



## 2 Results on DAMA/LIBRA-Phase1 and Perspectives of the Phase2 \*

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**Abstract.** The DAMA/LIBRA experiment consists of  $\sim 250$  kg of highly radio-pure NaI(Tl) and it is in data taking in the underground Laboratory of Gran Sasso (LNGS). The data collected in its first 7 annual cycles, corresponding to the so called DAMA/LIBRA-phase1, have been released. Considering also of the former DAMA/NaI experiment (their cumulative exposure is  $1.33 \text{ ton} \times \text{yr}$ ), the data of 14 independent annual cycles have been analysed to exploit the model-independent Dark Matter (DM) annual modulation signature. An annual modulation effect has been observed at  $9.3 \sigma$  C.L., giving evidence for the presence of DM particles in the galactic halo. No systematic or side reaction able to mimic the exploited DM signature has been found or suggested by anyone. At present DAMA/LIBRA is running after an upgrade of the experiment in its phase2 with increased sensitivity. The model independent result of DAMA is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear and particle Physics. Here, after briefly reporting the DAMA model independent results, the recent analysis in terms of Mirror Dark Matter candidate will be mentioned.

**Povzetek.** Experiment DAMA/LIBRA, ki je postavljen v podzemeljskem laboratoriju Gran Sasso (LNGS), uporablja  $\sim 250$  kg NaI(Tl) z visoko čistočo. Posebej predstavijo analizo meritev Faze I iz zadnjih sedmih let, tem meritvam pa dodajo tudi meritve sedmih let predhodnega experimenta DAMA/NaI (s kumulativno ekspozicijo  $1.33 \text{ ton} \times \text{let}$ ). Letno modulacijo sipanih delcev potrdijo z zanesljivostjo  $9.3 \sigma$ , kar je, ob sistematičnem iskanju drugih vzrokov za izmerjeno modulacijo, mogoče pripisati samo prisotnosti delcev temne snovi v

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galaktičnem haloju. Zdaj teče posodobljen experiment, faza 2, s povečano občutljivostjo merjenja ozadja. Rezultate poskusa je mogoče razložiti z različnimi modeli, ki poskušajo pojasniti temno snov v vesolju. Omenijo možnost, da pojasni prisotnost temne snovi delec, ki pripada zrcalni temni snovi.

## 2.1 Introduction

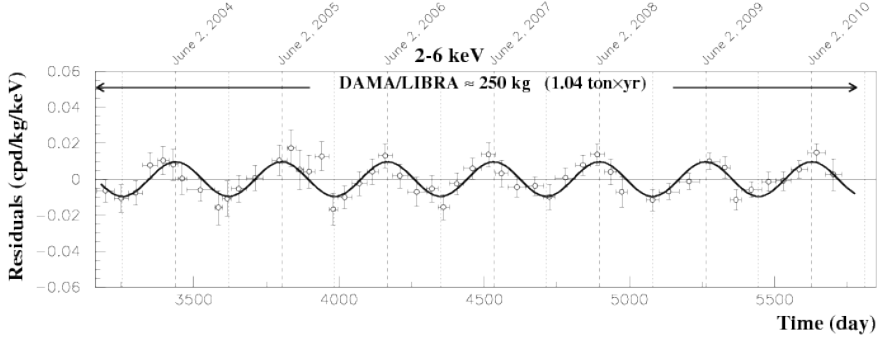
The DAMA project is based on the development and use of low background scintillators. In particular, the second generation DAMA/LIBRA apparatus [1–15], as the former DAMA/NaI (see for example Refs. [8,16,17] and references therein), is further investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature [18]. At present DAMA/LIBRA is running in its phase2 with increased sensitivity.

The signature exploited by DAMA/LIBRA (the model independent DM annual modulation) is a consequence of the Earth’s revolution around the Sun; in fact, the Earth should be crossed by a larger flux of DM particles around  $\simeq 2$  June (when the projection of the Earth orbital velocity on the Sun velocity with respect to the Galaxy is maximum) and by a smaller one around  $\simeq 2$  December (when the two velocities are opposite). This DM annual modulation signature is very effective since the effect induced by DM particles must simultaneously satisfy many requirements: the rate must contain a component modulated according to a cosine function (1) with one year period (2) and a phase peaked roughly  $\simeq 2$  June (3); this modulation must only be found in a well-defined low energy range, where DM particle induced events can be present (4); it must apply only to those events in which just one detector of many actually “fires” (*single-hit* events), since the DM particle multi-interaction probability is negligible (5); the modulation amplitude in the region of maximal sensitivity must be  $\simeq 7\%$  for usually adopted halo distributions (6), but it can be larger (even up to  $\simeq 30\%$ ) in case of some possible scenarios. Thus this signature is model independent and it allows the test a large range of cross sections and halo densities. This DM signature might be mimicked only by systematic effects or side reactions able to account for the whole observed modulation amplitude and to simultaneously satisfy all the requirements given above. No one is available [1–4,7,8,12,19,16,17,13].

## 2.2 The annual modulation results

The total exposure of DAMA/LIBRA–phase1 is  $1.04 \text{ ton} \times \text{yr}$  in 7 annual cycles; when including also the data collected by the first generation DAMA/NaI experiment, the exposure is  $1.33 \text{ ton} \times \text{yr}$ , corresponding to 14 annual cycles [2–4,8].

To investigate the presence of an annual modulation in the data many analyses have been carried out. Here, as example, the time behaviour of the experimental residual rate of the *single-hit* scintillation events for DAMA/NaI and DAMA/LIBRA–phase1 in the (2–6) keV energy interval is plotted in Fig. 2.1. The  $\chi^2$  test excludes the hypothesis of absence of modulation in the data (P-value =  $2.2 \times 10^{-3}$ ). 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



**Fig.2.1.** Experimental residual rate of the *single-hit* scintillation events measured by DAMA/NaI and DAMA/LIBRA-phase1 in the (2–6) keV energy interval as a function of the time. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the cosinusoidal functions expected for a Dark Matter signal (period 1 yr and phase June 2<sup>nd</sup>) and modulation amplitudes,  $A$ , as obtained by the fit on the data. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2<sup>nd</sup>), while the dotted vertical lines correspond to the minimum.

period  $T = \frac{2\pi}{\omega} = 1$  yr and a phase  $t_0 = 152.5$  day (June 2<sup>nd</sup>) 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  $(0.0112 \pm 0.0012)$  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<sup>nd</sup> and is fully consistent with the value independently determined by Maximum Likelihood analysis [4]<sup>1</sup>. The run test and the  $\chi^2$  test on the data have shown that the modulation amplitudes singularly calculated for each annual cycle of DAMA/NaI and DAMA/LIBRA-phase1 are normally fluctuating around their best fit values [2–4].

We have also performed a power spectrum analysis of the *single-hit* residuals of DAMA/LIBRA-phase1 and DAMA/NaI [8], obtaining a clear principal mode in the (2–6) keV energy interval at a frequency of  $2.737 \times 10^{-3} \text{ d}^{-1}$ , corresponding to a period of  $\simeq 1$  year, while only aliasing peaks are present in other energy intervals.

Absence of any other significant background modulation in the energy spectrum has been verified in energy regions not of interest for DM [4]; it is worth noting that the obtained results account for 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 whole measured modulation amplitude) is available (see also discussions e.g. in Refs. [1–4,7,8,12,13]).

<sup>1</sup> 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 [20–22] and the caustics [23].

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, the residual rates of the *single-hit* events measured over the DAMA/LIBRA-phase1 annual cycles are reported in Ref. [4] together with the residual rates of the *multiple-hit* events, in the (2–6) keV energy interval. A clear modulation is present in the *single-hit* events, while the fitted modulation amplitude of the *multiple-hit* residual rate in the same energy region (2–6) keV is well compatible with zero:  $-(0.0005 \pm 0.0004)$  cpd/kg/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). 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.

By performing a maximum-likelihood analysis of the *single-hit* scintillation events, it is possible to extract from the data the modulation amplitude,  $S_m$ , as a function of the energy considering  $T = 1$  yr and  $t_0 = 152.5$  day. Again the results have shown that positive signal is present in the (2–6) keV energy interval, while  $S_m$  values compatible with zero are present just above; for details see Ref. [4]. Moreover, as described in Refs. [2–4,8], the observed annual modulation effect is well distributed in all the 25 detectors, the annual cycles and the energy bins at 95% C.L. Further performed analyses confirm that the evidence for the presence of an annual modulation in the data satisfy all the requirements of a DM signal.

Sometimes naive statements were put forward as the fact that in nature several phenomena may show some kind of periodicity. The point is whether they might mimic the annual modulation signature in DAMA/LIBRA (and former DAMA/NaI), i.e. whether they might be not only quantitatively able to account for the observed modulation amplitude but also able to satisfy at the same time all the requirements of the DM annual modulation signature. The same is also for side reactions. A deep investigation is reported in Refs. [1–4] and references therein; additional arguments can be found in Refs. [7,8,12,13]. 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 measured modulation amplitude have been obtained (see Refs. [2–4]). 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 [16,17]. In particular, in Ref. [13] a simple and intuitive way why the neutrons, the muons

and the solar neutrinos cannot give any significant contribution to the DAMA annual modulation results is outlined.

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

As regards comparisons, we recall that no direct model independent comparison is possible in the field when different target materials and/or approaches are used; the same is for the strongly model dependent indirect searches. In particular, the DAMA model independent evidence is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear and particle Physics; for examples some given scenarios and parameters are discussed e.g. in Refs. [2,8,16] and references therein. Further large literature is available on the topics. In conclusion, both negative results and possible positive hints reported in literature are compatible with the DAMA model-independent DM annual modulation results in various scenarios considering also the existing experimental and theoretical uncertainties.

Recently an investigation of possible diurnal effects in the *single-hit* low energy scintillation events collected by DAMA/LIBRA-phase1 has been carried out [12]. In particular, a model-independent diurnal effect with the sidereal time is expected for DM because of Earth rotation. At the present level of sensitivity the presence of any 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 DM diurnal modulation amplitude expected, because of the Earth diurnal motion, on the basis of the DAMA DM annual modulation results is below the present sensitivity [12]. It will be possible to investigate such a diurnal effect with adequate sensitivity only when a much larger exposure will be available; moreover better sensitivities can also be achieved by lowering the software energy threshold as in the presently running DAMA/LIBRA-phase2.

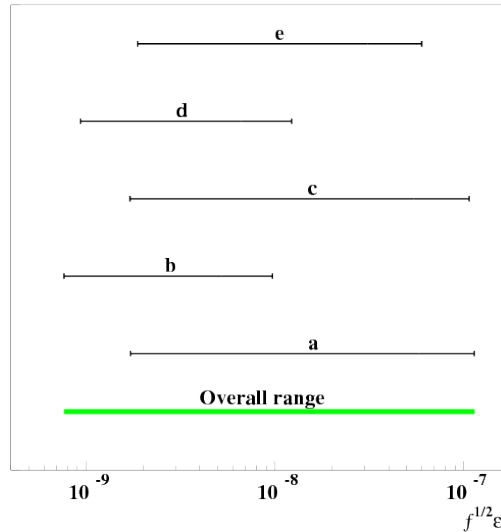
For completeness we recall that recently we have performed also an analysis considering the so called “Earth Shadow Effect” [14]. Other rare processes have also been searched for by DAMA/LIBRA-phase1; see for details Refs. [9–11].

## 2.3 The case of asymmetric mirror matter

The model independent annual modulation effect observed by the DAMA experiments can be related to a variety of interaction mechanisms of DM particles with the detector materials (see for example Ref. [8]). Among all the many possibilities recently the case where the signal is induced by mirror-type dark matter candidates in some scenarios has been considered in collaboration with A. Addazi and Z. Berezhiani (see Ref. [15] and references therein). Here we just recall some arguments.

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. Such a dark sector would consist of elementary leptons (similar to our electron) and baryons (similar to our proton or neutron) composed of shadow quarks which are confined by strong gauge interactions like in our QCD. These two types of particles can be combined in atoms by electromagnetic

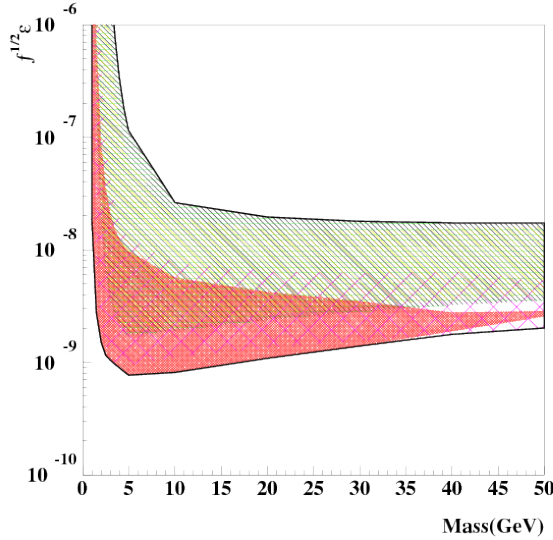
forces mediated by dark photons. The stability of the dark proton is guaranteed by the conservation law of the related baryon number, as the stability of our proton is related to the conservation of the ordinary baryon number. On the other hand, the cosmological abundance of DM in the Universe can be induced by the violation of such baryon number in the early Universe which could produce dark baryon asymmetry by mechanisms similar to those considered for the primordial baryogenesis in the observable sector. In this respect, such type of DM is also known as asymmetric dark matter [15]. In the asymmetric mirror matter considered scheme, 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 our 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. Taking the mirror weak scale e.g. of the order of 10 TeV, the mirror electron would become two orders of magnitude heavier than our electron while the mirror nucleons  $p'$  and  $n'$  only about 5 times heavier than the ordinary nucleons. Then 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. Owing to the large mass of mirror electron, mirror atoms should be more compact and tightly bound with respect to ordinary atoms. Asymmetric mirror model can be considered as a natural benchmark for more generic types of atomic dark matter with *ad hoc* chosen parameters.



**Fig. 2.2.** DAMA allowed intervals for the  $\sqrt{f}\epsilon$  parameter, obtained by marginalizing all the models for each considered scenario as given in Ref. [15]. The overall range is also reported [15].

The annual modulation observed by DAMA in the framework of asymmetric mirror matter has been analysed in the light of the very interesting interaction

portal which is kinetic mixing  $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$  of two massless states, ordinary photon and mirror photon. This mixing mediates the mirror atom (that are very compact objects) scattering off the ordinary target nuclei in the NaI(Tl) detectors at DAMA/LIBRA set-up with the Rutherford-like cross sections.



**Fig. 2.3.** 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. The  $M_{A'}$  interval from few GeV up to 50 GeV is explored. These 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 the five different scenarios are depicted in different hatching; the black line is the overall boundary [15].

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). In the analysis several uncertainties on the astrophysical, particle physics and nuclear physics models have been taken into account in the calculation. For detailed discussion see [15]. In particular in the analysis five scenarios have been considered depending on: i) the adopted quenching factors; ii) either inclusion or not of the channeling effect; iii) either inclusion or not of the Migdal effect. For each scenario the 138 halo models and the relative uncertainties have been considered. To estimate the free parameter of the analysis (e.g.  $\sqrt{f}\epsilon$  in the DM model) a comparison of the expectations of the mirror DM with the experimental results has been performed considering a  $\chi^2$  analysis [15].

In Fig. 2.2 the cumulative allowed intervals of the  $\sqrt{f}\epsilon$  parameter selected by the DAMA data for the mentioned scenario are depicted; the overall allowed band is also shown. The obtained values of the  $\sqrt{f}\epsilon$  parameter are well compatible with cosmological bounds.

Finally, 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. 2.3 where the  $M_{A'}$  interval from few GeV up to 50 GeV is explored. The five scenarios are reported with different hatching of the allowed regions; the black line is the overall boundary.

In conclusion, the allowed values for  $\sqrt{f}\epsilon$  in the case of mirror hydrogen atom,  $Z' = 1$ , ranges between  $7.7 \times 10^{-10}$  to  $1.1 \times 10^{-7}$ . The values within this overall range are well compatible with cosmological bounds.

## 2.4 DAMA/LIBRA-phase2 and perspectives

After a first upgrade of the DAMA/LIBRA set-up in 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 are reported in Ref. [6] where the feasibility to decrease the software energy threshold below 2 keV has also been demonstrated.

DAMA/LIBRA-phase2 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. This requires long and heavy full time dedicated work for reliable collection and analysis of very large exposures. Another upgrade at the end of 2012 was concluded: new-concept pre-amplifiers were installed. Further improvements are planned.

Finally, other possibility to further 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. 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 “general purpose” experiment with highly radiopure NaI(Tl) (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.

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