The DAMA annual modulation results
DAMA: an observatory for rare processes @LNGS

DAMA/LXe
DAMA/R&D
low bckg DAMA/Ge for sampling meas.
DAMA/NaI
DAMA/LIBRA

http://people.roma2.infn.it/dama
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

\[
\begin{align*}
\nu_{\text{sun}} &\sim 232 \text{ km/s (Sun velocity in the halo)} \\
\nu_{\text{orb}} &= 30 \text{ km/s (Earth velocity around the Sun)} \\
\gamma &= \pi/3 \\
\omega &= 2\pi/T \quad T = 1 \text{ year} \\
t_0 &= 2^{nd} \text{ June (when } v_\oplus \text{ is maximum)}
\end{align*}
\]

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

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

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) Just 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.

The DM annual modulation signature has a different origin and, thus, different peculiarities (e.g. the phase) with respect to those effects connected with the seasons instead.
DAMA/NaI: ≈100 kg NaI(Tl)


Results on rare processes:

• Possible Pauli exclusion principle violation  PLB408(1997)439
• CNC processes  PRC60(1999)065501
• Electron stability and non-paulian transitions in Iodine atoms (by L-shell)  PLB460(1999)235
• 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
• Investigation on diurnal effect  N.Cim.A112(1999)1541
• Exotic Dark Matter search  PRL83(1999)4918
• Annual Modulation Signature


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

total exposure (7 annual cycles)  0.29 ton x yr
The new DAMA/LIBRA set-up ~250 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

• **Radiopurity, performances, procedures, etc.** : NIMA592(2008)297
• **Results on rare processes**: PEP violation in Na and I: EPJC62(2009)327

view at end of detectors’ installation in the Cu box
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 Acqiris DC270 (2 channels 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

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold

~ 1 m concrete from GS rock

Polyethylene/paraffin

Installation

5.5-7.5 phe/keV

Glove-box for calibration

Electronics + DAQ

OPHG low radioactive copper
Low radioactive load
Gadmium foils
Polyethylene/Paraffin
Concrete from GS rock
Some on residual contaminants in new ULB NaI(Tl) detectors

α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/day

232Th residual contamination
From time-amplitude method. If 232Th chain at equilibrium: it ranges from 0.5 ppt to 7.5 ppt

238U residual contamination
First estimate: considering the measured α and 232Th activity, if 238U chain at equilibrium ⇒ 238U contents in new detectors typically range from 0.7 to 10 ppt

238U chain splitted into 5 subchains: 238U → 234U → 230Th → 226Ra → 210Pb → 206Pb

Thus, in this case: (2.1±0.1) ppt of 232Th; (0.35 ±0.06) ppt for 238U and: (15.8±1.6) μBq/kg for 234U + 230Th; (21.7±1.1) μBq/kg for 226Ra; (24.2±1.6) μBq/kg for 210Pb.

natK residual contamination
The analysis has given for the natK content in the crystals values not exceeding about 20 ppb

129I and 210Pb
129I/natI ≈1.7×10^{-13} for all the new detectors
210Pb in the new detectors: (5 - 30) μBq/kg.

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

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

... more on NIMA592(2008)297
DAMA/LIBRA calibrations

Low energy: various external gamma sources ($^{241}$Am, $^{133}$Ba) and internal X-rays or gamma’s ($^{40}$K, $^{125}$I, $^{129}$I), routine calibrations with $^{241}$Am

$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

High energy: external sources of gamma rays (e.g. $^{137}$Cs, $^{60}$Co and $^{133}$Ba) and gamma rays of 1461 keV due to $^{40}$K decays in an adjacent detector, tagged by the 3.2 keV X-rays

$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23) \cdot 10^{-4}$$

The signals (unlike low energy events) for high energy events are taken only from one PMT

Thus, here and hereafter keV means keV electron equivalent
# Infos about DAMA/LIBRA data taking

<table>
<thead>
<tr>
<th>Period</th>
<th>Mass (kg)</th>
<th>Exposure (kg × day)</th>
<th>$\alpha$-$\beta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-1</td>
<td>Sep. 9, 2003 – July 21, 2004</td>
<td>232.8</td>
<td>51405</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>July 21, 2004 – Oct. 28, 2005</td>
<td>232.8</td>
<td>52597</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>Oct. 28, 2005 – July 18, 2006</td>
<td>232.8</td>
<td>39445</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>July 19, 2006 – July 17, 2007</td>
<td>232.8</td>
<td>49377</td>
</tr>
<tr>
<td>DAMA/LIBRA-5</td>
<td>July 17, 2007 – Aug. 29, 2008</td>
<td>232.8</td>
<td>66105</td>
</tr>
<tr>
<td>DAMA/LIBRA-6</td>
<td>Nov. 12, 2008 – Sep. 1, 2009</td>
<td>242.5</td>
<td>58768</td>
</tr>
<tr>
<td>DAMA/LIBRA-1 to -6</td>
<td>Sep. 9, 2003 – Sep. 1, 2009</td>
<td>317697 = 0.87 ton×yr</td>
<td>0.519</td>
</tr>
</tbody>
</table>

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

Total exposure: $425428 \text{ kg} \times \text{day} = 1.17 \text{ ton} \times \text{yr}$

- calibrations: $\approx 72 \text{ M events from sources}$
- acceptance window eff: $82 \text{ M events} (\approx 3 \text{ M events/ keV})$

- EPJ C56(2008)333
- EPJ C67(2010)39

**First upgrade on Sept 2008:**
- replacement of some PMTs in HP N$_2$ atmosphere
- restore 1 detector to operation
- new Digitizers installed (U1063A Acqiris 1GS/s 8-bit High-Speed cPCI)
- new DAQ system with optical read-out installed

**New upgrade foreseen on fall 2010**

... continuously running
Cumulative low-energy distribution of the single-hit scintillation events

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

Experimental single-hit residuals rate vs time and energy

$A = (0.0183 \pm 0.0022)$ cpd/kg/keV

$\chi^2$/dof = 75.7/79  8.3 $\sigma$ C.L.

2-4 keV

Absence of modulation? No

$\chi^2$/dof = 147/80 \Rightarrow P(A=0) = 7 \times 10^{-6}$

2-5 keV

$A = (0.0144 \pm 0.0016)$ cpd/kg/keV

$\chi^2$/dof = 56.6/79  9.0 $\sigma$ C.L.

Absence of modulation? No

$\chi^2$/dof = 135/80 \Rightarrow P(A=0) = 1.1 \times 10^{-4}$

2-6 keV

$A = (0.0114 \pm 0.0013)$ cpd/kg/keV

$\chi^2$/dof = 64.7/79  8.8 $\sigma$ C.L.

Absence of modulation? No

$\chi^2$/dof = 140/80 \Rightarrow P(A=0) = 4.3 \times 10^{-5}$

The data favor the presence of a modulated behavior with proper features at 8.8 $\sigma$ C.L.
Modulation amplitudes measured in each one of the 13 one-year experiments (DAMA/NaI and DAMA/LIBRA)

<table>
<thead>
<tr>
<th></th>
<th>A (cpd/kg/keV)</th>
<th>$T = 2\pi/\omega \text{ (yr)}$</th>
<th>$t_0 \text{ (day)}$</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DAMA/NaI (7 years)</strong></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><strong>DAMA/LIBRA (6 years)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2+4) keV</td>
<td>0.0180 ± 0.0025</td>
<td>0.996 ± 0.002</td>
<td>135 ± 8</td>
<td>7.2σ</td>
</tr>
<tr>
<td>(2+5) keV</td>
<td>0.0134 ± 0.0018</td>
<td>0.997 ± 0.002</td>
<td>140 ± 8</td>
<td>7.4σ</td>
</tr>
<tr>
<td>(2+6) keV</td>
<td>0.0098 ± 0.0015</td>
<td>0.999 ± 0.002</td>
<td>146 ± 9</td>
<td>6.5σ</td>
</tr>
<tr>
<td><strong>DAMA/NaI + DAMA/LIBRA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2+4) keV</td>
<td>0.0194 ± 0.0022</td>
<td>0.996 ± 0.002</td>
<td>136 ± 7</td>
<td>8.8σ</td>
</tr>
<tr>
<td>(2+5) keV</td>
<td>0.0149 ± 0.0016</td>
<td>0.997 ± 0.002</td>
<td>142 ± 7</td>
<td>9.3σ</td>
</tr>
<tr>
<td>(2+6) keV</td>
<td>0.0116 ± 0.0013</td>
<td>0.999 ± 0.002</td>
<td>146 ± 7</td>
<td>8.9σ</td>
</tr>
</tbody>
</table>

• The modulation amplitudes for the (2 – 6) keV energy interval, obtained when fixing the period at 1 yr and the phase at 152.5 days, are:
  (0.019±0.003) cpd/kg/keV for DAMA/NaI and (0.010±0.002) cpd/kg/keV for DAMA/LIBRA.

• Thus, their difference: (0.009±0.004) cpd/kg/keV is ≈2σ, which corresponds to a modest, but non negligible probability.

The $\chi^2$ test ($\chi^2 = 9.3, 12.2$ and $10.1$ over 12 d.o.f. for the three energy intervals, respectively) and the run test (lower tail probabilities of 57%, 47% and 35% for the three energy intervals, respectively) accept at 90% C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.

 Compatibility among the annual cycles

DAMA/NaI (7 annual cycles: 0.29 ton x yr) +
DAMA/LIBRA (6 annual cycles: 0.87 ton x yr)
total exposure: 425428 kg×day = 1.17 ton×yr

A, T, $t_0$ obtained by fitting the single-hit data with $A\cos[\omega(t-t_0)]$
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/NaI (7 years) +
DAMA/LIBRA (6 years)
total exposure: 1.17 ton×yr

DAMA/LIBRA (6 years)
total exposure: 0.87 ton×yr

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

DAMA/LIBRA
2.697 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}

DAMA/NaI+LIBRA
2.735 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}

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

Clear annual modulation is evident in (2-6) keV while it is absent just above 6 keV
Rate behaviour above 6 keV

- **No Modulation above 6 keV**
  
  Mod. Ampl. (6-10 keV): cpd/kg/keV
  
  - DAMA/LIBRA-1: (0.0016 ± 0.0031)
  - DAMA/LIBRA-2: (0.0010 ± 0.0034)
  - DAMA/LIBRA-3: (0.0001 ± 0.0031)
  - DAMA/LIBRA-4: (0.0006 ± 0.0029)
  - DAMA/LIBRA-5: (0.0021 ± 0.0026)
  - DAMA/LIBRA-6: (0.0029 ± 0.0025)

  → statistically consistent with zero

- **No modulation in the whole energy spectrum:**
  studying integral rate at higher energy, $R_{90}$

- $R_{90}$ percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods

<table>
<thead>
<tr>
<th>Period</th>
<th>Mod. Ampl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-1</td>
<td>-(0.05±0.19) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>-(0.12±0.19) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>-(0.13±0.18) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>(0.15±0.17) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-5</td>
<td>(0.20±0.18) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-6</td>
<td>-(0.20±0.16) cpd/kg</td>
</tr>
</tbody>
</table>

  σ ≈ 1%, fully accounted by statistical considerations

• Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:

  consistent with zero

+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → $R_{90}$ ∼ tens cpd/kg → ∼ 100 σ far away

**No modulation above 6 keV**

This accounts for all sources of bckg and is consistent with studies on the various components
Multiple-hits events in the region of the signal

- Each detector has its own TDs read-out → pulse profiles of *multiple-hits* events (multiplicity > 1) acquired (exposure: 0.87 ton×yr).

- The same hardware and software procedures as those followed for *single-hit* events

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

\[
\text{multiple-hits events} = \text{Dark Matter particles events “switched off”}
\]

Evidence of annual modulation with proper features as required by the DM annual modulation signature:
- present in the *single-hit* residuals
- absent in the *multiple-hits* residual

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

\[
\begin{align*}
2\div4 \text{ keV: } A &= -(0.0011 \pm 0.0007) \text{ cpd/kg/keV} \\
2\div5 \text{ keV: } A &= -(0.0008 \pm 0.0005) \text{ cpd/kg/keV} \\
2\div6 \text{ keV: } A &= -(0.0006 \pm 0.0004) \text{ cpd/kg/keV}
\end{align*}
\]
Energy distribution of the modulation amplitudes

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

here \( T = 2\pi/\omega = 1 \text{ yr} \) and \( t_0 = 152.5 \text{ day} \)

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

total exposure: 425428 kg×day \( \approx 1.17 \text{ ton×yr} \)

![Graph showing energy distribution]

\( \Delta E = 0.5 \text{ keV bins} \)

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

The \( S_m \) values in the (6-20) keV energy interval have random fluctuations around zero with \( \chi^2 \) equal to 27.5 for 28 degrees of freedom.
Statistical distributions of the modulation amplitudes ($S_m$)

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

DAMA/LIBRA (6 years)
total exposure: 0.87 ton×yr

Each panel refers to each detector separately; 96 entries = 16 energy bins in 2-6 keV energy interval × 6 DAMA/LIBRA annual cycles (for crys 16, 1 annual cycle, 16 entries)

Standard deviations of the variable
$$(S_m - <S_m>) / \sigma$$
for the DAMA/LIBRA detectors

2-6 keV

$r.m.s. \approx 1$

$x = (S_m - <S_m>) / \sigma$,
$\chi^2 = \Sigma x^2$

Individual $S_m$ values follow a normal distribution since $(S_m - <S_m>) / \sigma$ 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 ($S_m$)

The line corresponds to an upper tail probability of 5%.

- The mean value of the twenty-five points is 1.066, 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 \( \leq 4 \times 10^{-4} \) cpd/kg/keV, if quadratically combined, or \( \leq 5 \times 10^{-5} \) cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2–6) keV energy interval.
- This possible additional error (\( \leq 4 \% \) or \( \leq 0.5 \% \), 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?

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

total exposure: 425428 kg×day = 1.17 ton×yr

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

For Dark Matter signals:

- \(|Z_m| \ll |S_m| \approx |Y_m|
- \(\omega = 2\pi/T\)
- \(t^* \approx t_0 = 152.5\) day
- \(T = 1\) 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>0.0111 ± 0.0013</td>
<td>-0.0004 ± 0.0014</td>
<td>0.0111 ± 0.0013</td>
<td>150.5 ± 7.0</td>
</tr>
<tr>
<td>6-14</td>
<td>-0.0001 ± 0.0008</td>
<td>0.0002 ± 0.0005</td>
<td>-0.0001 ± 0.0008</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 sizable 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% also in the two new running periods

<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>
<th>DAMA/LIBRA-5</th>
<th>DAMA/LIBRA-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>-(0.0001 ± 0.0061) °C</td>
<td>(0.0026 ± 0.0086) °C</td>
<td>(0.001 ± 0.015) °C</td>
<td>(0.0004 ± 0.0047) °C</td>
<td>(0.0001 ± 0.0036) °C</td>
<td>(0.0007 ± 0.0059) °C</td>
</tr>
<tr>
<td>Flux N₂</td>
<td>(0.13 ± 0.22) l/h</td>
<td>(0.10 ± 0.25) l/h</td>
<td>-(0.07 ± 0.18) l/h</td>
<td>-(0.05 ± 0.24) l/h</td>
<td>-(0.01 ± 0.21) l/h</td>
<td>-(0.01 ± 0.15) l/h</td>
</tr>
<tr>
<td>Pressure</td>
<td>(0.015 ± 0.030) mbar</td>
<td>-(0.013 ± 0.025) mbar</td>
<td>(0.022 ± 0.027) mbar</td>
<td>(0.0018 ± 0.0074) mbar</td>
<td>-(0.08 ± 0.12) ×10⁻² mbar</td>
<td>(0.07 ± 0.13) ×10⁻² mbar</td>
</tr>
<tr>
<td>Radon</td>
<td>-(0.029 ± 0.029) Bq/m³</td>
<td>-(0.030 ± 0.027) Bq/m³</td>
<td>(0.015 ± 0.029) Bq/m³</td>
<td>-(0.052 ± 0.039) Bq/m³</td>
<td>(0.021 ± 0.037) Bq/m³</td>
<td>-(0.028 ± 0.036) Bq/m³</td>
</tr>
<tr>
<td>Hardware rate above single photoelectron</td>
<td>-(0.20 ± 0.18) ×10⁻² Hz</td>
<td>(0.09 ± 0.17) ×10⁻² Hz</td>
<td>-(0.03 ± 0.20) ×10⁻² Hz</td>
<td>(0.15 ± 0.15) ×10⁻² Hz</td>
<td>(0.03 ± 0.14) ×10⁻² Hz</td>
<td>(0.08 ± 0.11) ×10⁻² 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)
Summarizing on a hypothetical background modulation

- No Modulation above 6 keV
- No modulation in the whole energy spectrum
  - + 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 2-6 keV *multiple-hits* residual rate

*multiple-hits* residual rate (green points) vs single-hit residual rate (red points)

No background modulation (and cannot mimic the signature): all this accounts for the all possible sources of bckg

Nevertheless, additional investigations performed ...
The $\mu$ case

Monte Carlo simulation
- muon intensity distribution
- Gran Sasso rock overburden map
- events where just one detector fires

Case of fast neutrons produced by $\mu$

\[ \Phi_\mu @ LNGS \approx 20 \, \mu m^2d^{-1} \text{ (±2% modulated)} \]

Measured neutron Yield @ LNGS: $Y=1+7 \times 10^{-4} \, n/\mu/(g/cm^2)$

\[ R_n = (\text{fast n by } \mu)/(\text{time unit}) = \Phi_\mu \cdot Y \cdot Meff \]

Hyp.: $M_{eff} = 15 \text{ tons}$; $g = \varepsilon \approx f_{AE} \approx f_{single} \approx 0.5$ (cautiously)

Knowing that: $M_{setup} \approx 250 \, kg$ and $\Delta E = 4keV$

Annual modulation amplitude at low energy due to $\mu$ modulation:

\[ S_m(\mu) = R_n \cdot g \cdot \varepsilon \cdot f_{AE} \cdot f_{single} = 2\% / (M_{setup} \cdot \Delta E) \]

\[ g = \text{geometrical factor}; \quad \varepsilon = \text{detection effic. by elastic scattering} \]

\[ f_{AE} = \text{energy window (E}>2keV \text{ effic.}); \quad f_{single} = \text{single hit effic.} \]

Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the multi-hits events

It cannot mimic the signature: already excluded also by $R_{90}$, by multi-hits analysis + different phase, etc.

Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:

- only events at low energy,
- only single-hit events,
- no sizable effect in the multiple-hit counting rate

But, its phase should be (much) larger than $\mu$ phase, $t_\mu$:

- if $\tau \ll T/2\pi$: $t_{side} = t_\mu + \tau$
- if $\tau \gg T/2\pi$: $t_{side} = t_\mu + T/4$

The phase of the muon flux at LNGS is roughly around middle of July and largely variable from year to year. Last meas. by LVD partially overlapped with DAMA/NaI and fully with DAMA/LIBRA: 1.5% modulation and phase=July 5th ± 15 d.

DAMA/NaI + DAMA/LIBRA measured a stable phase: May, 26th ± 7 days

This phase is 7.3 $\sigma$ far from July 15th and is 5.9 $\sigma$ far from July 5th

$R_{90}$, multi-hits, phase, and other analyses → NO
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>$&lt;2.5 \times 10^{-6}$ 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 $\rightarrow$ huge heat capacity $+ T$ continuously recorded</td>
<td>$&lt;10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td>NOISE</td>
<td>Effective full noise rejection near threshold</td>
<td>$&lt;10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td>ENERGY SCALE</td>
<td>Routine + intrinsic calibrations</td>
<td>$&lt;1-2 \times 10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>$&lt;10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>No modulation above 6 keV; no modulation in the (2-6) keV \textit{multiple-hits} events; this limit includes all possible sources of background</td>
<td>$&lt;10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured at LNGS</td>
<td>$&lt;3 \times 10^{-5}$ cpd/kg/keV</td>
</tr>
</tbody>
</table>

Thus, they cannot mimic the observed annual modulation effect.

\*they cannot satisfy all the requirements of annual modulation signature
Summarizing

- Presence of modulation for 13 annual cycles at $8.9\sigma$ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 13 independent experiments of 1 year each one.
- The total exposure by former DAMA/NaI and present DAMA/LIBRA is $1.17 \text{ ton} \times \text{yr}$ (13 annual cycles).
- In fact, as required by the DM annual modulation signature:

1) The *single-hit* events show a clear cosine-like modulation, as expected for the DM signal.

2) Measured period is equal to $(0.999 \pm 0.002) \text{ yr}$, well compatible with the 1 yr period, as expected for the DM signal.

3) Measured phase $(146 \pm 7)$ days is well compatible with the roughly about 152.5 days as expected for the DM signal.

4) The modulation is present only in the low energy $(2-6) \text{ keV}$ energy interval and not in other higher energy regions, consistently with expectation for the DM signal.

5) The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal.

6) The measured modulation amplitude in NaI(Tl) of the *single-hit* events in the $(2-6) \text{ keV}$ energy interval is: $(0.0116 \pm 0.0013)$ cpd/kg/keV ($8.9\sigma$ C.L.).

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available.
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

- No other experiment whose result can be directly compared in model independent way with those of DAMA/NaI and DAMA/LIBRA available.

- Available results from direct searches using different target materials and approaches do not give any robust conflict.

- Moreover, whatever hints from other direct searches must be interpreted; in any case large room of compatibility with DAMA is present.

- Possible model dependent positive hints from indirect searches not in conflict with DAMA; but interpretation and the evidence itself in indirect searches depend e.g. on bckg modeling (also including pulsars, supernovae remnants, ...), on DM spatial velocity distribution, either on forced boost factor or on unnatural clumpiness, etc.
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

WIMP: SI

![Graph showing WIMP: SI interpretation at 15 GeV and 100-120 GeV N.F.W.](image)

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

WIMP: SI & SD \( \theta = 2.435 \)

![Graph showing WIMP: SI & SD interpretation at 15 GeV and 100 GeV N.F.W.](image)

LDM, bosonic DM

\[
\frac{\sigma^{N_{\alpha}}}{A^{2}_{N_{\alpha}}} \sim \frac{\sigma^{I}}{A^{2}_{I}}
\]

![Graph showing LDM, bosonic DM interpretation at \( m_L = 0 \)](image)

Compatibility with several candidates; other ones are open

EPJC56(2008)333
Conclusions

- Positive evidence for the presence of DM particles in the galactic halo now supported at 8.9σ C.L. by the cumulative 1.17 ton × yr exposure over 13 annual cycles by the former DAMA/NaI and the present DAMA/LIBRA
- The modulation parameters determined with better precision
- Full sensitivity to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation
- Updated/new model dependent corollary investigations on the nature of the DM particle in progress also in the light of some recent strongly model dependent claims
- Investigations other than DM

What next?

- Upgrade in fall 2010 substituting all the PMTs with new ones having higher Q.E. to lower the experimental energy threshold, improve general features and disentangle among at least some of the possible scenarios
- Collect a suitable exposure in the new running conditions
- Investigate second order effects
- R&D toward a 1 ton ULB NaI(Tl) set-up experiment proposed in 1996 as a further step for an ultimate multi-ton & multi-purpose NaI(Tl) experiment