Signals from the dark Universe
The Dark Side of the Universe: experimental evidences ...

First evidence and confirmations:

1933 F. Zwicky: studying dispersion velocity of Coma galaxies
1936 S. Smith: studying the Virgo cluster
1974 two groups: systematical analysis of mass density vs distance from center in many galaxies

Other experimental evidences

✓ from LMC motion around Galaxy
✓ from X-ray emitting gases surrounding elliptical galaxies
✓ from hot intergalactic plasma velocity distribution in clusters
✓ ... 
✓ bullet cluster 1E0657-558

$M_{\text{visible Universe}} \ll M_{\text{gravitational effect}} \implies \text{about 90% of the mass is DARK}$
Primordial Nucleosynthesis

∼ 90% of the matter in the Universe is non baryonic
A large part of the Universe is in form of non baryonic Cold Dark Matter particles

Observations on:
- light nuclei abundance
- microlensings
- visible light.

The baryons give “too small” contribution

Ω_b ∼ 4%

Non baryonic Cold Dark Matter is dominant

Ω_M ∼ 0.26
Ω_Λ ∼ 0.74

The Universe is flat

Ω = Ω_Λ + Ω_M = close to 1
Ω = density/critical density

6 atoms of H/m³

Primordial Nucleosynthesis

Structure formation in the Universe

Ω_CDM ∼ 22%
Ω_HDM, ν < 1 %
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
  ![Diagram of scatterings on nuclei](image)

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

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

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

- **Interaction of ligth 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

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

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

  ![Diagram of inelastic Dark Matter](image)

- **… and more**

**... even WIMPs**
The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small, a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.

Drukier, Freese, Spergel PRD86
Freese et al. PRD88

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

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

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

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) 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.
DAMA/R&D
DAMA/LXe
DAMA/Ge
DAMA/NaI
DAMA/LIBRA

low bckg DAMA/Ge
for sampling meas.
meas. with $^{100}$Mo

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

http://people.roma2.infn.it/dama
**Competitiveness of NaI(Tl) set-up**

- Well known technology
- High duty cycle
- Large mass possible
- “Ecological clean” set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- High light response (5.5 - 7.5 ph.e./keV)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios on the contrary of other proposed target-materials (and approaches)
- Sensitive to both high (mainly by Iodine target) and low mass (mainly by Na target) candidates
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up
- Etc.

A low background NaI(Tl) also allows the study of several other rare processes:
possible processes violating the Pauli exclusion principle, CNC processes in $^{23}$Na and $^{127}$I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar axion search, ...
Development of highly radiopure scintillators by:

- Powder samples selection – among those accessible to industry in that period - by low background Ge deep underground
- Mass and atomic absorption spectrometry
- Neutron activation

- Study of standard and non-standard contaminants
- Chemical/physical purification of selected materials

- Selection of growing processes
- Additives selection
- Growing protocols
- Handling protocols

- Other materials selection (housing, optical grease, light guides, …)
- Assembling, transport, storage protocols

This needs many years of long and difficult work, many specific experience and time. Similar developments and measurements are themselves difficult experiments, etc.
Results on rare processes:

- Possible Pauli exclusion principle violation: PLB408(1997)439
- CNC processes: PRC60(1999)065501
- Search for solar axions: PLB515(2001)6
- Exotic Matter search: EPJ direct C14(2002)1
- Search for superdense nuclear matter: EPJ A23(2005)7
- Search for heavy clusters decays: EPJ A24(2005)51

Results on DM particles:

- PSD: PLB389(1996)757
- Annual Modulation Signature

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


**Results on DM particles:**

- DAMA/DAMA/NaI/NaI (≈≈ 100 kg NaI(Tl)) 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 x yr

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)

The new LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes) in the DAMA experiment

PMT +HV divider

Cu etching with super- and ultra-pure HCl solutions, dried and sealed in HP N₂

storing new crystals

improving installation and environment

eetching staff at work in clean room
(all operations involving crystals and PMTs -including photos- in HP N₂ atmosphere)

installing DAMA/LIBRA detectors
assembling a DAMA/LIBRA detector

filling the inner Cu box with further shield
closing the Cu box housing the detectors

view at end of detectors’ installation in the Cu box
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
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.

NIMA592(2008)297

- Dismounting/Installing protocol (with “Scuba” system)
- All the materials selected for low radioactivity
- Multicomponent passive shield
- 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 TVS641A (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

- 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

~ 1m concrete from GS rock
**Some on residual contaminants in new 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

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

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 for 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 sizeable surface pollution by Radon daughters, thanks to the new handling protocols

For details and other information see NIMA592(2008)297
**DAMA/LIBRA: calibrations at low energy**

Studied by using various external gamma sources ($^{241}$Am, $^{133}$Ba) and internal X-rays or gamma’s ($^{40}$K, $^{125}$I, $^{129}$I)

The curves superimposed to the experimental data have been obtained by simulations

- **Internal $^{40}$K**: 3.2 keV due to X-rays/Auger electrons (tagged by 1461 keV $\gamma$ in an adjacent detector).
- **Internal $^{125}$I**: 67.3 keV peak (EC from K shell + 35.5 keV $\gamma$) and composite peak at 40.4 keV (EC from L,M,... shells + 35.5 keV $\gamma$).
- **External $^{241}$Am source**: 59.5 keV $\gamma$ peak and 30.4 keV composite peak.
- **External $^{133}$Ba source**: 81.0 keV $\gamma$ peak.
- **Internal $^{129}$I**: 39.6 keV structure (39.6 keV $\gamma$ + $\beta$ spectrum).

**Linearity**

**Energy resolution**

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

Routine calibrations with $^{241}$Am
DAMA/LIBRA: calibrations at high energy

The data are taken on the full energy scale up to the MeV region by means QADC’s.

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

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

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

DAMA/LIBRA test runs: from March 2003 to September 2003

DAMA/LIBRA normal operation: from September 2003 to August 2004

High energy runs for TDs: September 2004
to allow internal $\alpha$’s identification
(approximative exposure $\approx 5000 \text{ kg } \times \text{ d}$)

DAMA/LIBRA normal operation: from October 2004

Data released here:
• four annual cycles: 0.53 ton $\times$ yr
• calibrations: acquired $\approx 44$ M events from sources
• acceptance window eff: acquired $\approx 2$ M events/keV

<table>
<thead>
<tr>
<th>Period</th>
<th>Exposure (kg$\times$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>51405</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>July 21, 2004 - Oct. 28, 2005</td>
<td>52597</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>Oct. 28, 2005 - July 18, 2006</td>
<td>39445</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>July 19, 2006 - July 17, 2007</td>
<td>40877</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1923824</td>
</tr>
</tbody>
</table>

Total exposure: $300555 \text{ kg} \times \text{day} = 0.82 \text{ ton} \times \text{yr}$

Two remarks:
• One PMT problems after 6 months. Detector out of trigger since Sep. 2003 (it will be put again in operation at the 2008 upgrading)
• Residual cosmogenic $^{125}$I presence in the first year in some detectors (this motivates the Sept. 2003 as starting time)
Cumulative low-energy distribution of the single-hit scintillation events

Single-hit events = each detector has all the others as anticoincidence

(Obviously differences among detectors are present depending e.g. on each specific level and location of residual contaminants, on the detector’s location in the 5x5 matrix, etc.)

Efficiencies already accounted for

About the energy threshold:

- The DAMA/LIBRA detectors have been calibrated down to the keV region. This assures a clear knowledge of the “physical” energy threshold of the experiment.
- It obviously profits of the relatively high number of available photoelectrons/keV (from 5.5 to 7.5).
- The two PMTs of each detector in DAMA/LIBRA work in coincidence with hardware threshold at single photoelectron level.
- Effective near-threshold-noise full rejection.
- The software energy threshold used by the experiment is 2 keV.
Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)  
Total exposure: 300555 kg$\times$day = 0.82 ton$\times$yr

Experimental single-hit residuals rate vs time and energy

The data favor the presence of a modulated behavior with proper features at $8.2\sigma$ C.L.

2-4 keV
A=$(0.0215\pm0.0026)$ cpd/kg/keV
$\chi^2$/dof = 51.9/66 $8.3\sigma$ C.L.

Absence of modulation? No
$\chi^2$/dof=117.7/67 ⇒ P(A=0) = 1.3\times10^{-4}$

2-5 keV
A=$(0.0176\pm0.0020)$ cpd/kg/keV
$\chi^2$/dof = 39.6/66 $8.8\sigma$ C.L.

Absence of modulation? No
$\chi^2$/dof=116.1/67 ⇒ P(A=0) = 1.9\times10^{-4}$

2-6 keV
A=$(0.0129\pm0.0016)$ cpd/kg/keV
$\chi^2$/dof = 54.3/66 $8.2\sigma$ C.L.

Absence of modulation? No
$\chi^2$/dof=116.4/67 ⇒ P(A=0) = 1.8\times10^{-4}$
Model-independent residual rate for single-hit events

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) total exposure: 300555 kg×day = 0.82 ton×yr

Results of the fits keeping the parameters free:

<table>
<thead>
<tr>
<th>Energy Interval</th>
<th>DAMA/NaI (7 years)</th>
<th>DAMA/LIBRA (4 years)</th>
<th>DAMA/NaI + DAMA/LIBRA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A (cpd/kg/keV)</td>
<td>t = 2π/ω (yr)</td>
<td>t₀ (day)</td>
</tr>
<tr>
<td>(2+4) keV</td>
<td>0.0252 ± 0.0050</td>
<td>1.01 ± 0.02</td>
<td>125 ± 30</td>
</tr>
<tr>
<td>(2+5) keV</td>
<td>0.0215 ± 0.0039</td>
<td>1.01 ± 0.02</td>
<td>140 ± 30</td>
</tr>
<tr>
<td>(2+6) keV</td>
<td>0.0200 ± 0.0032</td>
<td>1.00 ± 0.01</td>
<td>140 ± 22</td>
</tr>
<tr>
<td>(2+4) keV</td>
<td>0.0213 ± 0.0032</td>
<td>0.997 ± 0.002</td>
<td>139 ± 10</td>
</tr>
<tr>
<td>(2+5) keV</td>
<td>0.0165 ± 0.0024</td>
<td>0.998 ± 0.002</td>
<td>143 ± 9</td>
</tr>
<tr>
<td>(2+6) keV</td>
<td>0.0107 ± 0.0019</td>
<td>0.998 ± 0.003</td>
<td>144 ± 11</td>
</tr>
<tr>
<td>(2+4) keV</td>
<td>0.0223 ± 0.0027</td>
<td>0.996 ± 0.002</td>
<td>138 ± 7</td>
</tr>
<tr>
<td>(2+5) keV</td>
<td>0.0178 ± 0.0020</td>
<td>0.998 ± 0.002</td>
<td>145 ± 7</td>
</tr>
<tr>
<td>(2+6) keV</td>
<td>0.0131 ± 0.0016</td>
<td>0.998 ± 0.003</td>
<td>144 ± 8</td>
</tr>
</tbody>
</table>

Modulation amplitudes, A, of single year measured in the 11 one-year experiments of DAMA (NaI + LIBRA)

- The modulation amplitudes for the (2 – 6) keV energy interval, obtained when fixing exactly the period at 1 yr and the phase at 152.5 days, are: (0.019 ± 0.003) cpd/kg/keV for DAMA/NaI and (0.011 ± 0.002) cpd/kg/keV for DAMA/LIBRA.
- Thus, their difference: (0.008 ± 0.004) cpd/kg/keV is ≈ 2σ which corresponds to a modest, but non negligible probability.

χ² test (χ²/dof = 4.9/10, 3.3/10 and 8.0/10) and run test (lower tail probabilities of 74%, 61% and 11%) 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


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 (4 years)

Total exposure: 0.53 ton×yr

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

Total exposure: 0.82 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: \(2.705 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}\)
- DAMA/NaI+LIBRA: \(2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}\)

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

Clear annual modulation is evident in (2-6) keV while it is absence just above 6 keV
Can a hypothetical background modulation account for the observed effect?

- **No Modulation above 6 keV**

  Mod. Ampl. (6-10 keV): (0.0016 ± 0.0031), -(0.0010 ± 0.0034), -(0.0001 ± 0.0031) and -(0.0006 ± 0.0029) cpd/kg/keV for DAMA/LIBRA-1, DAMA/LIBRA-2, DAMA/LIBRA-3, DAMA/LIBRA-4; → they can be considered statistically consistent with zero

  In the same energy region where the effect is observed: no modulation of the multiple-hits events (see next slide)

- **No modulation in the whole spectrum:**

  - $R_{90}$ percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA-1,2,3,4 running periods → cumulative gaussian behaviour with $\sigma \approx 1\%$, fully accounted by statistical considerations
  - Fitting the behaviour with time, adding a term modulated according period and phase expected for Dark Matter particles: consistent with zero

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

- **No modulation in the background:**

  these results account for all sources of bckg (+ see later)
Multiple-hits events in the region of the signal - DAMA/LIBRA 1-4

- Each detector has its own TDs read-out → pulse profiles of multiple-hits events (multiplicity > 1) acquired (exposure: 0.53 ton×yr).

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

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

multiple-hits events = Dark Matter particles events “switched off”

Evidence of annual modulation with proper features as required by the DM annual modulation signature is present in the single-hit residuals, while it is absent in the multiple-hits residual rate.

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, $S_m$, for the total exposure

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

DAMA/Nal (7 years) + DAMA/LIBRA (4 years)

total exposure: $300555 \text{ kg} \times \text{day} = 0.82 \text{ ton} \times \text{yr}$

here $T = \frac{2\pi}{\omega} = 1 \text{ yr}$ and $t_0 = 152.5 \text{ day}$

$\Delta E = 0.5 \text{ keV bins}$

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

In fact, the $S_m$ values in the (6-20) keV energy interval have random fluctuations around zero with $\chi^2$ equal to 24.4 for 28 degrees of freedom
Statistical distributions of the modulation amplitudes ($S_m$)

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

DAMA/LIBRA (4 years)
total exposure: 0.53 ton$\times$yr

Each panel refers to each detector separately; 64 entries = 16 energy bins in 2–6 keV energy interval $\times$ 4 DAMA/LIBRA annual cycles

2–6 keV

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

\[ r.m.s. \approx 1 \]

Individual $S_m$ values follow a normal distribution since $(S_m-<S_m>)/\sigma$ is distributed as a Gaussian with a unitary standard standard deviation (r.m.s.)

$S_m$ statistically well distributed in all the detectors and annual cycles
Statistical analyses about modulation amplitudes ($S_m$)

\[ x = \frac{(S_m - \langle S_m \rangle)}{\sigma} \]
\[ \chi^2/d.o.f. = \sum x^2 \]

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

DAMA/LIBRA (4 years)
total exposure: 0.53 ton×yr

The line at \( \chi^2/d.o.f. = 1.31 \) corresponds to an upper tail probability of 5%.

Comparison with \( \chi^2 \) distribution with 64 d.o.f. gives: \( \chi^2/d.o.f. = 8.1/7 \)

The \( \chi^2/d.o.f. \) values range from 0.7 to 1.28 (64 d.o.f. = 16 energy bins × 4 annual cycles)

\[ \Rightarrow \] at 95% C.L. the observed annual modulation effect is well distributed in all the detectors.

- The mean value of the twenty-four points is 1.072, 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 \( \leq 5 \times 10^{-4} \) cpd/kg/keV, if quadratically combined, or \( \leq 7 \times 10^{-5} \) cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (\( \leq 4.7\% \) or \( \leq 0.7\% \), 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?

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

For Dark Matter signals:

- \(|Z_m| \ll |Y_m| \approx |S_m|\)
- \(\omega = \frac{2\pi}{T}\)
- \(t^* \approx t_0 = 152.5 \text{d}\)
- \(T = 1 \text{ year}\)

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</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>0.0122 ± 0.0016</td>
<td>-0.0019 ± 0.0017</td>
<td>0.0123 ± 0.0016</td>
<td>144.0 ± 7.5</td>
</tr>
<tr>
<td>6-14</td>
<td>0.0005 ± 0.0010</td>
<td>0.0011 ± 0.0012</td>
<td>0.0012 ± 0.0011</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 sizeable 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%

<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>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>$-(0.0001 \pm 0.0061) \degree C$</td>
<td>$(0.0026 \pm 0.0086) \degree C$</td>
<td>$(0.001 \pm 0.015) \degree C$</td>
<td>$(0.0004 \pm 0.0047) \degree C$</td>
</tr>
<tr>
<td>Flux $N_2$</td>
<td>$(0.13 \pm 0.22)$ l/h</td>
<td>$(0.10 \pm 0.25)$ l/h</td>
<td>$-(0.07 \pm 0.18)$ l/h</td>
<td>$-(0.05 \pm 0.24)$ l/h</td>
</tr>
<tr>
<td>Pressure</td>
<td>$(0.015 \pm 0.030)$ mbar</td>
<td>$-(0.013 \pm 0.025)$ mbar</td>
<td>$(0.022 \pm 0.027)$ mbar</td>
<td>$(0.0018 \pm 0.0074)$ mbar</td>
</tr>
<tr>
<td>Radon</td>
<td>$-(0.029 \pm 0.029)$ Bq/m$^3$</td>
<td>$-(0.030 \pm 0.027)$ Bq/m$^3$</td>
<td>$(0.015 \pm 0.029)$ Bq/m$^3$</td>
<td>$(0.052 \pm 0.039)$ Bq/m$^3$</td>
</tr>
<tr>
<td>Hardware rate above single photoelectron</td>
<td>$-(0.20 \pm 0.18) \times 10^{-2}$ Hz</td>
<td>$(0.09 \pm 0.17) \times 10^{-2}$ Hz</td>
<td>$-(0.03 \pm 0.20) \times 10^{-2}$ Hz</td>
<td>$(0.15 \pm 0.15) \times 10^{-2}$ 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)
**Temperature**

- Detectors in Cu housings directly in contact with multi-ton shield → huge heat capacity ($\approx 10^6$ cal/°C)
- Experimental installation continuously air conditioned (2 independent systems for redundancy)
- Operating T of the detectors continuously controlled

---

<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>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ (°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>
</tr>
</tbody>
</table>

Distribution of the root mean square values of the operating T within periods with the same calibration factors (typically $\approx 7$ days):

mean value $\approx 0.04$°C

Considering the slope of the light output $\approx -0.2$%/ °C:

relative light output variation $< 10^{-4}$:

$< 10^{-4}$ cpd/kg/keV ($< 0.5\% S_m^{\text{observed}}$)

---

**An effect from temperature can be excluded**

+ Any possible modulation due to temperature would always fail some of the peculiarities of the signature
Summarizing on a hypothetical background modulation in DAMA/LIBRA 1-4

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

\[ A = (0.9 \pm 1.1) \times 10^{-3} \text{ cpd/kg/keV} \]

\[ \sigma \approx 1\% \]

If a modulation present in the whole energy spectrum at the level found in the lowest energy region \( R_{90} \sim \text{tens cpd/kg} \) \( \sim 100 \sigma \) far away

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

Nevertheless, additional investigations performed ...
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 (\(^{24}\text{Na}, \, ^{128}\text{I}, \ldots\)) 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

**Measured fast neutron flux @ LNGS:**
\[ \Phi_n = 0.9 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \] (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:
\[ S_m^{(\text{fast n})} < 10^{-4} \text{ cpd/kg/keV} \] (< 0.5% \( S_m \) 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):
  \[ \Phi_n < 2.2 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \] (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 observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS.
Radon

- Three-level system to exclude Radon from the detectors:
- Walls and floor of the inner installation sealed in Supronyl (2 x 10^{-11} cm^2/s permeability).
- Whole shield in plexiglass box maintained in HP Nitrogen atmosphere in slight overpressure with respect to environment
- Detectors in the inner Cu box in HP Nitrogen atmosphere in slight overpressure with respect to environment continuously since several years measured values at level of sensitivity of the used radonmeter

Amplitudes for annual modulation of Radon external to the shield:

<flux> ≈ 320 l/h

Over pressure ≈ 3.1 mbar

Time behaviours of the environmental radon in the installation (i.e. after the Supronyl), from which in addition the detectors are excluded by other two levels of sealing!

<table>
<thead>
<tr>
<th>Radon (Bq/m^3)</th>
<th>DAMA/LIBRA-1</th>
<th>DAMA/LIBRA-2</th>
<th>DAMA/LIBRA-3</th>
<th>DAMA/LIBRA-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;(0.029 ± 0.029)</td>
<td>&lt;(0.030 ± 0.027)</td>
<td>(0.015 ± 0.029)</td>
<td>&lt;(0.052 ± 0.039)</td>
<td></td>
</tr>
</tbody>
</table>

NO DM-like modulation amplitude in the time behaviour of external Radon (from which the detectors are excluded), of HP Nitrogen flux and of Cu box pressure

Investigation in the HP Nitrogen atmosphere of the Cu-box

- Study of the double coincidences of γ’s (609 & 1120 keV) from ^{214}Bi Radon daughter
- Rn concentration in Cu-box atmosphere <5.8 · 10^{-2} Bq/m^3 (90% C.L.)
- By MC: < 2.5 · 10^{-5} cpd/kg/keV @ low energy for single-hit events (enlarged matrix of detectors and better filling of Cu box with respect to DAMA/NaI)
- An hypothetical 10% modulation of possible Rn in Cu-box:

<2.5 · 10^{-6} cpd/kg/keV (<0.01% S_m observed)

An effect from Radon can be excluded

+ any possible modulation due to Radon would always fail some of the peculiarities of the signature and would affect also other energy regions
Can the $\mu$ modulation measured by MACRO account for the observed effect?

Case of fast neutrons produced by muons

$\Phi_\mu @$ LNGS $\approx 20~\mu \text{ m}^{-2} \text{ d}^{-1}$  
Neutron Yield @ LNGS: $Y=1\div 7~10^{-4}~n/(\mu \text{ g/cm}^2)$  
$R_n = (\text{fast n by } \mu)/(\text{time unit}) = \Phi_\mu Y M_{\text{eff}}$

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

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

where:

- $\text{g} =$ geometrical factor
- $\varepsilon =$ detection efficiency by elastic scattering
- $f_{\Delta E} =$ energy window ($E>2\text{keV}$) efficiency
- $f_{\text{single}} =$ single hit efficiency

Hyp.: $M_{\text{eff}} = 15$ tons

Knowing that:

- $g \approx \varepsilon \approx f_{\Delta E} \approx f_{\text{single}} \approx 0.5$ (cautiously)
- $M_{\text{setup}} \approx 250$ kg and $\Delta E = 4\text{keV}$

$S_m^{(\mu)} < (0.4\div 3) \times 10^{-5} \text{ cpd/kg/keV}$

No

Moreover, this modulation also induces a variation in other parts of the energy spectrum. It cannot mimic the signature: already excluded also by $R_{90} +$ different phase, etc.
Can (whatever) possible cosmogenic products be considered as side effects?

**Hypothesis** (all the following items must be satisfied):

- the surviving muons can produce by spallation either unstable isotopes or exotic products;
- their decay or de-excitation or whatever else (mean-life: $\tau$) can produce:
  - only events at low energy,
  - only *single-hit* events,
  - no sizeable effect in the *multiple-hit* counting rate

The muon flux at LNGS ($\approx 20 \, \mu m^{-2} d^{-1}$) is yearly modulated ($\pm 2\%$) with phase roughly around middle of July

We expect in this hypothesis an annual modulation of the counting rate with a period one year (OK), but a phase (much) larger than July, 15th

DAMA/NaI + DAMA/LIBRA measured a phase of roughly May, 25th $\pm 10$ days

Also this hypothesis can be ruled out!

\[
\text{if } \tau \ll T/2\pi: \\
t_{\text{side}} = t_{\mu} + \tau
\]

\[
\text{if } \tau \gg T/2\pi: \\
t_{\text{side}} = t_{\mu} + \frac{T}{4}
\]
Summary of the results obtained in the additional investigations of possible systematics or side reactions (DAMA/LIBRA - NIMA592(2008)297 & EPJC56(2008)333)

<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 by MACRO</td>
<td>&lt;3×10⁻⁵ cpd/kg/keV</td>
</tr>
</tbody>
</table>

+ even if larger they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect
The positive model independent result by DAMA/NaI & DAMA/LIBRA

- Presence of modulation for 11 annual cycles at ~8.2σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 11 independent experiments of 1 year each one
- Absence of known sources of possible systematics and side processes able to quantitatively account for the observed modulation amplitude and to contemporaneously satisfy all the peculiarities of the signature

No other experiment whose result can be directly compared in model independent way is available so far
Model-independent evidence by DAMA/NaI and DAMA/LIBRA well compatible with several candidates (in several of the many astrophysical, nuclear and particle physics scenarios); other ones are open

Neutralino as LSP in 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

Light Dark Matter

Mirror Dark Matter

Elementary Black holes such as the Daemons

Sterile neutrino

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”, ...

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

Available results from direct searches using different target materials and approaches do not give any robust conflict
• In progress complete model dependent analyses by applying maximum likelihood analysis in time and energy to the events of the cumulative exposure to update allowed regions at given C.L., accounting both for all the info carried out by the data and for at least some of the many existing uncertainties in the field (as done by DAMA/NaI in Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125), and to enlarge the investigations to other ones

• Just to offer some naive feeling on the complexity of the argument:

  experimental $S_m$ values vs expected behaviours
  for some DM candidates in few of the many possible astrophysical, nuclear and particle physics scenarios and parameters values
Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$

WIMP DM candidate (as in [4]) considering elastic scattering on nuclei
SI dominant coupling $v_0 = 170$ km/s

About the same C.L. ...scaling from NaI

<table>
<thead>
<tr>
<th>Curve label</th>
<th>Halo model (see ref. [4, 34])</th>
<th>Local density (GeV/cm³)</th>
<th>Set as in [4]</th>
<th>DM particle mass</th>
<th>$\xi\sigma_{SI}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>$3.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$b$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$c$</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>$5.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$d$</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>B</td>
<td>100 GeV</td>
<td>$6.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$e$</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>A</td>
<td>120 GeV</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>


channeling contribution as in EPJC53(2008)205 considered for curve $b$
WIMP DM candidate (as in [4])

Elastic scattering on nuclei
SI & SD mixed coupling
\( v_0 = 170 \text{ km/s} \)

About the same C.L. …scaling from NaI

\[ \theta = 2.435 \]

<table>
<thead>
<tr>
<th>Curve label</th>
<th>Halo model</th>
<th>Local density ( \text{(GeV/cm}^3 )</th>
<th>Set as in [4]</th>
<th>DM particle mass</th>
<th>( \xi \sigma_{SI} ) (pb)</th>
<th>( \xi \sigma_{SD} ) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>( 10^{-7} )</td>
<td>2.6</td>
</tr>
<tr>
<td>g</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>( 1.4 \times 10^{-4} )</td>
<td>1.4</td>
</tr>
<tr>
<td>h</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>( 10^{-7} )</td>
<td>1.4</td>
</tr>
<tr>
<td>i</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>( 8.7 \times 10^{-6} )</td>
<td>8.7 \times 10^{-2}</td>
</tr>
<tr>
<td>j</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>A</td>
<td>100 GeV</td>
<td>( 10^{-7} )</td>
<td>1.7</td>
</tr>
<tr>
<td>k</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>A</td>
<td>100 GeV</td>
<td>( 1.1 \times 10^{-5} )</td>
<td>0.11</td>
</tr>
</tbody>
</table>

**Examples** for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$

- **LDM candidate**
  (as in MPLA23(2008)2125): inelastic interaction with electron or nucleus targets

- **Light bosonic candidate**
  (as in IJMPA21(2006)1445): axion-like particles totally absorbed by target material

**About the same C.L.**

**Curve r**: also pseudoscalar axion-like candidates (e.g. majoron) $m_a = 3.2 \text{ keV } g_{ae} = 3.9 \times 10^{-11}$

### Table

<table>
<thead>
<tr>
<th>Curve label</th>
<th>DM particle</th>
<th>Interaction</th>
<th>Set as in [4]</th>
<th>$m_H$</th>
<th>$\Delta$</th>
<th>Cross section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$</td>
<td>LDM</td>
<td>coherent</td>
<td>A</td>
<td>30 MeV</td>
<td>18 MeV</td>
<td>$\xi \sigma_m^{coh} = 1.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$m$</td>
<td>LDM</td>
<td>coherent</td>
<td>A</td>
<td>100 MeV</td>
<td>55 MeV</td>
<td>$\xi \sigma_m^{coh} = 9.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$n$</td>
<td>LDM</td>
<td>incoherent</td>
<td>A</td>
<td>30 MeV</td>
<td>3 MeV</td>
<td>$\xi \sigma_m^{inc} = 2.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>$o$</td>
<td>LDM</td>
<td>incoherent</td>
<td>A</td>
<td>100 MeV</td>
<td>55 MeV</td>
<td>$\xi \sigma_m^{inc} = 4.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>$p$</td>
<td>LDM</td>
<td>coherent</td>
<td>A</td>
<td>28 MeV</td>
<td>28 MeV</td>
<td>$\xi \sigma_m^{coh} = 1.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$q$</td>
<td>LDM</td>
<td>incoherent</td>
<td>A</td>
<td>88 MeV</td>
<td>88 MeV</td>
<td>$\xi \sigma_m^{inc} = 4.1 \times 10^{-2}$</td>
</tr>
<tr>
<td>$r$</td>
<td>LDM</td>
<td>on nuclei</td>
<td>–</td>
<td>60 keV</td>
<td>60 keV</td>
<td>$\xi \sigma_m^{coh} = 0.3 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

where we are ...

• DAMA/LIBRA over 4 annual cycles (0.53 ton×yr) confirms the results of DAMA/NaI (0.29 ton×yr)

• The cumulative confidence level for the model independent evidence for presence of DM particle in the galactic halo is 8.2 \( \sigma \) (total exposure 0.82 ton × yr)

• First upgrading of the experimental set-up in Sept. 2008

**Phase 1**

• Mounting of the "clean room" set-up in order to operate in HP N\(_2\) atmosphere
• Opening of the shield of DAMA/LIBRA set-up in HP N\(_2\) atmosphere
• Replacement of some PMTs in HP N\(_2\) atmosphere
• Closing of the shield

**Phase 2**

• Dismounting of the Tektronix TDs (Digitizers + Crates)
• Mounting of the new Acqiris TD (Digitizers + Crate)
• Mounting of the new DAQ system with optical read-out
• Test of the new TDs (*hardware*) and of the new required DAQ system (*software*)

• Since Oct. 2008 again in data taking
... and where we are going

- continuing data taking after the first upgrading
- Update corollary analyses in some of the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc.. Consider further ones also on the basis of literature

**Next upgrading**: replacement of all the PMTs with higher Q.E. ones.
- Production of new high Q.E. PMTs in progress
- Goal: lowering the energy threshold

- Analyses/data taking to investigate also other rare processes in progress/foreseen
- Long term data taking to improve the investigation, to disentangle at least some of the many possibilities, to investigate other features of DM particle component(s) and second order effects, etc.. (& results on other processes with higher sensitivity)

A possible highly radiopure NaI(Tl) multi-purpose set-up DAMA/1 ton (proposed by DAMA already in 1996) at R&D phase

Felix qui potuit rerum cognoscere causas (Virgilio, Georgiche, II, 489)