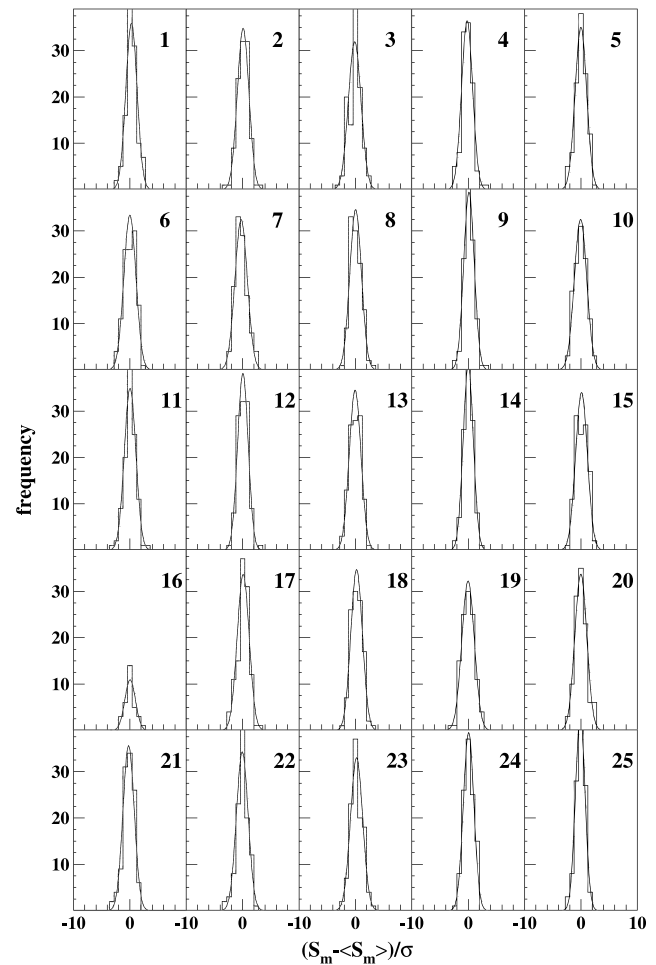
Defining  $\chi^2 = \sum x^2$ —where the sum is extended over all the 112 (32 for the detector restored after the upgrade in 2008)  $x$  values— $\chi^2/\text{d.o.f.}$  values ranging from 0.72 to 1.22 are obtained (see Fig. 10–top); they are all below the 95 % C.L. limit. Thus the observed annual modulation effect is well distributed in all the 25 detectors at 95 % C.L. The mean value of the 25  $\chi^2/\text{d.o.f.}$  is 1.030, slightly larger



**Fig. 8** Energy distribution of the  $S_m$  variable for the total cumulative exposure 1.33 ton  $\times$  yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while  $S_m$  values compatible with zero are present just above. In fact, the  $S_m$  values in the (6–20) keV energy interval have random fluctuations around zero with  $\chi^2$  equal to 35.8 for 28 degrees of freedom (upper tail probability of 15 %)

than 1. Although this can be still ascribed to statistical fluctuations (see before), let us ascribe it to a possible systematics. In this case, one would derive an additional error to the modulation amplitude measured in the (2–6) keV energy interval:  $\leq 3 \times 10^{-4}$  cpd/kg/keV, if quadratically combining the errors, or  $\leq 2 \times 10^{-5}$  cpd/kg/keV, if linearly combining them. This possible additional error:  $\leq 3$  % or  $\leq 0.2$  %, respectively, on the DAMA/LIBRA–phase1 modulation amplitude is an upper limit of possible systematic effects coming from the detector to detector differences.

Among further additional tests, the analysis of the modulation amplitudes as a function of the energy separately for the nine inner detectors and the remaining external ones has been carried out for the entire DAMA/LIBRA–phase1.



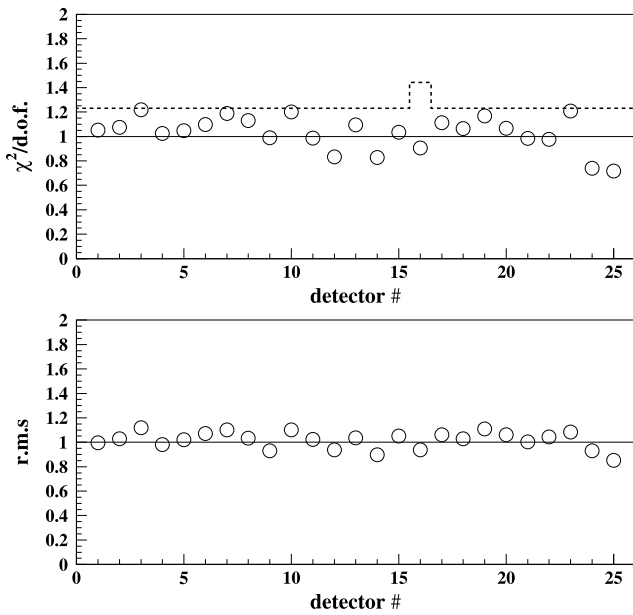
**Fig. 9** Distributions (histograms) of the variable  $\frac{S_m - \langle S_m \rangle}{\sigma}$ , where  $\sigma$  are the errors associated to the  $S_m$  values and  $\langle S_m \rangle$  are the mean values of the modulation amplitudes averaged over the detectors and the annual cycles for each considered energy bin (here  $\Delta E = 0.25$  keV). Each panel refers to a single DAMA/LIBRA detector (the detector 16 was out of trigger for the first five annual cycles [3]). The entries of each histogram are 112 (the 16 energy bins in the (2–6) keV energy interval and the seven DAMA/LIBRA–phase1 annual cycles) except for detector 16 (32 entries); the r.m.s. values are reported in Fig. 10–bottom. The superimposed curves are Gaussian fits



The obtained values are fully in agreement; in fact, the hypothesis that the two sets of modulation amplitudes as a function of the energy belong to same distribution has been verified by  $\chi^2$  test, obtaining:  $\chi^2/\text{d.o.f.} = 3.9/4$  and  $8.9/8$  for the energy intervals (2–4) and (2–6) keV, respectively ( $\Delta E = 0.5$  keV). This shows that the effect is also well shared between inner and outer detectors.

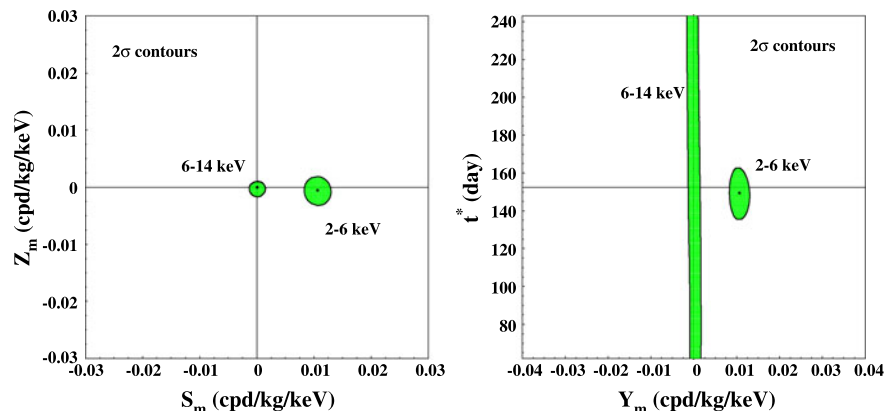
Let us, finally, release the assumption of a phase  $t_0 = 152.5$  day in the procedure to evaluate the modulation amplitudes. In this case the signal can be written as:

$$S_{ik} = S_{0,k} + S_{m,k} \cos \omega(t_i - t_0) + Z_{m,k} \sin \omega(t_i - t_0) \\ = S_{0,k} + Y_{m,k} \cos \omega(t_i - t^*). \tag{1}$$



**Fig. 10** *Top*:  $\chi^2/\text{d.o.f.}$  values of the  $S_m$  distributions around their mean value for each DAMA/LIBRA detector in the (2–6) keV energy interval for the entire DAMA/LIBRA–phase1. The dotted line corresponds to the upper tail probability of 5%; all the  $\chi^2/\text{d.o.f.}$  values are below this line and, thus, at 95 % C.L. the observed annual modulation effect is well distributed in all the detectors. *Bottom*: standard deviations of the  $x$  variable for the DAMA/LIBRA detectors in the phase1

**Fig. 11**  $2\sigma$  contours in the plane  $(S_m, Z_m)$  (left) and in the plane  $(Y_m, t^*)$  (right) for the (2–6) keV and (6–14) keV energy intervals. The contours have been obtained by the maximum likelihood method, considering the cumulative exposure of DAMA/NaI and DAMA/LIBRA–phase1. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. See text



For signals induced by DM particles one should expect: (i)  $Z_{m,k} \sim 0$  (because of the orthogonality between the cosine and the sine functions); (ii)  $S_{m,k} \simeq Y_{m,k}$ ; (iii)  $t^* \simeq t_0 = 152.5$  day. In fact, these conditions hold for most of the dark halo models; however, as mentioned above, slight differences can be expected in case of possible contributions from non-thermalized DM components, such as e.g. the SagDEG stream [25, 46, 48–51] and the caustics [52].

Considering cumulatively the data of DAMA/NaI and DAMA/LIBRA–phase1 (exposure  $1.33 \text{ ton} \times \text{yr}$ ) the obtained  $2\sigma$  contours in the plane  $(S_m, Z_m)$  for the (2–6) keV and (6–14) keV energy intervals are shown in Fig. 11—left while in Fig. 11—right the obtained  $2\sigma$  contours in the plane  $(Y_m, t^*)$  are depicted. The best fit values for the (2–6) and (6–14) keV energy intervals ( $1\sigma$  errors) for  $S_m$  versus  $Z_m$  and  $Y_m$  versus  $t^*$  are reported in Table 6.

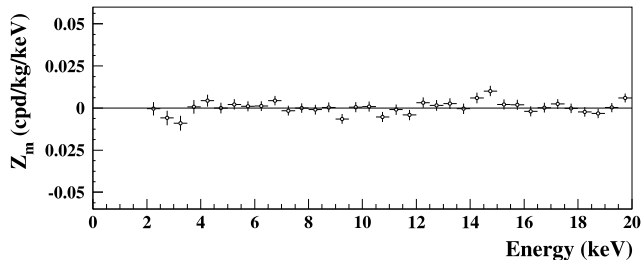
Finally, setting  $S_m$  in Eq. (1) to zero, the  $Z_m$  values as function of the energy have also been determined by using the same procedure. The values of  $Z_m$  as a function of the energy is reported in Fig. 12; they are expected to be zero. The  $\chi^2$  test applied to the data supports the hypothesis that the  $Z_m$  values are simply fluctuating around zero; in fact, for example in the (2–14) keV and (2–20) keV energy region the  $\chi^2/\text{d.o.f.}$  are equal to  $23.0/24$  and  $46.5/36$  (probability of 52 % and 11 %), respectively.

The behaviours of the  $Y_m$  and of the phase  $t^*$  variables as function of energy are shown in Fig. 13 for the cumulative exposure of DAMA/NaI and DAMA/LIBRA–phase1 ( $1.33 \text{ ton} \times \text{yr}$ ). The  $Y_m$  are superimposed with the  $S_m$  values with 1 keV energy bin (unlike Fig. 8 where the energy bin is 0.5 keV). As in the previous analyses, an annual modulation effect is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. No modulation is present above 6 keV and the phase is undetermined.

Sometimes naive statements were put forwards as the fact that in nature several phenomena may show some kind of periodicity. It is worth noting that the point is whether they might mimic the annual modulation signature

**Table 6** Best fit values for the (2–6) and (6–14) keV energy intervals ( $1\sigma$  errors) for  $S_m$  versus  $Z_m$  and  $Y_m$  versus  $t^*$ , considering the cumulative exposure of DAMA/NaI and DAMA/LIBRA–phase1. See also Fig. 11

E (keV)	$S_m$ (cpd/kg/keV)	$Z_m$ (cpd/kg/keV)	$Y_m$ (cpd/kg/keV)	$t^*$ (day)
2–6	$(0.0106 \pm 0.0012)$	$-(0.0006 \pm 0.0012)$	$(0.0107 \pm 0.0012)$	$(149.5 \pm 7.0)$
6–14	$(0.0001 \pm 0.0007)$	$(0.0000 \pm 0.0005)$	$(0.0001 \pm 0.0008)$	undefined

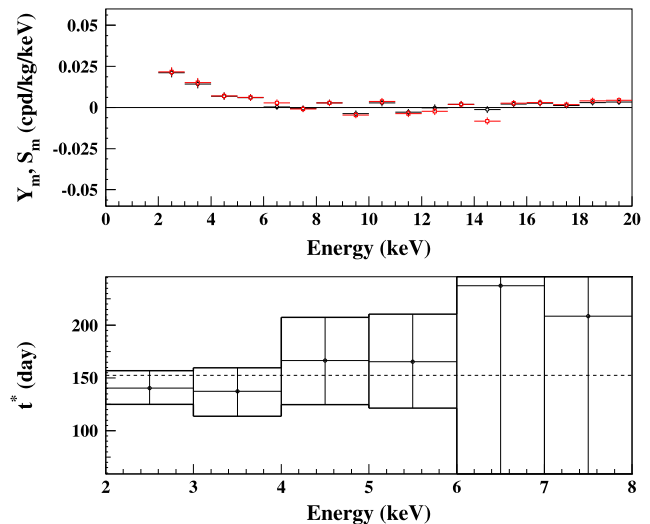
**Fig. 12** Energy distribution of the  $Z_m$  variable for the cumulative exposure of DAMA/NaI and DAMA/LIBRA–phase1, once setting  $S_m$  in Eq. (1) to zero. The energy bin is 0.5 keV. The  $Z_m$  values are expected to be zero. The  $\chi^2$  test applied to the data supports the hypothesis that the  $Z_m$  values are simply fluctuating around zero. See text

in DAMA/LIBRA (and former DAMA/NaI), i.e. whether they might be not only quantitatively able to account for the observed modulation amplitude but also able to contemporaneously satisfy all the requirements of the DM annual modulation signature. The same is also for side reactions. This has already been deeply investigated in Refs. [1–3] and references therein; the arguments and the quantitative conclusions, presented there, also apply to the entire DAMA/LIBRA–phase1 data. Additional arguments can be found in Refs. [6, 7, 54–60].

In conclusion, the model-independent DAMA results give evidence (at  $9.3\sigma$  C.L. over 14 independent annual cycles) for the presence of DM particles in the galactic halo.

In order to perform corollary investigation on the nature of the DM particles, model-dependent analyses are necessary;<sup>3</sup> thus, many theoretical and experimental parameters and models are possible and many hypotheses must also be exploited. In particular, the DAMA model-independent evidence is compatible with a wide set of astrophysical, nuclear and particle physics scenarios as also shown in literature. Moreover, both the negative results and all the possible positive hints, achieved so-far in the field, are largely compatible with the DAMA model-independent DM annual modulation results in many scenarios considering also the existing experimental and theoretical uncertainties; the same holds for indirect approaches. For a discussion see e.g. Ref. [7] and references therein.

<sup>3</sup>It is worth noting that it does not exist in direct and indirect DM detection experiments approaches which can offer such information independently on assumed models.

**Fig. 13** Top: Energy distributions of the  $Y_m$  variable (light data points; red colour) and of the  $S_m$  variable (solid data points; black) for the cumulative exposure of DAMA/NaI and DAMA/LIBRA–phase1. Here, unlike the data of Fig. 8, the energy bin is 1 keV. Bottom: Energy distribution of the phase  $t^*$  for the total exposure; here the errors are at  $2\sigma$ . The vertical scale spans over  $\pm$  a quarter of period around 2 June; other intervals are replica of it. An annual modulation effect is present in the lower energy intervals up to 6 keV and the phase agrees with that expected for DM induced signals. No modulation is present above 6 keV and thus the phase is undetermined. See text (Color figure online)

Finally, in order to increase the experimental sensitivity of DAMA/LIBRA and to disentangle—in the corollary investigation on the candidate particle(s)—at least some of the many possible astrophysical, nuclear and particle Physics scenarios [7], the decreasing of the software energy threshold has been pursued. Thus, at end of 2010 all the PMTs have been replaced with new ones having higher quantum efficiency [5]; then, the DAMA/LIBRA–phase2 is started.

### 3 Conclusions

The data of the new DAMA/LIBRA-7 annual cycle have further confirmed a peculiar annual modulation of the *single-hit* events in the (2–6) keV energy region satisfying all the many requirements of the DM annual modulation signature; the cumulative exposure by the former DAMA/NaI and DAMA/LIBRA–phase1 is  $1.33 \text{ ton} \times \text{yr}$ .

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) the measured period is equal to  $(0.998 \pm 0.002)$  yr well compatible with the 1 yr period as expected for the DM signal; (3) the measured phase  $(144 \pm 7)$  days is compatible with the roughly  $\simeq 152.5$  days 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-hit* ones as expected for the DM signal; (6) the measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2–6) keV energy interval is:  $(0.0112 \pm 0.0012)$  cpd/kg/keV ( $9.3 \sigma$  C.L.). No systematic or side processes able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available.

DAMA/LIBRA is continuously running in its new configuration (named DAMA/LIBRA–phase2) with a lower software energy threshold aiming to improve the knowledge on corollary aspects regarding the signal and on second order effects as discussed e.g. in Ref. [7].

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