Recent results from DAMA/LIBRA and perspectives
DAMA: an observatory for rare processes @LNGS

Roma2, Roma1, LNGS, IHEP/Beijing

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

http://people.roma2.infn.it/dama
DAMA/LXe: results on rare processes

Dark Matter Investigation

- Limits on recoils investigating the DMp-\(^{129}\)Xe elastic scattering by means of PSD
- Limits on DMp-\(^{129}\)Xe inelastic scattering
- Neutron calibration
- \(^{129}\)Xe vs \(^{136}\)Xe by using PSD → SD vs SI signals to increase the sensitivity on the SD component

Other rare processes:

- Electron decay into invisible channels
- Nuclear level excitation of \(^{129}\)Xe during CNC processes
- N, NN decay into invisible channels in \(^{129}\)Xe
- Electron decay: \(e^- \rightarrow \nu_e \gamma\)
- \(2\beta\) decay in \(^{136}\)Xe
- \(2\beta\) decay in \(^{134}\)Xe
- Improved results on \(2\beta\) in \(^{134}\)Xe, \(^{136}\)Xe
- CNC decay \(^{136}\)Xe → \(^{136}\)Cs
- N, NN, NNN decay into invisible channels in \(^{136}\)Xe

PLB465(1999)315
PLB493(2000)12
PRD61(2000)117301
Xenon01
PLB527(2002)182
PLB546(2002)23
Beyond the Desert (2003) 365
EPJA27 s01 (2006) 35

• 2\(\beta\) decay in \(^{100}\)Mo with the 4\(\pi\) low-bckg HPGe facility of LNGS (NPA846(2010)143)
• search for \(^7\)Li solar axions (NPA806(2008)388)
• \(\beta\beta\) decay of \(^{96}\)Ru and \(^{104}\)Ru (EPJA42(2009)171)
• meas. with a Li\(_2\)MoO\(_4\) (NIMA607(2009)573)
• \(\beta\beta\) decay of \(^{136}\)Ce and \(^{138}\)Ce (NPA824(2009)101)
• First observation of \(\alpha\) decay of \(^{190}\)Pt to the first excited level (137.2 keV) of \(^{186}\)Os (PRC83(2011)034603)
• \(\beta\beta\) decay of \(^{156}\)Dy, \(^{158}\)Dy (NPA859(2011)126)
+ Many other meas. already scheduled

DAMA/R&D set-up: results on rare processes

• Particle Dark Matter search with CaF\(_2\)(Eu)

- \(\alpha\) decay of natural Eu
- \(\beta\) decay of \(^{113}\)Cd
- \(\beta\beta\) decay of \(^{64}\)Zn, \(^{70}\)Zn, \(^{180}\)W, \(^{186}\)W
- \(\beta\beta\) decay of \(^{108}\)Cd and \(^{114}\)Cd
- \(\beta\beta\) decay of \(^{136}\)Ce, \(^{138}\)Ce and \(^{142}\)Ce with CeCl\(_3\)
- \(^{106}\)Cd, and \(^{116}\)Cd in progress

PLB436(1998)379

NIMA482(2002)728

DAMA/Ge & LNGS Ge facility

• RDs on highly radiopure NaI(Tl) set-up
• several RDs on low background PMTs
• qualification of many materials
• meas. on Li\(_6\)Eu(BO\(_3\))\(_3\) (NIMA572(2007)734)
• \(\beta\beta\) decay in \(^{100}\)Mo with the 4\(\pi\) low-bckg HPGe facility of LNGS (NPA846(2010)143)
• search for \(^7\)Li solar axions (NPA806(2008)388)
• \(\beta\beta\) decay of \(^{96}\)Ru and \(^{104}\)Ru (EPJA42(2009)171)
• meas. with a Li\(_2\)MoO\(_4\) (NIMA607(2009)573)
• \(\beta\beta\) decay of \(^{136}\)Ce and \(^{138}\)Ce (NPA824(2009)101)
• First observation of \(\alpha\) decay of \(^{190}\)Pt to the first excited level (137.2 keV) of \(^{186}\)Os (PRC83(2011)034603)
• \(\beta\beta\) decay of \(^{156}\)Dy, \(^{158}\)Dy (NPA859(2011)126)
+ Many other meas. already scheduled

+ CdWO\(_4\) and ZnWO\(_4\) radiopurity studies
(NIMA626-627(2011)31, NIMA615(2010)301)
Summary of searches for $\beta\beta$ decay modes in various isotopes (partial list)

T$_{1/2}$ experimental limits by DAMA (in red) and previous ones (in blue). All the limits are at 90% C.L. except for $0\nu2\beta^+$ in $^{136}$Ce and $2\beta^0\nu$ in $^{142}$Ce at 68% C.L. In green observed!

ARMONIA: New observation (green) of $2\nu2\beta^- 100$Mo$\rightarrow 100$Ru (g.s.$\rightarrow 0_1^+$) decay

- Many competitive limits obtained on lifetime of $2\beta^+$, $\epsilon\beta^+$ and $2\epsilon$ processes ($^{40}$Ca, $^{64}$Zn, $^{96}$Ru, $^{106}$Cd, $^{108}$Cd, $^{138}$Ba, $^{136}$Ce, $^{138}$Ce, $^{180}$W, $^{190}$Pt).
- The limits on $2\beta^-$ modes in $^{136}$Xe are the presently best ones for this isotope
- First searches for resonant $\beta\beta$ decays in some isotopes

Many publications on detectors developments and results Many future measurements in preparation
Some direct detection processes:

- Scatterings on nuclei
  - detection of nuclear recoil energy

  ![Diagram of scatterings on nuclei](image)

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

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

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

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

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

- Ionization:
  - Ge, Si

- Bolometer:
  - TeO$_2$, Ge, CaWO$_4$, ...

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

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

- ... 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

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

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) 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

\begin{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 \equiv S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]
\end{align*}

\(v_{\text{sun}} \sim 232\text{ km/s}\) (Sun velocity in the halo)
\(v_{\text{orb}} = 30\text{ km/s}\) (Earth velocity around the Sun)
\(\gamma = \pi/3, \quad \omega = 2\pi/T, \quad T = 1\text{ year}\)
\(t_0 = 2^{\text{nd}}\text{ June (when } v_{\oplus}\text{ is maximum)}\)
**DAMA/NaI: \(\approx 100 \text{ kg NaI(Tl)}\)**

**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

- Performances:

**Results on DM particles:**

- PSD

- Investigation on diurnal effect

- Exotic Dark Matter search

- Annual Modulation Signature

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

- Model independent evidence of a particle DM component in the galactic halo at 6.3\(\sigma\) C.L.
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
...calibration procedures
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc. NIMA592(2008)297

- 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
- Polyethylene/paraffin
- ~1m concrete from GS rock
- 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

- Gloves-box for calibration
- Electronics + DAQ
- Glove-box for calibration
- Electronics + DAQ

Electronics + DAQ

- OFHC low radioactive copper
- Low radioactive lead
- Cadmium foils
- Polyethylene/Paraffin
- Concrete from GS rock

- 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
- Polyethylene/paraffin
- ~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 (2chs per detector), 1 Gsample/s, 8 bit, bandwidth 250 MHz
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy
Some on residual contaminants in new 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 daugthers, thanks to the new handling protocols.

... more on NIMA592 (2008)297
Some on residual contaminants in NaI(Tl) detectors

\[ \alpha/e \text{ pulse shape discrimination has practically 100\% effectiveness in the MeV range} \]

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

**Time-amplitude method**: arrival time and energy of each event used for selection of fast decay chains in 232\text{Th} family

224\text{Ra} (\( Q_\alpha=5.8 \text{ MeV}, T_{1/2}=3.66 \text{ d} \)) \rightarrow 220\text{Rn} (\( Q_\alpha=6.4 \text{ MeV}, T_{1/2}=55.6 \text{ s} \))

\rightarrow 216\text{Po} (\( Q_\alpha=6.9 \text{ MeV}, T_{1/2}=0.145 \text{ s} \)) \rightarrow 212\text{Pb}

\( \alpha \) peaks as well as the distributions of the time intervals between the events are in a good agreement with those expected

\[ \alpha/\beta = 0.467(6) + 0.0257(10) \times E_\alpha [\text{MeV}] \]

\( \Rightarrow 228\text{Th} \) activity ranging from 2 to about 30 \( \mu\text{Bq/kg} \) in the DAMA/LIBRA detectors (in agreement with Bi-Po analysis)

If 232\text{Th} chain at equilibrium: 232\text{Th} contents in new detectors typically range from 0.5 ppt to 7.5 ppt
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 curves superimposed to the experimental data have been obtained by simulations

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
Examples of energy resolutions

**DAMA/LIBRAULB NaI(Tl)**

\[ \sigma/E(60\text{keV}) = 6.8\% \]

\[ \text{Co-57} \]

\[ \sigma/E @ 122\text{keV} = 16\% \]

\[ 241\text{Am} \]

\[ \text{XENON10} \]

\[ \sigma/E @ 122\text{keV} = 17\% \]

\[ \text{XENON10} \]

\[ \text{Co-57} \]

\[ \sigma/E @ 122\text{keV} = 13\% \]

\[ \text{at zero field} \]

---

**WARP**

Fig. 2. Energy spectra taken with external \(\gamma\)-ray sources, superimposed with the corresponding Monte Carlo simulations. (a) \(^{57}\text{Co}\) source \((E = 122\text{ keV, B.R. 85.6\%}, \text{and } 136\text{ keV, B.R. 10.7\%})\), (b) \(^{137}\text{Cs}\) source \((E = 662\text{ keV})\).

---

**ZEPLIN-II**

\[ \sigma/E @ 122\text{keV} = 16\% \]

---

**XENON10**

Figure 3. (left) S1 scintillation spectrum from a \(^{57}\text{Co}\) calibration. The light yield for the 122keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a \(^{137}\text{Cs}\) calibration. The light yield for the 662keV photo-absorption peak is 2.2 p.e./keV.

---

**NIMA 574 (2007) 83**

---

**AP 28 (2007) 287**

---

Fig. 5. Typical energy spectra for \(^{57}\text{Co}\) \(\gamma\)-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the \(^{57}\text{Co}\) \(\gamma\)-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.
Examples of energy resolutions

### DAMA/LIBRAULB NaI(Tl)

<table>
<thead>
<tr>
<th>Detector</th>
<th>liquid</th>
<th>phe/keV @ zero field</th>
<th>phe/keV @ working field</th>
</tr>
</thead>
<tbody>
<tr>
<td>WARP2.3l un PMT 8”</td>
<td></td>
<td></td>
<td>2.35</td>
</tr>
<tr>
<td>WARP2.3l 7 PMTs 2”</td>
<td>0.5-1  (deduced)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZEPLIN-II</td>
<td>1.1</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>ZEPLIN-III</td>
<td></td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>XENON10</td>
<td></td>
<td>2.2 ($^{137}$Cs), 3.1 ($^{57}$Co)</td>
<td></td>
</tr>
<tr>
<td>XENON100</td>
<td>2.7</td>
<td>1.57 ($^{137}$Cs), 2.2 ($^{57}$Co)</td>
<td></td>
</tr>
<tr>
<td>Neon</td>
<td>0.93</td>
<td>field not foreseen</td>
<td></td>
</tr>
</tbody>
</table>

DAMA/LIBRA: 5.5 – 7.5 phe/keV

---

Fig. 5. Typical energy spectra for $^{60}$Co $\gamma$-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the $^{57}$Co $\gamma$-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.

All experiments – except DAMA – use only calibration points at higher energy with extrapolation to low energy.
Noise rejection near the energy threshold

Typical pulse profiles of PMT noise and of scintillation event with the same area, just above the energy threshold of 2 keV

The different time characteristics of PMT noise (decay time of order of tens of ns) and of scintillation event (decay time about 240 ns) can be investigated building several variables

\[
X_1 = \frac{\text{Area (from 100 ns to 600 ns)}}{\text{Area (from 0 ns to 600 ns)}}
\]

\[
X_2 = \frac{\text{Area (from 0 ns to 50 ns)}}{\text{Area (from 0 ns to 600 ns)}}
\]

From the Waveform Analyser 2048 ns time window:

- The separation between noise and scintillation pulses is very good.
- Very clean samples of scintillation events selected by stringent acceptance windows.
- The related efficiencies evaluated by calibrations with $^{241}$Am sources of suitable activity in the same experimental conditions and energy range as the production data (efficiency measurements performed each ~10 days; typically $10^4$–$10^5$ events per keV collected)

This is the only procedure applied to the analysed data.
## Infos about DAMA/LIBRA data taking

<table>
<thead>
<tr>
<th>Period</th>
<th>Mass (kg)</th>
<th>Exposure (kg x 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></td>
<td>317697 = 0.87 ton\times yr</td>
<td>0.519</td>
</tr>
</tbody>
</table>

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

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

- **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

- **Second upgrade on Oct./Nov. 2010**
  - replacement of all the PMTs with higher Q.E. ones

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

- EPJC56(2008)333
- EPJC67(2010)39

... continuously running
Model Independent Annual Modulation Result

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

**2-4 keV**
- $A = (0.0183 \pm 0.0022) \text{ cpd/kg/keV}$
- $\chi^2/\text{dof} = 75.7/79 \quad 8.3\sigma \text{ C.L.}$

Absence of modulation? No
- $\chi^2/\text{dof}=147/80 \Rightarrow P(A=0) = 7 \times 10^{-6}$

**2-5 keV**
- $A = (0.0144 \pm 0.0016) \text{ cpd/kg/keV}$
- $\chi^2/\text{dof} = 56.6/79 \quad 9.0\sigma \text{ C.L.}$

Absence of modulation? No
- $\chi^2/\text{dof}=135/80 \Rightarrow P(A=0) = 1.1 \times 10^{-4}$

**2-6 keV**
- $A = (0.0114 \pm 0.0013) \text{ cpd/kg/keV}$
- $\chi^2/\text{dof} = 64.7/79 \quad 8.8\sigma \text{ C.L.}$

Absence of modulation? No
- $\chi^2/\text{dof}=140/80 \Rightarrow P(A=0) = 4.3 \times 10^{-5}$
Modulation amplitudes measured in each one of the 13 one-year experiments (DAMA/NaI and DAMA/LIBRA)

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.

<table>
<thead>
<tr>
<th></th>
<th>$A$ (cpd/kg/keV)</th>
<th>$T = 2\pi/\omega$ (yr)</th>
<th>$t_0$ (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$\pm$4) keV</td>
<td>$0.0252 \pm 0.0050$</td>
<td>$1.01 \pm 0.02$</td>
<td>$125 \pm 30$</td>
<td>$5.0\sigma$</td>
</tr>
<tr>
<td>(2$\pm$5) keV</td>
<td>$0.0215 \pm 0.0039$</td>
<td>$1.01 \pm 0.02$</td>
<td>$140 \pm 30$</td>
<td>$5.5\sigma$</td>
</tr>
<tr>
<td>(2$\pm$6) keV</td>
<td>$0.0200 \pm 0.0032$</td>
<td>$1.00 \pm 0.01$</td>
<td>$140 \pm 22$</td>
<td>$6.3\sigma$</td>
</tr>
<tr>
<td><strong>DAMA/LIBRA (6 years)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2$\pm$4) keV</td>
<td>$0.0180 \pm 0.0025$</td>
<td>$0.996 \pm 0.002$</td>
<td>$135 \pm 8$</td>
<td>$7.2\sigma$</td>
</tr>
<tr>
<td>(2$\pm$5) keV</td>
<td>$0.0134 \pm 0.0018$</td>
<td>$0.997 \pm 0.002$</td>
<td>$140 \pm 8$</td>
<td>$7.4\sigma$</td>
</tr>
<tr>
<td>(2$\pm$6) keV</td>
<td>$0.0098 \pm 0.0015$</td>
<td>$0.999 \pm 0.002$</td>
<td>$146 \pm 9$</td>
<td>$6.5\sigma$</td>
</tr>
<tr>
<td><strong>DAMA/NaI + DAMA/LIBRA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2$\pm$4) keV</td>
<td>$0.0194 \pm 0.0022$</td>
<td>$0.996 \pm 0.002$</td>
<td>$136 \pm 7$</td>
<td>$8.8\sigma$</td>
</tr>
<tr>
<td>(2$\pm$5) keV</td>
<td>$0.0149 \pm 0.0016$</td>
<td>$0.997 \pm 0.002$</td>
<td>$142 \pm 7$</td>
<td>$9.3\sigma$</td>
</tr>
<tr>
<td>(2$\pm$6) keV</td>
<td>$0.0116 \pm 0.0013$</td>
<td>$0.999 \pm 0.002$</td>
<td>$146 \pm 7$</td>
<td>$8.9\sigma$</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 $\sim2\sigma$ which corresponds to a modest, but non negligible probability.

A, T, $t_0$ obtained by fitting the single-hit data with $A \cos[\omega(t-t_0)]$

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

Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

DAMA/NaI (7 years)
total exposure: 0.29 ton×yr

DAMA/LIBRA (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
$2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$

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

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

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

Clear annual modulation is evident in (2-6) keV while it is 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
→ 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:

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

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)
total exposure: 425428 kg×day \( \approx 1.17 \text{ ton×yr} \)

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

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 on $S_m$

DAMA/LIBRA (6 years)
total exposure: 0.87 ton$\times$yr

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

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)
Statistical analyses about modulation amplitudes ($S_m$)

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

$\chi^2/d.o.f.$ 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 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.
Energy distributions of cosine ($S_m$) and sine ($Z_m$) modulation amplitudes

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

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

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

$t_0 = 152.5$ day ($2°$ June)

maximum at $2°$ June

as for DM particles

maximum at $1°$ September

$T/4$ days after $2°$ June

$\chi^2$ test in the (2-14) keV and (2-20) keV energy regions ($\chi^2$/dof = 21.6/24 and 47.1/36, probabilities of 60% and 10%, respectively) supports the hypothesis that the $Z_{m,k}$ values are simply fluctuating around zero.
Is there a sinusoidal contribution in the signal? Phase $\neq 152.5$ day?

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

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

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $\omega = 2\pi / T$
- $t^* \approx t_0 = 152.5 \text{ day}$

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 $\pm$ 0.0013</td>
<td>-0.0004 $\pm$ 0.0014</td>
<td>0.0111 $\pm$ 0.0013</td>
<td>150.5 $\pm$ 7.0</td>
</tr>
<tr>
<td>6-14</td>
<td>-0.0001 $\pm$ 0.0008</td>
<td>0.0002 $\pm$ 0.0005</td>
<td>-0.0001 $\pm$ 0.0008</td>
<td>--</td>
</tr>
</tbody>
</table>
Running conditions stable at a level better than 1% also in the two new running periods

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

<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 N$_2$</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) x10^{-2} mbar</td>
<td>(0.07 ± 0.13) x10^{-2} mbar</td>
</tr>
<tr>
<td>Radon</td>
<td>(0.029 ± 0.029) Bq/m$^3$</td>
<td>(0.030 ± 0.027) Bq/m$^3$</td>
<td>(0.015 ± 0.029) Bq/m$^3$</td>
<td>(0.052 ± 0.039) Bq/m$^3$</td>
<td>(0.021 ± 0.037) Bq/m$^3$</td>
<td>(0.028 ± 0.036) Bq/m$^3$</td>
</tr>
<tr>
<td>Hardware rate</td>
<td>(0.20 ± 0.18) x 10^{-2} Hz</td>
<td>(0.09 ± 0.17) x 10^{-2} Hz</td>
<td>(0.03 ± 0.20) x 10^{-2} Hz</td>
<td>(0.15 ± 0.15) x 10^{-2} Hz</td>
<td>(0.03 ± 0.14) x 10^{-2} Hz</td>
<td>(0.08 ± 0.11) x 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 $\rightarrow R_{90} \sim$ tens cpd/kg
  $\rightarrow \sim 100\sigma$ far away

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

\[ A = (0.3 \pm 0.9) \times 10^{-3} \text{ cpd/kg/keV} \]

DAMA/LIBRA

\[ \sigma \approx 1\% \]

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

Nevertheless, additional investigations performed ...
ΔE = 0.5 keV bins

The experimental $S_m$ cannot be due to $^{40}$K for many reasons.

No modulation of the double coincidence events (1461 keV-3 keV).

DM-like modulation amplitude: $-(0.117 \pm 0.094)$; $\chi^2$/dof=1.04

Sin-like modulation amplitude: $-(0.025 \pm 0.098)$; $\chi^2$/dof=1.05

Gaussian fluctuation around zero: $\chi^2$/dof=1.04

The $^{40}$K double coincidence events are not modulated

Any modulation contribution around 3 keV in the single-hit events from the hypothetical cases of: i) $^{40}$K "exotic" modulated decay; ii) spill-out effects from double to single events and viceversa, is ruled out at more than 10 $\sigma$

DAMA/LIBRA 0.87 ton$\times$yr
Can a possible thermal neutron modulation account for the observed effect?

- **Thermal neutrons flux measured at LNGS:**
  \[ \Phi_n = 1.08 \times 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \]  

- 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\% C.L.)

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

**Evaluation of the expected effect:**

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

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

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

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

**Already excluded also by R\(_{90}\) analysis**
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:

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

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

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS.
The $\mu$ case

MonteCarlo 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 $\approx 20 \, \mu \text{m}^{-2}\text{d}^{-1}$ (±2% modulated)

Measured neutron Yield @ LNGS: $Y=1\div7 \times 10^{-4} \, n/\mu/(g/cm^2)$

$R_n = (\text{fast n by } \mu)/(\text{time unit}) = \Phi_\mu \, Y \, M_{\text{eff}}$

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

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

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.

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, $t_\mu$:

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

It cannot mimic the signature: different phase

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

$$S^{(\mu)}_m = R_n \, g \, \varepsilon \, f_{AE} \, f_{\text{single}} \times 2\% \,(M_{\text{setup}} \, \Delta E)$$

$g$ = geometrical factor; $\varepsilon$ = detection effic. by elastic scattering

$F_{AE} = $ energy window ($E>2\text{keV}$) effic.; $f_{\text{single}} = $ 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.

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 and BOREXINO partially overlapped with DAMA/NaI and fully with DAMA/LIBRA: 1.5% modulation and phase LVD = July 5th ± 15 d, BOREXINO = July 6th ± 6 d

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

This phase is $7.1 \sigma$ far from July 15th and is $5.7 \sigma$ far from July 6th

$R_{90}$, multi-hits, phase, and other analyses
The DAMA: modulation amplitude
\[10^{-2} \text{cpd/kg/keV}, \text{in 2-6 keV energy range for single hit events; phase:}
\]
**May 26 \pm 7 days**
(stable over 13 years)

μ flux @ LNGS (MACRO, LVD, BOREXINO)
≈ \[3 \cdot 10^{-4} \text{m}^{-2}\text{s}^{-1}\]; modulation amplitude 1.5%; phase:
**July 6 \pm 6 days** (BOREXINO, CSN2 sept. 2010)

**No Compatibility**

**The DAMA phase is 5.7σ far from the LVD/BOREXINO phases of muons (7.3σ far from MACRO measured phase)**

1) if we assume for a while that the real value of the DAMA phase is June 16th (that is 3σ fluctuation from the measured value), it is well far from all the measured phases of muons by LVD, MACRO and BOREXINO, in all the years

2) Moreover, considering the seasonal weather condition in Gran Sasso, it is quite impossible that the maximum temperature of the outer atmosphere (on which μ flux modulation is dependent) is observed in the middle of June

Inconsistency of the phase between DAMA signal and μ modulation
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 $1.17 \text{ ton} \times \text{yr} (13 \text{ annual cycles})$.

- 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 $(0.999\pm0.002) \text{ yr}$, well compatible with the 1 yr period, as expected for the DM signal.

3. Measured phase $(146\pm7)$ days is well compatible with 152.5 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: $(0.0116 \pm 0.0013) \text{ cpd/kg/keV} (8.9\sigma \text{ C.L.})$.

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

a heavy $\nu$ of the 4-th family

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

Self interacting Dark Matter

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

WIMP: SI

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

WIMP: SI & SD $\theta = 2.435$

LDM, bosonic DM

$m_L = 0$

Compatibility with several candidates; other ones are open

EPJC56(2008)333
About interpretation

- Not a unique reference model for Dark Matter particles
- Not a single set of assumptions for parameters in the astrophysical, nuclear and particle physics related arguments
- Often comparisons are made in inconsistent way

model-dependent analysis: selecting just one model framework by fixing many parameters and by adopting several (astrophysical, nuclear and particle physics) assumptions

- which particle?
- which interaction couplings?
- which Form Factors for each target-material?
- which Spin Factors?
- which nuclear model framework?
- which scaling laws?
- which halo model, profile and parameters?
- is there a presence of non-thermalized components in the halo parameters?
- which velocity distribution?
- which parameters for velocity distribution?
- which instrumental quantities?
- ...

Exclusion plots have no “universal validity” (they depend on the recipe)

For example, which $L_{\text{eff}}$ in liquid Xenon experiments?


No experiment can be directly compared in model independent way with DAMA

1106.0653: “A lingering critical question is to what extent a determination of $L_{\text{eff}}$ performed using highly-optimized compact calibration detectors like those in ... can be applied with confidence to a much larger device like the XENON100 detector, featuring a small S1 light-detection efficiency (just ~6%), different hardware trigger configuration, data processing, etc.”
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 $^{23}$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 ...


Scaling laws of cross sections for the case of recoiling nuclei
- Different scaling laws for different DM particle:
  $$\sigma_A \propto \mu^2 A^2 (1 + \varepsilon_A)$$
  $$\varepsilon_A = 0 \quad \text{generally assumed}$$
  $$\varepsilon_A \approx \pm 1 \quad \text{in some nuclei? even for neutralino candidate in MSSM (see Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301)}$$

... and more ...
DAMA/NaI & DAMA/LIBRA vs
the recent results on 2010/11 (positive excesses)

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

- **CDMS**: after data selection and cuts, 2 Ge candidate recoils survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)

- **CRESST**: after data selection and cuts, 32 O candidate recoils survive in an exposure of \( \approx 400 \) kg x day (8.7±1.2 estimated as expected from residual background)

All these excesses, if interpreted in WIMP scenarios, are also compatible with the DAMA annual modulation result

Some recent literature discussing compatibility in various frameworks e.g.:

- Mirror DM in various scenarios (arXiv:1001.0096, Berezhiani et al.)
- Resonant DM (arXiv:0909.2900)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Composite DM (arXiv:1003.1144)
- Light scalar WIMP through Higgs portal (arXiv:1003.2595)
- SD Inelastic DM (arXiv:0912.4264)
- Complex Scalar Dark Matter (arXiv:1005.3328)
- Isospin-Violating Dark Matter (arXiv:1102.4331)
- ... and more considering the uncertainties
Supersymmetric expectations in MSSM

- Assuming for the neutralino a dominant purely SI coupling
- when releasing the gaugino mass unification at GUT scale: \( \frac{M_1}{M_2} \approx 0.5 \)

(where \( M_1 \) and \( M_2 \) are U(1) and SU(2) gaugino masses)

... windows for compatibility also in some recent model dependent results for COGENT (arXiv.org: 1003.0014)

Mirror Dark Matter

- DAMA compatible with O' interactions
- Recoil energy spectrum predicted for the CDMS II
- The two CDMS events are compatible with Fe' interactions

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.

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

W has two mass states \( \chi^+ \), \( \chi^- \) with \( \delta \) mass splitting.

- Kinematical constraint for iDM

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

DAMA/NaI+DAMA/LIBRA
Slices from the 3-dimensional allowed volume

- DAMA/NaI+DAMA/LIBRA
- The 3-dimensional allowed volume

**iDM interaction on Iodine nuclei**


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

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

arXiv:1007.2688

- For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with \( A \approx 205 \), 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.

- ArXiv:1007.2688

... and more considering experimental and theoretical uncertainties
what next

Continuously running

• Replacement of all the PMTs with higher Q.E. ones concluded

• New PMTs with higher Q.E.:

• Continuing data taking in the new configuration also below the present 2 keV software energy threshold

• Reaching even higher C.L. for the model independent result and highly precisely all the modulation parameters to further investigate among the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..

• Investigation on dark matter peculiarities and second order effect

• Special data taking for other rare processes.
Conclusions

• Positive evidence for the presence of DM particles in the galactic halo now supported at 8.9 $\sigma$ C.L. (cumulative exposure 1.17 ton $\times$ yr – 13 annual cycles DAMA/NaI and 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. That is not restricted to DM candidate inducing only nuclear recoils

• No experiment exists whose result can be directly compared in a model independent way with those by DAMA/NaI & DAMA/LIBRA

• Recent excesses in direct searches above an evaluated background are – when interpreted as induced by some DM candidates – 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.

• Investigations other than DM

What next?

• Upgrade in fall 2010 concluded: replacement of all PMTs with new ones having higher Q.E. to lower the software energy threshold and improve general features.

• Collect a suitable exposure in the new running conditions to improve the knowledge about the nature of the particles and on features of related astrophysical, nuclear and particle physics aspects.

• Investigate second order effects

• R&D towards a possible 1 ton ULB NaI(Tl) set-up experiment DAMA proposed in 1996

DAMA/LIBRA still the highest radiopure set-up in the field with the largest sensitive mass, full control of running conditions, the largest duty-cycle, exposure orders of magnitude larger than any other activity in the field, etc., and the only one which effectively exploits a model independent DM signature