DAMA results at Gran Sasso underground lab
Relic DM particles from primordial Universe

- SUSY (as neutralino or sneutrino in various scenarios)
- the sneutrino in the Smith and Weiner scenario
- sterile ν
- electron interacting dark matter
- a heavy ν of the 4-th family
- even a suitable particle not yet foreseen by theories

What accelerators can do:
- to demonstrate the existence of some of the possible DM candidates

What accelerators cannot do:
- to credit that a certain particle is the Dark Matter solution or the “single” Dark Matter particle solution...

+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

DM direct detection method using a model independent approach and a low-background widely-sensitive target material
Some direct detection processes:

- Scatterings on nuclei
  → detection of nuclear recoil energy

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

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

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

- 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
  e.g. sterile \( \nu \)

- Ionization:
  Ge, Si

- Bolometer:
  TeO\(_2\), Ge, CaWO\(_4\), ...

- Scintillation:
  NaI(Tl), LXe, CaF\(_2\)(Eu), ...

- DMp \( \rightarrow \) detection of light DMp (LDM) on \( e^- \) or nucleus with production of a lighter particle
  e.g. sterile \( \nu \)

- Some direct detection processes:

  - ... and more

- e.g. signals from these candidates are completely lost in experiments based on “rejection procedures” of the e.m. component of their rate
The annual modulation: a model independent signature for the investigation of DM 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 can point out its presence.

**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

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

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

The DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons.

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.

- \( v_{\text{sun}} \approx 232 \text{ km/s} \) (Sun vel in the halo)
- \( v_{\text{orb}} = 30 \text{ km/s} \) (Earth vel 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)
Roma2, Roma1, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev
+ in some studies on $\beta\beta$ decays (DST-MAE project): IIT - Ropar, India

DAMA: an observatory for rare processes @LNGS

DAMA/Crys
DAMA/LXe
DAMA/R&D
DAMA/Ge
DAMA/NaI
DAMA/LIBRA

http://people.roma2.infn.it/dama
The pioneer DAMA/NaI:
≈100 kg highly radiopure NaI(Tl)

**Performances:**

**Results on rare processes:**
- Possible Pauli exclusion principle violation
- CNC processes
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
- Search for solar axions
- Exotic Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLB408(1997)439</td>
<td>1997</td>
</tr>
<tr>
<td>PRC60(1999)065501</td>
<td>1999</td>
</tr>
<tr>
<td>PLB460(1999)235</td>
<td>1999</td>
</tr>
<tr>
<td>PLB515(2001)6</td>
<td>2001</td>
</tr>
<tr>
<td>EPJdirect C14(2002)1</td>
<td>2002</td>
</tr>
<tr>
<td>EPJA23(2005)7</td>
<td>2005</td>
</tr>
<tr>
<td>EPJA24(2005)51</td>
<td>2005</td>
</tr>
</tbody>
</table>

**Results on DM particles:**
- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- Annual Modulation Signature

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLB389(1996)757</td>
<td>1996</td>
</tr>
<tr>
<td>PRL83(1999)4918</td>
<td>1999</td>
</tr>
</tbody>
</table>

- 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×yr
Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: $^{232}$Th, $^{238}$U and $^{40}$K at level of $10^{-12}$ g/g

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving - including photos - in HP Nitrogen atmosphere)

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297; JINST 7 (2012) 03009
The curves superimposed to the experimental data have been obtained by simulations.

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.

\[
\sigma_{LE} = (0.448 \pm 0.035) \frac{1}{\sqrt{E(\text{keV})}} + (9.1 \pm 5.1) \cdot 10^{-3}
\]

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.

\[
\sigma_{HE} = (1.12 \pm 0.06) \frac{1}{\sqrt{E(\text{keV})}} + (17 \pm 23) \cdot 10^{-4}
\]

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.
Complete DAMA/LIBRA-phase1

<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>Sept. 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 - Sept. 1, 2009</td>
<td>242.5</td>
<td>58768</td>
</tr>
<tr>
<td>DAMA/LIBRA-7</td>
<td>Sept. 1, 2009 - Sept. 8, 2010</td>
<td>242.5</td>
<td>62098</td>
</tr>
</tbody>
</table>

DAMA/LIBRA-phase1: Sept. 9, 2003 - Sept. 8, 2010 | 379795 $\approx$ 1.04 ton\(\times\)yr | 0.518

DAMA/NaI + DAMA/LIBRA-phase1: 1.33 ton\(\times\)yr

**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

**START of DAMA/LIBRA – phase 2**

**Second upgrade on Oct./Nov. 2010**
- Replacement of all the PMTs with higher Q.E. ones from dedicated developments
- Goal: lowering the software energy threshold

Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

... continuously running

- EPJC56(2008)333
- EPJC67(2010)39
- EPJC73(2013)2648
- calibrations: $\approx$96 M events from sources
- acceptance window eff: 95 M events ($\approx$3.5 M events/keV)
Experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/NaI + DAMA/LIBRA-phase1

Total exposure: 487526 kg×day = 1.33 ton×yr

2-4 keV

\[ A = (0.0179 \pm 0.0020) \text{ cpd/kg/keV} \]

\[ \chi^2/\text{dof} = 87.1/86 \quad 9.0 \sigma \text{ C.L.} \]

Absence of modulation? No

\[ \chi^2/\text{dof} = 169/87 \Rightarrow P(A=0) = 3.7 \times 10^{-7} \]

2-5 keV

\[ A = (0.0135 \pm 0.0015) \text{ cpd/kg/keV} \]

\[ \chi^2/\text{dof} = 68.2/86 \quad 9.0 \sigma \text{ C.L.} \]

Absence of modulation? No

\[ \chi^2/\text{dof} = 152/87 \Rightarrow P(A=0) = 2.2 \times 10^{-5} \]

2-6 keV

\[ A = (0.0110 \pm 0.0012) \text{ cpd/kg/keV} \]

\[ \chi^2/\text{dof} = 70.4/86 \quad 9.2 \sigma \text{ C.L.} \]

Absence of modulation? No

\[ \chi^2/\text{dof} = 154/87 \Rightarrow P(A=0) = 1.3 \times 10^{-5} \]

The data favor the presence of a modulated behavior with proper features at 9.2\sigma \text{ C.L.}
The data of DAMA/NaI + DAMA/LIBRA-phase1 favor the presence of a modulated behavior with proper features at 9.2σ C.L.
DAMA/NaI & DAMA/LIBRA experiments main upgrades and improvements

July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector):
(i) TD VXI Tektronix;
(ii) Digital Unix DAQ system;
(iii) GPIB-CAMAC.

July 2002 DAMA/NaI data taking completed

On 2003 DAMA/LIBRA has begun first operations

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:
1. one detector recovered by replacing a broken PMT
2. a new optimization of some PMTs and HVs performed
3. all the TD replaced with new ones (U1063A Acqiris 8-bit 1GS/s DC270 High-Speed cPCI Digitizers)
4. a new DAQ with optical read-out installed.

The second DAMA/LIBRA upgrade in Fall 2010:
Replacement of all the PMTs with higher Q.E. ones from dedicated developments
(+new preamp in Fall 2012 and other developments in progress)

DAMA/LIBRA-phase2 in data taking
Modulation amplitudes (A), period (T) and phase (t₀) measured in DAMA/NaI and DAMA/LIBRA-phase1

DAMA/NaI (0.29 ton x yr) + DAMA/LIBRA-phase1 (1.04 ton x yr)

Total exposure: 487526 kg×day = 1.33 ton×yr

<table>
<thead>
<tr>
<th>DAMA/NaI+DAMA/LIBRA-phase1</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>(2-4) keV</td>
<td>0.0190 ±0.0020</td>
<td>0.996 ±0.0002</td>
<td>134 ± 6</td>
<td>9.5σ</td>
</tr>
<tr>
<td>(2-5) keV</td>
<td>0.0140 ±0.0015</td>
<td>0.996 ±0.0002</td>
<td>140 ± 6</td>
<td>9.3σ</td>
</tr>
<tr>
<td>(2-6) keV</td>
<td>0.0112 ±0.0012</td>
<td>0.998 ±0.0002</td>
<td>144 ± 7</td>
<td>9.3σ</td>
</tr>
</tbody>
</table>

χ² test (χ² = 9.5, 13.8 and 10.8 over 13 d.o.f. for the three energy intervals, respectively; upper tail probability 73%, 39%, 63%) and run test (lower tail probabilities of 41%, 29% and 23% 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
Power spectrum of single-hit residuals

DAMA/NaI (7 years) + DAMA/LIBRA-phase1 (7 years)
total exposure: 1.33 ton×yr

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

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


Given a set of data values $r_i, i = 1, \ldots, N$ at respective observation times $t_i$, the Lomb-Scargle periodogram is:

$$P_N(\omega) = \frac{1}{2 \sigma^2} \left\{ \sum_i \left( r_i - \bar{r} \right) \cos \omega(t_i - \tau) \right\}^2 + \left\{ \sum_i \left( r_i - \bar{r} \right) \sin \omega(t_i - \tau) \right\}^2 \right.$$ 

where: $\bar{r} = \frac{1}{N} \sum_i r_i$ and $\sigma^2 = \frac{1}{N-1} \sum_i (r_i - \bar{r})^2$

and, for each angular frequency $\omega = 2\pi f > 0$ of interest, the time-offset $\tau$ is:

$$\tan(2\omega \tau) = \frac{\sum_i \sin(2\omega t_i)}{\sum_i \cos(2\omega t_i)}$$

The Nyquist frequency is $\approx 3 \text{ y}^{-1} (\approx 0.008 \text{ d}^{-1})$; meaningless higher frequencies, washed off by the integration over the time binning.

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
  - (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
  - (0.0023 ± 0.0024) DAMA/LIBRA-7

  → 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

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

    | Period       | Mod. Ampl.             |
    |--------------|------------------------|
    | DAMA/LIBRA-1 | -(0.05±0.19) cpd/kg    |
    | DAMA/LIBRA-2 | -(0.12±0.19) cpd/kg    |
    | DAMA/LIBRA-3 | -(0.13±0.18) cpd/kg    |
    | DAMA/LIBRA-4 | (0.15±0.17) cpd/kg     |
    | DAMA/LIBRA-5 | (0.20±0.18) cpd/kg     |
    | DAMA/LIBRA-6 | -(0.20±0.16) cpd/kg    |
    | DAMA/LIBRA-7 | -(0.28±0.18) cpd/kg    |

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

- No modulation in the whole energy spectrum:

  - Studying integral rate at higher energy, \( R_{90} \)

  - No modulation above 6 keV

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

- Each detector has its own TDs readout → pulse profiles of *multiple-hits* events (multiplicity > 1) acquired (exposure: 1.04 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.
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/NaI + DAMA/LIBRA-phase1

Total exposure: \( 487526 \text{ kg} \times \text{day} \approx 1.33 \text{ ton} \times \text{yr} \)

\( \Delta E = 0.5 \) 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 35.8 for 28 degrees of freedom (upper tail probability 15%).
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 on $S_m$

DAMA/LIBRA-phase1 (7 years)

total exposure: 1.04 ton$\times$yr

Each panel refers to each detector separately; 112 entries = 16 energy bins in 2-6 keV energy interval $\times$ 7 DAMA/LIBRA-phase1 annual cycles (for crys 16, 2 annual cycle, 32 entries)

2-6 keV

Standard deviations of $(S_m - \langle S_m \rangle)/\sigma$
for each detectors

$r.m.s. \approx 1$

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

$\chi^2 = \Sigma x^2$

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, energy bin and annual cycles
Statistical analyses about modulation amplitudes ($S_m$)

$$x = (S_m - <S_m>) / \sigma,$$

$$\chi^2 / \text{d.o.f. values of } S_m \text{ distributions for each DAMA/LIBRA-phase1 detector in the (2–6) keV energy interval for the seven annual cycles.}$$

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

DAMA/LIBRA-phase1 (7 years) total exposure: 1.04 ton × yr

The $\chi^2 / \text{d.o.f.}$ values range from 0.72 to 1.22 for all 25 detectors $\Rightarrow$ at 95% C.L. the observed annual modulation effect is well distributed in all the detectors.

- The mean value of the twenty-five points is 1.030, 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 $\leq 3 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 2 \times 10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error ($\leq 3\%$ or $\leq 0.2\%$, 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/Nal (7 years) + DAMA/LIBRA-phase1 (7 years)

total exposure: 487526 kg×day = 1.33 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 = 152.5d
- T = 1 year

Slight differences from 2nd 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>0.0106 ± 0.0012</td>
<td>-0.0006 ± 0.0012</td>
<td>0.0107 ± 0.0012</td>
<td>149.5 ± 7.0</td>
</tr>
<tr>
<td>6-14</td>
<td>0.0001 ± 0.0007</td>
<td>0.0000 ± 0.0005</td>
<td>0.0001 ± 0.0008</td>
<td>--</td>
</tr>
</tbody>
</table>
Model independent result on possible diurnal effect in DAMA/LIBRA–phase1

- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.

- These residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Solar Time</th>
<th>Sidereal Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–4 keV</td>
<td>$\chi^2$/d.o.f. = 35.2/24 $\rightarrow$ P = 7%</td>
<td>$\chi^2$/d.o.f. = 28.7/24 $\rightarrow$ P = 23%</td>
</tr>
<tr>
<td>2–5 keV</td>
<td>$\chi^2$/d.o.f. = 35.5/24 $\rightarrow$ P = 6%</td>
<td>$\chi^2$/d.o.f. = 24.0/24 $\rightarrow$ P = 46%</td>
</tr>
<tr>
<td>2–6 keV</td>
<td>$\chi^2$/d.o.f. = 25.8/24 $\rightarrow$ P = 36%</td>
<td>$\chi^2$/d.o.f. = 21.2/24 $\rightarrow$ P = 63%</td>
</tr>
<tr>
<td>6–14 keV</td>
<td>$\chi^2$/d.o.f. = 25.5/24 $\rightarrow$ P = 38%</td>
<td>$\chi^2$/d.o.f. = 35.9/24 $\rightarrow$ P = 6%</td>
</tr>
</tbody>
</table>

+ run test to verify the hypothesis that the positive and negative data points are randomly distributed. The lower tail probabilities (in the four energy regions) are: 43, 18, 7, 26% for the solar case and 54, 84, 78, 16% for the sidereal case.

Thus, the presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity.
The time dependence of the counting rate

Expected signal counting rate in a given k-th energy bin:

\[ S_k[v_{lab}(t)] \simeq S_k[v_s] + \left[ \frac{\partial S_k}{\partial v_{lab}} \right]_{v_s} [V_{Earth} A_m \cos \omega (t - t_0) + V_r A_d \cos \omega_{rot} (t - t_d)] \]

The ratio \( R_{dy} \) of the diurnal over annual modulation amplitudes is a model independent constant:

\[ R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016 \]

at LNGS latitude

• Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval: \( (0.0097 \pm 0.0013) \text{ cpd/kg/keV} \)

• Thus, the expected value of the diurnal modulation amplitude is \(<1.5 \times 10^{-4} \text{ cpd/kg/keV.}\)

• When fitting the single-hit residuals with a cosine function with amplitude \( A_d \) as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.

\[ A_d < 1.2 \times 10^{-3} \text{ cpd/kg/keV (90\%CL)} \]

Present experimental sensitivity more modest than the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect.

<table>
<thead>
<tr>
<th>Energy</th>
<th>( A_d^{\text{exp}} ) (cpd/kg/keV)</th>
<th>( \chi^2 )/d.o.f.</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–4 keV</td>
<td>((2.0 \pm 2.1) \times 10^{-3})</td>
<td>27.8/23</td>
<td>22%</td>
</tr>
<tr>
<td>2–5 keV</td>
<td>(-(1.4 \pm 1.6) \times 10^{-3})</td>
<td>23.2/23</td>
<td>45%</td>
</tr>
<tr>
<td>2–6 keV</td>
<td>((1.0 \pm 1.3) \times 10^{-3})</td>
<td>20.6/23</td>
<td>61%</td>
</tr>
<tr>
<td>6–14 keV</td>
<td>((5.0 \pm 7.5) \times 10^{-4})</td>
<td>35.4/23</td>
<td>5%</td>
</tr>
</tbody>
</table>

The \( A_d \) values are compatible with zero, having random fluctuations around zero with \( \chi^2 \) equal to 19.5 for 18 dof.
Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation 

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)

### Additional investigations on the stability parameters

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>
<th>DAMA/LIBRA-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°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>
<td>(0.0001 ± 0.0036)</td>
<td>(0.0007 ± 0.0059)</td>
<td>(0.0000 ± 0.0054)</td>
</tr>
<tr>
<td>Flux N₂ (l/h)</td>
<td>(0.13 ± 0.22)</td>
<td>(0.10 ± 0.25)</td>
<td>-(0.07 ± 0.18)</td>
<td>-(0.05 ± 0.24)</td>
<td>-(0.01 ± 0.21)</td>
<td>-(0.01 ± 0.15)</td>
<td>-(0.00 ± 0.14)</td>
</tr>
<tr>
<td>Pressure (mbar)</td>
<td>(0.015 ± 0.030)</td>
<td>-(0.013 ± 0.025)</td>
<td>(0.022 ± 0.027)</td>
<td>(0.0018 ± 0.0074)</td>
<td>-(0.08 ± 0.12)×10⁻²</td>
<td>(0.07 ± 0.13)×10⁻²</td>
<td>-(0.26 ± 0.55)×10⁻²</td>
</tr>
<tr>
<td>Radon (Bq/m³)</td>
<td>-(0.029 ± 0.029)</td>
<td>-(0.030 ± 0.027)</td>
<td>(0.015 ± 0.029)</td>
<td>-(0.052 ± 0.039)</td>
<td>(0.021 ± 0.037)</td>
<td>-(0.028 ± 0.036)</td>
<td>(0.012 ± 0.047)</td>
</tr>
<tr>
<td>Hardware rate above single ph.e. (Hz)</td>
<td>-(0.20 ± 0.18)×10⁻²</td>
<td>(0.09 ± 0.17)×10⁻²</td>
<td>-(0.03 ± 0.20)×10⁻²</td>
<td>(0.15 ± 0.15)×10⁻²</td>
<td>(0.03 ± 0.14)×10⁻²</td>
<td>(0.08 ± 0.11)×10⁻²</td>
<td>(0.06 ± 0.10)×10⁻²</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
✓ Direct \( \mu \) interaction in DAMA/LIBRA set-up:

DAMA/LIBRA surface \( \approx 0.13 \, \text{m}^2 \)

\( \mu \) flux @ DAMA/LIBRA \( \approx 2.5 \, \mu \text{/day} \)

MonteCarlo simulation:
- muon intensity distribution
- Gran Sasso rock overburden map
- Single hit events

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

✓ Rate, \( R_n \), of fast neutrons produced by \( \mu \):

\[
R_n = \frac{\text{fast n by } \mu}{\text{time unit}} = \Phi_\mu \, Y \, M_{\text{eff}}
\]

- \( \Phi_\mu @ \text{LNGS} \approx 20 \, \mu \, \text{m}^2\text{d}^{-1} \, (\pm 1.5\% \, \text{modulated}) \)
- Measured neutron Yield @ LNGS:
  \[
  Y = 1 \div 7 \times 10^{-4} \, \text{n/\mu/(g/cm}^2\text{)}
  \]

Annual modulation amplitude at low energy due to \( \mu \) modulation:

\[
S_m^{(m)} = R_n \, g \, \varepsilon \, f_{DE} \, f_{\text{single}} \, 2\% \, / (M_{\text{setup}} \, \Delta E)
\]

\[
S_m^{(m)} < (0.3-2.4) \times 10^{-5} \, \text{cpd/kg/keV}
\]

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 by \( R_{90} \), by multi-hits analysis + different phase, etc.
Inconsistency of the phase between DAMA signal and $\mu$ modulation

$\mu$ flux @ LNGS (MACRO, LVD, BOREXINO) $\approx 3 \cdot 10^{-4}$ m$^{-2}$s$^{-1}$; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)

- the muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a “mean” of the muon phase of each year
- The DAMA: modulation amplitude $10^{-2}$ cpd/kg/keV, in 2-6 keV energy range for single hit events; phase:
  - May 26 ± 7 days (stable over 13 years)

considering the seasonal weather at LNGS, quite impossible that the max. temperature of the outer atmosphere (on which $\mu$ flux variation is dependent) is observed e.g. in June 15 which is 3 $\sigma$ from DAMA

The DAMA phase is 5.7$\sigma$ far from the LVD/BOREXINO phases of muons (7.1 $\sigma$ far from MACRO measured phase)

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
- pulses with time structure as scintillation light

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

\[
\begin{align*}
&\text{if } \tau < T/2\pi: & t_{\text{side}} &= t_\mu + \tau \\
&\text{if } \tau > T/2\pi: & t_{\text{side}} &= t_\mu + T/4
\end{align*}
\]

It cannot mimic the signature: different phase

Similar for the whole DAMA/LIBRA-phase
Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1


<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>

Thus, they cannot mimic the observed annual modulation effect.

+ they cannot satisfy all the requirements of annual modulation signature.
Final model independent result
DAMA/NaI + DAMA/LIBRA-phase1

- Presence of modulation for 14 annual cycles at $9.3\sigma$ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 14 independent experiments of 1 year each one.

- The total exposure by former DAMA/NaI and present DAMA/LIBRA is $1.33 \text{ ton} \times \text{yr} (14 \text{ annual cycles})$.

- 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 $(0.998\pm0.002) \text{ yr}$, well compatible with the 1 yr period, *as expected for the DM signal*.

  3. Measured phase $(144\pm7) \text{ days}$ is well compatible with $152.5 \text{ days}$, *as expected for the DM signal*.

  4. The modulation is present only in the low energy ($2-6) \text{ keV}$ 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-hits*, *as expected for the DM signal*.

  6. The measured modulation amplitude in NaI(Tl) of the *single-hit* events in ($2-6) \text{ keV}$ is: $(0.0112 \pm 0.0012) \text{ cpd/kg/keV}$ ($9.3\sigma$ 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

well compatible with several candidates (in many possible astrophysical, nuclear and particle physics scenarios)

Neutralino as LSP in various 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

Self interacting Dark Matter

Pseudoscalar, scalar or mixed light bosons with axion-like interactions

a heavy ν of the 4-th family

Heavy exotic candidates, as “4th family atoms”, …

Kaluza Klein particles

Elementary Black holes such as the Daemons

Sterile neutrino

… and more…

Possible model dependent positive hints from indirect searches (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.) not in conflict with DAMA results;

Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with positive excesses
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

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

\[ \theta = 2.435 \]

Compatibility with several candidates; other ones are open.

EPJC56(2008)333
IJMPA28(2013)1330022
...and experimental aspects...

- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling, ...
- ...

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters’ values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA
Examples of uncertainties in models and scenarios

Nature of the candidate and couplings

- WIMP class particles (neutrino, sneutrino, etc.): SI, SD, mixed SI&SD, preferred inelastic + e.m. contribution in the detection
- Light bosonic particles
- Kaluza-Klein particles
- Mirror dark matter
- Heavy Exotic candidate
- ...etc. etc.

Halo models & Astrophysical scenario

- Isothermal sphere ⇒ very simple but unphysical halo model
- Many consistent halo models with different density and velocity distribution profiles can be considered with their own specific parameters (see e.g. PRD61(2000)023512)
- Caustic halo model
- Presence of non-thermalized DM particle components
- Streams due e.g. to satellite galaxies of the Milky Way (such as the Sagittarius Dwarf)
- Multi-component DM halo
- Clumpiness at small or large scale
- Solar Wakes
- ...etc. ...

Form Factors for the case of recoiling nuclei

- Many different profiles available in literature for each isotope
- Parameters to fix for the considered profiles
- Dependence on particle-nucleus interaction
- In SD form factors: no decoupling between nuclear and Dark Matter particles degrees of freedom + dependence on nuclear potential

Spin Factors for the case of recoiling nuclei

- Calculations in different models give very different values also for the same isotope
- Depend on the nuclear potential models
- Large differences in the measured counting rate can be expected using:
  - either SD not-sensitive isotopes or SD sensitive isotopes depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the $^{25}$Na and $^{127}$I cases).

Instrumental quantities

- Energy resolution
- Efficiencies
- Quenching factors
- Channeling effects
- Their dependence on energy
- ...

Quenching Factor

- differences are present in different experimental determinations of $q$ for the same nuclei in the same kind of detector depending on its specific features (e.g. $q$ depends on dopant and on the impurities; in liquid noble gas e.g.on trace impurities, on presence of degassing/releasing materials, on thermodynamical conditions, on possibly applied electric field, etc); assumed 1 in bolometers
- channeling effects possible increase at low energy in scintillators (dL/dx)
- possible larger values of $q$ (AstropPhys33 (2010) 40) → energy dependence

... and more ...
**CoGeNT:**
low-energy rise in the spectrum ("irreducible" by the applied background reduction procedures) + annual modulation

**CDMS-Ge:**
after many data selections and cuts, 2 Ge recoil-like candidates survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)

**CRESST:**
after many data selections and cuts, 67 recoil-like candidates in the O/Ca bands survive in an exposure of 730 kg x day (expected residual background: 40-45 events, depending on minimization)

**CDMS-Si:**
after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

All those recoil-like excesses with respect to an estimated bckg surviving cuts as well as the CoGeNT result are compatible with the DAMA 9.3 σ C.L. annual modulation result in various scenarios
Case of DM particles inducing elastic scatterings on target-nuclei, SI case

Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent Quenching Factors (red);
7.5 σ C.L.

CoGeNT; qf at fixed assumed value
1.64 σ C.L.

Compatibility also with CRESST and CDMS, if the two CDMS-Ge, the three CDMS-Si and the CRESST recoil-like events are interpreted as relic DM interactions

PrD84(2011)055014, IJMPA28(2013)1330022

Including the Migdal effect
→ Towards lower mass/higher σ

Co-rotating halo,
Non thermalized component
→ Enlarge allowed region
towards larger mass

Combining channeling and energy dependence of q.f. (AstrPhys33 (2010) 40)
→ Towards lower σ
Case of DM particles inducing elastic scatterings on target-nuclei, SI case

Regions in the nucleon cross section vs DM particle mass plane

arXiv:1401.3295

- Non-Maxwellian halo model is considered.
- The DAMA regions are for both Maxwellian and non-Maxwellian halo models.
- Na quenching factor taken at the fixed value 0.3
- A fractional modulation amplitude corresponding to that found for CoGeNT data is assumed for DAMA.
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

Rhenium data [63] would be insensitive to up to a 100% modulation amplitude in a possible CDMS-Ge signal [63]. Liquid xenon (LUX, XENON-100) sensitivity to \( m_\chi < 12 \text{ GeV}/c^2 \) is presently under test, using an \(^{88}\text{Y}/\text{Be} \) neutron source [63].
Another example of compatibility

DM particle with preferred inelastic interaction

In the Inelastic DM (iDM) scenario, WIMPs scatter into an excited state, split from the ground state by an energy comparable to the available kinetic energy of a Galactic WIMP.

\[
\chi^- + N \rightarrow \chi^+ + N
\]

• iDM has two mass states \(\chi^+\), \(\chi^-\) with \(\delta\) mass splitting
• Kinematical constraint for iDM

\[
\frac{1}{2} \mu v^2 \geq \delta \iff v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}
\]

Slices from the 3-dimensional allowed volume

iDM interaction on Iodine nuclei

iDM interaction on Tl nuclei of the NaI(Tl) dopant?

arXiv:1007.2688

• For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with A~205, which are present as a dopant at the 10^{-3} level in NaI(Tl) crystals.

• Inelastic scattering WIMPs with large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

... and more considering experimental and theoretical uncertainties
DAMA/LIBRA phase 2 - running

Second upgrade on end of 2010:
all PMTs replaced with new ones of higher Q.E.

$\sigma/E @ 59.5 \text{ keV}$ for each detector with new PMTs with higher quantum efficiency (blu points) and with previous PMT EMI-Electron Tube (red points).

Quantum Efficiency features

The light responses

Energy (keV)

The limits are at 90% C.L.

JINST 7(2012)03009

• To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects

• Special data taking for other rare processes

Previous PMTs: 5.5-7.5 ph.e./keV
New PMTs: up to 10 ph.e./keV
The importance of studying second order effects and the annual modulation phase

High exposure and lower energy threshold can allow further investigation on:
- the nature of the DM candidates
- possible diurnal effects on the sidereal time
- astrophysical models

The annual modulation phase depends on:
• Presence of streams (as SagDEG and Canis Major) in the Galaxy
• Presence of caustics
• Effects of gravitational focusing of the Sun

A step towards such investigations:
⇒ DAMA/LIBRA-phase2
with lower energy threshold and larger exposure
+ further possible improvements (DAMA/LIBRA-phase3) and DAMA/1ton
Conclusions

- Positive evidence for the presence of DM particles in the galactic halo supported at 9.3σ C.L. (14 annual cycles DAMA/Nal and DAMA/LIBRA-phase1: 1.33 ton × yr)
- 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.
- Possible positive hints in direct searches are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties. *Indirect model dependent searches not in conflict*

- New PMTs with higher Q.E.
- **DAMA/LIBRA – phase2** in *continuous data taking* at lower software energy threshold (below 2 keV).
- Suitable exposure planned in the new configuration to deeper study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects.
- Investigation on dark matter peculiarities and second order effect
- Special data taking for other rare processes.

Moreover, works and efforts for:
- further improvement (phase3);
- DAMA/1ton set up;
- ADAMO project, anisotropic scintillators for directionality.