Abstract

The DAMA/NaI experiment (≃ 100 kg highly radiopure NaI(Tl)) was proposed, designed and realised to effectively investigate in a model independent way the presence of a Dark Matter particle component in the galactic halo by exploiting the annual modulation signature. With a total exposure of 107731 kg · day, collected over seven annual cycles deep underground at the Gran Sasso National Laboratory of the I.N.F.N., it has pointed out – at 6.3 σ C.L. – an effect which satisfies all the peculiarities of the signature and neither systematic effects nor side reactions able to mimic the signature were found. Moreover, several (but still few with respect to the possibilities) corollary model dependent quests for the candidate particle have been carried out. In this paper the obtained results are summarized and some perspectives are discussed at some extent.

Keywords: Dark Matter; WIMPs; underground Physics
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1 Introduction

The problem of the existence of Dark Matter in our Universe dates back to the astrophysical observations at the beginning of past century [1, 2], but the presence of Dark Matter in our Universe has been definitively accepted by the scientific community only about 40 years later, when two groups performed systematic measurements of the rotational velocities of celestial bodies in spiral galaxies [3]. After the '70 many other observations have further confirmed the presence of Dark Matter in the Universe and,
at present, the measurements are mainly devoted to the investigation of the quantity, of the distribution (from the cosmological scale down to the galactic one) and of the nature of the Dark Matter in the Universe. Recent measurements of the CMB temperature anisotropy by WMAP [4], analysed in the framework of the Big Bang cosmological scenario, support a density of the Universe: $\Omega = 1$, further crediting that most of the Universe is dark. Recently, it has been suggested from observations on the supernovae Ia at high red-shift as standard candles that about 73% of $\Omega$ might be in form of a dark energy [5]; the argument is still under investigation and presents some problems on possible theoretical interpretations. However, even in this scenario – where the matter density in the Universe would be $\Omega_m \sim 0.3$ [4, 6] – large space for Dark Matter particles in the Universe exists. In fact, the luminous matter can only account for a density $\simeq 0.005$ and the baryonic Dark Matter for $\simeq 0.04$. On the other hand, the contribution of Dark Matter particles relativistic at the decoupling time is also restricted to be $\lesssim 0.01$ by considerations on large scale structure formations [7]. Thus, most of the Dark Matter particles in the Universe, relics from the Big Bang, were non relativistic at decoupling time; they are named Cold Dark Matter particles (CDM). The CDM candidates have to be neutral, stable or quasi-stable (e.g. with a time decay of order of the age of the Universe) and have to weakly interact with ordinary matter. These features are respected by the axions (also investigated by DAMA/NaI [8]) and by a class of candidates named WIMPs (Weakly Interacting Massive Particles). In particular, in the Standard Model of particle Physics no particle can be a suitable candidate as CDM; thus, a new window beyond the Standard Model can be investigated.

Finally, several observations have suggested that our Galaxy should also be embedded in a dark halo with mass at least 10 times larger than that of the luminous matter. The verification of the presence of a Dark Matter particle component in the galactic halo has been the main goal of the DAMA/NaI experiment.

2 The DAMA/NaI experiment

The DAMA/NaI experiment was proposed in 1990 [9], designed and realized having the main aim to investigate in a model independent way the presence of a Dark Matter particle component in the galactic halo [10, 11, 12, 13, 14, 15, 16, 17, 18]. For this purpose, we planned to exploit the effect of the Earth revolution around the Sun on the Dark Matter particles interactions on the target-nuclei of suitable underground detectors. In fact, as a consequence of its annual revolution, the Earth should be crossed by a larger flux of Dark Matter particles in June (when its rotational velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one in December (when the two velocities are subtracted) (see Fig. 1). This offers an efficient model independent signature, able to test a large interval of cross sections and of halo densities; it is named annual modulation signature and was originally suggested in the middle of ’80 by [19].

In fact, the expected differential rate as a function of the recoil energy, $dR/dE_R$ (see ref. [18] for detailed discussion), depends on the WIMP velocity distribution and on the Earth’s velocity in the galactic frame, $\vec{v}_e(t)$. Projecting $\vec{v}_e(t)$ on the galactic
plane, one can write: \( v_e(t) = v_\odot + v_\oplus \cos \gamma \cos \omega (t - t_0) \). Here \( v_\odot \) is the Sun’s velocity with the respect to the galactic halo \( (v_\odot \simeq v_0 + 12 \text{ km/s}) \) and \( v_0 \) is the local velocity whose value is in the range 170-270 km/s \([12, 20]\); \( v_\oplus = 30 \text{ km/s} \) is the Earth’s orbital velocity around the Sun on a plane with inclination \( \gamma = 60^\circ \) with the respect to the galactic plane. Furthermore, \( \omega = 2\pi/T \) with \( T = 1 \text{ year} \) and roughly \( t_0 \approx 2^{nd} \text{ June} \) (when the Earth’s speed is at maximum). The Earth’s velocity can be conveniently expressed in unit of \( v_0 \):

\[
\eta(t) = \frac{v_e(t)}{v_0} = \eta_0 + \Delta \eta \cos \omega (t - t_0),
\]

\( \eta_0 = 1.04 - 1.07 \) is the yearly average of \( \eta \) and \( \Delta \eta = 0.05 - 0.09 \). Since \( \Delta \eta \ll \eta_0 \), the expected counting rate can be expressed by the first order Taylor approximation:

\[
\frac{dR}{dE_R} \eta(t) = \frac{dR}{dE_R} \eta_0 + \left( \frac{\partial}{\partial \eta} \left( \frac{dR}{dE_R} \right) \right)_{\eta = \eta_0} \Delta \eta \cos \omega (t - t_0).
\]

Averaging this expression in a \( k \)-th energy interval one obtains:

\[
S_k[\eta(t)] = S_k[\eta_0] + \left[ \frac{\partial S_k}{\partial \eta} \right]_{\eta_0} \Delta \eta \cos \omega (t - t_0) = S_{0,k} + S_{m,k} \cos \omega (t - t_0),
\]

(2)

with the contribution from the highest order terms less than 0.1%. Thus, the annual modulation signature is very distinctive since a WIMP-induced seasonal effect must simultaneously satisfy all the following requirements: (i) the rate must contain a component modulated according to a cosine function; (ii) with one year period; (iii) a phase that peaks roughly around \( \approx 2^{nd} \text{ June} \); (iv) this modulation must only be found in a well-defined low energy range, where WIMP induced recoils can be present; (v) it must apply to those events in which just one detector of many actually "fires", since the WIMP multi-scattering probability is negligible; (vi) the modulation amplitude in the region of maximal sensitivity must be \( \leq 7\% \) for usually adopted halo distributions, but it can be larger in case of some possible scenarios such as e.g. those in refs. \([21, 22]\). Only systematic effects able to fulfil these 6 requirements and to account for the whole
observed modulation amplitude could mimic this signature; thus, no other effect investigated so far in the field of rare processes offers a so stringent and unambiguous signature. With the present technology, the annual modulation signature remains the main signature of a WIMP signal.

Of course, the amount of the measured effect depends e.g.: i) on the sensitivity of the experiment to the coupling and to the particle physics features of the WIMP; ii) on the nuclear features of the used target-nucleus; iii) on the features of the dark halo and, in particular, on the spatial and velocity distributions of the Dark Matter particles. The quality of the running conditions also plays a crucial role to detect such a rare process.

Considering its main goal, DAMA/NaI has been designed by employing and further developing all the necessary low-background techniques and procedures. A detailed description of the set-up, of its radiopurity, of its performance, of the used hardware procedures, of the determination of the experimental quantities and of the data reduction has been given in refs. [23, 13, 14, 18]. Here only few arguments are addressed.

The DAMA/NaI experiment was located deep underground in the Gran Sasso National Laboratory of I.N.F.N. \(^3\), whose main features have been reported in [27, 28, 29, 30].

In particular, the NaI(Tl) scintillator was chosen as the best target material to investigate the process since it offers e.g.:

- well known technology
- reachable high radiopurity by material selections and protocols, by chemical/physical purifications, etc.
- large mass
- high duty cycle
- feasible well controlled operational conditions and monitoring
- routine calibrations feasible down to keV range in the same conditions as the production runs
- high light response, that is keV threshold reachable
- absence of the necessity of re-purification or cooling down/warming up procedures (implying high reproducibility, high stability, etc.)
- absence of microphonic noise and an effective noise rejection at threshold (time decay of NaI(Tl) pulses is hundreds ns, while that of noise pulses is tens ns)
- sensitivity to spin-independent (SI), spin-dependent (SD) and mixed (SI&SD) couplings as well as to several other existing scenarios

\(^3\)We take this occasion to remind that DAMA/NaI has been part of the DAMA project, which is also composed by several other low background set-ups, such as: i) DAMA/LXe (\(\approx 6.5\) kg pure liquid Xenon scintillator) \([24, 25]\); ii) DAMA/R&D, set-up devoted to tests on prototypes and small scale experiments \([26]\); iii) the new second generation large mass NaI(Tl) radiopure set-up DAMA/LIBRA (see later); iv) DAMA/Ge detector for sample measurements.
• sensitivity to both high (by Iodine target) and low (by Na target) mass candidates
• possibility to effectively investigate the annual modulation signature in all the needed aspects
• pulse shape discrimination feasible at reasonable level
• possibility to achieve significant results on several other rare processes
• no safety problems
• necessity of a relatively small underground space
• the lowest cost with the respect to every other considered technique

However, neither commercial low background NaI(Tl) detectors nor NaI(Tl) detectors grown with old technology (even after "revision") can reach the needed sensitivity; thus, a devoted special R&D was realized with the Crismatec company. In this framework, all the needed materials were selected and through devoted and severe protocols the final DAMA/NaI highly radiopure detectors were realized.

The performances of the nine 9.7 kg highly radiopure DAMA/NaI detectors, including their measured radiopurity, are discussed in details in [23, 14, 18]. The bare NaI(Tl) crystals are encapsulated in radiopure Cu housings; moreover, 10 cm long Tetrasil-B light guides act as optical windows on the two end faces of each crystals and are coupled to specially developed low background photomultipliers (PMT). The measured light response is 5.5 – 7.5 photoelectrons/keV depending on the detector. The two PMTs of a detector work in coincidence with hardware thresholds at the single photoelectron level in order to assure high efficiency for the coincidence at few keV level. The energy threshold of the experiment, 2 keV, is instead determined by means of X-rays sources and of keV range Compton electrons on the basis also of the features of the noise rejection procedures and of the efficiencies when lowering the number of available photoelectrons [23].

The detectors are enclosed in a sealed copper box, continuously maintained in HP Nitrogen atmosphere in slightly overpressure with respect to the external environment.

A suitable low background hard shield against electromagnetic and neutron background was realized using very high radiopure Cu and Pb bricks [23], Cd foils and 10/40 cm polyethylene/paraffin; the hard shield is also sealed in a plexiglas box and maintained in the high purity (HP) Nitrogen atmosphere. Moreover, about 1 m concrete (made from the Gran Sasso rock material) almost fully surrounds the hard shield outside the barrack and at its bottom, acting as a further neutron moderator.

A three-level sealing system from environmental Radon is effective. In fact, the inner part of the barrack, where the set-up is allocated, has the floor (above the concrete) and all the walls sealed by Supronyl (permeability: $2 \cdot 10^{-11} \text{cm}^2/\text{s}$ [31]) plastic and the entrance door is air-tight. A low level oxygen alarm informs the operator before entering the inner part of the barrack since the HP Nitrogen which fills both

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4 We remark that the low background technique requires very long and accurate work for the selection of low radioactive materials by sample measurements with HP-Ge detectors (placed deep underground in suitable hard shields) and/or by mass spectrometer analyses. Thus, these measurements are often difficult experiments themselves, depending on the required level of radiopurity.
the inner Cu box and the external plexiglas box is released in this closed environment. The Radon level inside the (sealed) barrack is continuously monitored and recorded with the production data [10, 11, 23, 13, 14, 18].

On the top of the shield a glove-box (also maintained in the HP Nitrogen atmosphere) is directly connected to the inner Cu box, housing the detectors, through Cu pipes. The pipes are filled with low radioactivity Cu bars (covered by 10 cm of low radioactive Cu and 15 cm of low radioactive Pb) which can be removed to allow the insertion of radioactive sources for calibrating the detectors in the same running condition, without any contact with external environment [23].

The whole installation is air-conditioned and the operating temperature as well as many other parameters are continuously monitored and acquired with the production data. Moreover, self-controlled computer processes automatically monitor several parameters and manage alarms [23, 14, 18].

The electronic chain and the data acquisition system operative up to summer 2000 have been described in ref. [23], while the new electronics and DAQ installed in summer 2000 have been described in ref. [18].

As regards other aspects, we recall that the linearity and the energy resolution of the detectors have been investigated using several radioactive sources [23, 14] such as, for the low energy region, $^{55}$Fe (5.9 keV X-rays), $^{109}$Cd (22 keV X-rays and 88 keV $\gamma$ line) and $^{241}$Am (59.5 keV $\gamma$ line) sources. In particular, in the production runs, the knowledge of the energy scale is assured by periodical calibrations with $^{241}$Am source and by monitoring (in the production data themselves summed every $\simeq$ 7 days) the position and energy resolution of the 46.5 keV $\gamma$ line of the $^{210}$Pb [23, 32, 10, 11, 13, 14, 18]. The latter peak was present – at level of few counts per day per kg (cpd/kg) – in the measured energy distributions mainly because of a contamination (by environmental Radon) of the external surface of the crystals’ Cu housings, occurred during the first period of the underground storage of the detectors.

The only procedure applied to the data regards the noise rejection, which is particularly efficient since the difference in time decay of the NaI(Tl) scintillation pulses and of the noise pulses is of order of hundreds ns; the procedure have been described e.g. in refs. [23, 13, 14]5.

All the periodical long calibration procedures [23, 32] and the time specifically allocated for maintenance and/or for improvements are the main components affecting the duty cycle of the experiment. Moreover, in the first period data have been taken only in the two extreme conditions for the annual modulation signature.

The energy threshold, the PMT gain and the electronic line stability are continuously verified and monitored during the data taking by the routine calibrations, by the position and energy resolution of the $^{210}$Pb line (see above) and by the study of the hardware rate behaviours with time.

Finally, we remind that the experiment took data up to MeV energy region despite the optimization was done for the keV energy range.

The measured low energy distributions of interest for the WIMP investigation have

\footnote{This procedure assures also the rejection of any possible contribution either from afterglows (when not already excluded by the dedicated 500 $\mu$s veto time; see above) induced by high energy events or from any possible Čerenkov pulse in the light guide or in the PMTs; in fact, they also have fast time decay (of order of tens ns).}
been given in refs. [33, 13, 14, 34], where the corrections for efficiencies and acquisition dead time have already been applied. We note that usually in DAMA/NaI the low energy distributions refer to those events where only one detector of many actually fires (that is, each detector has all the others in the same installation as veto; this assures a further background reduction, which is of course impossible when a single detector is used), single-hit events.

Moreover, the data taking of each annual cycle has been started before the expected minimum of the signal rate (which is roughly around \( \approx 2^{nd} \) December) and concluded after the expected maximum (which is roughly around \( \approx 2^{nd} \) June).

The DAMA/NaI set-up has exploited the WIMP annual modulation signature over seven annual cycles [10, 11, 12, 13, 14, 15, 16, 17, 18] and the following part of this paper will summarize the final model independent result, some of the corollary quests for the candidate particle, implications and perspectives. However, it is worth to remind that - thanks to its radiopurity and features - DAMA/NaI has also investigated other approaches for WIMPs in ref. [32, 33] and several other rare processes such as: possible processes violating the Pauli exclusion principle [35], CNC processes in \(^{23}\text{Na}\) and \(^{127}\text{I}\) [36], electron stability [34], searches for neutral SIMPs [37], for neutral nuclearites [37], for Q-balls [38] and for solar axions [8]; moreover, DAMA/NaI allowed also the study of nuclear transition to a possible superdense nuclear state [39] and possible two-body cluster decay of \(^{127}\text{I}\) [40].

### 3 The 6.3 \( \sigma \) C.L. model-independent evidence for a WIMP component in the galactic halo

As reported in ref. [18], a model independent investigation of the annual modulation signature has been realized by exploiting the time behaviour of the residual rates of the single-hit events in the lowest energy regions over the seven annual cycles (total exposure: 107731 kg · day) [10, 11, 12, 13, 14, 15, 16, 17, 18]. These experimental residual rates of the single-hit events are given by: 

\[
<r_{ijk} - \text{flat}_{jk}>_{jk},
\]

where \( r_{ijk} \) is the rate in the considered \( i \)-th time interval for the \( j \)-th detector in the \( k \)-th considered energy bin and \( \text{flat}_{jk} \) is the rate of the \( j \)-th detector in the \( k \)-th energy bin averaged over the cycles. The average is made on all the detectors (\( j \) index) and on all the energy bins in the considered energy interval.

This model independent approach offers an immediate evidence of the presence of an annual modulation of the rate of the single-hit events in the lowest energy region over the seven annual cycles as shown in Fig. 2, where the energy and time behaviours of the single-hit residual rates are depicted.

In particular, the data favour the presence of a modulated cosine-like behaviour at 6.3 \( \sigma \) C.L.; in fact, their fit for the (2–6) keV larger statistics energy interval offers a modulation amplitude equal to \((0.0200 \pm 0.0032) \) cpd/kg/keV, a phase: \( t_0 = (140 \pm 22) \) days and a period: \( T = (1.00 \pm 0.01) \) year, all parameters kept free in the fit. The period and phase agree with those expected in the case of a WIMP induced effect \((T = 1 \) year and \( t_0 \) roughly at \( \approx 152.5 \)-th day of the year). The \( \chi^2 \) test on the (2–6) keV residual rate in Fig. 2 disfavours the hypothesis of unmodulated behaviour giving a probability of \( 7 \cdot 10^{-4} \) \((\chi^2/d.o.f. = 71/37)\). Moreover, if the experimental residuals of
Fig. 2 are fitted fixing the period at 1 year and the phase at 2nd June, the following modulation amplitudes are obtained: (0.0233 ± 0.0047) cpd/kg/keV, (0.0210 ± 0.0038) cpd/kg/keV and (0.0192 ± 0.0031) cpd/kg/keV for the (2–4), (2–5) and (2–6) keV energy intervals, respectively.

In Fig. 3 the single-hit residual rate in a single annual cycle from the total exposure of 107731 kg · day is presented for two different energy intervals; as it can be seen the modulation is clearly present in the (2–6) keV energy region, while it is absent just above. The same conclusion is obtained by investigating the data by means of the Fourier analysis (performed according to ref. [41] including also the treatment of the

Figure 2: Experimental residual rate for single-hit events, in the (2–4), (2–5) and (2–6) keV energy intervals as a function of the time elapsed since January 1-st 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 curves represent the cosinusoidal functions behaviours expected for a WIMP signal with a period equal to 1 year and phase at 2nd June; the modulation amplitudes have been obtained by best fit. See text. The total exposure is 107731 kg · day.
experimental errors and of the time binning); in fact, the results shown in Fig. 4 show a clear peak for a period of 1 year in the (2–6) keV energy interval, while it is absent in the energy interval just above.

Figure 3: Experimental single-hit residual rate in a single annual cycle from the total exposure of $10^7$ kg · day for the (2–6) keV and (6–14) keV energy intervals. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The initial time is taken at August 7th. Fitting the data with a cosinusoidal function with period of 1 year and phase at 152.5 days, the following amplitudes are obtained: $(0.0195 \pm 0.0031)$ cpd/kg/keV and $-(0.0009 \pm 0.0019)$ cpd/kg/keV, respectively. Thus, a clear modulation is present in the lowest energy region, while it is absent just above.

A quantitative investigation of the whole energy spectrum up to MeV energy region has not shown modulation in any other energy interval (see e.g. [13, 14, 18] and few arguments given later).

Finally, in order to show if the modulation amplitudes are statistically well distributed in all the crystals, in all the annual cycles and in the energy bins, the distributions of the variable $\frac{S_m - \langle S_m \rangle}{\sigma}$ are reported in Fig. 5. The $S_m$ are the experimental modulation amplitudes for each detector, for each annual cycle and for each considered energy bin (taken as an example equal to 0.25 keV), $\sigma$ are their errors and the $\langle S_m \rangle$ represent the mean values of the modulation amplitudes over the detectors and the annual cycles for each energy bin. The left panel of Fig. 5 shows the distribution referred to the region of interest for the observed modulation, (2–6) keV, while the right panel includes also the energy region just above, (2–14) keV. Since this variable is distributed as a gaussian with an unitary standard deviation, the modulation amplitudes are statistically well distributed in all the crystals, in all the data taking periods and in all considered energy bins.

In conclusion, the data satisfy all the peculiar requirements, given above, for the WIMP model independent annual modulation signature. As mentioned, to mimic this signature, systematic effects or side reactions should not only be able to fully account for the measured modulation amplitude, but also to satisfy the peculiar requirements.
Figure 4: Power spectrum of the measured single-hit residuals for the (2–6) keV (continuous line) and (6–14) keV (dotted line) energy intervals calculated according to ref. [41], including also the treatment of the experimental errors and of the time binning. As it can be seen, the principal mode present in the (2–6) keV energy interval corresponds to a frequency of $2.737 \cdot 10^{-3} \text{ d}^{-1}$, that is to a period of $\approx 1$ year. A similar peak is not present in the (6–14) keV energy interval.

Figure 5: Distributions of the variable $\frac{S_m - \langle S_m \rangle}{\sigma}$ (where $\sigma$ is the error associated to the $S_m$) evaluated for each detector, for each annual cycle and each considered energy bin: i) in the region of interest for the observed modulation, (2–6) keV (left panel); ii) including also the energy region just above, (2–14) keV (right panel). See text.

as for a WIMP induced effect. A careful investigation of all the known possible sources of systematics and side reactions has been regularly carried out by DAMA/NaI and published at time of each data release [10, 11, 13, 14, 18].

No effect able to mimic the signature has been found; thus, upper limits (90% C.L.) on the possible contributions to the modulated amplitude have been calculated.
as summarized in Table 1; for a detailed quantitative discussion see ref. [14, 18]. In particular, they cannot account for the measured modulation amplitude because

Table 1: Summary of the results obtained by investigating the possible sources of systematics or of side reactions [18]. No systematics or side reaction has been found able to give a modulation amplitude different from zero; thus cautious upper limits (90% C.L.) have been calculated and are shown here in terms of the measured model independent modulation amplitude, \( S_{\text{mod}}^{\text{obs}} \). As it can be seen, none of them nor their cumulative effect could account for the measured modulation; moreover, as discussed in details in ref. [14, 18], they cannot mimic the signature.

<table>
<thead>
<tr>
<th>Source</th>
<th>Cautious upper limit (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radon</td>
<td>(&lt; 0.2% S_{\text{mod}}^{\text{obs}})</td>
</tr>
<tr>
<td>Temperature</td>
<td>(&lt; 0.5% S_{\text{mod}}^{\text{obs}})</td>
</tr>
<tr>
<td>Noise</td>
<td>(&lt; 1% S_{\text{mod}}^{\text{obs}})</td>
</tr>
<tr>
<td>Energy scale</td>
<td>(&lt; 1% S_{\text{mod}}^{\text{obs}})</td>
</tr>
<tr>
<td>Efficiencies</td>
<td>(&lt; 1% S_{\text{mod}}^{\text{obs}})</td>
</tr>
<tr>
<td>Background</td>
<td>(&lt; 0.5% S_{\text{mod}}^{\text{obs}})</td>
</tr>
<tr>
<td>Side reactions</td>
<td>(&lt; 0.3% S_{\text{mod}}^{\text{obs}})</td>
</tr>
</tbody>
</table>

In addition: no effect can mimic the signature

quantitatively not relevant and unable to satisfy all the peculiar requirements of the signature.

For the sake of completeness, we remind that possible diurnal effects – correlated both with the sidereal and with the solar time – have already been excluded by the analysis reported in [33].

In particular, as mentioned above, no modulation has been observed in the background; in fact, the whole energy spectrum up to MeV energy region has been analyzed and the presence of a background modulation in the whole energy spectrum has been excluded at a level much lower than the effect found in the lowest energy region [14, 18]. This result already accounts also for the background component due to the neutrons and the Radon; nevertheless, further additional independent and cautious analyses to estimate their possible contribution have been given in ref. [14, 18]. In fact, it has been demonstrated in [14, 18] that a modulation of neutron flux – possibly observed by the ICARUS coll. as reported in the ICARUS internal report TM03-01 – cannot quantitatively contribute to the DAMA/NaI observed modulation amplitude, even if the neutron flux would be assumed to be 100 times larger than measured at LNGS by several authors with different techniques over more than 15 years. Moreover, in no case the neutrons can mimic the signature since some of the peculiar requirements of the signature would fail. Similarly, any possible effect of the muon flux modulation reported by the MACRO experiment [27] is excluded both by quantitative investigation [14, 18] and by inability to fulfil all the peculiarities of the signature.

As regards the possibility of a contribution from the Radon, we remind that the
DAMA/NaI has three levels of insulation from the environmental air (see above). Moreover, the Radonmeter which continuously recorded the Radon level inside the barrack (that is external to the hard shield and to the detectors) typically measured values at level of its sensitivity and no modulation has been observed [10, 11, 13, 14, 18]. To be on the safest side, even the possible presence of Radon trace in the HP Nitrogen atmosphere inside the Cu box, housing the detectors, has been investigated by searching for the double coincidences of the gamma-rays (609 and 1120 keV) from $^{214}$Bi Radon daughter, obtaining an upper limit of: $< 4.5 \times 10^{-2}$ Bq/m$^3$ (90% C.L.).

It gives rise to the upper limit reported in Table 1 when assuming an hypothetical 10%, modulation of possible Radon in the HP Nitrogen atmosphere of the Cu box. Anyhow, it is worth to remark that in every case even a sizeable quantity of Radon nearby a detector cannot mimic the WIMP annual modulation signature since some of the peculiarities of the signature would fail.

For more detailed discussion see ref. [14, 18].

To perform a further relevant investigation, in 1999 we proposed to renew the electronic chain of DAMA/NaI removing the multiplexer system and equipping each detector with its own transient digitizer. This occurred in summer 2000, thus in the last two annual cycles the multiple-hits events and the single-hit events have been acquired and analyzed using the same identical hardware and the same identical software procedures. The multiple-hits events class – on the contrary of the single-hit one – does not include events induced by WIMPs since the probability that a WIMP scatters off more than one detector is negligible. The obtained results are depicted in Fig. 6. The fitted modulation amplitudes are: $A = (0.0195 \pm 0.0031)$ cpd/kg/keV and $A = -(3.9 \pm 7.9) \times 10^{-4}$ cpd/kg/keV for single-hit and multiple-hits residual rates,
respectively. Thus, evidence of annual modulation is present in the single-hit residuals (events class to which the WIMP-induced recoils 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 Dark Matter particle component in the galactic halo further excluding any side effect either from hardware or from software procedures or from background.

In conclusion, the presence of a Dark Matter particle component in the galactic halo is supported by DAMA/NaI at 6.3 $\sigma$ C.L. and the modulation amplitude measured over the 7 annual cycles in NaI(Tl) at the location of the Gran Sasso Laboratory for the (2 – 6) keV energy region is $(0.0200 \pm 0.0032) \text{ cpd/kg/keV}$. This is the experimental result of DAMA/NaI. It is model independent; no other experiment whose result can be directly compared with this one is available so far in the field of Dark Matter investigation.

4 Corollary results: quests for a candidate particle in some of the possible model frameworks

On the basis of the obtained model independent result, corollary investigations can also be pursued on the nature and coupling of the WIMP candidate. This latter investigation is instead model dependent and – considering the large uncertainties which exist on the astrophysical, nuclear and particle physics assumptions and on the parameters needed in the calculations – has no general meaning (as it is also the case of exclusion plots and of the WIMP parameters evaluated in the indirect detection experiments). Thus, it should be handled in the most general way as we have preliminarily pointed out with time passing in the past [10, 11, 12, 13, 14, 15, 16, 17] and we have discussed in some specific details in ref. [18].

It is worth to note that the results presented in the following are, of course, not exhaustive of the many possible scenarios which at present level of knowledge cannot be disentangled. Some of the open questions are: i) which is the right nature for the WIMP particle; ii) which is its right couplings with ordinary matter (mixed SI&SD, purely SI, purely SD or preferred inelastic); iii) which are the right form factors and related parameters for each target nucleus; iv) which is the right spin factor for each target nucleus; v) which are the right scaling laws (let us remind that even for the neutralino case in a MSSM framework with purely SI interaction the scenario could be drastically modified as pointed out in ref. [42]); vi) which is the right halo model and related parameters; vii) which are the right values of the experimental parameters within their uncertainties; etc.

As regards, in particular, the Dark Matter particle-nucleus elastic scattering, the differential energy distribution of the recoil nuclei can be calculated [32, 43, 18] by means of the differential cross section of the WIMP-nucleus elastic processes given by the sum of the SI and the SD contributions. In the SI case, the nuclear parameters can be decoupled from the particle parameters and the nuclear cross sections are usually scaled to a defined point-like SI Dark Matter particle-nucleon cross section, $\sigma_{SI}$. In
the SD case the notations [15]: \(tg\theta = \frac{a_n}{a_p}\), can be used, where \(a_{p,n}\) are the effective WIMP-nucleon coupling strengths for SD interactions. The mixing angle \(\theta\) is defined in the \([0, \pi]\) interval; in particular, \(\theta\) values in the second sector account for \(a_p\) and \(a_n\) with different signs. Also in the SD case all the nuclear cross sections are usually scaled to a defined point-like SD Dark Matter particle-nucleon cross section, \(\sigma_{SD}\) [18]. Thus, the energy distribution of the recoil rate can be written as a function of \(\sigma_{SI}\), \(\sigma_{SD}\) and \(\theta\). Another important parameter is the local density of the Dark Matter particles, \(\rho_W = \xi \rho_0\), where \(\rho_0\) is the local halo density and \(\xi (\xi \leq 1)\) is the fractional amount of local density of Dark Matter particles.

Among the ingredients entering in the model dependent analyses there are the nuclear SI and SD form factors, which generally depend on the nature of the involved particle. In ref. [18] the existing uncertainties in the usually adopted formulation for the SI case have been discussed as well as those for the SD one. It has also shown that the SD case is even more uncertain since the nuclear and particle physics degrees of freedom cannot be decoupled and a dependence on the assumed nuclear potential exists. Moreover, further significant uncertainties in the evaluation of the SD interaction rate also arise from the adopted spin factor for the single target-nucleus. In fact, the available calculated values are well different in different models and, in addition, at fixed model they depend on \(\theta\). Thus, not only the target nuclei should have spin different from zero (for example, this is not the case of Ar isotopes) to be sensitive to Dark Matter particles with a SD component in the coupling, but also well different sensitivities can be expected among odd-nuclei having an unpaired proton (as e.g. \(^{23}\)Na and \(^{127}\)I) and odd-nuclei having an unpaired neutron (as e.g. the odd Xe and Te isotopes and \(^{73}\)Ge).

Another scenario also considered in the corollary DAMA/NaI model dependent analyses is that of WIMPs with preferred inelastic scattering which has been suggested by [21]. In this case the Dark Matter particles can only inelastically scatter off nuclei going to excited levels with a \(\delta\) mass splitting. A specific model featuring a real component of the sneutrino (for which the mass splitting naturally arises) has been given in ref. [21]. It has been shown that for this inelastic scattering a kinematical constraint exists which favours target-detectors media with heavy nuclei (such as \(^{127}\)I) with the respect to those with lighter ones (such as e.g. \(^{nat}\)Ge). In fact, this process can only occur if the particle velocity is larger than a threshold value; this kinematical constraint becomes increasingly severe as the nucleus mass decreases [21]. Moreover, this model scenario implies some interesting peculiar features when exploiting the annual modulation signature; in fact – with the respect to the case of WIMP elastically scattering – it would give rise to an enhanced modulated component of the signal with respect to the unmodulated one and to largely different behaviours with energy for both the components (showing both higher mean values) [21]. The differential energy distribution of the recoil nuclei in the case of inelastic processes is function of \(\xi \sigma_p, m_W\) and \(\delta\), analogously as above other ingredients, as e.g. the form factor, play also a role [18].

As mentioned, the expected energy distribution for the scatterings of Dark Matter particles depends on \(\rho_W\) and on the velocity distribution of the Dark Matter particles at Earth’s position. The experimental observations regarding the dark halo of our Galaxy
do not allow to get information on them without introducing a model for the Galaxy matter density. The dark halo model widely used in the calculations carried out in the field of direct detection approaches is the naive isothermal sphere that corresponds to a spherical infinite system with a flat rotational curve. Despite its simplicity has favoured its wide use in the calculation of expected rate of Dark Matter particle-nucleus interaction, it doesn’t match with astrophysical observations and presents an unphysical behaviour. In fact, the density profile has a singularity in the origin and implies a total infinite mass of the halo unless introducing some cut-off at large radii. Thus, the use of more realistic halo models is mandatory since the model dependent results significantly vary. An extensive discussion about some of the more credited realistic halo models has been reported in ref. [17, 18] and have been considered in the results given in the following (see Table 2). In particular, the considered halo model classes correspond to: i) spherically symmetric matter density with isotropic velocity dispersion (A); ii) spherically symmetric matter density with non-isotropic velocity dispersion (B); iii) axisymmetric models (C); iv) triaxial models (D); v) moreover, in the case of axisymmetric models it is possible to include either an halo co-rotation or an halo counter-rotation. The parameters of each halo model have been chosen taking into account the available observational data. Thus, considering the allowed range for the local velocity of Dark Matter particles $v_0 = (220 \pm 50)$ km s$^{-1}$ (90% C.L.), the allowed range of local density $\rho_0$ has been evaluated [17] taking into account the following physical constraints: i) the amount of flatness of the rotational curve of our Galaxy, considering conservatively $0.8 \cdot v_0 \leq v_{\text{rot}}^{100} \leq 1.2 \cdot v_0$, where $v_{\text{rot}}^{100}$ is the value of rotational curve at distance of 100 kpc from the galactic center; ii) the maximal non dark halo components in the Galaxy, considering conservatively $1 \cdot 10^{10} M_\odot \lesssim M_{\text{vis}} \lesssim 6 \cdot 10^{10} M_\odot$ [44, 45]. Although a large number of self-consistent galactic halo models, in which the variation of the velocity distribution function is originated from the change of the halo density profile or of the potential, have been considered, still many other possibilities exist.

The proper knowledge of other quantities is also necessary such as e.g. the recoil/electron response ratio for the given nucleus in the given detector and energy range, (named quenching factor). Of course, significant differences are often present in literature for the measured value of this recoil/electron response ratio even for the same nucleus in the same kind of detector as shown in ref. [18].

In conclusion, just as a corollary of the model independent result over the seven annual cycles, in the following some of the many possible model dependent quests for a Dark Matter candidate are summarized. They have been obtained by considering the halo models previously mentioned for three of the possible values of the local velocity $v_0$: 170 km/s, 220 km/s and 270 km/s and for the halo density values as in the prescriptions of ref. [17, 18]. The escape velocity has been maintained at the fixed value: 650 km/s. Of course, it is worth to note that the present existing uncertainties affecting the knowledge of the escape velocity will significantly extend allowed regions e.g. in the cases of preferred inelastic WIMPs and of light mass WIMP candidates; its effect would be instead marginal at large WIMP masses. All these scenarios have been investigated in some discrete cases either considering the mean values of the parameters of the used nuclear form factors and of the measured quenching factors
Table 2: Summary of the considered consistent halo models [17, 18]. The labels in the first column identify the models. In the third column the values of the related considered parameters are reported [17, 18]; other choices are also possible as well as other halo models. The models of the Class C have also been considered including possible co-rotation and counter-rotation of the dark halo.

<table>
<thead>
<tr>
<th>Class A: spherical $\rho_W$, isotropic velocity dispersion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>Isothermal Sphere</td>
</tr>
<tr>
<td>A1</td>
<td>Evans’ logarithmic</td>
</tr>
<tr>
<td>A2</td>
<td>Evans’ power-law</td>
</tr>
<tr>
<td>A3</td>
<td>Evans’ power-law</td>
</tr>
<tr>
<td>A4</td>
<td>Jaffe</td>
</tr>
<tr>
<td>A5</td>
<td>NFW</td>
</tr>
<tr>
<td>A6</td>
<td>Moore et al.</td>
</tr>
<tr>
<td>A7</td>
<td>Kravtsov et al.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class B: spherical $\rho_W$, non-isotropic velocity dispersion (Osipkov–Merrit, $\beta_0 = 0.4$)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Evans’ logarithmic</td>
</tr>
<tr>
<td>B2</td>
<td>Evans’ power-law</td>
</tr>
<tr>
<td>B3</td>
<td>Evans’ power-law</td>
</tr>
<tr>
<td>B4</td>
<td>Jaffe</td>
</tr>
<tr>
<td>B5</td>
<td>NFW</td>
</tr>
<tr>
<td>B6</td>
<td>Moore et al.</td>
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<tr>
<td>B7</td>
<td>Kravtsov et al.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Class C: Axisymmetric $\rho_W$</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>C1</td>
<td>Evans’ logarithmic</td>
</tr>
<tr>
<td>C2</td>
<td>Evans’ logarithmic</td>
</tr>
<tr>
<td>C3</td>
<td>Evans’ power-law</td>
</tr>
<tr>
<td>C4</td>
<td>Evans’ power-law</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class D: Triaxial $\rho_W$ ($q = 0.8, p = 0.9$)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Earth on maj. axis, rad. anis.</td>
</tr>
<tr>
<td>D2</td>
<td>Earth on maj. axis, tang. anis.</td>
</tr>
<tr>
<td>D3</td>
<td>Earth on intern. axis, rad. anis.</td>
</tr>
<tr>
<td>D4</td>
<td>Earth on intern. axis, tang. anis.</td>
</tr>
</tbody>
</table>

(case A) or adopting the same procedure as in refs. [15, 16]. The latter one has been obtained by varying either: i) the mean values of the measured $^{23}$Na and $^{127}$I quenching factors [32] up to +2 times the errors; ii) the nuclear radius, $r_n$, and the nuclear surface thickness parameter, $s$, in the SI Form Factor [46] from their central values down to -20%; iii) the $b$ parameter in the considered SD form factor from the given value [47] down to -20% (case B). Moreover, we have also considered one of the possible more extreme cases where the Iodine nucleus parameters are fixed at the values of case B, while for the Sodium nucleus one considers: i) $^{23}$Na quenching factor at the lowest value measured in literature; ii) the nuclear radius, $r_n$, and the nuclear surface thickness parameter, $s$, in the SI Form Factor [46] from their central values up to +20%; iii) the $b$ parameter in the considered SD form factor from the given value.
Finally, no restriction on the mass of the Dark Matter particle has been adopted in these analyses; hence, we have just marked on those figures the lowest bound on the neutralino mass as derived from the LEP data in the adopted supersymmetric schemes based on GUT assumptions [48]. In fact, other model assumptions are possible and would imply significant variations of some accelerators bounds, allowing neutralino mass down to 6 GeV (see e.g. the recent refs. [49, 50, 51]); in addition, other low mass candidates can be considered as well. It is worth to note that the LEP model dependent mass limit – when considered – selects the WIMP-Iodine elastic scatterings as dominant because of the adopted scaling laws and of kinematical arguments, while DAMA/NaI is intrinsically sensitive both to low and high WIMP mass having both a light (the $^{23}$Na) and a heavy (the $^{127}$I) target-nucleus.

The results presented by DAMA/NaI on the corollary quests for the candidate particle over the seven annual cycles are calculated taking into account the time and energy behaviours of the single-hit experimental data. In particular, the likelihood function requires the agreement: i) of the expectations for the modulated part of the signal with the measured modulated behaviour for each detector and for each energy bin; ii) of the expectations for the unmodulated component of the signal with the respect to the measured differential energy distribution and - since ref. [13] - also with the bound on recoils obtained by pulse shape discrimination from the devoted DAMA/NaI-0 data[32]. The latter one acts in the likelihood procedure as an experimental upper bound on the unmodulated component of the signal and – as a matter of fact – as an experimental lower bound on the estimate of the background levels by the maximum likelihood procedure. Thus, the C.L.’s, we quote for allowed regions, already account for compatibility with the measured differential energy spectrum and with the measured upper bound on recoils. In particular, in the following for simplicity, the results of these corollary quests for the candidate particle are presented in terms of allowed regions obtained as superposition of the configurations corresponding to likelihood function values distant more than $4\sigma$ from the null hypothesis (absence of modulation) in each of the several (but still a limited number) of the possible model frameworks considered here. Obviously, these results are not exhaustive of the many scenarios possible at present level of knowledge (e.g. for some other recent ideas see [22, 42, 52]) and larger sensitivities than those reported in the following would be reached when including the effect of other existing uncertainties on assumptions and related parameters [18].

In the most general scenario – to which the DAMA/NaI target nuclei are fully sensitive – both the SI and the SD components of the cross section are present. In this general scenario the data give an allowed volume in the 4-dimensional space ($m_W$, $\xi\sigma_{SI}$, $\xi\sigma_{SD}$, $\theta$). Fig. 7 just shows slices of this 4-dimensional allowed volume in the plane $\xi\sigma_{SI}$ vs $\xi\sigma_{SD}$ for some of the possible $\theta$ and $m_W$ values for the considered model frameworks. We just note that experiments using either even-spin target nuclei (as Ar and most of Ge, Xe, Te isotopes) or odd-spin Ge, Xe or Te isotopes cannot explore most of the allowed volume. From the given figures it is clear that at present either a purely SI or a purely SD or mixed SI&SD configurations are compatible with the experimental data of the seven annual cycles.
Figure 7: Case of a WIMP with mixed SI&SD interaction in the given model frameworks. Coloured areas: example of slices (of the 4-dimensional allowed volume) in the plane $\xi_{\sigma_{SI}}$ vs $\xi_{\sigma_{SD}}$ for some of the possible $m_W$ and $\theta$ values. Four SD couplings are reported as examples: i) $\theta = 0$ ($a_n = 0$ and $a_p \neq 0$ or $|a_p| > |a_n|$) corresponding to a particle with null SD coupling to neutron; ii) $\theta = \pi/4$ ($a_p = a_n$) corresponding to a particle with the same SD coupling to neutron and proton; iii) $\theta = \pi/2$ ($a_n \neq 0$ and $a_p = 0$ or $|a_n| > |a_p|$) corresponding to a particle with null SD couplings to proton; iv) $\theta = 2.435$ rad ($\frac{a_n}{a_p} = -0.85$) corresponding to a particle with SD coupling through $Z_0$ exchange. The case $a_p = -a_n$ is nearly similar to the case iv). Inclusion of other existing uncertainties on parameters and models would further extend the regions; for example, the use of more favourable form factors and/or of more favourable spin factors than the considered ones would move them towards lower cross sections.

Often the purely SI interaction with ordinary matter is assumed to be dominant since e.g. most of the used target-nuclei are practically not sensitive to SD interactions (instead, $^{23}$Na and $^{127}$I nuclei are fully sensitive) and the theoretical calculations and comparisons are even much more complex and uncertain. Therefore, following the analogous procedure as the general case, we have exploited for the same model frameworks the purely SI scenario, obtaining the allowed region in the plane $m_W$ and $\xi\sigma_{SI}$ shown in Fig. 8 – left. Of course, best fit values of cross section and WIMP mass span over a large range in the considered model frameworks.

Moreover, configurations with $\xi\sigma_{SI}$ even much lower than those shown in Fig. 8 – left are accessible in case an even small SD contribution is present in the interaction
Figure 8: On the left : Case of a WIMP with dominant SI interaction for the given model frameworks. Region allowed in the plane \((m_W, \xi\sigma_{SI})\). The vertical dotted line represents a bound in case of a neutralino candidate when supersymmetric schemes based on GUT assumptions are adopted to analyse the LEP data; the low mass region is allowed for neutralino when other schemes are considered and for every other WIMP candidate; see text. While the area at WIMP masses above 200 GeV is allowed only for few configurations, the lower one is allowed by most configurations (the colored region gathers only those above the vertical line) [18]. The inclusion of other existing uncertainties on parameters and models would further extend the region; for example, the use of more favourable SI form factor for Iodine alone would move it towards lower cross sections. On the right : Example of the effect induced by the inclusion of a SD component different from zero on allowed regions given in the plane \(\xi\sigma_{SI} vs m_W\). In this example the Evans’ logarithmic axisymmetric C2 halo model with \(v_0 = 170\) km/s, \(\rho_0\) equal to the maximum value for this model and a given set of the parameters’ values (see [18]) have been considered. The different regions refer to different SD contributions for the particular case of \(\theta = 0\): \(\sigma_{SD} = 0\) pb (a), 0.02 pb (b), 0.04 pb (c), 0.05 pb (d), 0.06 pb (e), 0.08 pb (f). Analogous situation is found for the other model frameworks.

as shown as in an example in Fig. 8 – right. Analogous situation is found for other model frameworks. A comparison of the DAMA/NaI purely SI allowed region (given in Fig. 8 – left) with the theoretical expectations for a purely SI coupled neutralino candidate in a MSSM with gaugino mass unification at GUT scale released is shown in Fig. 9 as taken from ref [53].

Analogously, one can consider the pure SD coupling. In this scenario one obtain an allowed volume in the 3-dimensional space \((m_W, \xi\sigma_{SD}, \theta)\). Just examples of some slices of this allowed volume at given \(\theta\) is shown in Fig. 10. Considerations similar to the first case hold.

Finally, also the inelastic Dark Matter particle scenario has been analysed obtaining an allowed volume in the 3-dimensional space \((\xi\sigma_p, m_W, \delta)\). For simplicity, Fig. 11 shows just few slices of such an allowed volume at some given WIMP masses. We remind that in these calculations \(v_{esc}\) has been assumed at fixed value (as in the previous cases), while its present uncertainties can play a significant role in this scenario.
Figure 9: Figure taken from ref. [53]; theoretical expectations of $\xi\sigma_{SI}$ versus $m_W$ in the purely SI coupling for the particular case of a neutralino candidate in MSSM with gaugino mass unification at GUT scale released; the curve surrounds the DAMA/NaI purely SI allowed region as in Fig. 8-left.

Figure 10: Case of a WIMP with dominant SD interaction in the given model frameworks. Examples of slices (of the 3-dimensional allowed volume) in the plane ($m_W$, $\xi\sigma_{SD}$) with $\theta = 0$ and $\theta = 2.435$ ($Z_0$ coupling). For the definition of the vertical line and of the coloured area see previous figure caption. Inclusion of other existing uncertainties on parameters and models would further extend the SD allowed regions. For example, the use of more favourable SD form factors and/or more favourable spin factors would move them towards lower cross sections. Values of $\xi\sigma_{SD}$ lower than those corresponding to these allowed regions are possible also e.g. in case of an even small SI contribution.

of WIMP with preferred inelastic scattering.

In conclusion, the data of the seven annual cycles have also allowed corollary investigations on the features of the Dark Matter particle candidate in some of the many possible scenarios. However, although several scenarios have been investigated, these corollary analyses are not exhaustive at all because of the present poor knowledge on many astrophysical, nuclear and particle Physics needed assumptions. Thus, further efforts on the topics are in progress and a relevant contribution is expected by the new DAMA/LIBRA set-up, now running.
Figure 11: Case of a WIMP with preferred inelastic interaction in the given model frameworks. Examples of slices (coloured areas) of the allowed volumes (ξσₚ, δ, mₓ) for some mₓ values for WIMP with preferred inelastic interaction. Inclusion of other existing uncertainties on parameters and models would further extend the regions; for example, the use of a more favourable SI form factor for Iodine and different escape velocity would move them towards lower cross sections [18].

5 The present situation in the field

5.1 Direct detection

As already mentioned, no other experiment, whose result can be directly compared in a model independent way with that of DAMA/NaI, is available so far in the field of Dark Matter direct detection.

In fact, most of the activities, started in the 90’s, are still at R&D stage and/or have released marginal exposures with the respect to the many years of existence and to the several used detectors. This is the case of CDMS and EDELWEISS experiments, while the Zeplin experiment is more recent [54, 55, 56]. Since these experiments have claimed to have "excluded" DAMA/NaI, we will briefly point to the attention of the reader only few arguments. In particular, Table 3 summarizes some items for comparison.

Firstly, let us preliminarily assume as fully correct the "selected" number of events, the energy threshold, the energy scale, etc. quoted by those experiments (see Table 3) and let us consider if – at least under this hypothesis – their claims might be justified. The answer is obviously not; in fact: i) they give a single model dependent result using natGe or natXe target, while DAMA/NaI gives a model independent result using ²³Na and ¹²⁷I targets; ii) in the single (of the many possible) model scenario, they consider, they "fix" all the astrophysical, nuclear and particle physics assumptions at a single choice; the same is even for the experimental and theoretical parameters values needed in the calculations. In addition, DAMA/NaI is generally quoted there in an
Table 3: Features of the DAMA/NaI results on the WIMP annual modulation signature over the seven annual cycles [18] with those of refs. [54, 55, 56].

<table>
<thead>
<tr>
<th></th>
<th>DAMA/NaI</th>
<th>CDMS-II</th>
<th>Edelweiss-I</th>
<th>Zeplin-I</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signature</strong></td>
<td>Annual modulation</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Target-nuclei</strong></td>
<td>$^{23}$Na, $^{127}$I</td>
<td>$^{38}$Ge</td>
<td>$^{38}$Ge</td>
<td>$^{38}$Xe</td>
</tr>
<tr>
<td><strong>Technique</strong></td>
<td>well known</td>
<td>poorly experienced</td>
<td>poorly experienced</td>
<td>critical optical liquid/gas interface in this realization</td>
</tr>
<tr>
<td><strong>Target mass</strong></td>
<td>$\simeq$ 100 kg</td>
<td>0.75 kg</td>
<td>0.32 kg</td>
<td>$\simeq$ 3 kg</td>
</tr>
<tr>
<td><strong>Exposure</strong></td>
<td>$\simeq$ $(1.1 \cdot 10^5)$ kg · day</td>
<td>19.4 kg · day</td>
<td>30.5 kg · day</td>
<td>280 kg · day</td>
</tr>
<tr>
<td><strong>Depth of the experimental site</strong></td>
<td>1400 m</td>
<td>780 m</td>
<td>1700 m</td>
<td>1100 m</td>
</tr>
<tr>
<td><strong>Software energy threshold</strong></td>
<td>2 keV e.e. (5.5 – 7.5 p.e./keV)</td>
<td>10 keV e.e.</td>
<td>20 keV e.e.</td>
<td>2 keV e.e. (but: $\sigma/E = 100%$ mostly 1 p.e./keV; [56]) (2.5 p.e./keV for 16 days; [57])</td>
</tr>
<tr>
<td><strong>Quenching factor</strong></td>
<td>Measured</td>
<td>Assumed = 1</td>
<td>Assumed = 1 (see also [58])</td>
<td>Measured</td>
</tr>
<tr>
<td><strong>Measured event rate in low energy range</strong></td>
<td>$\simeq$ 1 cpd/kg/keV</td>
<td>??, claimed $\gamma$'s larger than CDMS-I ($\simeq 60$ cpd/kg/keV, $10^7$ events)</td>
<td>$\simeq 10^4$ events total</td>
<td>$\simeq 100$ cpd/kg/keV</td>
</tr>
<tr>
<td><strong>Claimed events after rejection procedures</strong></td>
<td>either 0 or 1</td>
<td>2 (claimed taken in a noisy period!)</td>
<td>$\simeq$ 20-50 cpd/kg/keV after rejection and ?? after standard PSD [56, 57]</td>
<td></td>
</tr>
<tr>
<td><strong>Events satisfying the signature in DAMA/NaI</strong></td>
<td>modulation amplitude integrated over the given exposure $\simeq 10^3$ events</td>
<td>insensitive</td>
<td>insensitive</td>
<td>insensitive</td>
</tr>
<tr>
<td><strong>Expected number of events from DAMA/NaI effect</strong></td>
<td>from few down to zero depending on the models (and on quenching factor)</td>
<td>from few down to zero depending on the models (and on quenching factor)</td>
<td>depends on the models (even zero)</td>
<td></td>
</tr>
</tbody>
</table>

uncorrect, partial and unupdated way and existing scenarios to which DAMA/NaI is fully sensitive – on the contrary of the others – are ignored.

Let us now briefly comment also some of the experimental aspects. In particular, the counting rate of the Ge bolometers experiments is very high and few/zero events are claimed after applying several strong and hardly safe rejection procedures (involv-
ing several orders of magnitude). They usually claim to have 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, but their results are, actually, largely based on "a priori" huge data selections and on the application of other preliminary rejection procedures (such as e.g. the one on the so-called surface electrons), which are generally poorly described and often not completely quantified. Moreover, most efficiencies and physical quantities entering in the interpretation of the claimed selected events have never been properly accounted; as an example, we mention the case of the bolometer quenching factor of the recoil target nuclei. In fact, for the bolometer signals the quenching factor (on which the energy threshold and the energy scale rely and, hence, also the claimed sensitivity for the given model dependent exclusion plots) is arbitrarily assumed to be exactly equal to one. Up to now, only one measurement has been made available for a given detector [58]; it offers the value: $0.87 \pm 10\%_{\text{stat.}} \pm 10\%_{\text{syst.}}$, which is – within the error – compatible with one, but – at the same time – also compatible with much smaller values. Thus, any bolometer result, obtained without considering e.g. the uncertainties about the unknown value of the quenching factor and, hence, about the energy threshold and energy scale, has to be considered partial and arbitrary. For completeness we also mention that the reproducibility of the results over different running periods has not been proved as well as the values of the effective sensitive volumes for the read-outs of the two signals for each event and related quantities; obviously, further uncertainties are present when, as done in some cases, a neutron background modeling and subtraction is pursued in addition.

As regards Zeplin-I [56, 57], a very low energy threshold is claimed (2 keV), although the light response is very poor: between $\simeq 1 \text{ ph.e./keV}$ [56] (for most of the time) and $\simeq 2.5 \text{ ph.e./keV}$ (claimed for 16 days) [57]. Moreover, a strong data filtering is applied to the high level of measured counting rate (see Table 3) by hardware vetoes, by fiducial volume cuts and, largely, by applying down to few keV a standard pulse shape discrimination procedure, although the LXe scintillation pulse profiles (pulse decay time $< 30 \text{ ns}$) are quite similar to the PMT noise events in the lower energy bins and in spite of the poor light response. Quantitative information on experimental quantities related to the used procedures has not yet been given [56, 57].

In conclusion, those claims for contradiction have intrinsically no scientific bases.

5.2 Indirect detection

The Dark Matter particles, via their annihilation either in the celestial bodies (such as Earth and Sun) or in the Galactic halo could give rise to high energy neutrinos, positrons, antiprotons and gamma rays. Therefore, they could be indirectly detected by looking either for "upgoing" muons – produced by $\nu_\mu$ – in underground, underwater or under-ice detectors or for antimatter and gamma rays in the space. However, it is worth to remark that no direct model independent comparison can be performed between the results obtained in direct and indirect searches.

\footnote{For comparison we remind that the data of the DAMA/LXe set-up, which has a similar light response, are analysed by using the much more realistic and safer software energy threshold of 13 keV [25].}

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In the case of "upgoing" muons in terrestrial detectors, the expected $\mu$ flux is the key quantity. However, several sources of uncertainties are present in the related estimates (and, therefore, in the obtained results) such as e.g. the assumption that a "steady state" has been reached in the considered celestial body and the estimate and subtraction of the existing competing processes, offered by the atmospheric neutrinos. Model dependent analyses with a similar approach have been carried out by large experiments deep underground such as e.g. MACRO and Superkamiokande. In particular, the case of the neutralino candidate in MSSM has been discussed in [59], showing that their model dependent results were not in conflict with DAMA/NaI.

As we mentioned, the annihilation of the Dark Matter particles in the galactic halo could also produce antimatter particles and gamma rays. The antimatter searches have to be carried out outside the atmosphere, i.e. on balloons or satellites. In particular, the Dark Matter particles annihilation would result in an excess of antiprotons or of positrons over an estimated background arising from other possible sources. The estimate and subtraction of such a background together with the influence of the Earth and of the galactic magnetic field on these particles plays a crucial role on the possibility of a reliable extraction of a signal. However, at present an excess of positrons with energy $\simeq 5 - 20$ GeV has been suggested by [60] and other experiments. Interpreted in terms of Dark Matter particles annihilation it gives a result not in conflict with the effect observed by DAMA/NaI [60].

As regards the possibility to detect $\gamma$'s from Dark Matter particles annihilation in the galactic halo, experiments in space are planned. However, at present it is difficult to estimate their possibilities considering e.g. the background level, the uncertainties in its reliable estimate and subtraction as well as the smallness of the expected signal (even more, if a subdominant component would be present) when properly calculated with rescaling procedure. However, in ref. [61, 62] the presence of a $\gamma$ excess from the center of the Galaxy in the EGRET data [63] has already been suggested. This excess match with a possible Dark Matter particles annihilation in the galactic halo [61, 62] and is not in conflict with the DAMA/NaI model independent result previously published.

For completeness, we remind that recently it has been suggested [64] that the positive hints from the indirect detection – namely the excess of positrons and of gamma rays in the space – and the effect observed by DAMA/NaI can also be described in a scenario with multi-component Dark Matter in the galactic halo, made of a subdominant component of heavy neutrinos of the 4th family and of a sterile dominant component. In particular (see Fig. 12), it has been shown that an heavy neutrino with mass around 50 GeV can account for all the observations, while the inclusion of possible clumpiness of neutrino density as well as new interactions in the heavy neutrino annihilation, etc. can lead to wider mass ranges: from about 46 up to about 75 GeV (see ref. [64] for details).
Figure 12: Figures taken from ref. [64]: Case of a subdominant heavy 4\textsuperscript{th} neutrino candidate in the plane local density fraction versus the heavy neutrino mass. The favorable region obtained from the DAMA/NaI data (grey dashed line when using the Evan’s halo model; solid line when using the other halo models) and the best-fit density parameters deduced from cosmic gamma-radiation (from halo and galactic center), positron and antiproton analysis are shown (left panel). The effect of the inclusion of possible neutrino clumpiness is also reported (right panel). See ref. [64] for details.

6 Toward the future: from DAMA/NaI to DAMA/LIBRA and beyond

The large merits of highly radiopure NaI(Tl) set-up have been demonstrated in the practice by DAMA/NaI which has been the highest radiopure set-up available in the field, has effectively pursued a model independent approach to investigate Dark Matter particles in the galactic halo collecting an exposure several orders of magnitude larger than those available in the field and has obtained many other complementary or by-products results.

In 1996 DAMA proposed to realize a ton set-up [65] and a new R&D project for highly radiopure NaI(Tl) detectors was funded at that time and carried out for several years in order to realize as an intermediate step the second generation experiment, successor of DAMA/NaI, with an exposed mass of about 250 kg.

Thus, new powders and other materials have been selected, new chemical/physical radiopurification procedures in NaI and TlI powders have been exploited, new growing/handling protocols have been developed and new prototypes have been built and tested. As a consequence of the results of this second generation R&D, the new experimental set-up DAMA/LIBRA (Large sodium Iodide Bulk for RAre processes), \(\simeq 250\) kg highly radiopure NaI(Tl) crystal scintillators (matrix of twenty-five \(\simeq 9.70\) kg NaI(Tl) crystals), was funded and realised. After the completion of the DAMA/NaI data taking in July 2002, the dismounting of DAMA/NaI occurred and the installation of DAMA/LIBRA started. In particular, the experimental site as well as many components of the installation itself have been implemented (environment, shield of PMTs, wiring, HP Nitrogen system, cooling water of air conditioner, electronics and
DAQ, etc.). In particular, all the Cu parts have been chemically etched before their installation following a new devoted protocol and maintained in HP Nitrogen atmosphere until the installation. All the procedures performed during the dismounting of DAMA/NaI and the installation of DAMA/LIBRA detectors have been carried out in HP Nitrogen atmosphere (see Fig. 13).

DAMA/LIBRA is taking data since March 2003 and the first data release will, most probably, occur when an exposure larger than that of DAMA/NaI will have been collected and analysed in all the aspects. Just as an example of the quality of the data taking, Fig. 14 shows the stability of the calibration factor and of the ratio of the peaks’ positions of the $^{241}$Am source during about one year of data taking.

The highly radiopure DAMA/LIBRA set-up is a powerful tool for further investigation on the Dark Matter particle component in the galactic halo having all the intrinsic merits already mentioned in section 2 and a larger exposed mass, an higher overall radiopurity and improved performances with the respect to DAMA/NaI. Thus, DAMA/LIBRA will further investigate the $6.3 \sigma$ C.L. model independent evidence pointed out by DAMA/NaI with increased sensitivity in order to reach even higher C.L.. Moreover, it will also offer an increased sensitivity to improve corollary quests on the nature of the candidate particle, trying to disentangle at least among some of the many different possible astrophysical, nuclear and particle physics models as well
In the following some of the main topics – not yet well known at present and which can affect whatever model dependent result and comparison – will be mentioned. They will be addressed by the highly radiopure DAMA/LIBRA in a way often unique and always reliable, cheap and competitive. They are:

- **the velocity and spatial distribution of the Dark Matter particles in the galactic halo.** It has been shown that the naive description of the galactic halo as an isothermal halo is an unphysical and non-realistic approximation which significantly affects model dependent evaluations (exclusion plots, allowed regions, etc.) and comparisons. Other modelings (not exhaustive at all), many of them based on N-bodies simulations, have been considered in literature and some of them have been discussed at some extent in [17, 18] and references therein. Some of these models could be significantly discriminated by DAMA/LIBRA.

- **the effects induced on the Dark Matter particles distribution in the galactic halo by contributions from satellite galaxies tidal streams.** Recently it has been pointed out [22] that contributions to the Dark Matter particles in the galactic halo should be expected from tidal streams from the Sagittarius Dwarf elliptical galaxy. Considering that this galaxy was undiscovered until 1994 and considering galaxy formation theories, one has to expect that also other satellite galaxies do exist and contribute as well. In particular, the Canis Major satellite Galaxy has been pointed out as reported in 2003 in ref. [66]; it can, in principle, play a very significant role being close to our galactic plane. At present, the best way to investigate the presence of a stream contribution is to determine in accurate way the phase of the annual modulation, $t_0$, as a function of the energy; in fact,
for a given halo model $t_0$ would be expected to be (slightly) different from 152.5 d and to vary with energy (see Fig. 15).

Figure 15: Expected behaviours of the phase, $t_0$, of the annual modulation signal as function of the energy when considering: i) only galactic halo (“no Sgr”); ii) galactic halo ($C2$ halo model with $v_0 = 220$ km/s, $\rho_0$ equal to the maximum value for this model) and a contribution from Sagittarius Dwarf galaxy (“C2”); iii) galactic halo ($A5$ halo model with $v_0 = 220$ km/s, $\rho_0$ equal to the maximum value for this model) and a contribution from Sagittarius Dwarf galaxy (“A5”). The contributions from Sagittarius Dwarf galaxy have been taken in both cases with a density equal to 4% of $\rho_0$. The light shadow region is the final result of DAMA/NaI on the $t_0$ value for the cumulative energy interval (2 – 6) keV, while the dark shadow region is the expectation on $t_0$ assuming an experiment with the same features as DAMA/NaI, an exposure of $3 \cdot 10^5$ kg · day and the same central value for $t_0$.

- the effects induced on the Dark Matter particles distribution in the galactic halo by the existence of caustics. It has been shown that the continuous infall of Dark Matter particles in the galactic gravitational field can form caustic surfaces and discrete streams in the Dark Matter particles halo [52]. The phenomenology to point out a similar scenario is analogous to that in the previous item; thus, DAMA/LIBRA can as well test this possibility.

- the detection of possible "solar wakes". As an additional verification of the possible presence of contributions from streams of Dark Matter particles in our
galactic halo, DAMA/LIBRA can investigate also the gravitational focusing effect of the Sun on the Dark Matter particle of a stream. In fact, one should expect two kinds of enhancements in the Dark Matter particles flow: one named "spike", which gives an enhancement of Dark Matter particle density along a line collinear with the direction of the incoming stream and of the Sun, and another, named "skirt", which gives a larger Dark Matter particle density on a surface of cone whose opening angle depends on the stream velocity. Thus, DAMA/LIBRA will investigate such a possibility with high sensitivity through second-order time-energy correlations.

- **the study of possible structures as clumpiness with small scale size.** Possible structures as clumpiness with small scale size could, in principle, be pointed out by exploiting a large exposure which can be collected by DAMA/LIBRA.

- **the coupling(s) of the Dark Matter particle with the $^{23}$Na and $^{127}$I and its nature.** As mentioned, several large uncertainties are linked to the coupling(s) between the Dark Matter particle and the target-nuclei. DAMA/LIBRA, exploiting a new large exposure, will allow to better constrain the related aspects. In addition, analyses in model frameworks suitable for e.g. mirror Dark Matter [67] and for particles from multi-dimensional Kaluza-Klein like theories will be performed as well and compared with the other scenarios analysed so far.

- **scaling laws and cross sections.** At present just simple scaling laws are used to scale all the nuclear cross sections to a common nucleon cross section; however, they are a large source of uncertainties in model dependent results and comparisons. For example, recently, it has been pointed out [42] that, even for the neutralino candidate, these assumptions (which hold in the case of model with one-nucleon current) are arbitrary when two-nucleon current with pion exchange are introduced. Thus, the presence of two target-nuclei in the NaI(Tl) detectors of DAMA/LIBRA could in principle offer a probe for that in the large exposure this experiment will collect.

A large work will be faced by DAMA/LIBRA, which is in addition the intrinsically most sensitive experiment in the field of Dark Matter because of its radiopurity, exposed mass and high duty cycle. These qualities will also allow DAMA/LIBRA to further investigate with higher sensitivity several other rare processes.

Finally, at present a third generation R&D effort toward the possible NaI(Tl) ton set-up has been funded and related works have already been started.

### 7 Conclusion

DAMA/NaI has been a pioneer experiment running at LNGS for several years and investigating as first the model independent WIMP annual modulation signature with suitable sensitivity and control of the running parameters. During seven independent experiments of one year each one, it has pointed out at 6.3 $\sigma$ C.L. the presence of a modulation satisfying all the many peculiarities of a WIMP induced effect. Neither
systematic effects nor side reactions able to account for the observed modulation amplitude and to contemporaneously satisfy all the requirements of the signature have been found. DAMA/NaI has also pointed out the complexity of corollary investigations on the nature of the candidate particle, because of the present poor knowledge on the many astrophysical, nuclear and particle physics aspects.

A second generation experiment DAMA/LIBRA has been realized and put in operation since March 2003. This new set-up, having a larger exposed mass and an higher overall radiopurity, will offer a significantly increased sensitivity to further investigate the Dark Matter particle component in the galactic halo pointed out at 6.3 $\sigma$ C.L. by DAMA/NaI. Moreover, further efforts towards the creation of ultimate radiopure NaI(Tl) set-ups are already in progress; in particular, a third generation R&D is in progress towards the possible 1 ton set-up we proposed in 1996.

References

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