DAMA/LIBRA RESULTS AND PERSPECTIVES OF THE SECOND STAGE

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The DAMA/LIBRA experiment is mainly dedicated to the investigation on DM particles in the Galactic halo by exploiting the model independent Dark Matter (DM) annual modulation signature. The present DAMA/LIBRA and the former DAMA/NaI (exposed masses: about 250 kg and about 100 kg of highly radiopure NaI(Tl), respectively) experiments have released so far a total exposure of 1.17 ton × yr collected over 13 annual cycles; they provide a model independent evidence of the presence of DM particles in the galactic halo at 8.9 σ C.L.. The data of another annual cycle in the same DAMA/LIBRA running conditions are at hand. After the substitution (at fall 2010) of all the photomultipliers (PMTs) with new ones, having higher quantum efficiency, DAMA/LIBRA has entered the phase 2; that substitution has allowed to lower the software energy threshold of the experiment in the present data taking. Future perspectives are mentioned.

1. Introduction

The DAMA project is an observatory for rare processes located deep underground at the Gran Sasso National Laboratory of the I.N.F.N. It is based on the development and use of low background scintillators. Profiting of the low background features of the realized set-ups, many rare processes are studied [1 - 21].

The main apparatus, DAMA/LIBRA, is investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature.

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 Dark Matter 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 Refs. [22, 23].

At present status of technology it is the only model independent signature available in direct Dark Matter investigation that can be effectively exploited.

The exploitation of the DM annual modulation signature with highly radiopure widely sensitive NaI(Tl) as target material can permit to answer – by direct detection and in a way largely independent on the nature of the candidate and on the astrophysical, nuclear and particle Physics assumptions – the main question: "Are there Dark Matter (DM) particles in the galactic halo?" The corollary question: "Which are exactly the nature of the DM particle(s) detected by the annual modulation signature and the related astrophysical, nuclear and particle Physics scenarios?" requires subsequent model dependent corollary analyses as those available in literature. One should stress that no approach exists able to investigate the nature of the candidate either in the direct and indirect DM searches which can offer these latter information independently on assumed astrophysical, nuclear and particle Physics scenarios.

In particular, it is worth noting that many possibilities exist about the nature and the interaction types of the DM particles as e.g.: SUSY particles (as neutralino or sneutrino in various scenarios), inelastic Dark Matter in various scenarios, electron interacting dark matter (including WIMP scenarios), a heavy neutrino of the 4-th family, sterile neutrino, Kaluza-Klein particles, self-interacting dark matter, axion-like (light pseudoscalar and scalar candidate), mirror dark matter in various scenarios, Resonant Dark Matter, DM from exotic 4th generation quarks, Elementary Black holes, Planckian objects, Daemons, Composite DM, Light scalar WIMP through Higgs portal, Complex Scalar Dark Matter, specific two higgs doublet models, exothermic DM, Secluded WIMPs, Asymmetric DM, Isospin-Violating Dark Matter, Singlet DM, Specific GU, SuperWIMPs , WIMPzilla, etc. (see in the literature). Moreover, even a suitable particle not yet foreseen by theories could be the solution or one of the solutions. It is worth noting that often WIMP is adopted as a synonymous of Dark Matter particle, referring usually to a particle with spin-independent elastic scattering on nuclei; on the contrary, WIMP identifies a class of Dark Matter candidates that can have different phenomenologies and interaction types. This is true also when considering a precise candidate as for example the neutralino; in fact the basic supersymmetric theory has a very large number of parameters that are by the fact unknown and, depending on the assumptions, they can present well different features and preferred interaction types. Often constrained SUGRA models (which allow easier calculations for the predictions e.g. at accelerators) are presented as SUSY or as the only way to SUSY, which is not the case. Other open aspects, which have large impact on model dependent investigations and comparisons, are e.g. which is the right description of the dark halo and related parameters, which is the right related atomic/nuclear and particle physics, etc. as well as the fundamental question on how many kinds of Dark Matter particles exist in the Universe[1]. It is also worth noting that the accelerators could prove the existence of some possible Dark Matter candidate particles, but they could never credit by themselves that a certain particle is in the halo as the solution or the only solution for Dark Matter particle(s). Moreover, Dark Matter candidate particles and scenarios (even for neutralino candidate) exist which cannot be investigated at accelerators. Thus, in order to pursue a widely sensitive direct detection of DM particles, model independent approach, ultra-low-background suitable target material, very large exposure and full control of the running conditions are mandatory.

2. Short summary of the results

The DAMA/LIBRA data released so far correspond to six annual cycles for an exposure of 0.87 ton $\times$ yr [13, 14]. Considering these data together with those previously collected by DAMA/NaI over 7 annual cycles (0.29 ton $\times$ yr), the total exposure collected over 13 annual cycles is 1.17 ton $\times$ yr; this is orders of magnitude larger than the exposures typically released in the field.

The DAMA/NaI set up and its performances are described in Refs. [1, 3, 4, 5], while the DAMA/LIBRA set-up and its performances are described in Refs. [12, 14]. The sensitive part of the DAMA/LIBRA set-up is made of 25 highly radiopure NaI(Tl) crystal scintillators placed in a 5-rows by 5-columns matrix; each crystal is coupled to two low background photomultipliers working in coincidence at single photoelectron level. The detectors are placed inside a sealed copper box flushed with HP nitrogen and surrounded by a low background and massive shield made of Cu/Pb/Cd-foils/polyethylene/paraffin; 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. The installation has a 3-fold levels sealing system that excludes the detectors from environmental air. The whole installation is air-conditioned and the temperature is continuously monitored and recorded. The detectors' responses range from 5.5 to 7.5 photoelectrons/keV. Energy calibrations with X-rays/γ sources are regularly carried out down to few keV in the same conditions as the production runs. A software energy threshold of 2 keV is considered. The experiment takes data up to the MeV scale and thus it is also sensitive to high energy signals. For all the details see Ref. [12].

Several kinds of analyses on the model-independent DM annual modulation signature have been performed (see Refs. [13, 14] and references therein). Here Fig. 1 shows the time behaviour of the experimental residual rates of the *single-hit* events collected by DAMA/NaI and by DAMA/LIBRA in the (2 - 6) keV energy interval [13, 14]. The superimposed curve is the cosinusoidal function: A cos $\omega(t-t_0)$ with a period $T = 2\pi/\omega = 1$ yr, with a phase $t_0 = 152.5$ day (June 2nd), and modulation amplitude, A, obtained by best fit over the 13 annual cycles.

The hypothesis of absence of modulation in the data can be discarded [13, 14] and, when the period and the phase are released in the fit, values well compatible with those expected for a DM particle induced effect are obtained [14]; for example, in the cumulative (2 - 6) keV energy interval: A = (0.0116 $\pm$ 0.0013) cpd/kg/keV, T =(0.999 $\pm$ 0.002) yr and $t_0 = (146\pm7)$ day.

Summarizing, the analysis of the *single-hit* residual rate favours the presence of a modulated cosine-like behaviour with proper features at 8.9 σ C.L. [14].

The same data of Fig. 1 have also been investigated by a Fourier analysis, obtaining a clear peak corresponding to a period of 1 year [14]; this analysis in other energy regions shows instead only aliasing peaks.

[1] Consider the richness in particles of the luminous Universe which is just 0.007 of the density of the Universe with respect to about 0.22 of the Dark Matter attributed to relic particles by the combination of the results of WMAP, of the SN type IA and clusters observations.

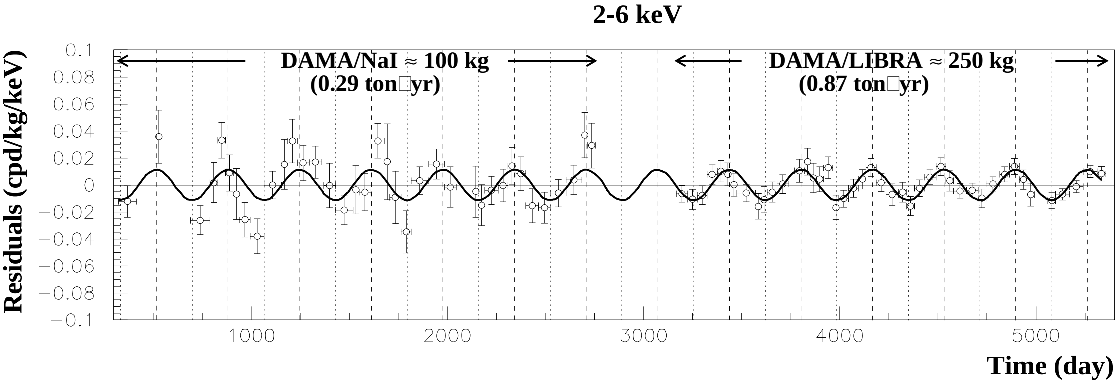

Fig. 1. Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/NaI over seven and by DAMA/LIBRA over six annual cycles in the (2 - 6) keV energy interval as a function of the time [4, 5, 13, 14]. The zero of the time scale is January 1st of the first year of data taking. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve is A cos $\omega(t-t_0)$ with period $T = 2\pi/\omega = 1$ yr, phase $t_0 = 152.5$ day (June 2nd) and modulation amplitude, A, equal to the central value obtained by best fit over the whole data: cumulative exposure is 1.17 ton × yr. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2nd), while the dotted vertical lines correspond to the minimum. See Refs. [13, 14] and text.

Thus, this allows the study the background behaviour in the same energy interval of the observed positive effect. The result of the analysis is reported in Fig. 2 where it is shown the residual rate of the *single-hit* events measured over the six DAMA/LIBRA annual cycles, as collected in a single annual cycle, together with the residual rates of the *multiple-hits* events, in the same considered energy interval. A clear modulation is present in the *single-hit* events, while the fitted modulation amplitudes for the *multiple-hits* residual rate are well compatible with zero [14].

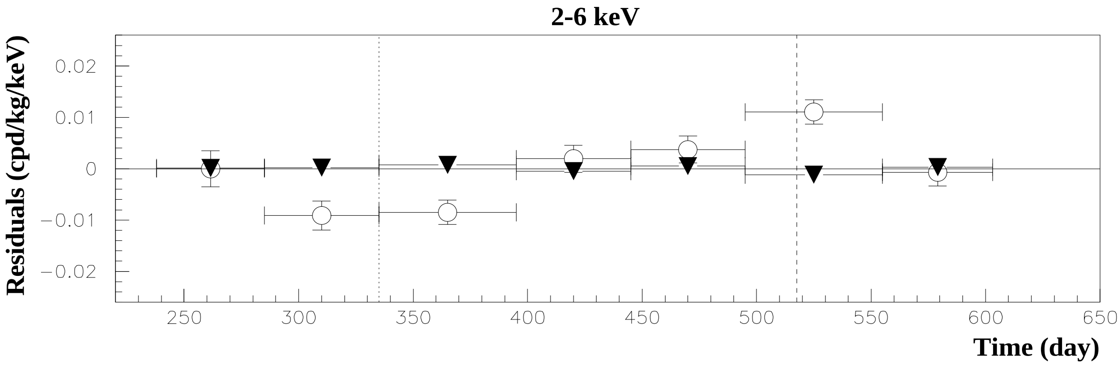

Fig. 2. Experimental residual rates over the six DAMA/LIBRA annual cycles for *single-hit* events (open circles) (class of events to which DM events belong) and for *multiple-hit* events (filled triangles) (class of events to which DM events do not belong). They have been obtained by considering for 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. The errors of the *multiple-hit* residual rates are slightly smaller that the filled triangles symbol. See text and Refs. [13, 14].

Similar results were previously obtained also for the DAMA/NaI case [5]. Thus, again evidence of annual modulation with proper features, as 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-hits* 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 further excluding any side effect either from hardware or from software procedures or from background.

The annual modulation present at low energy has also been analyzed by depicting the differential modulation amplitudes, S_m, as a function of the energy; the S_m is the modulation amplitude of the modulated part of the signal obtained by maximum likelihood method over the data, considering T = 1 yr and $t_0 = 152.5$ day. The S_m values are reported as function of the energy in Fig. 3. It can be inferred that a positive signal is present in the (2 - 6) keV energy interval, while S_m values compatible with zero are present just above; in particular, the S_m values in the (6 - 20) keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom. It has been also verified that the measured modulation amplitudes are statistically well distributed in all the crystals, in all the annual cycles and energy bins; these and other discussions can be found in Ref. [14].

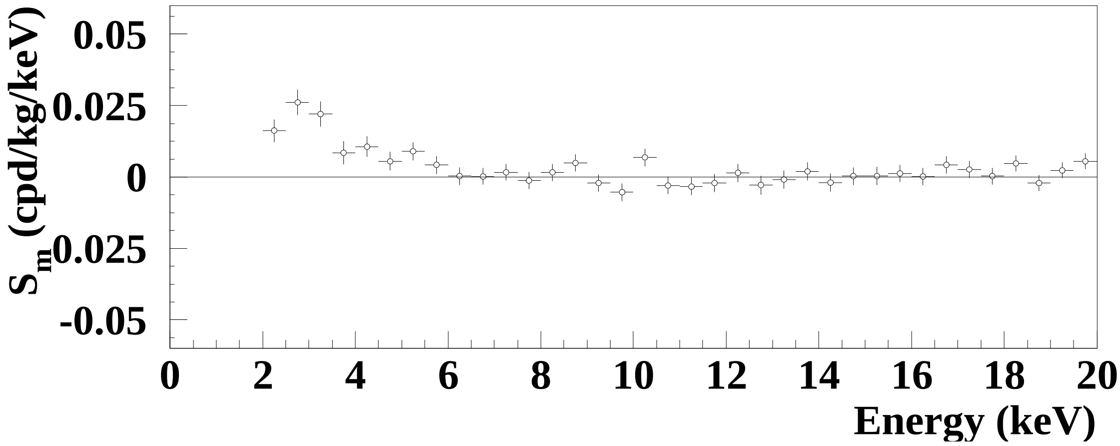

Fig. 3. Energy distribution of the modulation amplitudes S_m for the total cumulative exposure 1.17 ton×yr obtained by maximum likelihood analysis. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6 - 20) keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom. See Refs. [13, 14] and text.

In order to release in the maximum likelihood procedure the assumption of the phase fixed at t_0 = 152.5 day, the signal has been alternatively written as: $S_{0,k} + S_{m,k} \cos \omega(t-t_0) + Z_{m,k} \sin \omega(t-t_0) = S_{0,k} + Y_{m,k} \cos \omega(t-t^*)$, where $S_{0,k}$ and $S_{m,k}$ are the constant part and the modulation amplitude of the signal in k-th energy interval. Obviously, for signals induced by DM particles one would expect: i) $Z_{m,k} \approx 0$ (because of the orthogonality between the cosine and the sine functions); ii) $S_{m,k} \approx Y_{m,k}$; iii) $t^* \approx t_0$ = 152.5 day. In fact, these conditions hold for most of the dark halo models; however, it is worth noting that slight differences in the phase could be expected in case of possible contributions from non-thermalized DM components, such as e.g. the SagDEG stream [6] and the caustics [24]. The 2σ contours in the plane (S_m, Z_m) for the (2 - 6) keV and (6 - 14) keV energy intervals and those in the plane (Y_m , t^*) are reported in Fig. 4 [14]. The best fit values for the (2 - 6) keV energy interval are (1σ errors): S_m = (0.0111 ± 0.0013) cpd/kg/keV; Z_m= –(0.0004 ± 0.0014) cpd/kg/keV; Y_m = (0.0111 ± 0.0013) cpd/kg/keV; t^*= (150.5 ± 7.0) day; while for the (6 - 14) keV energy interval are: S_m= –(0.0001 ± 0.0008) cpd/kg/keV; Z_m = (0.0002 ± 0.0005) cpd/kg/keV; Y_m= –(0.0001 ± 0.0008) cpd/kg/keV and t^* obviously not determined. These results confirm those achieved by other kinds of analyses. In particular, a modulation amplitude is present in the lower energy intervals and the period and the phase agree with those expected for DM induced signals. For more detailed discussions see Ref. [14].

Both the data of DAMA/LIBRA and of DAMA/NaI fulfil all the requirements of the DM annual modulation signature.

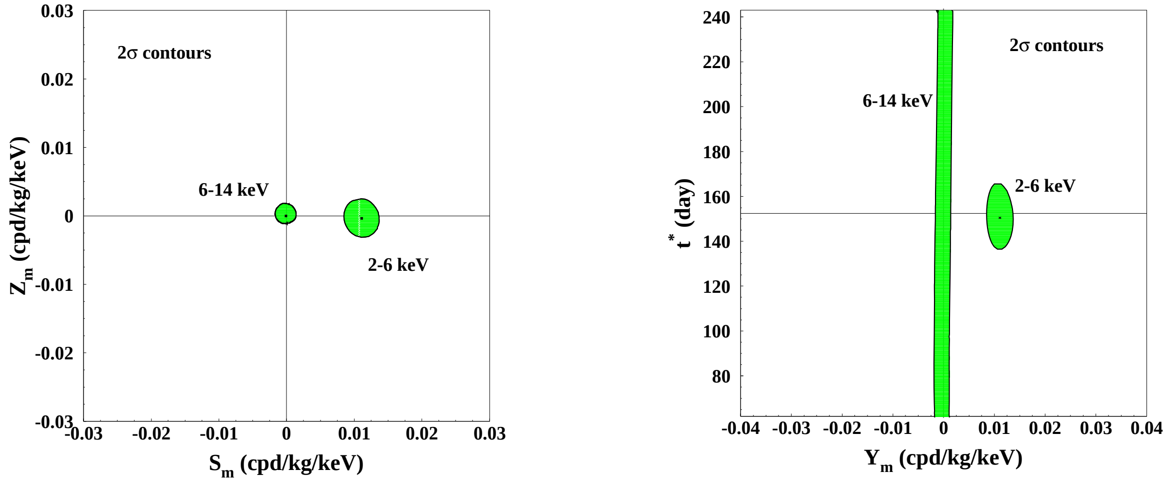

Fig. 4. 2σ contours in the plane (S_m, Z_m) (*left*) and in the plane (Y_m, t^*) (*right*) for the (2 - 6) keV and (6 - 14) keV energy intervals. The contours have been obtained by the maximum likelihood method, considering the cumulative exposure of 1.17 ton × yr. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. See Refs. [13, 14] and text.

Sometimes wrong statements were put forwards 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 contemporaneously satisfy all the requirements of the DM annual modulation signature; the same is also for side reactions.

Careful investigations on absence of any significant systematics or side reaction able to account for the measured modulation amplitude and to simultaneously satisfy all the requirements of the signature have been quantitatively carried out (see e.g. Refs. [4, 5, 12 - 14, 17, 25], and Refs therein). No systematics or side reactions able to mimic the signature (that is, able to account for the measured modulation amplitude and simultaneously satisfy all the requirements of the signature) has been found or suggested by anyone over more than a decade.

The obtained 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, 4 - 7, 18 - 21] and in Appendix A of Ref. [13]. Further large literature is available on the topics [26]; other possibilities are open. Here we just recall the recent papers [27, 28] where the DAMA/NaI and DAMA/LIBRA results, which fulfill all the many peculiarities of the model independent DM annual modulation signature, are examined under the particular hypothesis of a light-mass DM candidate particle interacting with the detector nuclei by coherent elastic process. In particular, in Ref. [27] allowed regions are given for DM candidates interacting by elastic scattering on nuclei including some of the existing uncertainties; comparison with theoretical expectations for neutralino candidate and with the recent possible positive hint by CoGeNT [29] are also discussed there (Fig. 5), while comparison with possible positive hint by Cresst [30] is discussed in Ref. [28].

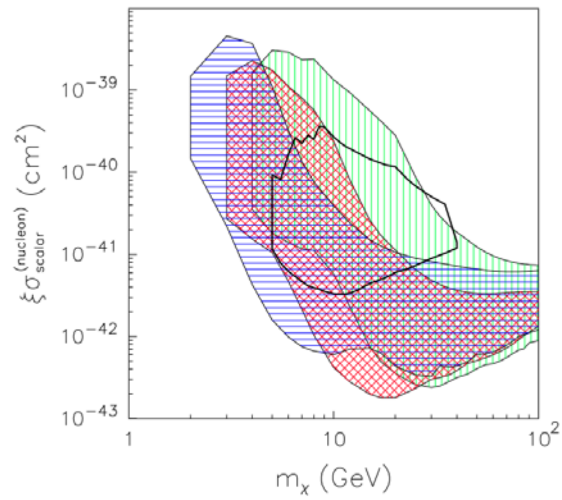

Fig. 5. Regions in the nucleon cross section vs DM particle mass plane allowed by DAMA in three different instances for the Na and I quenching factors: i) without including the channeling effect [(green) vertically-hatched region], ii) by including the channeling effect [(blue) horizontally-hatched region)], and iii) without the channeling effect using the energy-dependent Na and I quenching factors [27] [(red) cross-hatched region]. The velocity distributions and the same uncertainties as in Refs. [4, 5] are considered here. The allowed region obtained for the CoGeNT experiment, including the same astrophysical models as in Refs. [4,5] and assuming for simplicity a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters, is also reported and denoted by a (black) thick solid line. For details see Ref. [27].

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 (e.g. [31, 32, 33] claim model-dependent exclusion under many largely arbitrary assumptions (see for example discussions in [4, 5, 13, 34, 35]); often some critical points exist in their experimental aspects (e.g. use of marginal exposures, determination of the energy threshold, of the energy resolution and of the energy scale in the few keV energy region of interest, multiple selection procedures, non-uniformity of the detectors response, absence of suitable periodical calibrations in the same running conditions and in the claimed low energy region, stabilities, tails/overlapping of the populations of the subtracted events and of the considered recoil-like ones, well known side processes mimicing recoil-like events, etc.), and the existing experimental and theoretical uncertainties are generally not considered in their presented model dependent result. Moreover, implications of the DAMA results are generally presented in incorrect/partial/unupdated way.

As regards the strongly model dependent indirect searches their results are restricted to some DM candidates and physical scenarios under particular specific assumptions, and require also the modeling of the existing – and largely unknown – competing background for the secondary particles they are looking for. No quantitative comparison can be directly performed between the results obtained in direct and indirect searches because it strongly depends on assumptions and on the considered model framework. In particular, a comparison would always require the calculation and the consideration of all the possible configurations for each given particle model (e.g., for neutralino: in the allowed parameters space), as a biunivocal correspondence between the observables in the two kinds of experiments does not exist. We just mention here that neither negative nor possible positive indications are at present in conflict with the DAMA model independent result.

Finally, for completeness we remind: i) the recent possible positive hints presented by CoGeNT [29] and Cresst [30] exploiting different approaches/different target materials; ii) the uncertainties in the model dependent results and comparisons; iii) the relevant argument of the methodological robustness [36]. In particular, the general considerations on comparisons reported in Appendix A of Ref. [13] still hold; on the other hand, whatever possible “positive” result has to be interpreted and a large room of compatibility with the DAMA annual modulation evidence is present.

3. Perspectives

A first upgrade of the DAMA/LIBRA set-up was performed in September 2008. One detector was recovered by replacing a broken PMT and a new optimization of some PMTs and HVs was done; the transient digitizers were replaced with new ones, having better performances and a new DAQ with optical read-out was installed.

A further and more important upgrade has been performed in the end of 2010 when all the PMTs have been replaced with new ones having higher quantum efficiency; details on the reached performances are reported in Ref. [37]. This allows a lower software energy threshold and, hence, the improvement of the performance and of the sensitivity for deeper corollary information on the nature of the DM candidate particle(s) and on the various related astrophysical, nuclear and particle Physics scenarios. Since January 2011 the DAMA/LIBRA experiment is again in data taking in the new configuration, named DAMA/LIBRA-phase 2.

The purpose of the last upgrade of the running second generation DAMA/LIBRA set-up is: i) to increase the experimental sensitivity lowering the software energy threshold of the experiment; 2) to improve the investigation on the nature of the Dark Matter particle and related astrophysical, nuclear and particle physics arguments; 3) to investigate other signal features; 4) to improve the sensitivity in the investigation of rare processes other than Dark Matter as done by the former DAMA/NaI apparatus in the past [8] and by itself so far [15, 16]. This requires long and heavy full time dedicated work for reliable collection and analysis of very large exposures, as DAMA collaboration has always done.

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