Particle Dark Matter in the galactic halo: results from DAMA/LIBRA
Some direct detection processes:

- **Scatterings on nuclei**
  → detection of nuclear recoil energy
  
  ![Diagram of scatterings on nuclei](image)

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

  ![Diagram of excitation](image)

- **Conversion of particle into e.m. radiation**
  → detection of γ, X-rays, e⁻

  ![Diagram of conversion](image)

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

  ![Diagram of interaction](image)

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

  ![Diagram of interaction](image)

- **Inelastic Dark Matter:** \( W + N \rightarrow W^* + N \)
  → \( W \) has Two mass states \( \chi^+, \chi^- \) with \( \delta \) mass splitting

  ![Diagram of inelastic dark matter](image)

  → Kinematical constraint for the inelastic scattering of \( \chi^- \) on a nucleus
  \[
  \frac{1}{2} \mu v^2 \geq \delta \iff v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}
  \]

- **Ionization:** Ge, Si
- **Bolometer:** TeO₂, Ge, CaWO₄, ...
- **Scintillation:** NaI(Tl), LXe, CaF₂(Eu), ...

... even WIMPs

**e.g. signals from these candidates are completely lost in experiments based on "rejection procedures" of the e.m. component of their rate**

**Ionization:** Ge, Si

**Bolometer:** TeO₂, Ge, CaWO₄, ...

**Scintillation:** NaI(Tl), LXe, CaF₂(Eu), ...

... also other ideas ...

**e.g. sterile ν**

**... 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

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

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

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

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

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: 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
DAMA/NaI: \( \approx 100 \text{ kg NaI(Tl)} \)


**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 $6.3 \sigma$ C.L.

Total exposure (7 annual cycles) \( 0.29 \text{ ton x yr} \)
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

closing the Cu box housing the detectors

view at end of detectors’ installation in the Cu box

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297
- Results on rare processes: PEP violation in Na and I: EPJC62(2009)327
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.

NIMA592(2008)297

Polyethylene/paraffin

- 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

Installation

5.5-7.5 phe/keV

- 1m concrete from GS rock
- 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 (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

Glove-box for calibration

OPHC low radioactive copper
Low radioactive load
Gadmium foils
Polyethylene/Paraffin
Concrete from GS rock
Some on residual contaminants in new ULB 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 \( \alpha/\text{kg/day} \)

\( ^{232}\text{Th} \) 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 splitted 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\( \pm \)0.1) ppt of \( ^{232}\text{Th} \); (0.35 \( \pm \)0.06) ppt for \( ^{238}\text{U} \)

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

\( ^{\text{nat}}\text{K} \) residual contamination

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

\( ^{129}\text{I} \) and \( ^{210}\text{Pb} \)

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

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

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

... 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

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

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

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

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 \times day)</th>
<th>$\alpha$-$\beta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-1</td>
<td>232.8</td>
<td>51405</td>
<td>0.562</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>232.8</td>
<td>52597</td>
<td>0.467</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>232.8</td>
<td>39445</td>
<td>0.591</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>232.8</td>
<td>49377</td>
<td>0.541</td>
</tr>
<tr>
<td>DAMA/LIBRA-5</td>
<td>232.8</td>
<td>66105</td>
<td>0.468</td>
</tr>
<tr>
<td>DAMA/LIBRA-6</td>
<td>242.5</td>
<td>58768</td>
<td>0.519</td>
</tr>
<tr>
<td>DAMA/LIBRA-1 to -6</td>
<td>317697</td>
<td>= 0.87 ton\times yr</td>
<td>0.519</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Exposure (kg \times day)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>317697</td>
<td>0.59139445</td>
</tr>
<tr>
<td>242.5</td>
<td>0.46752597</td>
</tr>
<tr>
<td>232.8</td>
<td>0.56251405</td>
</tr>
<tr>
<td>232.8</td>
<td>0.519317697</td>
</tr>
<tr>
<td>242.5</td>
<td>0.54149377</td>
</tr>
<tr>
<td>232.8</td>
<td>Nov. 12, 2008 – Sep. 1, 2009</td>
</tr>
<tr>
<td>242.5</td>
<td>Jul 9, 2003 – Jul 18, 2006</td>
</tr>
<tr>
<td>242.5</td>
<td>Jul 21, 2004 – Oct. 28, 2005</td>
</tr>
<tr>
<td>232.8</td>
<td>Sep. 9, 2003 – July 21, 2004</td>
</tr>
<tr>
<td>242.5</td>
<td>Jul 17, 2007 – Aug. 29, 2008</td>
</tr>
</tbody>
</table>

\[ \text{total exposure: } 425428 \text{ kg} \times \text{day} = 1.17 \text{ ton} \times \text{yr} \]

- **First upgrade on Sept 2008:**
  - replacement of some PMTs in HP N\textsubscript{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

- **calibrations:** \approx 72 M events from sources
- **acceptance window eff:** 82 M events (\approx 3M events/keV)

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

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

Efficiencies already accounted for

3.2 keV, tagged by 1461 keV γ in an adjacent detector
Model Independent Annual Modulation Result

experimental single-hit residuals rate vs time and energy

Acos[ω(t-t₀)] ; continuous lines: t₀ = 152.5 d, T = 1.00 y

DAMA/LIBRA 1-6 (0.87 ton × yr)

The data favor the presence of a modulated behavior with proper features at 8.8σ C.L.

2-4 keV
A=(0.0183±0.0022) cpd/kg/keV
χ²/dof = 75.7/79  8.3 σ C.L.
Absence of modulation? No
χ²/dof=147/80 ⇒ P(A=0) = 7×10⁻⁶

2-5 keV
A=(0.0144±0.0016) cpd/kg/keV
χ²/dof = 56.6/79  9.0 σ C.L.
Absence of modulation? No
χ²/dof=135/80 ⇒ P(A=0) = 1.1×10⁻⁴

2-6 keV
A=(0.0114±0.0013) cpd/kg/keV
χ²/dof = 64.7/79  8.8 σ C.L.
Absence of modulation? No
χ²/dof=140/80 ⇒ P(A=0) = 4.3×10⁻⁵

The fit has been done on the DAMA/NaI & DAMA/LIBRA data (1.17 ton × yr)
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 = 2π/ω (yr)</th>
<th>t₀ (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 χ² test (χ² = 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, t₀ obtained by fitting the single-hit data with Acos[ω(t-t₀)]
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 (6 years)
total exposure: 0.87 ton×yr

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)
total exposure: 1.17 ton×yr

Principal mode in the 2-6 keV region:
DAMA/NaI
2.737 × 10⁻³ d⁻¹ ≈ 1 yr⁻¹

DAMA/LIBRA
2.697 × 10⁻³ d⁻¹ ≈ 1 yr⁻¹

DAMA/NaI + LIBRA
2.735 × 10⁻³ d⁻¹ ≈ 1 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 absent just above 6 keV
Rate behaviour above 6 keV

- **No Modulation above 6 keV**

  ![Residuals plot](image)

  Mod. Ampl. (6-10 keV): cpd/kg/keV
  - (0.0016 ± 0.0031) DAMA/LIBRA-1
  - (0.0010 ± 0.0034) DAMA/LIBRA-2
  - (0.0001 ± 0.0031) DAMA/LIBRA-3
  - (0.0006 ± 0.0029) DAMA/LIBRA-4
  - (0.0021 ± 0.0026) DAMA/LIBRA-5
  - (0.0029 ± 0.0025) DAMA/LIBRA-6

  → 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>

  \( \sigma \approx 1\% \), fully accounted by statistical considerations

+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region \( \rightarrow R_{90} \sim \text{tens cpd/kg} \rightarrow \sim 100 \sigma \) 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\(\times\)yr).

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

\[
\begin{align*}
2\text{÷}4 \text{ keV:} & \quad A = -(0.0011 \pm 0.0007) \text{ cpd/kg/keV} \\
2\text{÷}5 \text{ keV:} & \quad A = -(0.0008 \pm 0.0005) \text{ cpd/kg/keV} \\
2\text{÷}6 \text{ keV:} & \quad A = -(0.0006 \pm 0.0004) \text{ cpd/kg/keV}
\end{align*}
\]

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.
Energy distribution of the modulation amplitudes

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

Here \( T = \frac{2\pi}{\omega} = 1 \) yr and \( t_0 = 152.5 \) day

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

Total exposure: 425428 kg×day \( \approx 1.17 \) ton×yr

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) $\langle S_m \rangle = $ mean values over the detectors and the annual cycles for each energy bin; $\sigma = $ error associated to the $S_m$

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

DAMA/LIBRA (6 years)

total exposure: 0.87 ton$\times$yr

Standard deviations of the variable

$$(S_m - \langle S_m \rangle)/\sigma$$

for the DAMA/LIBRA detectors

$r.m.s. \approx 1$

$$x=(S_m - \langle S_m \rangle)/\sigma,$$

$$\chi^2=\sum x^2$$

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 ($S_m$)

$x = (S_m - \langle S_m \rangle) / \sigma$

$\chi^2 = \sum x^2$

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

The $\chi^2/d.o.f.$ values range from 0.7 to 1.22 (96 d.o.f. = 16 energy bins × 6 annual cycles) for 24 detectors ⇒ at 95% C.L. the observed annual modulation effect is well distributed in all these detectors.

The remaining detector has $\chi^2/d.o.f. = 1.28$ exceeding the value corresponding to that C.L.; this also is statistically consistent, considering that the expected number of detectors exceeding this value over 25 is 1.25.

- 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|
- \(\omega = 2\pi/T\)
- \(t^* \approx t_0 = 152.5\text{d}\)
- \(T = 1\text{ year}\)

Slight differences from 2\(^{nd}\) 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>Parameter</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><strong>Temperature</strong></td>
<td>((-0.0001 \pm 0.0061) ^\circ C)</td>
<td>((0.0026 \pm 0.0086) ^\circ C)</td>
<td>((0.001 \pm 0.015) ^\circ C)</td>
<td>((0.0004 \pm 0.0047) ^\circ C)</td>
<td>((0.0001 \pm 0.0036) ^\circ C)</td>
<td>((0.0007 \pm 0.0059) ^\circ C)</td>
</tr>
<tr>
<td><strong>Flux (N_2)</strong></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>
<td>((-0.01 \pm 0.21) \text{ l/h})</td>
<td>((-0.01 \pm 0.15) \text{ l/h})</td>
</tr>
<tr>
<td><strong>Pressure</strong></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>
<td>((-0.08 \pm 0.12) \times \text{10}^2 \text{ mbar})</td>
<td>((0.07 \pm 0.13) \times \text{10}^2 \text{ mbar})</td>
</tr>
<tr>
<td><strong>Radon</strong></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>
<td>((0.021 \pm 0.037) \text{ Bq/m}^3)</td>
<td>((-0.028 \pm 0.036) \text{ Bq/m}^3)</td>
</tr>
<tr>
<td><strong>Hardware rate above single photoelectron</strong></td>
<td>((-0.20 \pm 0.18) \times \text{10}^2 \text{ Hz})</td>
<td>((0.09 \pm 0.17) \times \text{10}^2 \text{ Hz})</td>
<td>((-0.03 \pm 0.20) \times \text{10}^2 \text{ Hz})</td>
<td>((0.15 \pm 0.15) \times \text{10}^2 \text{ Hz})</td>
<td>((0.03 \pm 0.14) \times \text{10}^2 \text{ Hz})</td>
<td>((0.08 \pm 0.11) \times \text{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)
Summarizing on a hypothetical background modulation

- **No Modulation above 6 keV**
- **No modutation in the whole energy spectrum**
  
  \[ A = (0.3 \pm 0.9) \times 10^{-3} \text{ cpd/kg/keV} \]
  
  + if a modulation present in the whole energy spectrum at the level found in the lowest energy region \( \rightarrow R_{90} \sim \text{tens cpd/kg} \)
  
  \( \rightarrow \sim 100\sigma \text{ far away} \)

- **No modulation in the 2-6 keV multiple-hits residual rate**

\[ (R_{90} - \langle R_{90} \rangle)/\langle R_{90} \rangle > \]

*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$^{-2}$d$^{-1}$ (±2% modulated)
- Measured neutron Yield @ LNGS: $Y=1+7 \times 10^{-4}$ n/µ/(g/cm$^2$)
- $R_n = \text{(fast n by } \mu)/\text{ (time unit)} = \Phi_\mu \times M_{\text{eff}}$

Hyp.: $M_{\text{eff}} = 15$ tons; $g = \epsilon \approx f_{\Delta E} \approx f_{\text{single}} \approx 0.5$ (cautiously)
Knowing that: $M_{\text{setup}} \approx 250$ kg and $\Delta E=4$keV

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.

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

$$S_m^{(\mu)} = R_n \times g \times \epsilon \times f_{\Delta E} \times f_{\text{single}} \times 2\% / (M_{\text{setup}} \Delta E)$$

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

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

$\mathbf{NO}$
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:

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

- 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
  - Already excluded also by \( R_{90} \) analysis

**MC simulation of the process**

- When \( \Phi_n = 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \):
  - \( 7 \times 10^{-5} \text{ cpd/kg/keV} \)
  - \( 1.4 \times 10^{-5} \text{ cpd/kg/keV} \)
Can a possible fast neutron modulation account for the observed effect?

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.

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

\[ S_{m}^{(\text{fast n})} < 10^{-4} \text{ cpd/kg/keV} \quad (< 0.5\% S_{m}^{\text{observed}}) \]

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

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

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;2.5×10⁻⁶ 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→ 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 ×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 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;3×10⁻⁵ cpd/kg/keV</td>
</tr>
</tbody>
</table>

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect
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 ton \(\times\) 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) 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) 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) 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

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

WIMP: SI & SD $\theta = 2.435$

LDM, bosonic DM

$\sigma^{N\alpha}_{N} \sim \sigma^{I}_{I}\frac{A_{N}^{2}}{A_{I}^{2}}$

$m_L = 0$

Compatibility with several candidates; other ones are open
The case of Light Dark Matter (LDM)

Investigation on the direct detection of LDM candidate particles by considering inelastic scattering channels on the electron or on the nucleus

- LDM particle: $\nu_H$ with mass $m_H$

- As result of the inelastic interaction a lighter particle ($\nu_L$) is produced and the target $T$ (either nucleus or electrons) recoils with an energy which can be detectable

- $\nu_L$ is neutral and weakly interacting with ordinary matter and it is able to escape the detector.

- LDM can be either a boson or a fermion

- Extensions of the Standard Model provide Dark Matter candidates with sub-GeV mass able to contribute to the Warm Dark Matter (such as e.g. keV-scale sterile $\nu$, axino or gravitino)

- MeV-scale particles (e.g. axino, gravitino, heavy neutrinos, moduli fields from string theories, Elko fermions) have been proposed as dark matter and as source of 511 keV $\gamma$'s from the Galactic center, due either to DM annihilation or to decay in the bulge

- Supersymmetric models exist where the LSP naturally has a MeV-scale mass and the other phenomenological properties, required to generate the 511 keV $\gamma$'s in the galactic bulge
Perspectives of DAMA/LIBRA

• Continuously running

• **Next upgrade**: replacement of all the PMTs with higher Quantum Efficiency (Q.E.) PMTs.

• New PMTs with higher Q.E. in production: 16 prototypes already tested; five of them have been accepted; 4 new prototypes at hand now

• Continuing data taking for many years in the new configuration.

• Special data taking for other rare processes.

• Update corollary analyses with the new data to disentangle among the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..

• **Goals:**
  
  ➢ lowering the energy threshold (presently, at 2 keV)
  
  ➢ improvement of the acceptance efficiency
  
  ➢ increase the sensitivity in the *model independent* analysis (amplitude, phase, second order effects, …)
  
  ➢ improvement of the sensitivity in the *model dependent* analyses, allowing to better disentangle several astrophysical, particle physics and nuclear physics scenarios
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/Nal 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