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
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 can point out its presence.

Drukier, Freese, Spergel PRD86
Freese et al. PRD88

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 peculiarities (e.g. the phase) than those effects correlated with the seasons

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

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

Expected rate in given energy bin changes because the revolution motion of the Earth around the Sun, which is moving in the Galaxy

\[ v_{\text{sun}} \approx 232 \text{ km/s} \] (Sun velocity in the halo)
\[ v_{\text{orb}} = 30 \text{ km/s} \] (Earth velocity around the Sun)

\[ \gamma = \pi/3, \quad \omega = 2\pi/T \quad T = 1 \text{ year} \]
\[ t_0 = 2^{\text{nd}} \text{June (when } v_{\odot} \text{ is maximum)} \]
The pioneer DAMA/NaI:
≈100 kg highly radiopure 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

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

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

total exposure (7 annual cycles) 0.29 ton\times yr
The 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)

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

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
  IPP in $^{241}\text{Am}$ decay: to appear on EPJA (arXiv:1305.2318)
...calibration procedures
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.

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

Installation

- 5.5-7.5 phe/keV
- ~1m concrete from GS rock

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waweform 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

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

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

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

\( ^{232}\text{Th residual contamination} \)

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

\( ^{238}\text{U residual contamination} \)

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

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

Thus, in this case: (2.1\( \pm \)0.1) ppt of \( ^{232}\text{Th} \); (0.35 \( \pm \)0.06) ppt for \( ^{238}\text{U} \) and: (15.8\( \pm \)1.6) \( \mu \)Bq/kg for \( ^{234}\text{U} + ^{230}\text{Th} \); (21.7\( \pm \)1.1) \( \mu \)Bq/kg for \( ^{226}\text{Ra} \); (24.2\( \pm \)1.6) \( \mu \)Bq/kg for \( ^{210}\text{Pb} \).

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

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

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

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

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

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

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

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

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

**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

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

Thus, here and hereafter keV means keV electron equivalent.
DAMA/LIBRA data taking

<table>
<thead>
<tr>
<th>Period</th>
<th>Mass (kg)</th>
<th>Exposure (kg x day)</th>
<th>$\alpha / \beta$</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>232.8</td>
<td>317697</td>
<td>0.519</td>
</tr>
</tbody>
</table>

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

total exposure: $425428 \text{ kg x day} = 1.17 \text{ ton x yr}$

- 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

The annual cycle 2009/10 will be released soon – End of the DAMA/LIBRA – phase 1

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

Two annual cycles at lower energy threshold at hand...

... continuously running

• calibrations: ~72 M events from sources

• acceptance window eff: 82 M events (~3M events/keV)

EPJC56(2008)333

EPJC67(2010)39
Multiple hits events = Dark Matter particle “switched off”

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

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 90% C.L.
Power spectrum of single-hit residuals

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

Principal mode in the 2-6 keV region:
\[2.735 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}\]

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


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

Frequency range: [0, 0.06] \text{ d}^{-1} \text{ or } [0, 22] \text{ y}^{-1}

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

Violet:
CL obtained with Montecarlo procedure for Lomb Scargle periodogram as in DAMA papers

From the formula:
\[\text{CL} = 1 - e^{-S}\]

- CL=99.7\% → S = 5.8
- CL=95.5\% → S = 3.1
- CL=90.0\% → S = 2.3
- CL=68.3\% → S = 1.15
Energy distribution of the modulation amplitudes

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

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

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)
total exposure: 425428 kg×day ≈ 1.17 ton×yr

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

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

a) $S_m$ for each detector, each annual cycle and each considered energy bin (here 0.25 keV)
b) $<S_m>$ = 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×yr

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

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

\[ x = (S_m - \langle S_m \rangle)/\sigma, \]
\[ \chi^2 = \sum x^2 \]

**Statistical analyses about modulation amplitudes (\( S_m \))**

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

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

- The mean value of the twenty-five points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of \( \leq 4 \times 10^{-4} \) cpd/kg/keV, if quadratically combined, or \( \leq 5 \times 10^{-5} \) cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (\( \leq 4\% \) or \( \leq 0.5\% \), respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects.

**DAMA/LIBRA (6 years)**

- total exposure: 0.87 ton\( \times \)yr
**Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?**

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

For Dark Matter signals:

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

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

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>S_m (cpd/kg/keV)</th>
<th>Z_m (cpd/kg/keV)</th>
<th>Y_m (cpd/kg/keV)</th>
<th>t* (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-6</td>
<td>0.0111 ± 0.0013</td>
<td>-0.0004 ± 0.0014</td>
<td>0.0111 ± 0.0013</td>
<td>150.5 ± 7.0</td>
</tr>
<tr>
<td>6-14</td>
<td>-0.0001 ± 0.0008</td>
<td>0.0002 ± 0.0005</td>
<td>-0.0001 ± 0.0008</td>
<td>--</td>
</tr>
</tbody>
</table>
The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about $S_m$ already exclude any sizable presence of systematical effects.

---

**Additional investigations on the stability parameters**

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

Running conditions stable at a level better than 1% also in the two new running periods

<table>
<thead>
<tr>
<th></th>
<th>DAMA/LIBRA-1</th>
<th>DAMA/LIBRA-2</th>
<th>DAMA/LIBRA-3</th>
<th>DAMA/LIBRA-4</th>
<th>DAMA/LIBRA-5</th>
<th>DAMA/LIBRA-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>$-(0.0001 \pm 0.0061)^\circ\text{C}$</td>
<td>$(0.0026 \pm 0.0086)^\circ\text{C}$</td>
<td>$(0.001 \pm 0.015)^\circ\text{C}$</td>
<td>$(0.0004 \pm 0.0047)^\circ\text{C}$</td>
<td>$(0.0001 \pm 0.0036)^\circ\text{C}$</td>
<td>$(0.0007 \pm 0.0059)^\circ\text{C}$</td>
</tr>
<tr>
<td>Flux $N_2$</td>
<td>$(0.13 \pm 0.22)^\text{l/h}$</td>
<td>$(0.10 \pm 0.25)^\text{l/h}$</td>
<td>$-(0.07 \pm 0.18)^\text{l/h}$</td>
<td>$-(0.05 \pm 0.24)^\text{l/h}$</td>
<td>$-(0.01 \pm 0.21)^\text{l/h}$</td>
<td>$-(0.01 \pm 0.15)^\text{l/h}$</td>
</tr>
<tr>
<td>Pressure</td>
<td>$(0.015 \pm 0.030)^\text{mbar}$</td>
<td>$-(0.013 \pm 0.025)^\text{mbar}$</td>
<td>$(0.022 \pm 0.027)^\text{mbar}$</td>
<td>$(0.0018 \pm 0.0074)^\text{mbar}$</td>
<td>$-(0.08 \pm 0.12) \times 10^{-2}^\text{mbar}$</td>
<td>$(0.07 \pm 0.13) \times 10^{-2}^\text{mbar}$</td>
</tr>
<tr>
<td>Radon</td>
<td>$-(0.029 \pm 0.029)^\text{Bq/m}^3$</td>
<td>$-(0.030 \pm 0.027)^\text{Bq/m}^3$</td>
<td>$(0.015 \pm 0.029)^\text{Bq/m}^3$</td>
<td>$(0.052 \pm 0.039)^\text{Bq/m}^3$</td>
<td>$(0.021 \pm 0.037)^\text{Bq/m}^3$</td>
<td>$-(0.028 \pm 0.036)^\text{Bq/m}^3$</td>
</tr>
<tr>
<td>Hardware rate</td>
<td>$-(0.20 \pm 0.18) \times 10^{-2}^\text{Hz}$</td>
<td>$(0.09 \pm 0.17) \times 10^{-2}^\text{Hz}$</td>
<td>$-(0.03 \pm 0.20) \times 10^{-2}^\text{Hz}$</td>
<td>$(0.15 \pm 0.15) \times 10^{-2}^\text{Hz}$</td>
<td>$(0.03 \pm 0.14) \times 10^{-2}^\text{Hz}$</td>
<td>$(0.08 \pm 0.11) \times 10^{-2}^\text{Hz}$</td>
</tr>
<tr>
<td>above single</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>photoelectron</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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)
No role for $^{40}$K in the experimental $S_m$

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

Double coincidences

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

$r.m.s. = 1.032 \pm 0.053$

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

The $^{40}$K double coincidence events are not modulated
Can a possible thermal neutron modulation account for the observed effect?

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

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

MC simulation of the process

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

- \( 7 \times 10^{-5} \text{ cpd/kg/keV} \)
- \( 1.4 \times 10^{-3} \text{ cpd/kg/keV} \)
Can a possible fast neutron modulation account for the observed effect?

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

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

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

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

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

*Experimental upper limit on the fast neutrons flux “surviving” the neutron shield in DAMA/LIBRA:*

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

Moreover, a possible fast n modulation would induce:

- a variation in all the energy spectrum (steady environmental fast neutrons always accompanied by thermalized component)
  
  already excluded also by \( R_{90} \)

- a modulation amplitude for multiple-hit events different from zero
  
  already excluded by the multiple-hit events

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

DAMA/LIBRA surface $\approx 0.13 \text{ m}^2$

$\mu$ flux @ DAMA/LIBRA $\approx 2.5 \mu$/day

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

It cannot mimic the signature: already excluded by $R_9$, by multi-hits analysis + different phase, etc.

Rate, $R_n$, of fast neutrons produced by $\mu$:

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

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

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

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

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

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

In contrast, it cannot mimic the signature: already excluded by $R_9$, 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 $7 \pm 6$ d, June $29 \pm 6$ d (Borexino)

but

- 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 $26 \pm 7$ days (stable over 13 years)

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, $t_\mu$:

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

It cannot mimic the signature: different phase
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>

Thus, they cannot satisfy all the requirements of annual modulation signature
Summarizing the model independent annual modulation result

- Presence of modulation for 13 annual cycles at $8.9\sigma$ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 13 independent experiments of 1 year each one

- The total exposure by former DAMA/NaI and present DAMA/LIBRA is $1.17 \text{ ton} \times \text{ yr (13 annual cycles)}$

- In fact, as required by the DM annual modulation signature:

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

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

  3. Measured phase $(146\pm7) \text{ days}$ 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) 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) 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
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

**WIMP: SI**

- Evans power law
- $15 \text{ GeV}$
- $100-120 \text{ GeV}$

**WIMP: SI & SD**

- Evans power law
- $15 \text{ GeV}$
- $100 \text{ GeV}$

**LDM, bosonic DM**

- $\sigma^N_a / A^2_{N_a} \approx \sigma^I / A^2_I$
- $m_L = 0$

Compatibility with several candidates; other ones are open

EPJC56(2008)333
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

---

...models...
- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

---

...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, ...
- ...

---

**DAMA vs possible positive hints 2010-13**

- **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 candidate recoils survive in an exposure of 194.1 kg x day. Estimated residual background 0.8

- **CRESST:** after many data selections and cuts, 67 candidate recoils 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 candidate recoils survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

All compatible with the DAMA 8.9 $\sigma$ C.L. annual modulation result in various scenarios
Case of DM particles inducing elastic scatterings on target-nuclei

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.

DMp

DMp’

N

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)

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

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

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

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

• Positive evidence for the presence of DM particles in the galactic halo supported at 8.9 σ C.L. (13 annual cycles: 1.17 ton \times 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. That is not restricted to DM candidate inducing only nuclear recoils
• 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

DAMA/LIBRA – phase 2 perspectives

• **Continuing data taking** in the new configuration with lower software energy threshold (below 2 keV).
• New preamplifiers and trigger modules realized to further implement low energy studies.
• 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.

A new annual cycle will be released soon – End of the DAMA/LIBRA – phase 1

• New PMTs with higher Q.E.: two annual cycles at hand...