EPJ Web of Conferences **164**, 01013 (2017)
*ICNFP 2016*
DOI: 10.1051/epjconf/201716401013

# Highlights on signals from Dark Matter particles

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**Abstract.** Many experimental observations and theoretical arguments have pointed out that a large fraction of the Universe is composed by Dark Matter particles. Many possibilities are open on the nature and interaction types of such relic particles. In particular, this paper summarizes the main results obtained by exploiting the model independent Dark Matter annual modulation signature for the presence of Dark Matter particles in the galactic halo by DAMA experiment.

## 1 Introduction

Experimental observations and theoretical arguments have pointed out that most of the matter in the Universe has a non baryonic nature and is in form of Dark Matter (DM) particles. Many candidates – different in nature and with different and various interaction types – as DM particles of the Universe have been proposed within theories beyond the Standard Model of particle physics.

Depending on the DM candidate, the interaction processes can be various. Moreover, many other experimental and theoretical uncertainties exist and must be properly considered in a suitable interpretation and comparison among experiments of direct detection of DM particles.

Large efforts are dedicated all over the world to investigate the DM with different strategies and techniques that can give complementary information. However, let us briefly comment few items. Firstly, the DM indirect search – that is the study of possible products either of decay or of annihilation of DM particles in the galactic halo or in celestial body – is performed as by-product of experiments located underground, under-water, under-ice, or in space. The interpretation of such a study is strongly dependent on the chosen assumptions for the modeling of the background and is restricted to some DM candidates with peculiar features. Therefore, all that shows the intrinsic uncertainties of the DM indirect searches to unambiguously assess presence of DM in the galactic halo. On the other hand,

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experiments at accelerators may prove – when they can state a solid model independent result – the existence of some possible DM candidate particles, but they could never credit by themselves that a certain particle is a/the only solution for DM particle(s). Moreover, DM candidate particles and scenarios (even e.g. in the case of the neutralino candidate) exist which cannot be investigated at accelerators.

In order to pursue a widely sensitive direct detection of DM particles in the galactic halo, a model independent approach, a ultra-low-background suitable target material, a very large exposure and the full control of running conditions are strictly necessary.

In conclusion, suitable experiments offering a model independent signature for the presence of DM particles in the galactic halo are mandatory.

## 2 DM model independent signature

To obtain a reliable signature for the presence of DM particles in the galactic halo, it is necessary to exploit a suitable model independent signature. With the present technology, one feasible and able to test a large range of cross sections and of DM particle halo densities, is the so-called DM annual modulation signature [1]. The annual modulation of the signal rate originates from the Earth revolution around the Sun. In fact, as a consequence of its annual revolution around the Sun, which is moving in the Galaxy traveling 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 ~2 June (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around ~2 December (when the two velocities are subtracted). Thus, this signature has a different origin and peculiarities than effects correlated with seasons (consider the expected value of the phase as well as the other requirements listed below). This DM annual modulation signature is very distinctive since the effect induced by DM particles must simultaneously satisfy all the following requirements: (1) the rate must contain a component modulated according to a cosine function; (2) with one year period; (3) with a phase that peaks roughly around ~ 2nd June; (4) this modulation must be present only in a well-defined low energy range, where DM particles can induce signals; (5) it must be present only in those events where just a single detector, among all the available ones in the used set-up, actually "fires" (*single-hit* events), since the probability that DM particles experience multiple interactions is negligible; (6) the modulation amplitude in the region of maximal sensitivity has to be $\lesssim 7\%$ in case of usually adopted halo distributions, but it may be significantly larger in case of some particular scenarios such as e.g. those in Ref. [2, 3]. This signature is model independent and might be mimicked only by systematic effects or side reactions able to simultaneously satisfy all the requirements given above; no one is available. At present status of technology it is the only DM model independent signature available in direct DM investigation that can be effectively exploited.

## 3 DAMA DM annual modulation results with highly radiopure NaI(Tl)

The DM annual modulation signature has been exploited with large exposure – using highly radiopure NaI(Tl) as target material – by the former DAMA/NaI ($\simeq$ 100 kg sensitive mass) experiment [4–13], and by the currently running DAMA/LIBRA ($\simeq$ 250 kg sensitive mass) [14–28], within the DAMA project. The DAMA project is dedicated to the development and use of low background scintillators for underground physics.

In particular, the experimental observable in DAMA experiments is the modulated component of the signal in NaI(Tl) target and not the constant part of it, as done in the other approaches aforementioned.

The full description of the DAMA/LIBRA set-up and performances during the phase1 and phase2 (presently running) and other related arguments have been discussed in details in Refs. [14–17, 19–21, 26] and references therein. Here we just remind 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 Ref. [8, 10, 14] 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 [14]. 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 [8, 14]. Energy calibration with X-rays/$\gamma$ sources are regularly carried out in the same running condition down to few keV [14]; 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 (for details see Ref. [14]). The radiopurity, the procedures and details are discussed in Ref. [14–17, 21] and references therein.

The data of DAMA/LIBRA–phase1 correspond to 1.04 ton × yr collected in 7 annual cycles; when including also the data of the DAMA/NaI experiment the total exposure is 1.33 ton × yr collected in 14 annual cycles. In order to investigate the presence of an annual modulation with proper features in the data, many analyses have been carried out. All these analyses point out the presence of an annual modulation satisfying all the requirements of the signature [15–17, 21]. In Fig. 1, as example, it is plotted the time behaviour of the experimental residual rate of the *single-hit* scintillation events for DAMA/LIBRA–phase1 in the (2–6) keV energy interval. When fitting the *single-hit* residual rate of DAMA/LIBRA–phase1 together with the DAMA/NaI ones, 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 following modulation amplitude is obtained: $A = (0.0110 \pm 0.0012)$ cpd/kg/keV, corresponding to 9.2 $\sigma$ C.L..

When the period, and the phase are kept free in the fitting procedure, the modulation amplitude is (0.0112 ± 0.0012) cpd/kg/keV (9.3 $\sigma$ C.L.), the period $T = (0.998 \pm 0.002)$ year and the phase $t_0 = (144 \pm 7)$ day, values well in agreement with expectations for a DM annual modulation signal. In particular, the phase is consistent with about June $2^{nd}$ and is fully consistent with the value independently determined by Maximum Likelihood analysis [17].

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 [12, 29, 30] and the caustics [31]. For more details see Ref. [17].

The modulation amplitudes singularly calculated for each annual cycle of DAMA/NaI and DAMA/LIBRA–phase1 are compatible among them and are normally fluctuating around their best fit values [15–17]. In particular, for the (2–6) keV energy interval the $\chi^2$ is 10.8 over 13 *d.o.f.* corresponding to an upper tail probability of 63%, while the *run test* yields a lower tail probabilities of 23%. 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.

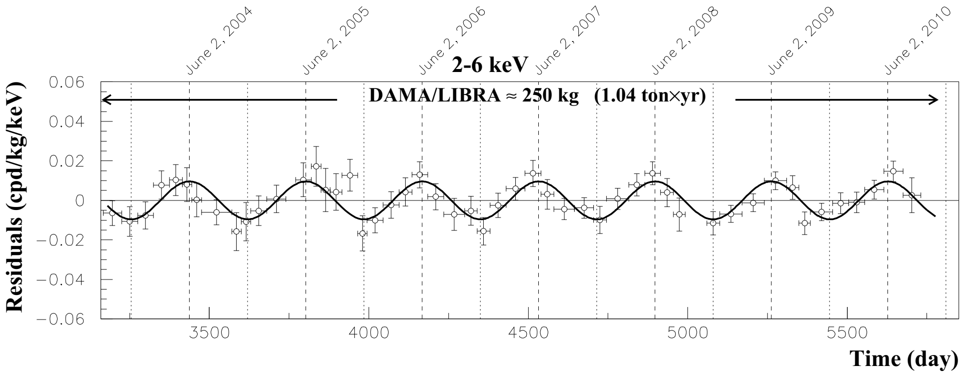

**Figure 1.** Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time. The superimposed curve is the cosinusoidal function behaviour $A\cos\omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, a phase $t_0 = 152.5$ day (June $2^{nd}$) and modulation amplitude, $A$, equal to the central 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 $2^{nd}$), while the dotted vertical lines correspond to the minimum.

The DAMA/LIBRA–phase1 *single-hit* residuals of Fig. 1 and those of DAMA/NaI have also been investigated by a Fourier analysis. The data analysis procedure has been described in details in Ref. [21]. A clear peak corresponding to a period of 1 year is evident for the (2–6) keV energy interval; the same analysis in the (6–14) keV energy region shows only aliasing peaks instead. Neither other structure at different frequencies has been observed (see also Ref. [21]).

Absence of any other significant background modulation in the energy spectrum has been verified in energy regions not of interest for DM; e.g. the measured rate integrated above 90 keV, $R_{90}$, as a function of the time has been analysed [17]. Similar result is obtained in other energy intervals. 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. [14–17, 20, 21, 25, 32–38]).

A further relevant investigation in the DAMA/LIBRA–phase1 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. 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. 2 the residual rates of the *single-hit* events measured over the DAMA/LIBRA–phase1 annual cycles are reported, as collected in a single cycle, together with the residual rates of the *multiple-hit* events, in the (2–6) keV energy interval. 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: $-(0.0005 \pm 0.0004)$ cpd/kg/keV in the energy region (2–6) keV. Thus, again evidence of annual modulation with the features 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

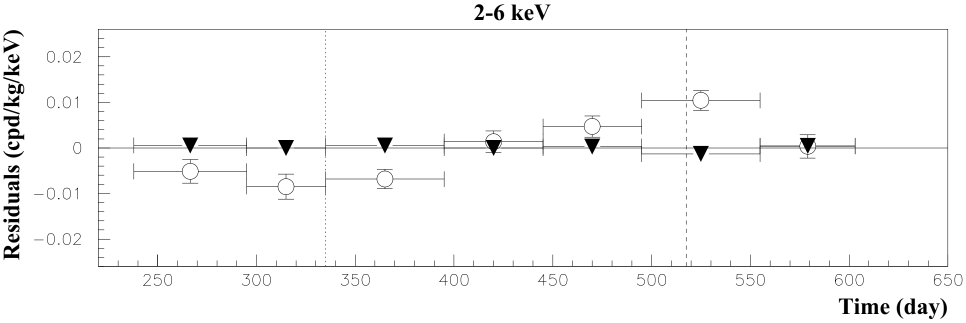

**Figure 2.** Experimental residual rates of DAMA/LIBRA–phase1 *single-hit* events (open circles), class of events to which DM events belong, and for *multiple-hit* events (filled triangles), class of events to which DM events do not belong. They have been obtained by considering for each class of events 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 $7^{th}$. 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 [11].

results were also obtained for the last two annual cycles of the DAMA/NaI experiment [11]. 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 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 considering $T$ =1 yr and $t_0$ = 152.5 day. For such purpose the likelihood function of the *single-hit* experimental data in the $k-$th energy bin is defined as: $\mathbf{L_k} = \mathbf{\Pi}_{ij} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!}$, 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 $\mu_{ijk} = \left[b_{jk} + S_{ik}\right] M_j \Delta t_i \Delta E \epsilon_{jk}$. 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 $y_k = -2ln(\mathbf{L_k}) - const$ 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. 3 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 described in Ref. [15–17, 21], the observed annual modulation effect is well distributed in all the 25 detectors at 95% C.L.

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. 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

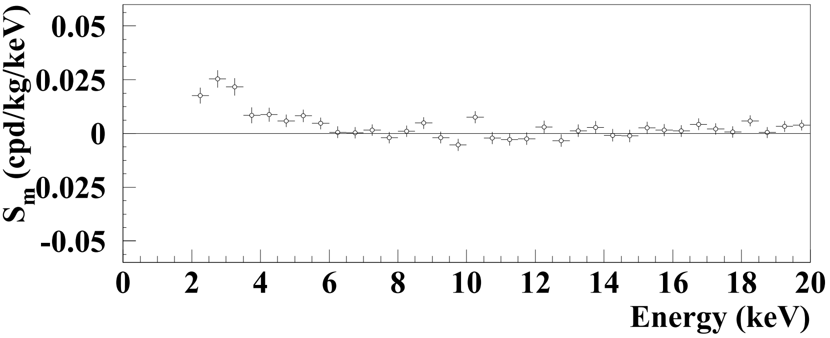

**Figure 3.** Energy distribution of the $S_m$ variable for the total cumulative exposure 1.33 ton×yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while $S_m$ values compatible with zero are present just above. In fact, the $S_m$ values in the (6–20) keV energy interval have random fluctuations around zero with $\chi^2$ equal to 35.8 for 28 degrees of freedom (upper tail probability of 15%).

has been verified by $\chi^2$ test, obtaining: $\chi^2/d.o.f. = 3.9/4$ 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:

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

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 [12, 29, 30] and the caustics [31].

Considering cumulatively the data of DAMA/NaI and DAMA/LIBRA–phase1 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.

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 $Z_m$ are well compatible with zero, as expected [15–17].

No modulation has been found in any possible source of systematics or side reactions; thus, cautious upper limits on possible contributions to the DAMA/LIBRA–phase1 measured modulation amplitude have been obtained (see Refs. [9–11, 15–17, 20, 26]). It is worth noting that they do not quantitatively account for the measured modulation amplitudes, and also are not able to simultaneously satisfy all the many requirements of the signature. Similar analyses have also been performed for the DAMA/NaI data [10, 11].

Sometimes naive statements were put forward 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 in DAMA/NaI and in DAMA/LIBRA, 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 for side reactions too. This has already been deeply investigated and discussed in DAMA literature.

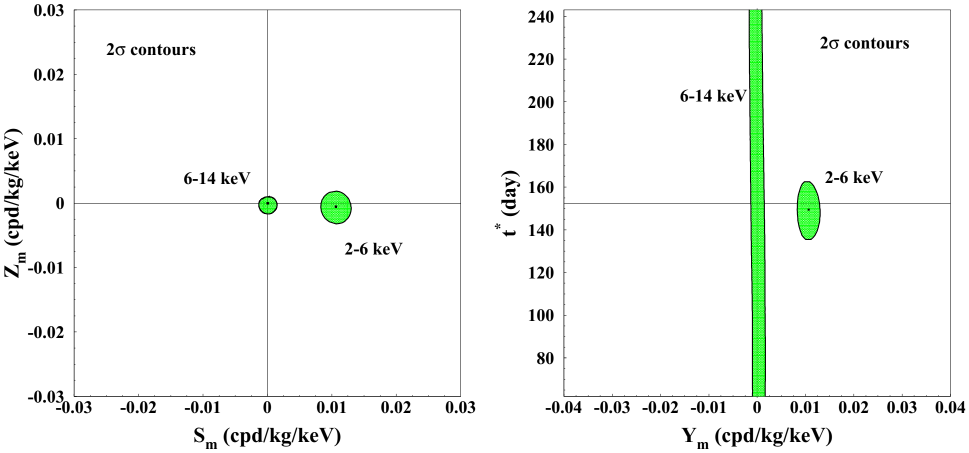

**Figure 4.** $2\sigma$ contours in the plane $(S_m, Z_m)$ (*left*) and in the plane $(Y_m, t^*)$ (*right*) for the (2–6) keV and (6–14) keV energy intervals. The contours have been obtained by the maximum likelihood method, considering the cumulative exposure of DAMA/NaI and DAMA/LIBRA–phase1. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. See text.

**Table 1.** Summary of the contributions to the total neutron flux at LNGS; the value, $\Phi^{(n)}_{0,k}$, the relative modulation amplitude, $\eta_k$, and the phase, $t_k$, of each component is reported. It is also reported the counting rate, $R_{0,k}$, in DAMA/LIBRA for *single-hit* events, in the $(2-6)$ keV energy region induced by neutrons, muons and solar neutrinos, detailed for each component. The modulation amplitudes, $A_k$, are reported as well, while the last column shows the relative contribution to the annual modulation amplitude observed by DAMA/LIBRA, $S_m^{exp} \simeq 0.0112$ cpd/kg/keV [17]. For details see Ref. [26] and references therein.

| Source | | $\Phi^{(n)}_{0,k}$ (neutrons cm$^{-2}$ s$^{-1}$) | $\eta_k$ | $t_k$ | $R_{0,k}$ (cpd/kg/keV) | $A_k = R_{0,k}\eta_k$ (cpd/kg/keV) | $A_k/S_m^{exp}$ |
|---|---|---|---|---|---|---|---|
| SLOW neutrons | thermal n ($10^{-2} - 10^{-1}$ eV) | $1.08 \times 10^{-6}$ | $\simeq 0$<br>however $\ll 0.1$ | – | $< 8 \times 10^{-6}$ | $\ll 8 \times 10^{-7}$ | $\ll 7 \times 10^{-5}$ |
| | epithermal n (eV-keV) | $2 \times 10^{-6}$ | $\simeq 0$<br>however $\ll 0.1$ | – | $< 3 \times 10^{-3}$ | $\ll 3 \times 10^{-4}$ | $\ll 0.03$ |
| FAST neutrons | fission, $(\alpha, n) \to$ n (1-10 MeV) | $\simeq 0.9 \times 10^{-7}$ | $\simeq 0$<br>however $\ll 0.1$ | – | $< 6 \times 10^{-4}$ | $\ll 6 \times 10^{-5}$ | $\ll 5 \times 10^{-3}$ |
| | $\mu \to$ n from rock (> 10 MeV) | $\simeq 3 \times 10^{-9}$ | 0.0129 | end of June | $\ll 7 \times 10^{-4}$ | $\ll 9 \times 10^{-6}$ | $\ll 8 \times 10^{-4}$ |
| | $\mu \to$ n from Pb shield (> 10 MeV) | $\simeq 6 \times 10^{-9}$ | 0.0129 | end of June | $\ll 1.4 \times 10^{-3}$ | $\ll 2 \times 10^{-5}$ | $\ll 1.6 \times 10^{-3}$ |
| | $\nu \to$ n (few MeV) | $\simeq 3 \times 10^{-10}$ | 0.03342* | Jan. 4th* | $\ll 7 \times 10^{-5}$ | $\ll 2 \times 10^{-6}$ | $\ll 2 \times 10^{-4}$ |
| | direct $\mu$ | $\Phi_0^{(\mu)} \simeq 20\ \mu$ m$^{-2}$d$^{-1}$ | 0.0129 | end of June | $\simeq 10^{-7}$ | $\simeq 10^{-9}$ | $\simeq 10^{-7}$ |
| | direct $\nu$ | $\Phi_0^{(\nu)} \simeq 6 \times 10^{10}\ \nu$ cm$^{-2}$s$^{-1}$ | 0.03342* | Jan. 4th* | $\simeq 10^{-5}$ | $3 \times 10^{-7}$ | $3 \times 10^{-5}$ |

* 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.

In particular, in Refs. [20, 26] a quantitative evaluation why the neutrons, the muons and the solar neutrinos cannot give any significant contribution to the DAMA annual modulation results and cannot mimic this signature is outlined. Table 1 summarizes the safety upper limits on the contributions to the observed modulation amplitude due to the total neutron flux at LNGS, either from $(\alpha, n)$ reactions, from fissions and from muons' and solar-neutrinos' interactions in the rocks and in the lead around the experimental set-up; the direct contributions of muons and solar neutrinos are reported there too.

In any case no systematic effects or side reactions able to account for the whole observed modulation amplitude and to simultaneously satisfy all the requirements of the exploited DM signature have been found. A detailed discussion about all the related arguments can be found in Refs. [9–11, 14–17, 20, 21, 25, 26].

Analyses on the presence of possible diurnal effects in the DAMA/LIBRA–phase1 data [25] and on the so called "Earth Shadow Effect" [27] will be summarized in the following. Finally, the annual modulation result has been also interpreted in terms of Asymmetric Mirror DM [28], as briefly shown later.

## 4 Implications and comparisons

The long-standing annual-modulation evidence measured in DAMA experiments is model-independent, i.e. in particular independent on theoretical interpretations of the identity of DM and specifics of its interactions. It can be related to a variety of interaction mechanisms of DM particles with the detector materials and is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear and particle physics. For example, some of the scenarios available in literature and the different parameters are discussed in Refs. [4–7, 10–13, 15, 21] and references therein, and recently e.g. in Refs. [28, 39] . Further large literature is available on the topics (see for example in Ref. [21]) and many possibilities are open.

It is worth noting that no other experiment exists, whose result can be directly compared in a model-independent way with those by DAMA/NaI and DAMA/LIBRA. Some activities claim model-dependent exclusion under many largely arbitrary assumptions (see for example discussions in Ref. [10, 11, 15, 40–42]). Moreover, often some critical points exist in their experimental aspects, as mentioned above, and the existing experimental and theoretical uncertainties are generally not considered in their presented single model dependent result; moreover, implications of the DAMA results are often presented in incorrect/partial/unupdated way. Both the accounting of the existing uncertainties and the existence of alternative scenarios (see literature) allow one to note that model dependent results by indirect and direct experiments actually are not in conflict with the DAMA model independent result.

The model independent annual modulation effect observed by the DAMA experiments has been investigated in terms of many DM candidates. Here we just recall the case of a mirror-type dark matter candidates in some scenarios [28].

In the framework of asymmetric mirror matter, the DM originates from hidden (or shadow) gauge sectors which have particles and interaction content similar to that of ordinary particles. It is assumed that the mirror parity is spontaneously broken and the electroweak symmetry breaking scale $v'$ in the mirror sector is much larger than that in the Standard Model, $v = 174$ GeV. In this case, the mirror world becomes a heavier and deformed copy of our world, with mirror particle masses scaled in different ways with respect to the masses of the ordinary particles. Then, in this scenario dark matter would exist in the form of mirror hydrogen composed of mirror proton and electron, with mass of about 5 GeV which is a rather interesting mass range for dark matter particles.

The data analysis in the Mirror DM model framework allows the determination of the $\sqrt{f}\epsilon$ parameter (where $f$ is the fraction of DM in the Galaxy in form of mirror atoms and $\epsilon$ is the coupling constant). In the analysis several uncertainties on the astrophysical, particle physics and nuclear physics models have been taken into account in the calculation. The obtained values of the $\sqrt{f}\epsilon$ parameter in the case of mirror hydrogen atom ranges between $7.7 \times 10^{-10}$ to $1.1 \times 10^{-7}$; they are well compatible with cosmological bounds [28].

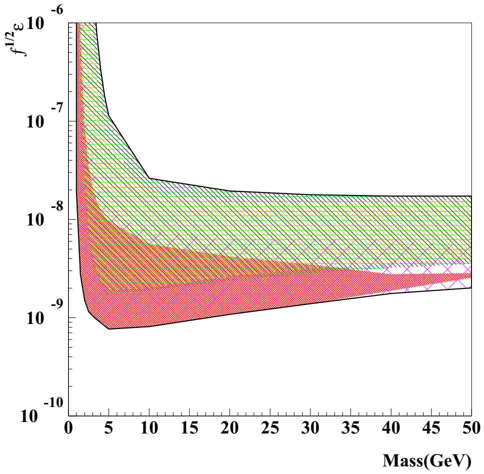

**Figure 5.** Allowed regions for the $\sqrt{f}\epsilon$ parameter as function of mirror hydrogen mass, obtained by marginalizing all the models for each considered scenario. The allowed intervals identify the $\sqrt{f}\epsilon$ values corresponding to C.L. larger than $5\sigma$ from the *null hypothesis*, that is $\sqrt{f}\epsilon = 0$. The allowed regions corresponding to five different scenarios are depicted in different hatching; the black line is the overall boundary; for details see Ref. [28].

In addition, releasing the assumption $M_{A'} \simeq 5m_p$, the allowed regions for the $\sqrt{f}\epsilon$ parameter as function of $M_{A'}$, mirror hydrogen mass, obtained by marginalizing all the models for each considered scenario, are shown in Fig. 5.

## 5 Diurnal modulation

The results obtained by investigating the presence of possible diurnal variation in the low-energy *single-hit* scintillation events collected by DAMA/LIBRA–phase1 (1.04 ton × year exposure) have been analysed in terms of a DM second order model-independent effect due to the Earth diurnal rotation around its axis [25]. In particular, the data were analysed using the sidereal time referred to Greenwich, often called GMST.

This daily modulation of the rate on the sidereal time, expected when taking into account the contribution of the Earth rotation velocity, has several requirements as the DM annual modulation effect does. The interest in this signature is that the ratio $R_{dy}$ of this diurnal modulation amplitude over the annual modulation amplitude is a model independent constant at given latitude; considering the LNGS latitude one has $R_{dy} = \frac{S_d}{S_m} \simeq 0.016$.

Taking into account $R_{dy}$ and the DM annual modulation effect pointed out by DAMA/LIBRA–phase1 for *single-hit* events in the low energy region, it is possible to derive the diurnal modulation amplitude expected for the same data. In particular, when considering the (2–6) keV energy interval, the observed annual modulation amplitude in DAMA/LIBRA–phase1 is: ($0.0097 \pm 0.0013$) cpd/kg/keV [17] and the expected value of the diurnal modulation amplitude is $\simeq 1.5\times 10^{-4}$ cpd/kg/keV.

Fig. 6 shows the time and energy behaviour of the experimental residual rates of *single-hit* events both as a function of solar (*left*) and of sidereal (*right*) time, in the (2–6) keV interval. The used time bin is 1 (either solar or sidereal) hour.

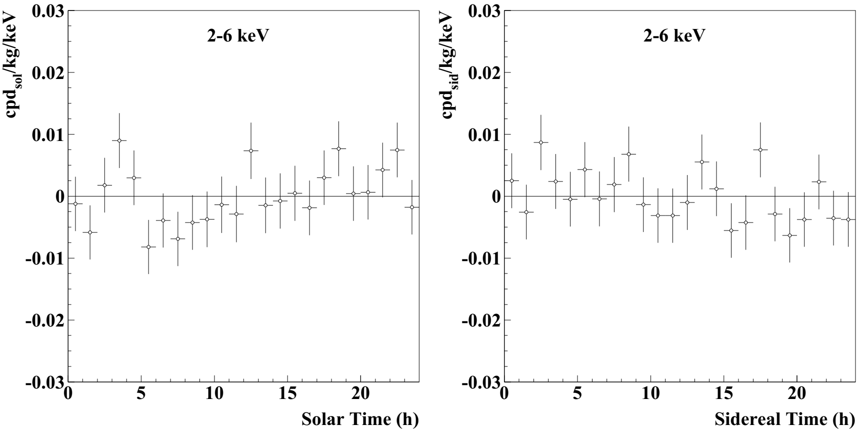

**Figure 6.** Experimental model-independent diurnal residual rate of the *single-hit* scintillation events, measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the hour of the solar (*left*) and sidereal (*right*) day. The experimental points present the errors as vertical bars and the associated time bin width (1 hour) as horizontal bars. The cumulative exposure is 1.04 ton × yr. See Ref. [25] for details.

The null hypothesis (absence of residual rate diurnal variation) has been tested by a $\chi^2$ test and run test [25]. Thus, the presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity (see Fig. 6).

In order to compare the experimental data with the DM diurnal effect due to the Earth rotation around its axis, the sidereal diurnal modulation amplitude of the (2–6) keV energy interval is taken into account: $A_d^{exp} = -(1.0 \pm 1.3) \times 10^{-3}$ cpd/kg/keV. Following the Feldman-Cousins procedure an upper limit can be obtained for the measured diurnal modulation amplitude: $A_d^{exp} < 1.2 \times 10^{-3}$ cpd/kg/keV (90% C.L.); thus, the effect of DM diurnal modulation (expected amplitude $\simeq 1.5\times 10^{-4}$ cpd/kg/keV) is out the present sensitivity [25].

In conclusion, at that level of sensitivity of DAMA/LIBRA–phase1 the presence of a significant diurnal variation and of diurnal time structures in the data can be excluded for both the cases of solar and sidereal time. In particular, the sidereal diurnal modulation amplitude expected – because of the Earth diurnal motion – on the basis of the DAMA DM annual modulation results cannot be investigated at the present sensitivity; DAMA/LIBRA–phase2, presently running, with a lower software energy threshold [19] can also offer the possibility to increase sensitivity to such an effect.

## 6 Daily effect on the sidereal time due to the shadow of the Earth

The results obtained in the investigation of possible diurnal effects for low-energy *single-hit* scintillation events of DAMA/LIBRA–phase1 have been analysed in terms of Earth Shadow Effect, a model-dependent effect that is expected for DM candidates inducing only nuclear recoils and having high cross-section ($\sigma_n$) with ordinary matter [27].

In fact a diurnal variation of the low energy rate could be expected for these specific candidates, because of the different thickness of the shield due to the Earth during the sidereal day, eclipsing the wind of DM particles. The induced effect should be a daily variation of their velocity distribution, and therefore of the signal rate measured deep underground. However, this effect is very small and would be appreciable only in case of high cross-section spin independent coupled candidates. Such candidates must constitute a little fraction ($\xi$) of the Galactic dark halo in order to fulfil the positive

DAMA result on annual modulation. By the fact, this analysis decouples $\xi$ from $\sigma_n$. Considering the measured DM annual modulation effect and the absence – at the present level of sensitivity – of diurnal effects, the analysis selects allowed regions in the three-dimensional space: $\xi$, $\sigma_n$ and DM particle mass in some model scenarios; for details see Ref. [27].

## 7 Conclusions and Perspectives

The cumulative exposure with ultra low background NaI(Tl) target by the former DAMA/NaI and DAMA/LIBRA–phase1 is 1.33 ton × yr (orders of magnitude larger than those available in the field) giving a model-independent positive evidence at 9.3 $\sigma$ C.L. for the presence of DM candidates in the galactic halo with full sensitivity to many kinds of astrophysical, nuclear and particle physics scenarios. Other rare processes have also been searched for by DAMA/LIBRA-phase1 (see for details Refs. [22–24]) and by DAMA/NaI [43].

After the phase1, an important upgrade has been performed when all the PMTs have been replaced with new ones having higher Quantum Efficiency (QE). In this new configuration a software energy threshold below 2 keV has been reached [19]. DAMA/LIBRA is thus in its phase2, and after optimization periods it is continuously running with higher sensitivity.

The main goals of DAMA/LIBRA–phase2 are: (1) to increase the experimental sensitivity thanks to the lower software energy threshold of the experiment; (2) to improve the corollary investigation on the nature of the DM particle and related astrophysical, nuclear and particle physics arguments; (3) to investigate other signal features; (4) to investigate rare processes other than DM with high sensitivity.

Future improvements to increase the sensitivity of the set-up can be considered by using high QE and ultra-low background PMTs directly coupled to the NaI(Tl) crystals. In this way a further large improvement in the light collection and a further lowering of the software energy threshold would be obtained.

Finally, for completeness, we also mention that low background $ZnWO_4$ crystal scintillators have recently been proposed within the DAMA collaboration for the study of the directionality of DM candidates inducing just nuclear recoils. The features and performances of such anisotropic scintillators are very promising [44] and are under exploration.

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