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Recent results from DAMA/LIBRA–phase1 and perspectives

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The DAMA/LIBRA–phase1 and the former DAMA/NaI data (cumulative exposure 1.33 ton × yr, corresponding to 14 annual cycles) give evidence at 9.3 σ C.L. for the presence of Dark Matter (DM) particles in the galactic halo, on the basis of the exploited model independent DM annual modulation signature by using highly radiopure NaI(Tl) target. Results and comparisons will be briefly recalled. Recent analyses on possible diurnal effects and on the Earth shadowing effect (the latter holds only for some DM candidates) will be mentioned. Finally, the perspectives of the running DAMA/LIBRA–phase2 will be mentioned.

Keywords: Scintillation detectors, elementary particle processes, Dark Matter

1 Introduction

About 80 years of experimental observations and theoretical arguments have pointed out that a large fraction of the Universe is composed of Dark Matter particles.

For completeness, it is worth recalling that some efforts to find alternative explanations of Dark Matter have been proposed such as e.g. *MOdified Gravity Theory* (MOG) and *MOdified Newtonian Dynamics* (MOND); they hypothesize that the theory of gravity is incomplete and that a new gravitational theory might explain the

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experimental observations. However, not only is there no proof of their basic idea, but also e.g.: i) there is no general underlying principle; ii) they are generally unable to account for all small and large scale observations; iii) they fail to accurately reproduce the Bullet Cluster; iv) generally they require some amount of DM particles as seeds for the structure formation.

A wide zoology of particles beyond the standard model is available in literature with suitable features to be candidates for Dark Matter particles. On the other hand accelerators may demonstrate the existence of some of the DM candidates, but they cannot credit by themselves that a certain particle is a DM solution or the only DM particle solution; moreover, DM candidates and scenarios exist (even for the neutralino candidate) for which accelerators cannot give any information.

Moreover, having the aim to detect DM particles one should not only have in mind the wide candidates zoology, but also the many different possibilities of interaction with the various exposed materials. In fact, also depending on that, the signal can be in recoiling nuclei or in electromagnetic channel or mixed. There is an extensive related literature available.

The presently running DAMA/LIBRA experiment ($\simeq$250 kg of full sensitive target-mass) [1–16], as well as the former DAMA/NaI ($\simeq$100 kg of full sensitive target-mass) [17–23], has the main aim to investigate the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature (originally suggested in [24, 25]).

As a consequence of the Earth's revolution around the Sun, which is moving in the Galaxy, the Earth should be crossed by a larger flux of DM particles around $\simeq$2 June and by a smaller one around $\simeq$2 December*. This DM annual modulation signature is very distinctive since the effect induced by DM particles must simultaneously satisfy all the following requirements: the rate must contain a component modulated according to a cosine function (1) with one year period (2) and a phase that peaks roughly $\simeq$2 June (3); this modulation must only be found in a well-defined low energy range, where DM particle induced events can be present (4); it must apply only to those events in which just one detector of many (9 in DAMA/NaI and 25 in DAMA/LIBRA) 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 the case of some possible scenarios.

Thus, this signature is model independent and very effective; moreover, the developed highly radio-pure NaI(Tl) target-detectors [1] and the adopted procedures assure sensitivity to a wide range of DM candidates (both inducing nuclear recoils and/or electromagnetic radiation), interaction types and astrophysical, nuclear and particle Physics scenarios.

The DM annual modulation signature could 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. None are available or suggested by anyone over more than a decade [1, 2, 7, 8, 10, 11, 20].

The full description of the DAMA/LIBRA set-up and performances during the

*The DM annual modulation signature has a different origin and peculiarities than the seasons on the Earth and than effects correlated with seasons (consider the expected value of the phase as well as other requirements listed below).

phase1 and phase2 (presently running) and other related arguments have been discussed in detail in [1–4,6–8,11] and references therein. The radio-purity, the protocols, the procedures and the details are discussed in [1–4, 6–8, 11] and references therein.

2 DM annual modulation results

The total exposure of DAMA/LIBRA–phase1 is: 1.04 ton × yr collected in seven annual cycles; when including also that of the first generation DAMA/NaI experiment it is 1.33 ton × yr, corresponding to 14 annual cycles. The variance of the cosine during the DAMA/LIBRA–phase1 data taking is 0.518, showing that the set-up has been operating evenly throughout the years [2, 8].

Many independent data analyses have been carried out [2, 8] and all of them confirm the presence of a peculiar annual modulation in the *single-hit* scintillation events in the (2–6) keV energy interval, which – in agreement with the requirements of the DM signature – is absent in other parts of the energy spectrum and in the *multiple-hit* scintillation events in the same (2–6) keV energy interval (this latter condition correspond to "switching off the beam" of DM particles). All the analyses and details can be found in the given literature. In particular, Fig. 1 shows the time behaviour of the experimental residual rates of the *single-hit* scintillation events for DAMA/NaI [20] and DAMA/LIBRA–phase1 [2–4, 8] cumulatively in the (2–6) keV energy interval.

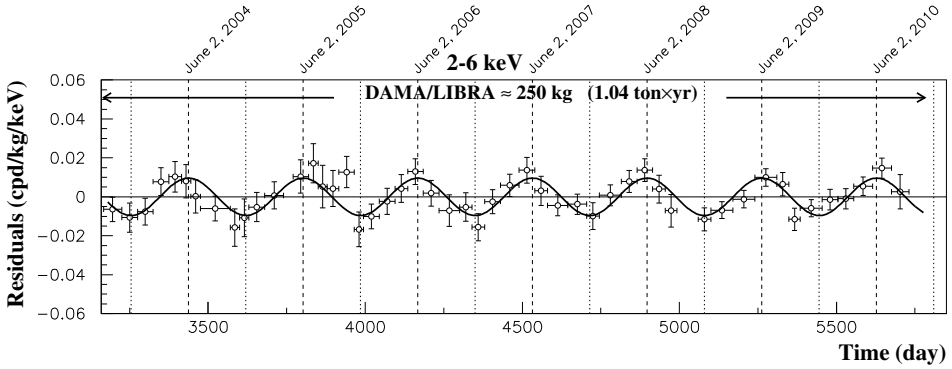


Figure 1 Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time. The time scale is maintained the same of the previous DAMA papers for coherence. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. The superimposed 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 $2^{\rm nd}$) 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 $2^{\rm nd}$), while the dotted vertical lines correspond to the minimum.

The DAMA/LIBRA–phase1 data give evidence for the presence of DM particles in the galactic halo, on the basis of the exploited model independent DM annual

modulation signature by using highly radio-pure NaI(Tl) target, at 7.5 σ C.L.. Including also the first generation DAMA/NaI experiment (cumulative exposure 1.33 ton $\times$ yr, corresponding to 14 annual cycles), the C.L. is 9.3 σ. In particular, with the cumulative exposure the modulation amplitude of the single-hit events in the (2–6) keV energy interval, measured in NaI(Tl) target, is (0.0112 $\pm$ 0.0012) cpd/kg/keV; the measured phase is (144 $\pm$ 7) days (corresponding to May 24 $\pm$ 7 days) and the measured period is (0.998 $\pm$ 0.002) year, values well in agreement with those expected for the DM particles.

In addition we recall that no modulation has been found in any possible source of systematics or side reactions; thus, cautious upper limits (90% C.L.) on possible contributions to the DAMA/LIBRA–phase1 measured modulation amplitude have been derived (see e.g. [2–4]). It is worth noting that they do not quantitatively account for the measured modulation amplitudes, and are not able to simultaneously satisfy all the many requirements of the signature. Similar analyses have also been carried out for the DAMA/NaI data [20].

No other experimental result has been verified over such a long time so accurately and with various significant upgrades of the set-ups.

In particular, in [7, 11] 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 (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 signature are available. A detailed discussion about all the related arguments can be found in [1–4, 7, 8, 10, 11, 16, 20, 26].

With reference to comparisons, it is worth noting that no direct model independent comparison is possible in the field when different target materials and/or approaches are used; the same applies to the strongly model dependent indirect searches.

In order to perform corollary investigations on the nature of the DM particles, model-dependent analyses are necessary[†]. Thus, many theoretical and experimental parameters and models are possible (see e.g. in [2, 8, 13, 27–30] and in literature) and many hypotheses must also be exploited, while specific experimental and theoretical assumptions are generally adopted in the field assuming a single arbitrary scenario without accounting for neither existing uncertainties nor for alternative possible scenarios, interaction types, etc.

The obtained DAMA 9.3 σ C.L. model independent evidence is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophys-

[†]For completeness, it is worth recalling that there is no existing approach to investigate the nature of the candidate in the direct and indirect DM searches, which can offer this information independently on assumed astrophysical, nuclear and particle physics scenarios. On the other hand, searches for new particles beyond the Standard Model of particle physics at accelerators cannot credit by themselves that a certain particle is in the halo as a solution or the only solution for DM particles, and – in addition – DM candidates and scenarios (even for the neutralino) exist which cannot be investigated there.

Table 1 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, $S_m^{\rm exp} \simeq 0.0112$ cpd/kg/keV [4]. For details see [11] 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)	$A_k/S_m^{\rm exp}$
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.

ical, nuclear and particle physics [2,5,8,17,18,20,27–29]. Further extensive literature is available on the topics (see for example in the bibliography of [8,31,32]). In fact, both the negative results and all the possible positive hints are largely compatible with the DAMA model-independent DM annual modulation results in various scenarios considering also the existing experimental and theoretical uncertainties; the same holds for the strongly model dependent indirect approaches.

It is worth noting that these DAMA experiments are not only sensitive to DM particles with spin-independent coupling inducing just nuclear recoils, but also to other couplings and to other DM candidates as those giving rise to part or all the signal in electromagnetic form. Finally, scenarios exist in which other kind of targets/approaches are disfavoured or even blind.

Two recent analyses on the DAMA/LIBRA–phase1 data are also summarised in the following. In the first one the presence of possible diurnal effects has been investigated [10], while in the second one the so called "Earth Shadow Effect" has been considered [12]. A study on these effects has been extensively given in the quoted references, the results will be briefly addressed.

2.1 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 [10]. 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, also presents some specific requirements. In particular the interest in this signature is also that the ratio R_{dy} of this DM diurnal modulation amplitude over the DM annual modulation amplitude is a model independent constant at given latitude; considering the LNGS latitude one has:

$$R_{dy} = \frac{S_d}{S_m} \simeq 0.016\,. \tag{1}$$

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 [4], thus the expected value of the diurnal modulation amplitude is $\simeq 1.5 \times 10^{-4}$ cpd/kg/keV.

For completeness Fig. 2 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 intervals. The used time bin is 1 (either solar or sidereal) hour. See [10] for details.

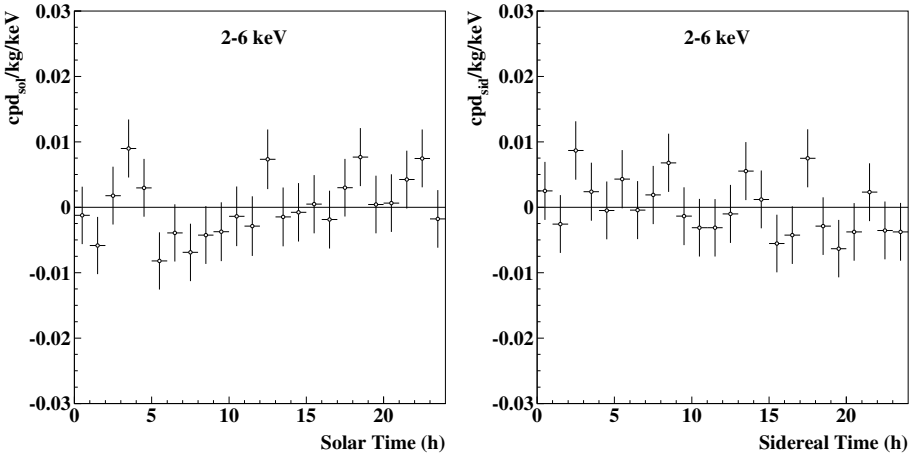


Figure 2 Experimental model-independent diurnal residual rate of the *single-hit* scintillation events, measured by DAMA/LIBRA–phase1 in the (2–6) keV energy intervals as a function of the hour of the solar (*left*) and sidereal (*right*) day. The experimental points present the errors as vertical bars and the associated time bin width (1 hour) as horizontal bars. The cumulative exposure is 1.04 ton × yr. See [10] for details.

The null hypothesis (absence of residual rate diurnal variation) has been tested by a χ^2 test, obtaining $\chi^2/\text{d.o.f.} = 25.8/24 \rightarrow \text{P} = 36\%$ for the solar time and χ^2/d.o.f.

$= 21.2/24 \rightarrow \mathrm{P} = 63\%$ for sidereal time. Thus, no diurnal variation with a significance of 95% C.L. is found at the reached level of sensitivity.

In addition to the χ^2 test, another independent statistical test has been applied: the run test [10]; 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.

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: $A_d^{\mathrm{exp}} = -(1.0 \pm 1.3) \times 10^{-3}$ cpd/kg/keV. Following the Feldman–Cousins procedure an upper limit can be obtained for the measured diurnal modulation amplitude: $A_d^{\mathrm{exp}} < 1.2 \times 10^{-3}$ cpd/kg/keV (90% C.L.); thus, the DAMA/LIBRA–phase1 experimental sensitivity is not sufficient to point out this second order diurnal effect (expected amplitude $\simeq 1.5 \times 10^{-4}$ cpd/kg/keV).

In conclusion, at the 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 [6] can also offer the possibility to increase sensitivity to such an effect.

2.2 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 the 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 [12].

In fact a diurnal variation of the low energy rate could be expected [33,34] 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 the 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, $\vec{v}_e(t)$[‡], 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

[‡]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.

between a minimum and a maximum which depend on the laboratory position on the Earth. In particular the larger the allowed range of θ the larger is the resulting effect. 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 $\psi = (48.1)^\circ$ and $\phi_0 = (42.4)^\circ$ depend on the orientation of the Earth axis in the galactic frame [35].

In fact, the diurnal variation of the velocity distribution and of the counting rate proves undetectable for cross-sections on proton $\leq 10^{-3}$ pb, 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 can allow us to investigate in some model scenarios high cross sections (σ_p) DM particle component (with small ξ) in the dark halo and decouple ξ from σ_p.

In particular, for each set of parameters [12], one can evaluate the $\xi\sigma_n$ allowed values as:

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

This corresponds, once including the experimental uncertainties on $S_m^{\rm exp}$, 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, $m_{\rm DM}$ can be studied. In [12], results in a considered scenario and details are given.

2.3 Directionality with anisotropic scintillators

For completeness, we also mention a different approach for the direct detection of DM candidates inducing just nuclear recoils; it is based on the study of the correlation of the nuclear recoil direction with the Earth's velocity [36]. This approach has relevant technical difficulties, when the detection of the short nuclear recoil track is pursued; similar activities are up to now at R&D stage.

An interesting possibility is offered by anisotropic scintillators [37,38]. They have different light responses depending on the nucleus recoil direction with respect to the scintillator's axes. Since the response to γ/β radiation is isotropic instead, these detectors can offer the possibility to efficiently study anisotropy of nuclear recoils [37–40].

So directionality can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day. In fact the diurnal Earth rotation changes the impinging direction of the DM particle flux and therefore the mean direction of the recoil nuclei induced by DM particle with respect to the crystal axes.

Low background $ZnWO_4$ crystal scintillators have recently been proposed because their light output and pulse shape depend on the direction of the impinging DM candidate (inducing nuclear recoils) with respect to the crystal axes. Both these anisotropic features can provide two independent ways to exploit the directionality

approach; the features and performances of such scintillators are very promising [41] and will be explored in future.

3 Conclusions

The cumulative exposure with ultra low background NaI(Tl) target by the former DAMA/NaI and DAMA/LIBRA–phase1 is 1.33 ton × yr giving a model-independent positive evidence at 9.3 σ 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. At the end of 2010 an important upgrade has been performed on DAMA/LIBRA when all the PMTs have been replaced with new ones – developed with HAMAMATSU co. – having higher Quantum Efficiency (Q.E.). In this new configuration a software energy threshold below 2 keV has been reached [6]. DAMA/LIBRA is thus in its phase2 and it is continuously running with higher sensitivity.

Future improvements to increase the sensitivity of the set-up can be considered by using high Q.E. 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 could be obtained.

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