Signals from the Universe: the DAMA/LIBRA results

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Some direct detection processes:

- Scatterings on nuclei
  → detection of nuclear recoil energy

- Conversion of particle into e.m. radiation
  → detection of $\gamma$, X-rays, $e^-$

- Excitation of bound electrons in scatterings on nuclei
  → detection of recoil nuclei + e.m. radiation

- Interaction only on atomic electrons
  → detection of e.m. radiation

- Interaction of light DMp (LDM) on $e^-$ or nucleus with production of a lighter particle
  → detection of electron/nucleus recoil energy

- Inelastic Dark Matter: $W + N \rightarrow W^* + N$
  → $W$ has Two mass states $\chi^+$, $\chi^-$ with $\delta$ mass splitting
  → Kinematical constraint for the inelastic scattering of $\chi^-$ on a nucleus
    \[
    \frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}
    \]

- Ionization: Ge, Si
- Bolometer: $\text{TcO}_2$, Ge, $\text{CaWO}_4$
- Scintillation: NaI(Tl), L$\text{Xe}$, CaF$_2$(Eu), ...

- Inelastic Dark Matter: $\chi^+ + N \rightarrow \chi^+ + N$
  e.g. signals from these candidates are completely lost in experiments based on “rejection procedures” of the e.m. component of their rate

- Interaction of light DMp (LDM) on $e^-$ or nucleus with production of a lighter particle
  → detection of electron/nucleus recoil energy

- ... and more
The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.

Drukier, Freese, Spergel PRD86
Freese et al. PRD88

- $v_{\text{sun}} \approx 232 \text{ km/s}$ (Sun velocity in the halo)
- $v_{\text{orb}} = 30 \text{ km/s}$ (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$, $T = 1 \text{ year}$
- $t_0 = 2^{nd} \text{ June}$ (when $v_{\oplus}$ is maximum)

\[ v_{\oplus}(t) = v_{\text{sun}} + v_{\text{orb}} \cos \gamma \cos[\omega(t-t_0)] \]

\[ S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \approx S_{0,k} + S_{m,k} \cos[\omega(t-t_0)] \]

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) For single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be $<7\%$ for usually adopted halo distributions, but it can be larger in case of some possible scenarios

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements.
DAMA/R&D
DAMA/LXe
DAMA/Ge
DAMA/NaI
DAMA/LIBRA

Roma2, Roma1, LNGS, IHEP/Beijing

- by-products and small scale expts.: INR-Kiev
- neutron meas.: ENEA-Frascati
- in some studies on $\beta\beta$ decays (DST-MAE project): IIT Kharagpur, India

DAMA: an observatory for rare processes @LNGS

low bckg DAMA/Ge
meas. with $^{100}$Mo
for sampling meas.
Results on rare processes:

- Possible Pauli exclusion principle violation: PLB408(1997)439
- CNC processes: PRC60(1999)065501
- Search for solar axions: PLB515(2001)6
- Exotic Matter search: EPJ direct C14(2002)1
- Search for superdense nuclear matter: EPJ A23(2005)7
- Search for heavy clusters decays: EPJ A24(2005)51

Results on DM particles:

- PSD: PLB389(1996)757
- Annual Modulation Signature


Model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

Total exposure (7 annual cycles): 0.29 ton x yr
The new DAMA/LIBRA set-up \( \sim 250 \text{ kg NaI(Tl)} \)  
(Large sodium Iodide Bulk for RAre processes)

As a result of a second generation R&D for more radiopure NaI(Tl)  
by exploiting new chemical/physical radiopurification techniques  
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

installing DAMA/LIBRA detectors

assembling a DAMA/ LIBRA detector

filling the inner Cu box with further shield

detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

view at end of detectors’ installation in the Cu box

- **Radiopurity, performances, procedures, etc.**: NIMA592(2008)297  
- **Results on rare processes**: Possible processes violating the Pauli exclusion principle in Na and I: EPJC62(2009)327
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.

NIMA592(2008)297

- Dismounting/Installing protocol (with “Scuba” system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waveform Analyzer TVS641A (2ch per detector), 1 Gsample/s, 8 bit, bandwidth 250 MHz
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy
Some on residual contaminants in new NaI(Tl) detectors

\( \alpha/e \) pulse shape discrimination has practically 100% effectiveness in the MeV range

The measured \( \alpha \) yield in the new DAMA/LIBRA detectors ranges from 7 to some tens \( \alpha/\text{kg/day} \)

Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling.

\[ ^{232}\text{Th residual contamination} \]
From time-amplitude method. If \(^{232}\text{Th} \) chain at equilibrium: it ranges from 0.5 ppt to 7.5 ppt

\[ ^{238}\text{U residual contamination} \]
First estimate: considering the measured \( \alpha \) and \(^{232}\text{Th} \) activity, if \(^{238}\text{U} \) chain at equilibrium \( \Rightarrow \) \(^{238}\text{U} \) contents in new detectors typically range from 0.7 to 10 ppt

\(^{238}\text{U} \) chain split into 5 subchains: \(^{238}\text{U} \rightarrow ^{234}\text{U} \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \rightarrow ^{210}\text{Pb} \rightarrow ^{206}\text{Pb} \)

Thus, in this case: (2.1±0.1) ppt of \(^{232}\text{Th} \); (0.35 ±0.06) ppt for \(^{238}\text{U} \)

and: (15.8±1.6) \( \mu \text{Bq/kg} \) for \(^{234}\text{U} + ^{230}\text{Th} \); (21.7±1.1) \( \mu \text{Bq/kg} \) for \(^{226}\text{Ra} \); (24.2±1.6) \( \mu \text{Bq/kg} \) for \(^{210}\text{Pb} \).

\[ ^{nat}\text{K residual contamination} \]
The analysis has given for the \(^{nat}\text{K} \) content in the crystals values not exceeding about 20 ppb

\[ ^{129}\text{I} \text{ and } ^{210}\text{Pb} \]
\(^{129}\text{I} /^{nat}\text{I} \approx 1.7 \times 10^{-13} \) for all the new detectors

\(^{210}\text{Pb} \) in the new detectors: (5 - 30) \( \mu \text{Bq/kg} \).

No sizeable surface pollution by Radon daughters, thanks to the new handling protocols

\[ ^{nat}\text{I} /^{nat}\text{I} \approx 1.7 \times 10^{-13} \text{ for all the new detectors} \]

... more on NIMA592(2008)297
Infos about DAMA/LIBRA data taking

DAMA/LIBRA test runs: from March 2003 to September 2003
DAMA/LIBRA normal operation: from September 2003 to August 2004
High energy runs for TDs: September 2004
to allow internal $\alpha$'s identification
(approximative exposure $\approx 5000 \text{ kg } \times \text{ d}$)
DAMA/LIBRA normal operation: from October 2004

Data released here:
- four annual cycles: $0.53 \text{ ton } \times \text{ yr}$
- calibrations: acquired $\approx 44 \text{ M events}$ from sources
- acceptance window eff: acquired $\approx 2 \text{ M events/keV}$

<table>
<thead>
<tr>
<th>Period</th>
<th>Exposure (kg×day)</th>
<th>$\alpha - \beta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-1</td>
<td>Sept. 9, 2003 - July 21, 2004</td>
<td>51405</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>July 21, 2004 - Oct. 28, 2005</td>
<td>52597</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>Oct. 28, 2005 - July 18, 2006</td>
<td>39445</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>July 19, 2006 - July 17, 2007</td>
<td>49377</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>192824</td>
</tr>
</tbody>
</table>

**Two remarks:**

- One PMT problems after 6 months. Detector out of trigger since Sep. 2003 (since Sept. 2008 again in operation)
- Residual cosmogenic $^{125}$I presence in the first year in some detectors (this motivates the Sept. 2003 as starting time)

DAMA/Nal (7 years) + DAMA/LIBRA (4 years)
total exposure: $300555 \text{ kg×day} = 0.82 \text{ ton×yr}$

DAMA/LIBRA is continuously running
Cumulative low-energy distribution of the single-hit scintillation events

Single-hit events = each detector has all the others as anticoincidence

(Obviously differences among detectors are present depending e.g. on each specific level and location of residual contaminants, on the detector’s location in the 5x5 matrix, etc.)

Efficiencies already accounted for

DAMA/LIBRA (4 years) total exposure: 0.53 ton×yr

Experimental energy threshold: 3.2 keV, tagged by 1461 keV γ in an adjacent detector

About the energy threshold:

- The DAMA/LIBRA detectors have been calibrated down to the keV region. This assures a clear knowledge of the “physical” energy threshold of the experiment.
- It obviously profits of the relatively high number of available photoelectrons/keV (from 5.5 to 7.5).
- The two PMTs of each detector in DAMA/LIBRA work in coincidence with hardware threshold at single photoelectron level.
- Effective near-threshold-noise full rejection.
- The software energy threshold used by the experiment is 2 keV.
Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)  Total exposure: 300555 kg\times day = 0.82 ton\times yr

Experimental single-hit residuals rate vs time and energy.

\[ A = (0.0215 \pm 0.0026) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 51.9/66 \quad 8.3 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof} = 117.7/67 \Rightarrow P(A=0) = 1.3 \times 10^{-4} \]

2-4 keV

\[ A = (0.0176 \pm 0.0020) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 39.6/66 \quad 8.8 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof} = 116.1/67 \Rightarrow P(A=0) = 1.9 \times 10^{-4} \]

2-5 keV

\[ A = (0.0129 \pm 0.0016) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 54.3/66 \quad 8.2 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof} = 116.4/67 \Rightarrow P(A=0) = 1.8 \times 10^{-4} \]

The data favor the presence of a modulated behavior with proper features at 8.2\sigma \text{ C.L.}
Model-independent residual rate for single-hit events

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) total exposure: 300555 kg×day = 0.82 ton×yr

Results of the fits keeping the parameters free:

<table>
<thead>
<tr>
<th></th>
<th>A (cpd/kg/keV)</th>
<th>T = 2π/ω (yr)</th>
<th>t₀ (day)</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/NaI (7 years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2+4) keV</td>
<td>0.0252 ± 0.0050</td>
<td>1.01 ± 0.02</td>
<td>125 ± 30</td>
<td>5.0σ</td>
</tr>
<tr>
<td>(2+5) keV</td>
<td>0.0215 ± 0.0039</td>
<td>1.01 ± 0.02</td>
<td>140 ± 30</td>
<td>5.5σ</td>
</tr>
<tr>
<td>(2+6) keV</td>
<td>0.0200 ± 0.0032</td>
<td>1.00 ± 0.01</td>
<td>140 ± 22</td>
<td>6.3σ</td>
</tr>
<tr>
<td>DAMA/LIBRA (4 years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2+4) keV</td>
<td>0.0213 ± 0.0032</td>
<td>0.997 ± 0.002</td>
<td>139 ± 10</td>
<td>6.7σ</td>
</tr>
<tr>
<td>(2+5) keV</td>
<td>0.0165 ± 0.0024</td>
<td>0.998 ± 0.002</td>
<td>143 ± 9</td>
<td>6.9σ</td>
</tr>
<tr>
<td>(2+6) keV</td>
<td>0.0107 ± 0.0019</td>
<td>0.998 ± 0.003</td>
<td>144 ± 11</td>
<td>5.6σ</td>
</tr>
<tr>
<td>DAMA/NaI + DAMA/LIBRA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2+4) keV</td>
<td>0.0223 ± 0.0027</td>
<td>0.996 ± 0.002</td>
<td>138 ± 7</td>
<td>8.3σ</td>
</tr>
<tr>
<td>(2+5) keV</td>
<td>0.0178 ± 0.0020</td>
<td>0.998 ± 0.002</td>
<td>145 ± 7</td>
<td>8.9σ</td>
</tr>
<tr>
<td>(2+6) keV</td>
<td>0.0131 ± 0.0016</td>
<td>0.998 ± 0.003</td>
<td>144 ± 8</td>
<td>8.2σ</td>
</tr>
</tbody>
</table>

Modulation amplitudes, A, of single year measured in the 11 one-year experiments of DAMA (NaI + LIBRA)

- The modulation amplitudes for the (2 – 6) keV energy interval, obtained when fixing exactly the period at 1 yr and the phase at 152.5 days, are: (0.019 ± 0.003) cpd/kg/keV for DAMA/NaI and (0.011 ± 0.002) cpd/kg/keV for DAMA/LIBRA.
- Thus, their difference: (0.008 ± 0.004) cpd/kg/keV is ≈ 2σ which corresponds to a modest, but non negligible probability.

\(\chi^2\) test (\(\chi^2/\text{dof} = 4.9/10, 3.3/10\) and \(8.0/10\)) and run test (lower tail probabilities of 74%, 61% and 11%) accept at 90% C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.

Compatibility among the annual cycles
**Power spectrum of single-hit residuals**


Treatment of the experimental errors and time binning included here

- **2-6 keV vs 6-14 keV**
  - DAMA/NaI (7 years)
    - total exposure: 0.29 ton×yr
  - DAMA/LIBRA (4 years)
    - total exposure: 0.53 ton×yr
  - DAMA/NaI (7 years) + DAMA/LIBRA (4 years)
    - total exposure: 0.82 ton×yr

Principal mode in the 2-6 keV region:
- DAMA/NaI
  - $2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$
- DAMA/LIBRA
  - $2.705 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$
- DAMA/NaI+LIBRA
  - $2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$

Not present in the 6-14 keV region (only aliasing peaks)

Clear annual modulation is evident in (2-6) keV while it is absence just above 6 keV
Can a hypothetical background modulation account for the observed effect?

- No Modulation above 6 keV

- No modulation in the whole spectrum:
  - $R_{90}$ percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA-1,2,3,4 running periods
  - Fitting the behaviour with time, adding a term modulated according period and phase expected for Dark Matter particles: consistent with zero

Moreover, if a modulation present in the whole energy spectrum at the level found in the lowest energy region $→ R_{90} \sim$ tens cpd/kg $→ \sim 100\,\sigma$ far away

No modulation in the background: these results account for all sources of bckg (+ see later)
Multiple-hits events in the region of the signal - DAMA/LIBRA 1-4

- Each detector has its own TDs read-out → pulse profiles of multiple-hits events (multiplicity > 1) acquired (exposure: 0.53 ton×yr).
- The same hardware and software procedures as the ones followed for single-hit events

signals by Dark Matter particles do not belong to multiple-hits events, that is:

multiple-hits events = Dark Matter particles events "switched off"

Evidence of annual modulation with proper features as required by the DM annual modulation signature is present in the single-hit residuals, while it is absent in the multiple-hits residual rate.

This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background.

2÷4 keV:  \( A = -(0.0004 \pm 0.0008) \) cpd/kg/keV
2÷5 keV:  \( A = -(0.0005 \pm 0.0007) \) cpd/kg/keV
2÷6 keV:  \( A = -(0.0004 \pm 0.0006) \) cpd/kg/keV
Modulation amplitudes, $S_{m,k}$, as function of the energy

The likelihood function of the single-hit experimental data in the $k$-th energy bin is defined as:

$$L_k = \prod_{ij} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!}$$

$N_{ijk}$ is the number of events collected in the $i$-th time interval (hereafter 1 day), by the $j$-th detector and in the $k$-th energy bin.

$N_{ijk}$ follows a Poissonian distribution with expectation value:

$$\mu_{ijk} = [b_{jk} + R_k(t)M_j\Delta t_i\Delta E\epsilon_{jk}]M_j\Delta t_i\Delta E\epsilon_{jk} = [b_{jk} + S_{0,k} + S_{m,k}\cos(\omega(t_i - t_0))]M_j\Delta t_i\Delta E\epsilon_{jk}$$

The $b_{jk}$ are the background contributions, $M_j$ is the mass of the $j$-th detector, $\Delta t_i$ is the detector running time during the $i$-th time interval, $\Delta E$ is the chosen energy bin, $\epsilon_{jk}$ is the overall efficiency.

The usual procedure is to minimize the function $y_k = -2\ln(L_k) - \text{const}$ for each energy bin; the free parameters of the fit are the $(b_{jk} + S_{0,k})$ contributions and the $S_{m,k}$ parameter.

The $S_{m,k}$ is the modulation amplitude of the modulated part of the signal obtained by maximum likelihood method over the data considering $T=2\pi/\omega=1$ yr and $t_0=152.5$ day.
Energy distribution of the modulation amplitudes, $S_m$, for the total exposure

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

total exposure: 300555 kg×day = 0.82 ton×yr

here $T=2\pi/\omega=1$ yr and $t_0=152.5$ day

A clear modulation is present in the (2-6) keV energy interval, while $S_m$ values compatible with zero are present just above

In fact, the $S_m$ values in the (6-20) keV energy interval have random fluctuations around zero with $\chi^2$ equal to 24.4 for 28 degrees of freedom
Statistical distributions of the modulation amplitudes ($S_m$)

a) $S_m$ values for each detector, each annual cycle and each considered energy bin (here 0.25 keV)
b) $\langle S_m \rangle =$ mean values over the detectors and the annual cycles for each energy bin; $\sigma =$ errors associated to each $S_m$

DAMA/LIBRA (4 years) 
total exposure: 0.53 ton×yr

Each panel refers to each detector separately; 64 entries = 16 energy bins in 2–6 keV energy interval × 4 DAMA/LIBRA annual cycles

$2$–$6$ keV

Individual $S_m$ values follow a normal distribution since $(S_m-\langle S_m \rangle)/\sigma$ is distributed as a Gaussian with a unitary standard deviation (r.m.s.)

$S_m$ statistically well distributed in all the detectors and annual cycles
Statistical analyses about modulation amplitudes \((S_m)\)

\[ x = \frac{(S_m - \langle S_m \rangle)}{\sigma} \]

\[ \chi^2 = \sum x^2 \]

\(\chi^2/d.o.f.\) values of \(S_m\) distributions for each DAMA/LIBRA detector in the (2–6) keV energy interval for the four annual cycles.

The line at \(\chi^2/d.o.f. = 1.31\) corresponds to an upper tail probability of 5%.

Comparison with \(\chi^2\) distribution with 64 d.o.f. gives: \(\chi^2/d.o.f. = 8.1/7\)

The \(\chi^2/d.o.f.\) values range from 0.7 to 1.28 (64 d.o.f. = 16 energy bins × 4 annual cycles)

\[ \Rightarrow \text{ at 95% C.L. the observed annual modulation effect is well distributed in all the detectors.} \]

- The mean value of the twenty-four points is 1.072, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of \(\leq 5 \times 10^{-4}\) cpd/kg/keV, if quadratically combined, or \(\leq 7 \times 10^{-5}\) cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (\(\leq 4.7\%\) or \(\leq 0.7\%\), respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects.
Is there a sinusoidal contribution in the signal?

Phase ≠ 152.5 day?

\[ R(t) = S_0 + S_m \cos[\omega(t-t_0)] + Z_m \sin[\omega(t-t_0)] = S_0 + Y_m \cos[\omega(t-t^*)] \]

For Dark Matter signals:

- \(|Z_m| \ll |S_m| \approx |Y_m|\)
- \(\omega = 2\pi/T\)
- \(t^* \approx t_0 = 152.5d\)
- \(T = 1\) year

Slight differences from 2\textsuperscript{nd} June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)

<table>
<thead>
<tr>
<th>(E) (keV)</th>
<th>(S_m) (cpd/kg/keV)</th>
<th>(Z_m) (cpd/kg/keV)</th>
<th>(Y_m) (cpd/kg/keV)</th>
<th>(t^*) (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-6</td>
<td>0.0122 ± 0.0016</td>
<td>-0.0019 ± 0.0017</td>
<td>0.0123 ± 0.0016</td>
<td>144.0 ± 7.5</td>
</tr>
<tr>
<td>6-14</td>
<td>0.0005 ± 0.0010</td>
<td>0.0011 ± 0.0012</td>
<td>0.0012 ± 0.0011</td>
<td>--</td>
</tr>
</tbody>
</table>
The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about $S_m$ already exclude any sizeable presence of systematical effects.

**Additional investigations on the stability parameters**

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation

Running conditions stable at a level better than 1%

<table>
<thead>
<tr>
<th></th>
<th>DAMA/LIBRA-1</th>
<th>DAMA/LIBRA-2</th>
<th>DAMA/LIBRA-3</th>
<th>DAMA/LIBRA-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>$-(0.0001 \pm 0.0061) , ^\circ \text{C}$</td>
<td>$(0.0026 \pm 0.0086) , ^\circ \text{C}$</td>
<td>$(0.001 \pm 0.015) , ^\circ \text{C}$</td>
<td>$(0.0004 \pm 0.0047) , ^\circ \text{C}$</td>
</tr>
<tr>
<td>Flux $\text{N}_2$</td>
<td>$(0.13 \pm 0.22) , \text{l/h}$</td>
<td>$(0.10 \pm 0.25) , \text{l/h}$</td>
<td>$-(0.07 \pm 0.18) , \text{l/h}$</td>
<td>$-(0.05 \pm 0.24) , \text{l/h}$</td>
</tr>
<tr>
<td>Pressure</td>
<td>$(0.015 \pm 0.030) , \text{mbar}$</td>
<td>$-(0.013 \pm 0.025) , \text{mbar}$</td>
<td>$(0.022 \pm 0.027) , \text{mbar}$</td>
<td>$(0.0018 \pm 0.0074) , \text{mbar}$</td>
</tr>
<tr>
<td>Radon</td>
<td>$-(0.029 \pm 0.029) , \text{Bq/m}^3$</td>
<td>$-(0.030 \pm 0.027) , \text{Bq/m}^3$</td>
<td>$(0.015 \pm 0.029) , \text{Bq/m}^3$</td>
<td>$-(0.052 \pm 0.039) , \text{Bq/m}^3$</td>
</tr>
<tr>
<td>Hardware rate above single photoelectron</td>
<td>$-(0.20 \pm 0.18) \times 10^{-2} , \text{Hz}$</td>
<td>$(0.09 \pm 0.17) \times 10^{-2} , \text{Hz}$</td>
<td>$-(0.03 \pm 0.20) \times 10^{-2} , \text{Hz}$</td>
<td>$(0.15 \pm 0.15) \times 10^{-2} , \text{Hz}$</td>
</tr>
</tbody>
</table>

All the measured amplitudes well compatible with zero

+none can account for the observed effect

(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)
An effect from temperature can be excluded

Any possible modulation due to temperature would always fail some of the peculiarities of the signature

### Temperature

- Detectors in Cu housings directly in contact with multi-ton shield
  → huge heat capacity (∼10⁶ cal/°C)
- Experimental installation continuously air conditioned (2 independent systems for redundancy)
- Operating T of the detectors continuously controlled

**Distribution of the root mean square values of the operating T within periods with the same calibration factors (typically ∼7 days):**

<table>
<thead>
<tr>
<th></th>
<th>DAMA/LIBRA-1</th>
<th>DAMA/LIBRA-2</th>
<th>DAMA/LIBRA-3</th>
<th>DAMA/LIBRA-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (°C)</td>
<td>-(0.0001 ± 0.0061)</td>
<td>(0.0026 ± 0.0086)</td>
<td>(0.001 ± 0.015)</td>
<td>(0.0004 ± 0.0047)</td>
</tr>
</tbody>
</table>

**mean value ∼ 0.04°C**

Considering the slope of the light output ∼ -0.2%/ °C:
relative light output variation < 10⁻⁴:

< 10⁻⁴ cpd/kg/keV (< 0.5% Sm<sub>observed</sub>)

**An effect from temperature can be excluded**
Can a possible thermal neutron modulation account for the observed effect?

- Thermal neutrons flux measured at LNGS:
  \[ \Phi_n = 1.08 \times 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \ (N.Cim.A101(1989)959) \]

- Experimental upper limit on the thermal neutrons flux “surviving” the neutron shield in DAMA/LIBRA:
  - studying triple coincidences able to give evidence for the possible presence of \(^{24}\text{Na}\) from neutron activation:
    \[ \Phi_n < 1.2 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \ (90\% \text{C.L.}) \]

- Two consistent upper limits on thermal neutron flux have been obtained with DAMA/NaI considering the same capture reactions and using different approaches.

Evaluation of the expected effect:

- Capture rate = \( \Phi_n \sigma_n N_T < 0.022 \) captures/day/kg

  **HYPOTHESIS:** assuming very cautiously a 10% thermal neutron modulation:

  \[ S_m^{(\text{thermal n})} < 0.8 \times 10^{-6} \text{ cpd/kg/keV} \ (< 0.01\% \text{ S}_m \text{ observed}) \]

In all the cases of neutron captures (\(^{24}\text{Na},^{128}\text{I}, \ldots\)) a possible thermal n modulation induces a variation in all the energy spectrum

Alreaduy excluded also by \( R_{90} \) analysis

**MC simulation of the process**

When \( \Phi_n = 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \):

\[ 7 \times 10^{-5} \text{ cpd/kg/keV} \]

\[ 1.4 \times 10^{-3} \text{ cpd/kg/keV} \]
Can a possible fast neutron modulation account for the observed effect?

No

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield.

Measured fast neutron flux @ LNGS:
\[ \Phi_n = 0.9 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \] (Astropart.Phys.4 (1995)23)

By MC: differential counting rate above 2 keV \( \approx 10^{-3} \) cpd/kg/keV

HYPOTHESIS: assuming - very cautiously - a 10% neutron modulation:
\[ S_m^{(\text{fast n})} < 10^{-4} \text{ cpd/kg/keV} \] (< 0.5% \( S_m \) observed)

• Experimental upper limit on the fast neutrons flux “surviving” the neutron shield in DAMA/LIBRA:
  - through the study of the inelastic reaction \( ^{23}\text{Na}(n,n')^{23}\text{Na}^*(2076 \text{ keV}) \) which produces two \( \gamma \)'s in coincidence (1636 keV and 440 keV):
    \[ \Phi_n < 2.2 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \] (90%C.L.)
  - well compatible with the measured values at LNGS. This further excludes any presence of a fast neutron flux in DAMA/LIBRA significantly larger than the measured ones.

Moreover, a possible fast n modulation would induce:
  - a variation in all the energy spectrum (steady environmental fast neutrons always accompanied by thermalized component)
    already excluded also by \( R_{90} \)
  - a modulation amplitude for multiple-hit events different from zero
    already excluded by the multiple-hit events

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS.
Summary of the results obtained in the additional investigations of possible systematics or side reactions

<table>
<thead>
<tr>
<th>Source</th>
<th>Main comment</th>
<th>Cautious upper limit (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADON</td>
<td>Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.</td>
<td>&lt;2.5 \times 10^{-6} \text{ cpd/kg/keV}</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded</td>
<td>&lt;10^{-4} \text{ cpd/kg/keV}</td>
</tr>
<tr>
<td>NOISE</td>
<td>Effective full noise rejection near threshold</td>
<td>&lt;10^{-4} \text{ cpd/kg/keV}</td>
</tr>
<tr>
<td>ENERGY SCALE</td>
<td>Routine + intrinsic calibrations</td>
<td>&lt;1-2 \times 10^{-4} \text{ cpd/kg/keV}</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>&lt;10^{-4} \text{ cpd/kg/keV}</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>No modulation above 6 keV; no modulation in the (2-6) keV multiple-hits events; this limit includes all possible sources of background</td>
<td>&lt;10^{-4} \text{ cpd/kg/keV}</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured by MACRO</td>
<td>&lt;3 \times 10^{-5} \text{ cpd/kg/keV}</td>
</tr>
</tbody>
</table>

+ even if larger they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

- Presence of modulation for 11 annual cycles at ~8.2σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 11 independent experiments of 1 year each one
- Absence of known sources of possible systematics and side processes able to quantitatively account for the observed modulation amplitude and to satisfy contemporaneously all the peculiarities of the signature

Well compatible with several candidates (in several of the many astrophysical, nuclear and particle physics scenarios); other ones are open

- Neutralino as LSP in SUSY theories
- Various kinds of WIMP candidates with several different kind of interactions
- Pure SI, pure SD, mixed + Migdal effect +channeling,… (from low to high mass)
- WIMP with preferred inelastic scattering
- Mirror Dark Matter
- Light Dark Matter
- Sterile neutrino
- Dark Matter (including some scenarios for WIMP) electron-interacting
- Elementary Black holes such as the Daemons
- … and more
- Pseudoscalar, scalar or mixed light bosons with axion-like interactions
- Self interacting Dark Matter
- Heavy exotic candidates, as “4th family atoms”, ...
- Neutralino as LSP in SUSY theories
- Kaluza Klein particles

Possible model dependent positive hints from indirect searches not in conflict with DAMA results
(but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.)

Available results from direct searches using different target materials and approaches do not give any robust conflict
Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$.

WIMP DM candidate (as in [4]) considering elastic scattering on nuclei

SI dominant coupling

$\nu_0 = 170 \text{ km/s}$

- Not best fit
- About the same C.L.

<table>
<thead>
<tr>
<th>Curve label</th>
<th>Halo model (see ref. [4, 34])</th>
<th>Local density (GeV/cm$^3$)</th>
<th>Set as in [4]</th>
<th>DM particle mass</th>
<th>$\xi\sigma_{SI}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>$3.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$b$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$c$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>$5.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$d$</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>B</td>
<td>100 GeV</td>
<td>$6.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$e$</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>A</td>
<td>120 GeV</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

channeling contribution as in EPJC53(2008)205 considered for curve $b$

...scaling from NaI

Examples for few of the many possible scenarios superimposed to the measured modulation amplitues $S_{m,k}$

**WIMP DM candidate (as in [4])**

Elastic scattering on nuclei SI & SD mixed coupling $v_0 = 170$ km/s

$\theta = 2.435$

<table>
<thead>
<tr>
<th>Curve label</th>
<th>Halo model (see ref. [4, 34])</th>
<th>Local density (GeV/cm$^3$)</th>
<th>Set as in [4]</th>
<th>DM particle mass</th>
<th>$\xi\sigma_{SI}$ (pb)</th>
<th>$\xi\sigma_{SD}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>$10^{-7}$</td>
<td>2.6</td>
</tr>
<tr>
<td>$g$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>$1.4 \times 10^{-4}$</td>
<td>1.4</td>
</tr>
<tr>
<td>$h$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>$10^{-7}$</td>
<td>1.4</td>
</tr>
<tr>
<td>$i$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>$8.7 \times 10^{-6}$</td>
<td>$8.7 \times 10^{-2}$</td>
</tr>
<tr>
<td>$j$</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>A</td>
<td>100 GeV</td>
<td>$10^{-7}$</td>
<td>1.7</td>
</tr>
<tr>
<td>$k$</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>A</td>
<td>100 GeV</td>
<td>$1.1 \times 10^{-5}$</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$

**LDM candidate** (as in MPLA23(2008)2125):
inelastic interaction with electron or nucleus targets

**Light bosonic candidate** (as in IJMPA21(2006)1445):
axion-like particles totally absorbed by target material

- Not best fit
- About the same C.L.

\[
\frac{\sigma N a}{A^2 N a} \simeq \frac{\sigma I}{A^2 I}
\]

\[
\sigma N a \simeq \sigma I
\]

\(m_L = 0\)

\(m_{\alpha} = 3.2\) keV \(g_{\alpha e e} = 3.9 \times 10^{-11}\)

**Curve r**: also pseudoscalar axion-like candidates (e.g. majoron)

(NFW halo model as in [4, 34], local density = 0.17 GeV/cm³, local velocity = 170 km/s)

<table>
<thead>
<tr>
<th>Curve label</th>
<th>DM particle</th>
<th>Interaction</th>
<th>Set as in [4]</th>
<th>(m_{\alpha})</th>
<th>(\Delta)</th>
<th>Cross section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>LDM</td>
<td>coherent</td>
<td>A</td>
<td>30 MeV</td>
<td>18 MeV</td>
<td>(\xi\sigma_{m\alpha}^{coh} = 1.8 \times 10^{-6})</td>
</tr>
<tr>
<td>m</td>
<td>LDM</td>
<td>coherent</td>
<td>A</td>
<td>100 MeV</td>
<td>55 MeV</td>
<td>(\xi\sigma_{m\alpha}^{coh} = 9.8 \times 10^{-6})</td>
</tr>
<tr>
<td>n</td>
<td>LDM</td>
<td>incoherent</td>
<td>A</td>
<td>30 MeV</td>
<td>3 MeV</td>
<td>(\xi\sigma_{m\alpha}^{inc} = 2.2 \times 10^{-2})</td>
</tr>
<tr>
<td>o</td>
<td>LDM</td>
<td>incoherent</td>
<td>A</td>
<td>100 MeV</td>
<td>55 MeV</td>
<td>(\xi\sigma_{m\alpha}^{inc} = 4.6 \times 10^{-2})</td>
</tr>
<tr>
<td>p</td>
<td>LDM</td>
<td>coherent</td>
<td>A</td>
<td>28 MeV</td>
<td>28 MeV</td>
<td>(\xi\sigma_{m\alpha}^{coh} = 1.6 \times 10^{-6})</td>
</tr>
<tr>
<td>q</td>
<td>LDM</td>
<td>incoherent</td>
<td>A</td>
<td>88 MeV</td>
<td>88 MeV</td>
<td>(\xi\sigma_{m\alpha}^{inc} = 4.1 \times 10^{-2})</td>
</tr>
<tr>
<td>r</td>
<td>LDM</td>
<td>on electrons</td>
<td>–</td>
<td>60 keV</td>
<td>60 keV</td>
<td>(\xi\sigma_{m\alpha}^{inc} = 0.3 \times 10^{-6})</td>
</tr>
</tbody>
</table>

Conclusions: where DAMA is and is going to

- DAMA/LIBRA over 4 annual cycles (0.53 ton×yr) confirms the results of DAMA/NaI (0.29 ton×yr)
- The cumulative confidence level for the model independent evidence for presence of DM particle in the galactic halo is 8.2 σ (total exposure 0.82 ton × yr)

- **First upgrading of the experimental set-up in Sept. 2008**
  - Opening of the shield of DAMA/LIBRA set-up in HP N₂ atmosphere
  - Replacement of some PMTs in HP N₂ atmosphere
  - Dismounting of the Tektronix TDs and mounting of the new Acqiris TDs and of the new DAQ system with optical read-out
  - **Since Oct. 2008 again in data taking**
- Continuing the data taking
- Update corollary analyses in some possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..
- Analyses/data taking to investigate also other rare processes in progress/foreseen

- **Next upgrading**: replacement of all the PMTs with higher Q.E. ones
- Production of new high Q.E. PMTs in progress
- Goal: lowering the energy thresholds of the detectors

- Long term data taking to improve the investigation, to disentangle at least some of the many possibilities, to investigate other features of DM particle component(s) and second order effects, etc..

**Felix qui potuit rerum cognoscere causas** (Virgilio, Georgiche, II, 489)

A possible highly radiopure NaI(Tl) multi-purpose set-up DAMA/1 ton (proposed by DAMA in 1996) at R&D phase

To deep investigate Dark Matter phenomenology at galactic scale