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The Dark Universe and the detection of Dark Matter

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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. Moreover, the poor knowledge of many fundamental astrophysical, nuclear and particle Physics aspects and of some experimental and theoretical parameters, the different used approaches and target materials, etc. make challenging the comparisons and the implications of the different experimental efforts. Some general arguments are addressed here and future perspectives are mentioned. A particular care will be given to the 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. Results from the other experiments using different procedures, different techniques and different target-materials will be shortly addressed as well as implications and experimental perspectives.

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, as e.g.: 1) elastic scatterings on target nuclei with either spin-independent or spin-dependent or mixed coupling; moreover, an additional electromagnetic contribution can arise, in case of few GeV candidates, from the excitation of bound electrons by the recoiling nuclei [1]; 2) inelastic scatterings on target nuclei with either spin-independent or spin-dependent or mixed coupling in various scenarios [2, 3, 4, 5, 6, 7]; 3) interaction of light DM either on electrons or on nuclei with production of a lighter particle [8]; 4) preferred interaction with electrons [9]; 5) conversion of DM particles into electromagnetic radiation [10]; 6) etc.. Often, the elastic scattering on target nuclei is the considered interaction process, but other processes are possible and considered in literature, as those aforementioned where also electromagnetic radiation is produced. Hence, considering the richness of particle possibilities and the existing uncertainties on related astrophysical (e.g. halo model and related parameters, etc.), nuclear (e.g. form factors, spin factors, scaling laws, etc.) and particle physics (e.g. particle nature, interaction types, etc.), a widely-sensitive model independent approach is mandatory. Most activities in the field are instead based on a particular *a priori* assumption on the nature of the DM particle and of its interaction, in order to try to overcome the limitation arising from their generally large originally measured counting rate.

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.

Before summarizing the efforts of the most important direct detection experiments, 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, 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.

2. The Dark Matter particles detection

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.

Indeed, most activities in the field release marginal exposures even after many years underground; they do not offer suitable information e.g. about operational stability and procedures during the running periods, and generally base their analysis on a particular *a priori* assumption on the nature of the DM particle and its interaction, and of all the used parameters.

In particular, the applied rejection and subtraction procedures to reduce the experimental counting rate, in order to derive a set of recoil-like candidates, is pursued by experiments as CDMS, EDELWEISS, CRESST, XENON, LUX, etc.. It is worth noting that the applied subtraction procedures are statistical and cannot offer an unambiguous identification of the presence of DM particle elastic scatterings because of the known existing recoil-like indistinguishable background; tails of the subtracted populations can play a role as well. Finally, the electromagnetic component of the counting rate, statistically "rejected" in this approach, can contain either the signal or part of it, and it will be lost. In the following few main experimental activities are mentioned as examples. Some arguments can be also found in Ref. [11, 12].

In the double read-out bolometric technique, the heat signal and the ionization signal are used in order to discriminate between electromagnetic and recoil-like events. This technique is used by CDMS and EDELWEISS collaborations. In particular, the CDMS-II detector consisted of 19 Ge bolometers of about 230 g each one and of 11 Si bolometers of about 100 g each one. The experiment released data for an exposure of about 194 kg × day using only 10 Ge detectors in the analysis (discarding all the data collected with the other ones) and considering selected time periods for each detector [13]. EDELWEISS employed a target fiducial mass of about 2 kg of Ge and has released data for an exposure of 384 kg × day collected in two different periods (July-Nov 08 and April 09-May 10) with a 17% reduction of exposure due to run selection [14]. These two experiments claim an "event by event" discrimination between noise + electromagnetic background and recoil + recoil-like (neutrons, end-range alphas, fission fragments,...) events by comparing the bolometer and the ionizing signals for each event. Thus, their results are, actually, largely based on huge data selections, as for example, the time cut analysis used to remove the so-called surface electrons that are distributed in both the electromagnetic and recoil bands. The stability, the nonlinear response and the robustness of the reconstruction procedure are key points, as well as the associated systematical errors. In these experiments few recoil-like

events survive the many selections/subtractions cuts applied in the data analysis; these events are generally interpreted in terms of background. As regards, in particular, their application to the search for time dependence of the data (such as the annual modulation signature), it would require – among other – to face the objective difficulty to control all the operating conditions – at the needed level ($< 1\%$) – despite of the required periodical procedures e.g. for cooling and for calibration and owing to the limitation arising from the low duty cycle. For example, the attempt by CDMS-II to search for annual modulation in Ge target has been performed with a marginal exposure by using only 8 detectors over 30 and using – among others – data that are not continuous over the whole annual periods considered in the analysis [15] the use of non-overlapping time periods, collected with detectors having different background rate within the signal box does not allow one to get any reliable result in the investigation of an effect at few percent level (see e.g. arguments in Ref. [16]).

Other data taking was dedicated to measurements using a calorimetric technique, named CDMSlite, which relies on voltage-assisted Luke-Neganov amplification of the ionization energy deposited by particle interactions [17]. The data were collected with a single 0.6 kg germanium detector running for ten live days at the Soudan Underground Laboratory. A low energy threshold of 170 eV$_{ee}$ (electron equivalent) was claimed [17], while recent data taking achieved even lower energy threshold [18]. In the meanwhile SuperCDMS at SNOlab [19] reported preliminary results corresponding to an exposure of 577 kg × days with an increased mass of 9.0 kg (15 detectors of 600 g each) and with increased detectors' performances [20]. Eleven events were observed not fully compatible with background expectation, even assuming the correctness of all the adopted procedures [20].

The results of CDMS-II with the Si detectors were published in two close-in-time data releases [21, 22]; while no events in six detectors (corresponding exposure of only 55.9 kg×day before analysis cuts) were reported in the former [21], three events in eight detectors (corresponding raw exposure of 140.2 kg×day) were reported over the residual background, estimated after subtraction: $\simeq 0.4$ in the second one [22]. The latter result could be interpreted – under certain assumptions – in terms of a DM candidate with spin-independent interaction and a mass around 10 GeV, which is compatible with some interpretations of the model independent DM annual modulation result already reported by DAMA in terms of this kind of DM candidate and with some other hints reported by CoGeNT (see later).

In the meanwhile EDELWEISS was in data taking in the period July 2014 – April 2015 and restarted in June 2015 with 36 detectors installed corresponding to a target fiducial mass of more than 14 kg of Ge [23]; new results collected with eight FID (Full Inter Digitized) detectors (582 kg × day) have been recently presented [24].

The CRESST experiment exploits the double read-out bolometric technique, using the heat signal due to an interacting particle in the CaWO$_4$ crystals and the produced scintillation light. A statistical discrimination of nuclear recoil-like events from electromagnetic radiation is performed. As regards the applied cuts and selection procedures, most of the above discussion still holds. A previous run (8 detectors of 300 g each one, for an exposure of about 730 kg × day) showed that, after selections, 67 nuclear recoil-like events were observed in the Oxygen band [25]. The background contribution estimated by authors ranges from 37 to 43 events, and does not account for all the observed events. The remaining number of events and their energy distribution could be interpreted – under certain assumptions – in terms of a DM candidate with spin-independent interaction and a mass in the range of 10-30 GeV. This result has been not confirmed in the last run [26], where a more marginal exposure has been used (52 kg × day and energy threshold of 307 eV), confirming the difficulties to manage the systematics in such experiments.

The new version of CRESST (CRESST-III) will use new detector modules of 24 g each trying to attain low energy thresholds. Projects of large mass bolometers are also planned in Europe

(EURECA) and at SNOlab.

The XENON project uses instead dual phase liquid/gas detectors. Experiments exploiting such technique (as also LUX, DARKSIDE) perform statistical discrimination between nuclear recoil-like candidates and electromagnetic component of the measured counting rate through the ratio of the prompt scintillation signal ($S1$) and the delayed signal ($S2$) due to drifted electrons in the gaseous phase. The XENON100 experiment has released data taken in the years 2011–2012 for an exposure of 224.6 days, using a fiducial volume of just 34 kg of Xenon target mass [27]. See related discussions in literature about the detector response of such devices, in particular, to low energy recoils [11, 12, 28]. The technical performance of the apparata, confirmed also by similar experiments, has shown e.g. that: i) the detectors are affected by large non-uniformity; some kind of corrections may be estimated and applied, but significant systematics has to be accounted for; ii) the response of these detectors is not linear, i.e. the number of photoelectrons/keV depends on the energy scale and depends also on the applied electric field; iii) the physical energy threshold is not suitably proved iv) the use of energy calibration lines from Xe activated by neutrons cannot be applied as routine and the studies on a possible calibration with internal sources in the same running conditions have not been realized so far; v) despite of the small light response (2.28 photoelectron/keVee), an energy threshold at 1.3 keVee is claimed; vi) the energy resolution is poor; vii) in the scale-up of the detectors the performances deteriorate; viii) the behaviour of the light yield for recoils at low energy is uncertain in every case. LUX – a dual phase TPC filled with Xenon – reports the first results corresponding to an exposure of 85.3 days, using a fiducial volume of 118 kg [29]; the last data release refers to about 1.4×10^4 kg $\times$ day [30]. On the other hand, the first result of DARKSIDE has been obtained with the TPC filled with atmospheric Argon for an exposure of 1422 kg $\times$ day [31]. Similar considerations, as above, hold about the robustness of these results. Moreover, such considerations become still more restrictive when considering the future plans of larger set-ups [11, 12].

A positive hint for a signal of light DM candidates inducing just nuclear elastic scatterings has been also reported by the CoGeNT experiment [32, 33]. The set-up is composed by a 440 g, p-type point contact (PPC) Ge diode, with a very low energy threshold at 0.4 keVee. It is located in the Soudan Underground Laboratory. In the data analysis no discrimination between electromagnetic radiation and nuclear recoils is applied; only noise events are rejected. The experiment observes more events than they expect from estimate of the background in the energy range 0.4-3.2 keVee. The energy spectrum of these events is compatible – under certain assumptions – with a signal produced by the interaction of a DM particle with a mass around 10 GeV. In addition, considering an exposure of 146 kg $\times$ days CoGeNT experiment also reports an evidence at about 2.2σ C.L. of an annual modulation of the counting rate in (0.5-2) keVee with phase and period compatible – although the small confidence level – with a DM signal [33]. This result is compatible with interpretations of the DM model-independent annual modulation result already reported by DAMA in terms of this kind of DM candidate and with the possible hint reported above. A new data release is planned in the incoming months, and CoGeNT is upgrading towards C-4 with the aim to improve by a factor four the total mass, to decrease the total background and to reduce substantially the energy threshold; Soudan is still the laboratory. Other activities exploiting Ge detectors are Texono and CDEX at CJPL, the Chinese underground laboratory.

Finally, activities using inorganic scintillators are in progress and at the R&D stage; in particular here we remind the efforts of the long-standing ANAIS project whose goal is to run about 100 kg of NaI(Tl) at Canfranc laboratory in Spain [34].

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

3. 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 [35]. 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 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). 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 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. [6, 36]. 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.

4. 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 (≃ 100 kg sensitive mass) experiment [1, 8, 9, 10, 37, 38, 39, 40, 41, 42], and by the currently running DAMA/LIBRA (≃ 250 kg sensitive mass) [43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57], 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. [43, 44, 45, 46, 48, 49, 55, 50] 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. [43, 37, 39] 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 [43]. 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 [43, 37]. Energy calibration with X-rays/γ sources are regularly carried out in the same running condition down to few keV [43]; 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. [43]). The radiopurity, the procedures and details are discussed in Ref. [43, 44, 45, 46, 50] and references therein.
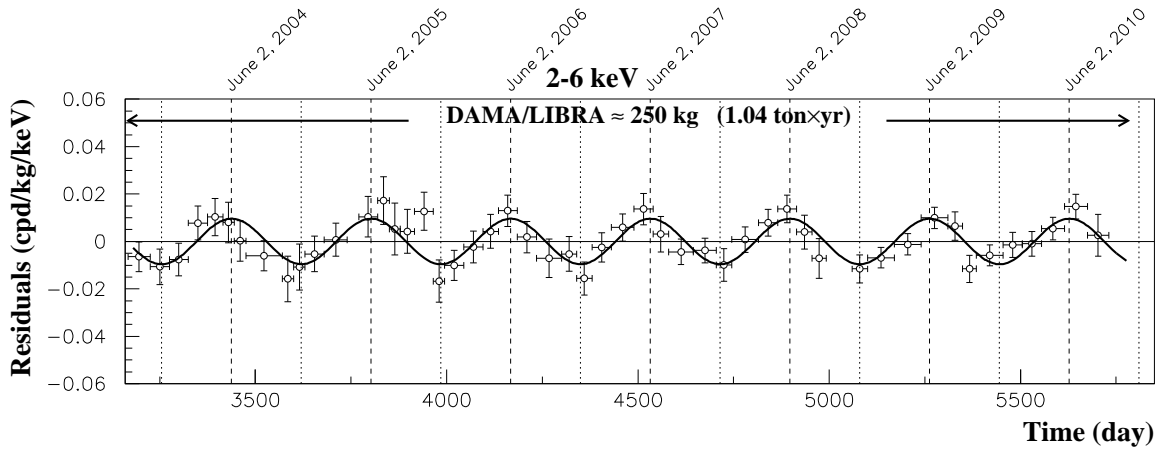

Figure 1. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time. The superimposed curve is the cosinusoidal function behaviour $A\cos\omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, a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

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 [44, 45, 46, 50]. 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 2nd) 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 σ 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 σ 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 2nd and is fully consistent with the value independently determined by Maximum Likelihood analysis [46].

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 [41, 58, 59] and the caustics [60]. For more details see Ref. [46].

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 [44, 45, 46]. In particular, for the (2–6) keV energy interval the χ^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.

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. [50]. A clear peak corresponding to a period of 1 year (see Fig. 2 – *left*) is evident for the (2–6) keV 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. [50]).
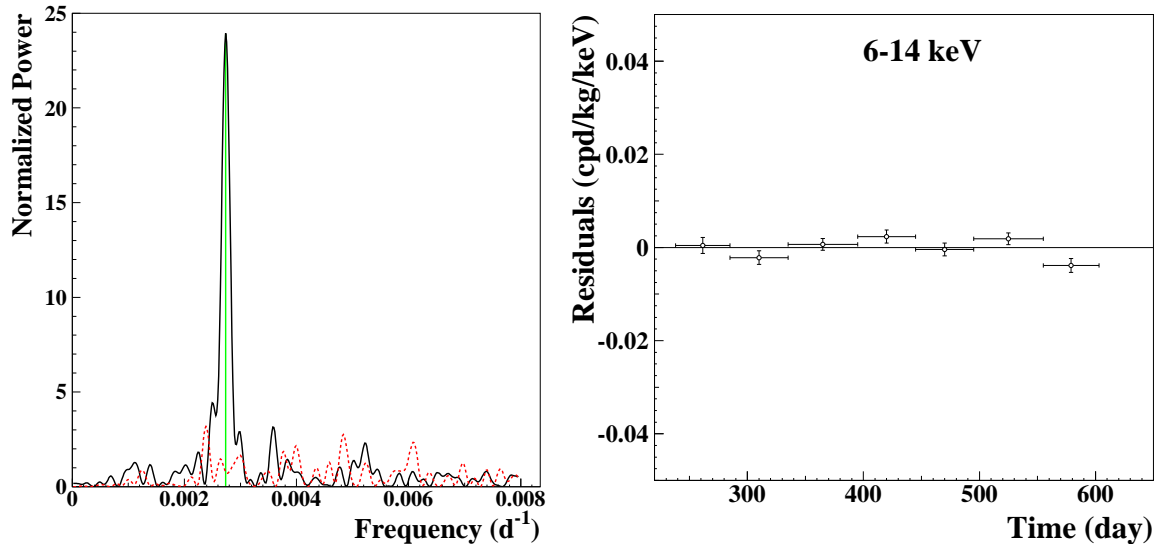

Figure 2. *Left:* Power spectrum of the measured *single-hit* residuals in the (2–6) keV (solid lines) and (6–14) keV (dotted lines) energy intervals calculated according to Ref. [50], including also the treatment of the experimental errors and of the time binning. The data refer to DAMA/NaI and DAMA/LIBRA–phase1. As it can be seen, the principal mode present in the (2–6) keV energy interval corresponds to a frequency of 2.737×10^{-3} d^{-1} (vertical lines), corresponding to a period of $\simeq 1$ year. A similar peak is not present in the (6–14) keV energy interval. *Right:* Experimental *single-hit* residuals in the (6–14) keV energy region 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. The amplitude is well compatible with zero: A=(0.00032 $\pm$ 0.00076) cpd/kg/keV.

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 [46]. Similar result is obtained in other energy intervals; for example Fig. 2 – *right* shows the *single-hit* residuals in the (6–14) keV energy region 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 Ref. [43, 44, 45, 46, 49, 50, 54, 61, 62, 63, 64, 65, 66, 67]).
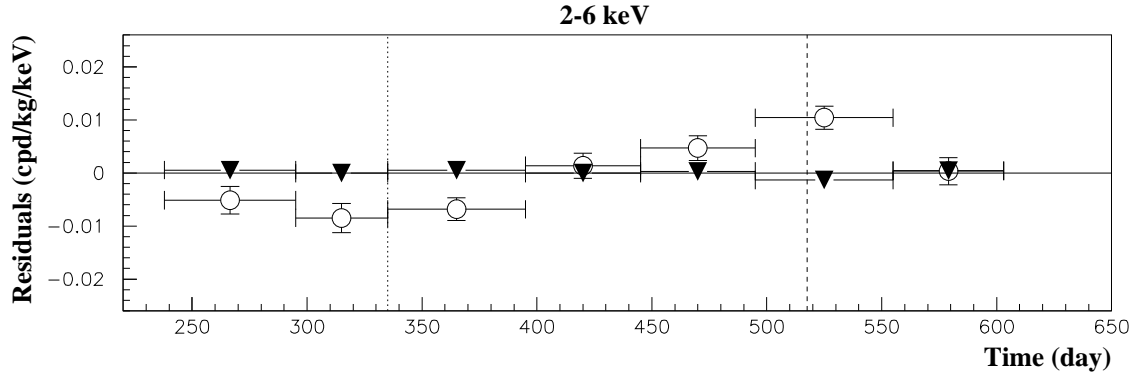

Figure 3. Experimental residual rates of DAMA/LIBRA–phase1 *single-hit* events (open circles), class of events to which DM events belong, and for *multiple-hit* events (filled triangles), class of events to which DM events do not belong. They have been obtained by considering for each class of events 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 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 [40].

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. 3 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 results were also obtained for the last two annual cycles of the DAMA/NaI experiment [40]. 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 $\mu_{ijk} = [b_{jk} + S_{ik}] M_j \Delta t_i \Delta E \epsilon_{jk}$. The b_{jk} are the background contributions, M_j is the mass of the $j-$th detector, Δt_i is the detector running time during the i-th time interval, ΔE is the chosen energy bin, ϵ_{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. 4 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 χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability of 15%). All this confirms the previous analyses.
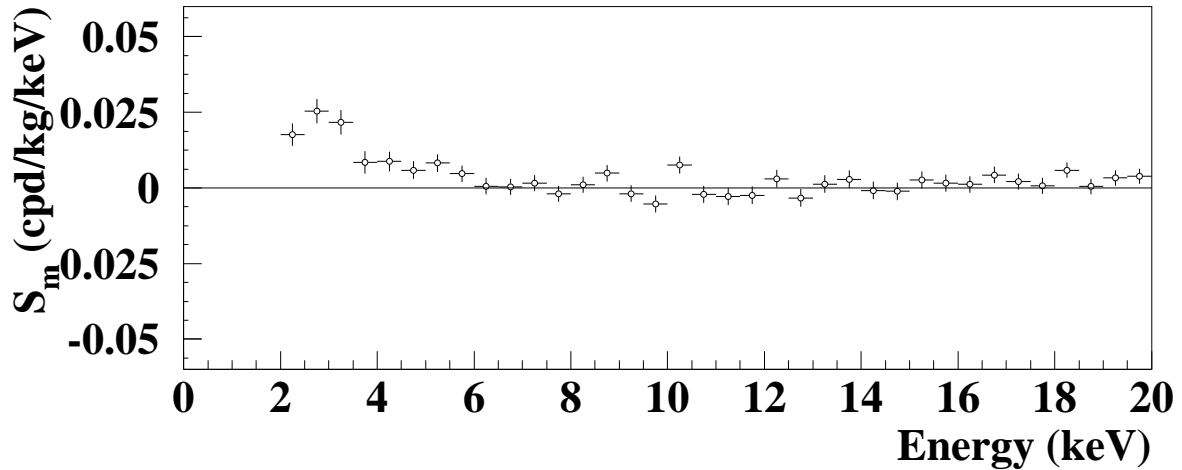

Figure 4. Energy distribution of the S_m variable for the total cumulative exposure 1.33 ton×yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability of 15%).

As described in Ref. [44, 45, 46, 50], 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 has been verified by χ^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:

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

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 [41, 58, 59] and the caustics [60].

Table 1. Best fit values for the (2–6) and (6–14) keV energy intervals (1σ 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. 5.

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

Considering cumulatively the data of DAMA/NaI and DAMA/LIBRA–phase1 the obtained 2σ contours in the plane (S_m, Z_m) for the (2–6) keV and (6–14) keV energy intervals are shown in Fig. 5–*left* while in Fig. 5–*right* the obtained 2σ contours in the plane (Y_m, t^*) are depicted. The best fit values for the (2–6) and (6–14) keV energy intervals (1σ errors) for S_m versus Z_m and Y_m versus t^* are reported in Table 1.

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 [44, 45, 46].

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. [44, 45, 46, 38, 39, 40, 49, 55]). 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 [39, 40].

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.

In particular, in Refs. [49, 55] 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 2 summarizes the safety upper limits on the contributions to the observed modulation amplitude due to the total neutron flux at LNGS, either from (α, 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
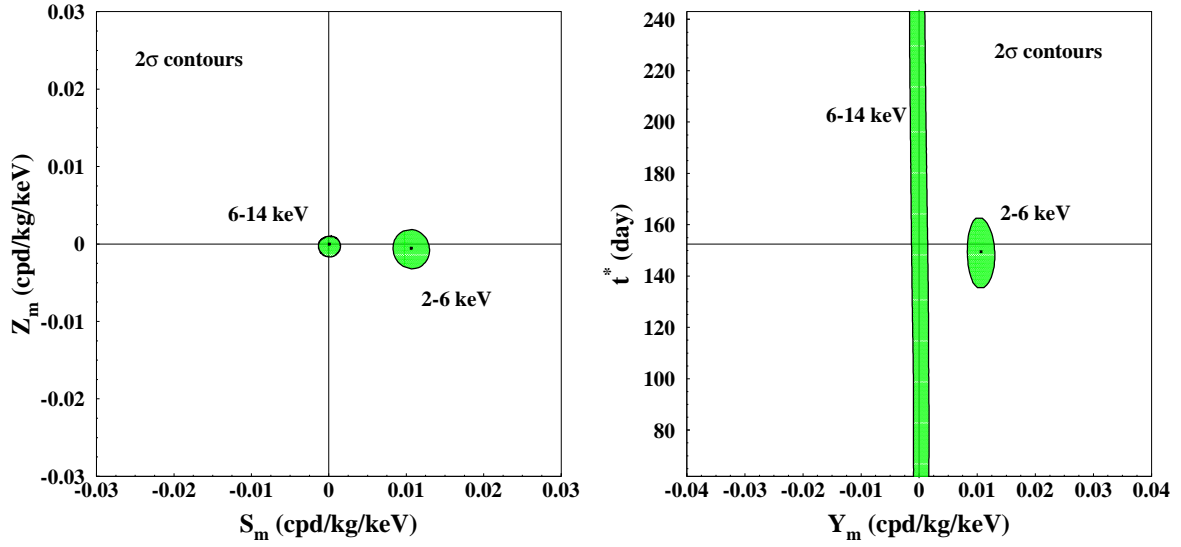
Figure 5. 2σ contours in the plane (S_m, Z_m) (*left*) and in the plane (Y_m, t^*) (*right*) for the $(2-6)$ keV and $(6-14)$ keV energy intervals. The contours have been obtained by the maximum likelihood method, considering the cumulative exposure of DAMA/NaI and DAMA/LIBRA–phase1. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. See text.

Table 2. Summary of the contributions to the total neutron flux at LNGS; the value, $\Phi_{0,k}^{(n)}$, the relative modulation amplitude, η_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 [46]. For details see Ref. [55] and references therein.

	Source	$\Phi_{0,k}^{(n)}$ (neutrons cm^{-2} s^{-1})	η_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)	1.08×10^{-6}	$\simeq 0$ however $\ll 0.1$	–	$< 8 \times 10^{-6}$	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6}	$\simeq 0$ 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)	$\simeq 0.9 \times 10^{-7}$	$\simeq 0$ 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 μ	$\Phi_0^{(\mu)} \simeq 20 \ \mu$ m^{-2}d^{-1}	0.0129	end of June	$\simeq 10^{-7}$	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi_0^{(\nu)} \simeq 6 \times 10^{10} \ \nu$ cm^{-2}s^{-1}	0.03342*	Jan. 4th*	$\simeq 10^{-5}$	3×10^{-7}	3×10^{-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.

signature have been found. A detailed discussion about all the related arguments can be found in Refs. [43, 44, 45, 46, 49, 50, 54, 38, 39, 40, 55].

Analyses on the presence of possible diurnal effects in the DAMA/LIBRA–phase1 data [54] and on the so called "Earth Shadow Effect" [56] will be summarized in the following. Finally, the annual modulation result has been also interpreted in terms of Asymmetric Mirror DM [57], as briefly shown later.

5. 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. [39, 40, 10, 41, 1, 42, 9, 8, 44, 50] and references therein, and recently e.g. in Refs. [68, 57] . Further large literature is available on the topics (see for example in Ref. [50]) 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. [39, 44, 40, 11, 12, 28]). 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.

5.1. The case of Asymmetric Mirror DM

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 [57].

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 ϵ 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 7.7×10^{-10} to 1.1×10^{-7}; they are well compatible with cosmological bounds [57].

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
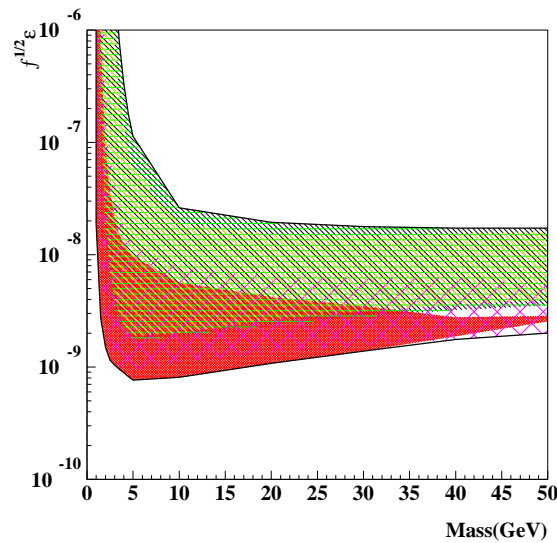
Figure 6. Allowed regions for the $\sqrt{f}\epsilon$ parameter as function of mirror hydrogen mass, obtained by marginalizing all the models for each considered scenario. The allowed intervals identify the $\sqrt{f}\epsilon$ values corresponding to C.L. larger than 5σ from the *null hypothesis*, that 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. [57].

considered scenario, are shown in Fig. 6. Five scenarios are reported with different hatching of the allowed regions.

6. Other signatures?

In the framework of direct DM investigations crystal scintillators represent a reliable technology to investigate model independent signatures. An apparatus made by an array of such detectors, in addition to the already mentioned advantages, allows a long term stability and effective routine calibrations down to keV energy region in the same conditions as production runs. Moreover due to the wide choice of nuclei and isotopes, they are sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios. In particular in order to disentangle in the corollary investigation on the candidate particle(s) at least some of the many possible astrophysical, nuclear and particle Physics scenarios and related experimental and theoretical uncertainties, the decreasing of the software energy threshold and higher exposures are necessary.

Finally, the only effective method for such studies is the investigation of a model independent signature and of second order effects.

Many topics can be investigated:

- the peculiarities of the annual modulation phase;
- the peculiarities of the DM interaction mechanisms;
- the velocity and spatial distribution of the DM particles in the galactic halo;
- the effects induced on the DM particles distribution in the galactic halo by contributions from satellite galaxies tidal streams;
- the effects induced on the DM particles distribution in the galactic halo by the possible existence of caustics;
- the detection of possible solar wakes or gravitational focusing effect of the Sun on the DM particle;

- the investigation of possible diurnal effects and so on.

Some of these studies already started with DAMA/LIBRA–phase1([54, 50, 69] and references therein), but a further important step towards such investigations will be represented by the larger exposure collected by DAMA/LIBRA–phase2, with lower energy threshold.

6.1. 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 [54]. 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:

$$R_{dy} = \frac{S_d}{S_m} \simeq 0.016 \tag{2}$$

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 ± 0.0013) cpd/kg/keV [46] and the expected value of the diurnal modulation amplitude is $\simeq 1.5 \times 10^{-4}$ cpd/kg/keV.

Fig. 7 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 and (6–14) keV intervals. The used time bin is 1 (either solar or sidereal) hour.

The null hypothesis (absence of residual rate diurnal variation) has been tested by a χ^2 test, obtaining the results given in Table 3; there the upper tail probabilities (P-values), calculated by the standard χ^2 distribution, are also reported. Thus, no diurnal variation with a significance of 95% C.L. is found at the reached level of sensitivity.

Table 3. Test of absence of diurnal effect in the DAMA/LIBRA–phase1 data. The P-values, calculated by the standard χ^2 distribution, are also shown. As can be seen, the χ^2 test supports the hypothesis that the diurnal residual rates in DAMA/LIBRA–phase1 are simply fluctuating around zero.

Energy	Solar Time	Sidereal Time
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24 → P = 6%

In addition to the χ^2 test, another independent statistical test has been applied: the run test [54] ; it verifies the hypothesis that the positive and negative data points are randomly distributed. The lower tail probabilities are equal to: 7% and 26% in the (2–6) and (6-14) keV energy region, respectively, for the solar case and 78% and 16% in the (2–6) and (6-14) keV energy region, respectively, for the sidereal case. Thus, in conclusion the presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity (see Fig. 7).
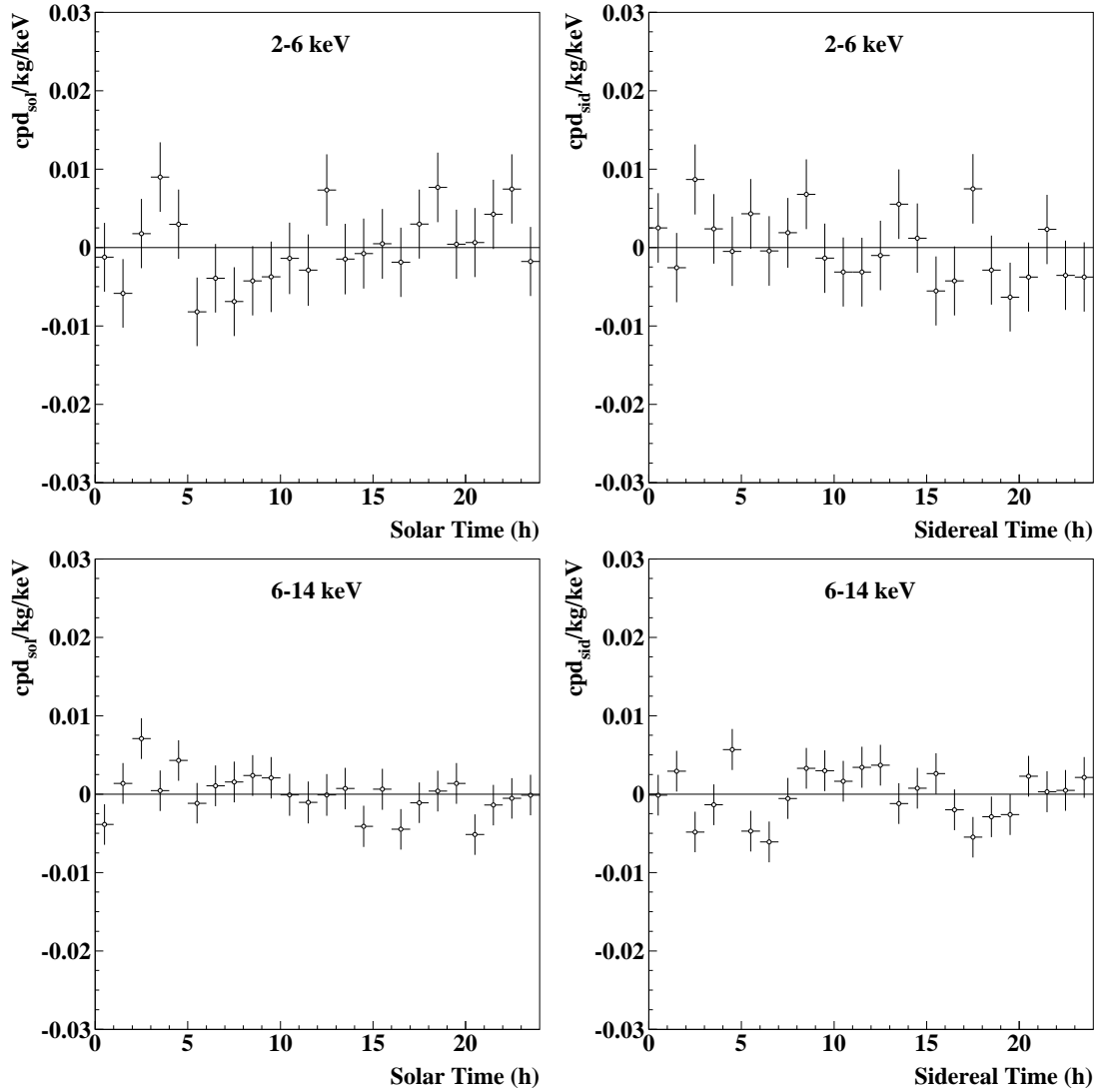
Figure 7. Experimental model-independent diurnal residual rate of the *single-hit* scintillation events, measured by DAMA/LIBRA–phase1 in the (2–6) and (6–14) keV energy intervals as a function of the hour of the solar (*left*) and sidereal (*right*) day. The experimental points present the errors as vertical bars and the associated time bin width (1 hour) as horizontal bars. The cumulative exposure is 1.04 ton × yr. See Ref. [54] for details.

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 [54].

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 [48] can also offer the possibility to increase sensitivity to such an effect.

6.2. 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 (1.04 ton × year exposure) have been analysed in terms of Earth Shadow Effect, a model-dependent effect that could be expected in case of DM candidates inducing just nuclear recoils and having high cross-section with ordinary matter, which implies low DM local density in order to fulfil the DAMA/LIBRA DM annual modulation results [56].

In fact a diurnal variation of the low energy rate could be expected [70, 71] for these specific candidates, because during the sidereal day the Earth shields a given detector with a variable thickness, eclipsing the wind of DM particles. The induced effect should be a daily variation of their velocity distribution, therefore of their flux and, of course, 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 that could constitute a little fraction (ξ) in the Galactic dark halo.

The Earth's velocity in the galactic frame, $\vec{v}_e(t)$[1], defines an angle, θ, with the vector joining the center of the Earth to the position of the laboratory. Because of the Earth's rotational motion, the θ angle varies with the diurnal sidereal time and ranges between a minimum and a maximum which depend on the laboratory position on the Earth. In particular the larger is the allowed range of θ the larger is the effect resulting. The time dependence of θ can be expressed as a function of the laboratory latitude, λ, according to $\cos\theta(t) = \cos\psi\cos\lambda\cos(\omega t + \phi_0) + \sin\psi\sin\lambda$, where $\omega = (2\pi/24^h)$ is the Earth's angular rotational velocity and t the sidereal time in hours. The angles $\psi = (48.1)^0$ and $\phi_0 = (42.4)^0$ depend on the orientation of the Earth axis in the galactic frame [72].

By the fact, the diurnal variation of the velocity distribution and of the counting rate proves undetectable for cross-sections on nucleon $\sigma_n \leq 10^{-3}$ pb (being the latter dependent on the DM particle mass m_{DM}), since the Earth is practically transparent to similar particles, while high cross-section values give velocity distributions (and counting rates) significantly dependent on the considered time interval, producing a well detectable diurnal effect.

A study on diurnal variation in the rate with suitable exposure and stability could allow to investigate in some model scenarios high cross sections DM particle component (with small ξ) in the dark halo and decouple ξ from σ_n.

In particular, for each set of parameters [56], one can evaluate the $\xi\sigma_n$ allowed values as:

$$\xi\sigma_n = \frac{S_m^{exp}}{S'_{m,(2-4)keV}(m_{DM},\sigma_n)}. \tag{3}$$

This corresponds, once including the experimental uncertainties on S_m^{exp}, to a band in the ξ vs σ_n plane.

Finally, for each considered set of parameters the three-dimensional allowed region in the parameter's space: ξ, σ_n, m_{DM} can be studied including the positive results from the DM annual modulation analysis of the DAMA/LIBRA–phase1 data [46], as reported for example in Fig. 8. In this considered scenario for quenching factors Q_I with *channeling* effect [56], B parameters set, $v_0 = 220$ km/s and $m_{DM} = 60$ GeV, the obtained upper limits on ξ do exclude $\sigma_n > 0.05$ pb and $\xi > 10^{-3}$. When also including other uncertainties as other halo models, etc. the results would be extended [56].

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[1] The Earth's orbital speed around the Sun, which is the most relevant component for the annual modulation signature among the terms contributing to $\vec{v}_e(t)$, can be neglected in the present case because the data, taken in different periods during the year, contribute approximately to the same diurnal time intervals.
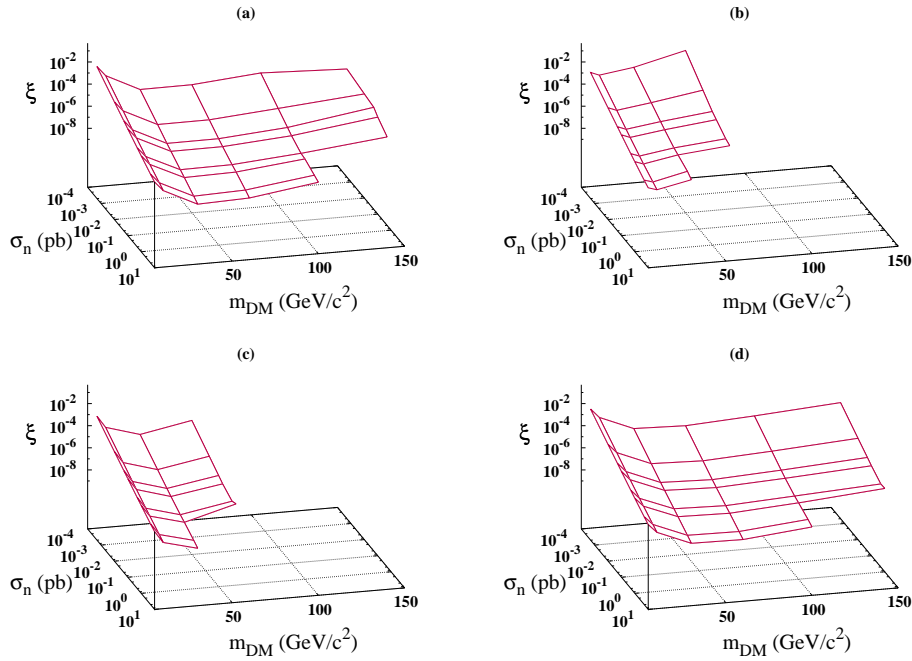
Figure 8. Examples of the mean values of the allowed region of ξ as function of σ_n and m_{DM}, represented as an allowed surface. The plots have been obtained for $v_0 = 220$ km/s by considering different scenarios regarding quenching factors value and other uncertainties [56]. We note that the "thickness" of the allowed regions around the surfaces is $\leq \pm 30\%$; therefore, for simplicity it is not represented in these figures. Finally, we recall that other uncertainties not considered here are present and can extend the result [56].

6.3. Directionality with anisotropic scintillators

The directionality approach – based on the study of the correlation between the recoil direction of the target nuclei and the Earth motion in the galactic rest frame – can offer a good approach to study those DM candidate particles able to induce just nuclear recoils. In fact, the dynamics of the rotation of the Milky Way galactic disc through the halo of DM causes the Earth to experience a wind of DM particles apparently flowing along a direction opposite to that of the solar motion relative to the DM halo. Hence, in the case of DM candidate particles interacting with nuclei the induced nuclear recoils are expected to be strongly correlated with the impinging direction of DM, while the background events are not; therefore, the study of the nuclear recoils direction can offer a way for pointing out the presence of these DM candidate particles.

In the practice, this approach has some technical difficulties because it is arduous to detect the short recoil track. Different techniques are under consideration but, up to now, they are at R&D stage and have not produced yet competitive results in the field (see e.g. DRIFT [73], DMTPC [74], DAMIC [75], or NEWS [76]). In fact, they are generally limited by the difficulty of detecting very short tracks and of achieving high stability, large sensitive volume and very good spatial resolution.

To overcome such a difficulty, it has been suggested the use of anisotropic scintillator detectors [77, 78, 79]; their use was proposed for the first time in Ref. [77] and revisited in Ref. [78]. In particular, low background ZnWO$_4$ crystal scintillators have been recently proposed since their features and performances are very promising [80]. In fact, both the light output and the scintillation pulse shape depend on the impinging direction of heavy particles (p, alpha, nuclear

recoils, etc.) with respect to the crystal axes and can supply two independent ways to study the directionality and to discriminate the electromagnetic background (that does not give rise to any anisotropic effects).

Other advantages offered by $ZnWO_4$ detectors are very good radio-purity levels (about 0.1 cpd/kg/keV at low energy) and the potentiality to reach energy thresholds at keV level. Both these features can also be improved (e.g., the light yield shows a significant enhancement when working at low temperatures – about 100 K – and better radiopurity levels can be reached with dedicated R&D). A detailed discussion can be found in Ref. [80].

7. DAMA/LIBRA–phase2 and perspectives

After a first upgrade of the DAMA/LIBRA set-up in September 2008, a more important upgrade has been performed at the end of 2010 when all the PMTs have been replaced with new ones having higher Quantum Efficiency (Q.E.), realized with a special dedicated development by HAMAMATSU co.. Details on the developments and on the reached performances in the operative conditions are reported in Ref. [48]. We remind that up to October 2010 low background PMTs, developed by EMI-Electron Tubes with dedicated R&D, were used; the light yield and other response features already allowed in DAMA/NaI and DAMA/LIBRA–phase1 a software energy threshold of 2 keV in the data analysis. The feasibility to decrease the software energy threshold below 2 keV in the new configuration has been demonstrated [48].

Since the fulfillment of this upgrade, DAMA/LIBRA–phase2 – after optimization periods – is continuously running in order: (1) to increase the experimental sensitivity lowering the 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 and second order effects. This requires long and heavy full time dedicated work for reliable collection and analysis of very large exposures. DAMA/LIBRA also continue its study on several other rare processes [51, 52, 53, 54, 55, 56, 57].

Another upgrade at the end of 2012 was successfully concluded: new-concept preamplifiers were installed, with suitable operative and electronic features; in particular, they allow the direct connection of the signal to the relative channel of the Transient Digitizer (TD). Moreover, further improvements are planned; in particular, new trigger modules have been prepared and ready to be installed.

In the future DAMA/LIBRA will also continue its study on several other rare processes [51, 52, 53] as also the former DAMA/NaI apparatus did [81].

Finally, further improvements to increase the sensitivity of the set-up can be considered; in particular, the use of high Q.E. and ultra-low background PMTs directly coupled to the NaI(Tl) crystals is an interesting possibility[2]. This possible configuration can allow a further large improvement in the light collection and a further lowering of the software energy threshold. Moreover, efforts towards a possible highly radiopure NaI(Tl) "general purpose" experiment (DAMA/1ton) having full sensitive mass of 1 ton (we already proposed in 1996 as a general purpose set-up) have been continued in various aspects.

8. Conclusions

Large efforts are in progress with different approaches and target materials to investigate various kinds of DM candidates and scenarios. Due to the difficulty of measuring at very low energy, several techniques still would require further work for results' qualifications before enlarging their target mass.

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[2] However, this would require the disassembling of the detectors since the light guides act at present also as optical windows.

As regards the possibility to exploit the directionality for some DM candidates, new efforts have to be encouraged towards a first realistic exploitation.

The DM model independent annual modulation signature with widely sensitive target materials still remains a major approach, offering an unique possibility for detection; it requires well known techniques, full proved detector stability, well known and proved detector response in all the aspects, etc. At present the DAMA positive model independent evidence for the presence of DM particles in the galactic halo is supported at very high confidence level. It has been shown in literature that this is compatible with many DM scenarios.

I have been also recalled the recent possible positive hints exploiting different approaches and different target materials, and the existing uncertainties in the model dependent results and comparisons.

Finally very useful complementary results can arise from experiment exploiting other target detectors and approaches adopting adequately safe experimental procedures.

9. Acknowledgements

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