PROCEEDINGS OF SCIENCE

# Dark Matter with DAMA/LIBRA

**R. Bernabei,**[a,b] **P. Belli,**[a,b,*] **F. Cappella,**[c,d] **V. Caracciolo,**[a,b] **R. Cerulli,**[a,b] **C.J. Dai,**[e] **A. d'Angelo,**[c,d] **A. Incicchitti,**[c,d] **X.H. Ma,**[e] **V. Merlo,**[a,b] **F. Montecchia,**[b,f] **X.D. Sheng**[e] **and Z.P. Ye**[e,g]

[a] *Dip. Fisica, Università di Roma "Tor Vergata", 00133 Rome, Italy*
[b] *INFN sezione di Roma "Tor Vergata", 00133 Rome, Italy*
[c] *Dip. Fisica, Università di Roma "La Sapienza", 00185 Rome, Italy*
[d] *INFN sezione di Roma, 00185 Rome, Italy*
[e] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 100049 Beijing, PR China*
[f] *Dipartimento Ingegneria Civile e Ingegneria Informatica, Università di Roma "Tor Vergata", 00133 Rome, Italy*
[g] *University of Jinggangshan, Ji'an, Jiangxi, PR China*

*E-mail:* pierluigi.belli@roma2.infn.it

The long-standing model-independent annual modulation effect measured by DAMA deep underground at the Gran Sasso National Laboratory (LNGS) of the I.N.F.N. with different experimental configurations is summarized. In particular, the DAMA/LIBRA–phase2 apparatus, $\simeq$ 250 kg highly radio-pure NaI(Tl), profits from a lower software energy threshold with the respect to DAMA/LIBRA–phase1. DAMA/LIBRA–phase2 confirms the evidence of a signal that meets all the requirements of the model independent Dark Matter annual modulation signature, at 11.8 $\sigma$ C.L. in the energy region (1–6) keV. In the energy region (2–6) keV, where data are also available from DAMA/NaI and DAMA/LIBRA–phase1, the achieved C.L. for the full exposure (2.86 ton $\times$ yr, 22 annual cycles) is 13.7 $\sigma$; the modulation amplitude of the *single-hit* scintillation events is: (0.01014 ± 0.00074) cpd/kg/keV, and the measured period and phase are well in agreement with those expected for DM particles. No systematics or side reaction able to mimic the exploited DM signature (i.e. to account for the whole measured modulation amplitude and to simultaneously satisfy all the requirements of the signature), has been found or suggested by anyone throughout some decades thus far.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

*Speaker





PoS(EPS-HEP2021)154

## 1. Introduction

The DAMA/LIBRA [1–20] experiment, as the pioneer DAMA/NaI [21, 22], has the main aim to investigate the presence of DM particles in the galactic halo by exploiting the DM annual modulation signature (originally suggested in Ref. [23, 24]). In addition, the developed highly radio-pure NaI(Tl) target-detectors [1, 6, 9, 25] ensure sensitivity to a wide range of DM candidates, interaction types and astrophysical scenarios (see e.g. Ref. [19], and references therein). The origin of the DM annual modulation signature and of its peculiar features is due to the Earth's revolution around the Sun, which is moving in the Galaxy; thus, the Earth should be crossed by a larger flux of DM particles around $\simeq$ 2 June (when the projection of the Earth orbital velocity on the Sun velocity is maximum) and by a smaller one around $\simeq$ 2 December (when the two velocities are opposite). 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 $\lesssim 7\%$ of the constant part of the signal for usually adopted halo distributions (6), but it can be larger in case of some proposed scenarios such as e.g. those reported in Ref. [19] (even up to $\simeq 30\%$). Thus this signature has many peculiarities and, in addition, it allows to test a wide range of parameters in many possible astrophysical, nuclear and particle physics scenarios. 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.

The full description of the DAMA/LIBRA set-up and the adopted procedures during the phase1 and phase2 and other related arguments have been discussed in details e.g. in Refs. [1–6, 15–20].

At the end of 2010 all the photomultipliers (PMTs) were replaced by a second generation PMTs Hamamatsu R6233MOD, with higher quantum efficiency (Q.E.) and with lower background with respect to those used in phase1; they were produced after a dedicated R&D in the company, and tests and selections were described in Refs. [6, 25]. The new PMTs have Q.E. in the range 33-39% at 420 nm, wavelength of NaI(Tl) emission, and in the range 36-44% at peak. The commissioning of the DAMA/LIBRA–phase2 experiment was successfully performed in 2011, allowing the achievement of the software energy threshold at 1 keV, and the improvement of some detector's features such as energy resolution and acceptance efficiency near software energy threshold [6]. The light response of the detectors during phase2 typically ranges from 6 to 10 photoelectrons/keV, depending on the detector. Energy calibration with X-rays/$\gamma$ sources are regularly carried out in the same running condition down to few keV (for details see e.g. Ref. [1]; in particular, double coincidences due to internal X-rays from $^{40}$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. 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 energy.

## 2. The DAMA/LIBRA–phase2 results

The details of the annual cycles of DAMA/LIBRA–phase2 are reported in Ref. [20]. The first annual cycle was dedicated to the commissioning and to the optimizations towards the achievement of the 1 keV software energy threshold [6]. Thus, the considered annual cycles of DAMA/LIBRA–phase2 are eight (exposure of 1.53 ton×yr); when considering also the former DAMA/NaI and DAMA/LIBRA–phase1, the exposure is 2.86 ton×yr. The duty cycle of the DAMA/LIBRA–phase2 experiment is high, ranging between 76% and 86%. The routine calibrations and, in particular, the data collection for the acceptance windows efficiency mainly affect it.

Residual rates versus time for 1 keV energy threshold are reported in Ref. [20]. The former DAMA/LIBRA–phase1 and the new DAMA/LIBRA–phase2 residual rates of the *single-hit* scintillation events are reported in Fig. 1. The energy interval is from 2 keV, the software energy threshold of DAMA/LIBRA–phase1, up to 6 keV. The data of Fig. 1 and those of DAMA/NaI have 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 $2^{nd}$) as expected by the DM annual modulation signature. The obtained $\chi^2/d.o.f.$ is 130/155 and the modulation amplitude $A = (0.00996 \pm 0.00074)$ cpd/kg/keV is obtained. When

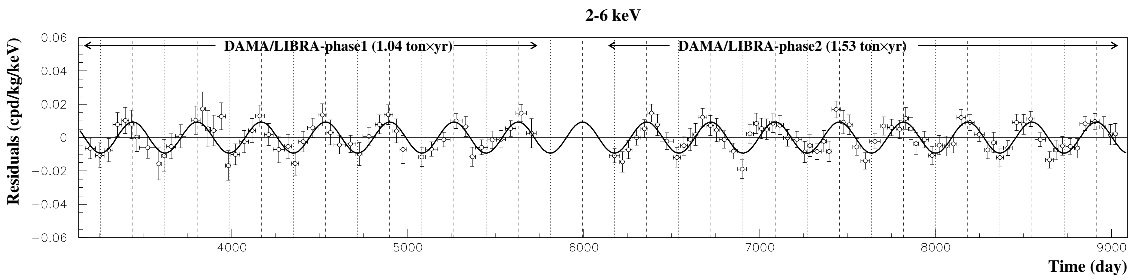


**Figure 1:** Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy intervals as a function of the time. The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, a phase $t_0 = 152.5$ day (June $2^{nd}$) and modulation amplitude, $A$, equal to the central value obtained by best fit.

the period and the phase are kept free in the fitting procedure, the achieved C.L. for the full exposure (2.86 ton×yr) is $13.7\sigma$; the modulation amplitude of the *single-hit* scintillation events is: $(0.01014 \pm 0.00074)$ cpd/kg/keV, the measured phase is $(142.4 \pm 4.2)$ days and the measured period is $(0.99834 \pm 0.00067)$ yr, all these values are well in agreement with those expected for DM particles.

Absence of any significant background modulation in the energy spectrum has also been verified in the present data taking for energy regions not of interest for DM. For example, the measured rate integrated above 90 keV, $R_{90}$, as a function of the time, has been analysed; the distribution of its percentage variations with respect to the mean values for all the detectors in DAMA/LIBRA–phase2 shows a cumulative gaussian behaviour with $\sigma \simeq 1\%$, well accounted for by the statistical spread expected from the used sampling time. Similar result is obtained in other energy intervals (see for example Fig. 2). 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 Ref. [1–5, 7, 8, 15–17, 19]).



PoS(EPS-HEP2021)154

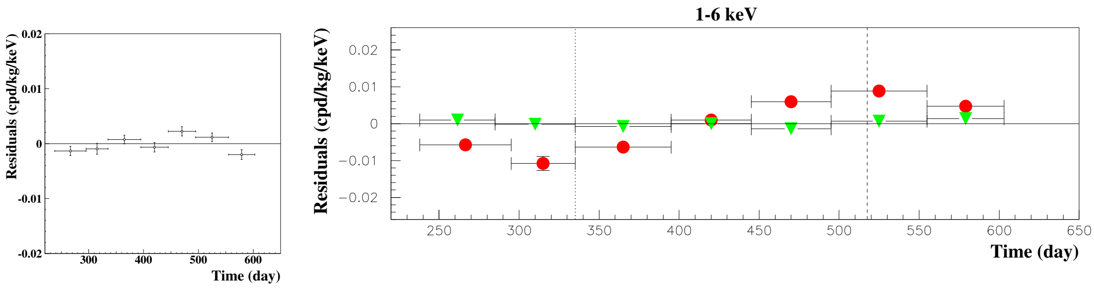


**Figure 2:** *Left:* Experimental *single-hit* residuals in the (10–20) keV energy regions for the eight annual cycles of DAMA/LIBRA–phase2 as if they were collected in a single annual cycle. The modulation amplitude is compatible with zero: $A = (0.0007 \pm 0.0005)$ cpd/kg/keV. *Right:* Experimental residual rates of the eight annual cycles of DAMA/LIBRA–phase2 for *single-hit* events (filled red on-line circles), class of events to which DM events belong, and for *multiple-hit* events (filled green on-line 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. Analogous results were obtained for DAMA/NaI (two last annual cycles) and DAMA/LIBRA–phase1 [2–5, 22].

A further relevant investigation on DAMA/LIBRA–phase2 data 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. 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 to compare 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. 2 the residual rates of the *single-hit* scintillation events collected during DAMA/LIBRA–phase2 are reported, as collected in a single cycle, together with the residual rates of 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 amplitude for the *multiple-hit* residual rate is well compatible with zero: $(0.00030 \pm 0.00032)$ cpd/kg/keV in the (1–6) keV energy region. 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.

The *single-hit* residuals have also been investigated by a Fourier analysis. The data analysis procedure has been described in details in Ref. [5]. A clear peak corresponding to a period of 1 year is evident in the low energy intervals; the same analysis in the (6–14) keV energy region shows only aliasing peaks instead. Neither other structure at different frequencies has been observed.

The annual modulation present at low energy can also be pointed out by depicting the energy dependence of the modulation amplitude, $S_m(E)$, obtained by maximum likelihood method considering fixed period and phase: $T$ =1 yr and $t_0$ = 152.5 day. The modulation amplitudes for the whole data sets: DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 (total exposure 2.86 ton×yr) are plotted in Fig. 3; the data below 2 keV refer only to the DAMA/LIBRA-phase2 exposure (1.53 ton×yr). It can be inferred that positive signal is present in the (1–6) keV energy interval (a new data point below 1 keV has been added, see later), while $S_m$ values compatible with zero are present just above. All this confirms the previous analyses. The test of the hypothesis that the $S_m$ values in the (6–14) keV energy interval have random fluctuations around zero yields $\chi^2/d.o.f.$ equal to 20.3/16 (P-value = 21%).

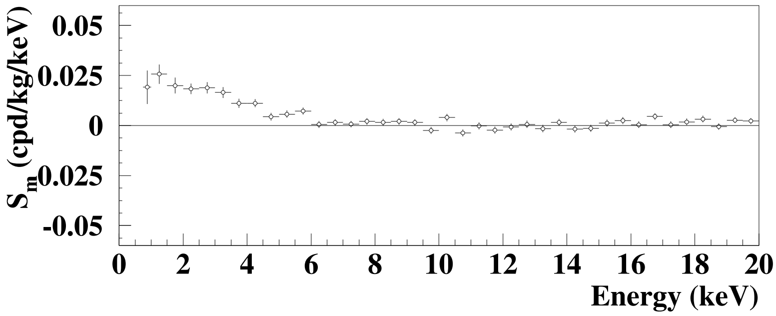


**Figure 3:** Modulation amplitudes, $S_m$, as function of the energy in keV(ee) for the whole data sets: DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 (total exposure 2.86 ton×yr) above 2 keV; below 2 keV only the DAMA/LIBRA-phase2 exposure (1.53 ton × yr) is available and used. A clear modulation 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 $\chi^2/d.o.f.$ equal to 42.2/28 (P-value is 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 14% and 23%.

It has been verified that the observed annual modulation effect is well distributed in all the 25 detectors. In particular, the modulation amplitudes $S_m$ integrated in the range (2–6) keV for each of the 25 detectors for the DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 periods have random fluctuations around the weighted averaged value confirmed by the $\chi^2$ analysis. Thus, the hypothesis that the signal is well distributed over all the 25 detectors is accepted.

Among further additional tests, the analysis of the modulation amplitudes separately for the nine inner detectors and the external ones has been carried out for DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2, as already done for the other data sets [2–5, 15–17, 19]. The obtained values are fully in agreement; in fact, the hypothesis that the two sets of modulation amplitudes belong to same distribution has been verified by $\chi^2$ test, obtaining e.g.: $\chi^2/d.o.f.$ = 1.9/6 and 36.1/38 for the energy intervals (1–4) and (1–20) keV, respectively ($\Delta E$ = 0.5 keV). This shows that the effect is also well shared between inner and outer detectors.

To test the hypothesis that the modulation amplitudes calculated for each DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 annual cycle are compatible and normally fluctuating around their mean values, the $\chi^2$ test and the *run test* have been used. This analysis confirms that the data collected in all the annual cycles with DAMA/LIBRA–phase1 and phase2 are statistically compatible and can be considered together [20].

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

$$\begin{aligned} S_i(E) &= S_0(E) + S_m(E)\cos\omega(t_i - t_0) + Z_m(E)\sin\omega(t_i - t_0) \\ &= S_0(E) + Y_m(E)\cos\omega(t_i - t^*). \end{aligned} \tag{1}$$

For signals induced by DM particles one should expect: i) $Z_m \sim 0$ (because of the orthogonality between the cosine and the sine functions); ii) $S_m \simeq Y_m$; iii) $t^* \simeq t_0 = 152.5$ day. These conditions hold for most of the dark halo models; however, slight differences can be expected in case of possible contributions from non-thermalized DM components (see e.g. Ref. [19] and references therein).

Considering cumulatively the data of DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 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. 4–*left* while in Fig. 4–*right* the obtained $2\sigma$ contours in the plane $(Y_m, t^*)$ are depicted. Moreover, Fig. 4 also shows only for DAMA/LIBRA–phase2 the $2\sigma$ contours in the (1–6) keV energy interval. The best fit values are reported in Ref. [20].

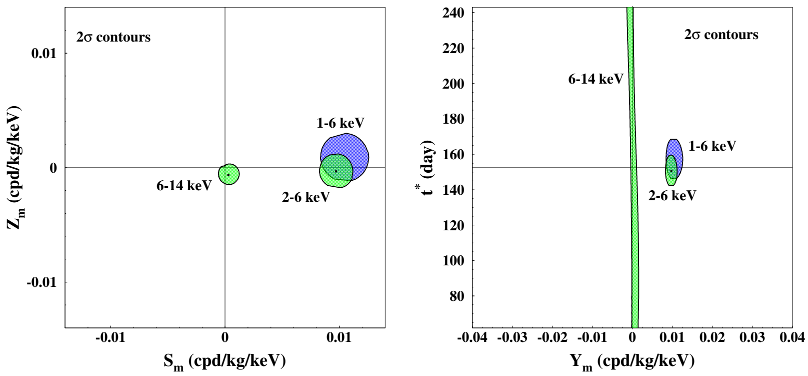


**Figure 4:** $2\sigma$ contours in the plane $(S_m, Z_m)$ (*left*) and in the plane $(Y_m, t^*)$ (*right*) for: i) DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV and (6–14) keV energy intervals (light areas, green on-line); ii) only DAMA/LIBRA–phase2 in the (1–6) keV energy interval (dark areas, blue on-line). The contours have been obtained by the maximum likelihood method. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals.

Setting $S_m = 0$ in eq. (1), the $Z_m$ values have also been determined by using the same procedure for DAMA/NaI, DAMA/LIBRA–phase1 and phase2 data sets; they are expected to be zero. The $\chi^2$ test supports the hypothesis that the $Z_m$ values are simply fluctuating around zero; in fact, in the (1–20) keV energy region the $\chi^2/d.o.f.$ is equal to 40.6/38 corresponding to a P-value = 36%.

No systematic or side processes able to mimic the signature, i.e. able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude, has been found or suggested by anyone throughout some decades thus far (see e.g. Ref. [1–5, 7, 8, 15–19, 21, 22]).

In particular, arguments related to any possible role of some natural periodical phenomena have been discussed and quantitatively demonstrated to be unable to mimic the signature (see references; e.g. Refs. [7, 8]). Thus, on the basis of the exploited signature, the model independent DAMA results give evidence at $13.7\sigma$ C.L. (over 22 independent annual cycles and in various experimental configurations) for the presence of DM particles in the galactic halo.

The DAMA model independent evidence is compatible with a wide set of astrophysical, nuclear and particle physics scenarios for high and low mass candidates inducing nuclear recoil and/or electromagnetic radiation, as also shown in various literature. Moreover, both the negative results and all the possible positive hints, achieved so-far in the field, can be 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. [5] and references therein.

## 3. Perspectives

To further increase the experimental sensitivity of DAMA/LIBRA and to disentangle some of the many possible astrophysical, nuclear and particle physics scenarios in the investigation on the DM candidate particle(s), an increase of the exposure in the lowest energy bin and a further decreasing of the software energy threshold are needed. This is pursued by running DAMA/LIBRA–phase2 and upgrading the experimental set-up to lower the software energy threshold below 1 keV with high acceptance efficiency.

Firstly, particular efforts for lowering the software energy threshold have been done in the already-acquired data of DAMA/LIBRA–phase2 by using the same technique as before with dedicated studies on the efficiencies. As consequence, a new data point has been added in the modulation amplitude as function of energy down to 0.75 keV, see Fig. 3. A modulation is also present below 1 keV. This preliminary result confirms the necessity to lower the software energy threshold by a hardware upgrade and an improved statistics in the first energy bin.

This dedicated hardware upgrade of DAMA/LIBRA–phase2 is in progress. It consists in equipping all the PMTs with miniaturized low background new concept preamplifier and miniaturized HV divider mounted on the same socket, and related improvements of the electronic chain, mainly the use of higher vertical resolution 14-bit digitizers. The aim of this upgrade is the improvement of the experimental sensitivity through a lower software energy threshold and a large acceptance efficiency.

## References

[1] R. Bernabei et al., *The DAMA/LIBRA apparatus*, *Nucl. Instr. and Meth. A* **592** (2008) 297.

[2] R. Bernabei et al., *First results from DAMA/LIBRA and the combined results with DAMA/NaI*, *Eur. Phys. J. C* **56** (2008) 333.

[3] R. Bernabei et al., *New results from DAMA/LIBRA*, *Eur. Phys. J. C* **67** (2010) 39.

[4] R. Bernabei et al., *Final model independent result of DAMA/LIBRA–phase1*, *Eur. Phys. J. C* **73** (2013) 2648.

[5] R. Bernabei et al., *Dark Matter Investigation by DAMA at Gran Sasso*, *Int. J. of Mod. Phys. A* **28** (2013) 1330022.

[6] R. Bernabei et al., *Performances of the new high quantum efficiency PMTs in DAMA/LIBRA*, *JINST* **7** (2012) P03009.

[7] R. Bernabei et al., *No role for muons in the DAMA annual modulation results*, *Eur. Phys. J. C* **72** (2012) 2064.



PoS(EPS-HEP2021)154

[8] R. Bernabei et al., *No role for neutrons, muons and solar neutrinos in the DAMA annual modulation results*, *Eur. Phys. J. C* **74** (2014) 3196.

[9] DAMA coll., *issue dedicated to DAMA*, *Int. J. of Mod. Phys. A* **31** (2016) and refs therein.

[10] R. Bernabei et al., *Investigating Earth shadowing effect with DAMA/LIBRA–phase1*, *Eur. Phys. J. C* **75** (2015) 239.

[11] P. Belli et al., *Observations of annual modulation in direct detection of relic particles and light neutralinos*, *Phys. Rev. D* **84** (2011) 055014.

[12] A. Addazi et al., *DAMA annual modulation effect and asymmetric mirror matter*, *Eur. Phys. J. C* **75** (2015) 400.

[13] R. Bernabei et al., *On corollary model-dependent analyses and comparisons*, *Int. J. of Mod. Phys. A* **31** (2016) 1642009.

[14] R. Cerulli et al., *DAMA annual modulation and mirror Dark Matter*, *Eur. Phys. J. C* **77** (2017) 83.

[15] R. Bernabei et al., *First Model Independent Results from DAMA/LIBRA–phase2*, *Universe* **4** (2018) 116.

[16] R. Bernabei et al., *First Model Independent Results from DAMA/LIBRA–phase2*, *Nucl. Phys. At. Energy* **19** (2018) 307.

[17] R. Bernabei, *New model independent results from the first six full annual cycles of DAMA/LIBRA–phase2*, in proceedings of *Bled Workshops in Physics*, **19** n. 2 (2018) 27.

[18] R. Bernabei et al., *Improved Model-Dependent Corollary Analyses after the First Six Annual Cycles of DAMA/LIBRA–phase2*, *Nucl. Phys. At. Energy* **20(4)** (2019) 317.

[19] R. Bernabei et al., *The DAMA project: Achievements, implications and perspectives*, *Prog. Part. Nucl. Phys.* **114** (2020) 103810.

[20] R. Bernabei et al., *The dark matter: DAMA/LIBRA and its perspectives*, in proceedings of *Sixteenth Marcel Grossmann Meeting* (2021) (World Scientific).

[21] R. Bernabei el al., *Dark Matter search*, *La Rivista del Nuovo Cimento* **26** n.1 (2003) 1-73.

[22] R. Bernabei et al., *Dark Matter particles in the Galactic halo: results and implications from DAMA/NaI*, *Int. J. Mod. Phys. D* **13** (2004) 2127, and refs. therein.

[23] K.A. Drukier et al., *Detecting cold dark-matter candidates*, *Phys. Rev. D* **33** (1986) 3495.

[24] K. Freese et al., *Signal modulation in cold-dark-matter detection*, *Phys. Rev. D* **37** (1988) 3388.

[25] R. Bernabei and A. Incicchitti, *Low background techniques in NaI(Tl) setups*, *Int. J. of Mod. Phys. A* **32** (2017) 1743007.