Signals from Dark Universe: 
DAMA/LIBRA at LNGS

R. Cerulli
INFN-LNGS

ISNP 2009
Mumbai, INDIA
December, 2009
The Dark Side of the Universe: experimental evidences ...

First evidence and confirmations:
1934  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

\[ M_{\text{visible Universe}} \ll M_{\text{gravitational effect}} \Rightarrow \text{about 90\% of the mass is DARK} \]
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.

Non baryonic Cold Dark Matter is dominant

Ω_b ∼ 4%

The baryons give “too small” contribution

~ 90% of the matter in the Universe is non baryonic

Concordance model

Ω = Ω_Λ + Ω_M = close to 1

Ω = density/critical density

Ω_Λ ≈ 0.74

Ω_M ≈ 0.26

The Universe is flat

Primordial Nucleosynthesis

Structure formation in the Universe

Ω_{CDM} ∼ 22%

Ω_{HDM, ψ} < 1%
Relic DM particles from primordial Universe

- SUSY (as neutralino or sneutrino in various scenarios)
- the sneutrino in the Smith and Weiner scenario
- sterile ν
- electron interacting dark matter
- a heavy ν of the 4-th family
- even a suitable particle not yet foreseen by theories
- axion-like (light pseudoscalar and scalar candidate)
- self-interacting dark matter
- mirror dark matter
- Kaluza-Klein particles (LKK)
- heavy exotic candidates, as "4th family atoms", ...
- Elementary Black holes, Planckian objects, Daemons
- (& invisible axions, ν's)
- Right halo model and parameters?
- Non thermalized components?
- Caustics?
- clumpiness?
- Composition?
- DM multicomponent also in the particle part?
- Right related nuclear and particle physics?

etc... etc...
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**
  
  \[ \text{→ detection of nuclear recoil energy} \]

  ![Diagram of scatterings on nuclei]

- **Excitation of bound electrons in scatterings on nuclei**
  
  \[ \text{→ detection of recoil nuclei + e.m. radiation} \]

- **Conversion of particle into e.m. radiation**
  
  \[ \text{→ detection of } \gamma, \text{ X-rays, } e^- \]

- **Interaction only on atomic electrons**
  
  \[ \text{→ detection of e.m. radiation} \]

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

  \[ \text{→ Kinematical constraint for the inelastic scattering of } \chi^- \text{ on a nucleus} \]

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

- **Interaction of ligth DMp (LDM)**
  
  \[ \text{on } e^- \text{ or nucleus with production of a lighter particle} \]

  \[ \text{→ detection of electron/nucleus recoil energy} \]

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

- **... even WIMPs**

- **... also other possibilities...**

- **... and more**
The direct detection experiments can be classified in two classes, depending on what they are based:

1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a “model-independent” signature

2. on the use of uncertain techniques of rejection of electromagnetic background (adding systematical effects and lost of candidates with part or pure electromagnetic productions)
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

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

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

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.
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
- Routine calibrations feasible down to keV range in the same conditions as the production runs
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- Absence of microphonic noise + effective noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)
- High light response (5.5 - 7.5 ph.e./keV)
- Sensitive to SI, SD, SI&SD couplings and to other existing scenarios, on the contrary of many other proposed target-nuclei
- Sensitive to both high (by Iodine target) and low mass (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 such as: 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, ...
Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati
+ in some studies on $^{76}$Ge decays (DST-MAE project): IIT Kharagpur, India)

DAMA: an observatory for rare processes @LNGS

DAMA/LXe  DAMA/R&D  low bckg DAMA/Ge for sampling meas.

DAMA/NaI  meas. with $^{100}$Mo

DAMA/LIBRA

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

Dark Matter Investigation

• Limits on recoils investigating the DP-129Xe elastic scattering by means of PSD
• Limits on DP-129Xe inelastic scattering
• Neutron calibration

129Xe vs 136Xe 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 129Xe during CNC processes
• N, NN decay into invisible channels in 129Xe
• Electron decay: \( e^+ \rightarrow \nu e' \gamma \)
• 2β decay in 136Xe
• 2β decay in 134Xe
• Improved results on 2β in 134Xe, 136Xe
• CNC decay 136Xe → 136Cs
• N, NN, NNN decay into invisible channels in 136Xe

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

• Particle Dark Matter search with CaF2(Eu)

DAMA/Ge & LNGS Ge facility

• RDs on highly radiopure NaI(Tl) set-up;
• several RDs on low background PMTs;
• qualification of many materials
• measurements with a Li6Eu(BO3)3 crystal (NIMA572(2007)734)
• measurements with 106Mo sample investigating ββ decay in the 4π low-bckg HP Ge facility of LNGS (to appear on Nucl. Phys. and Atomic Energy)
• search for 7Li solar axions (NPA806(2008)388)

+Many other meas. already scheduled for near future
**DAMA/NaI : \(\approx100 \text{ kg NaI(Tl)}\)**


**Results on rare processes:**

- Possible Pauli exclusion principle violation
  - PLB408(1997)439
- CNC processes
  - PRC60(1999)065501
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
  - PLB460(1999)235
- 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
- Investigation on diurnal effect
- Exotic Dark Matter search
  - PRL83(1999)4918
- Annual Modulation Signature

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

*total exposure (7 annual cycles) \(0.29 \text{ ton x yr}\)*
The new DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)
As a result of a second generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

installing DAMA/LIBRA detectors

filling the inner Cu box with further shield

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

assembling a DAMA/LIBRA detector

closing the Cu box housing the detectors

• Radiopurity, performances, procedures, etc.: NIMA592(2008)297
• Results on DM particles: Annual Modulation Signature: EPJC56(2008)333
• Results on rare processes: Possible processes violating the Pauli exclusion principle in Na and I: EPJC62(2009)327
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)

DAMA/LIBRA ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

PMT + HV divider

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

storing new crystals

etching staff at work in clean room

improving installation and environment
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 Wawefom 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

Polyethylene/paraffin

Electronics + DAQ

Installation

Glove-box for calibration

OPMG low radioactive copper
Low radioactive lead
Gadmmium foils
Polyethylene/paraffin
Concrete from GS rock

~ 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 crystals: 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 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 sizeable 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

![Linearity](Image1)

![Energy resolution](Image2)

**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

![Linearity](Image3)

![Energy resolution](Image4)

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: $0.53 \text{ ton } \times \text{ yr}$
- calibrations: acquired $\approx 44 \text{ M events from sources}$
- acceptance window eff: acquired $\approx 2 \text{ M events/keV}$

Two remarks:
- One PMT problems after 6 months. Detector out of trigger since Sep. 2003 (since Sept. 2008 again in operation)
- Residual cosmogenic $^{125}\text{I}$ presence in the first year in some detectors (this motivates the Sept. 2003 as starting time)

<table>
<thead>
<tr>
<th>Period</th>
<th>Exposure (kg × day)</th>
<th>$\alpha - \beta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-1</td>
<td>Sept. 9, 2003 - July 21, 2004</td>
<td>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>49377</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>192824</td>
</tr>
</tbody>
</table>

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

DAMA/LIBRA is continuously running
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.

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

3.2 keV, tagged by 1461 keV γ in an adjacent detector
Experimental *single-hit* residuals rate vs time and energy

- Model-independent investigation of the annual modulation signature has been carried out by exploiting the time behaviour of the residual rates of the *single-hit* events in the lowest energy regions of the DAMA/LIBRA data.

- These residual rates are calculated from the measured rate of the *single-hit* events (obviously corrections for the overall efficiency and for the acquisition dead time are already applied) after subtracting the constant part:

\[
\left\langle r_{ijk} - \text{flat}_{jk} \right\rangle_{jk}
\]

- \( r_{ijk} \) is the rate in the considered \( i \)-th time interval for the \( j \)-th detector in the \( k \)-th energy bin

- \( \text{flat}_{jk} \) is the rate of the \( j \)-th detector in the \( k \)-th energy bin averaged over the cycles.

- The average is made on all the detectors (\( j \) index) and on all the energy bins (\( k \) index)

- The weighted mean of the residuals must obviously be zero over one cycle.
Model Independent Annual Modulation Result

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

experimental single-hit residuals rate vs time and energy

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

**2-4 keV**

A = (0.0215 ± 0.0026) cpd/kg/keV

χ²/dof = 51.9/66  **8.3 σ C.L.**

Absence of modulation? No

χ²/dof = 117.7/67  ⇒  P(A=0) = 1.3×10⁻⁴

**2-5 keV**

A = (0.0176 ± 0.0020) cpd/kg/keV

χ²/dof = 39.6/66  **8.8 σ C.L.**

Absence of modulation? No

χ²/dof = 116.1/67  ⇒  P(A=0) = 1.3×10⁻⁴

**2-6 keV**

A = (0.0129 ± 0.0016) cpd/kg/keV

χ²/dof = 54.3/66  **8.2 σ C.L.**

Absence of modulation? No

χ²/dof = 116.4/67  ⇒  P(A=0) = 1.8×10⁻⁴
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>A (cpd/kg/keV)</th>
<th>T = 2π/ω (yr)</th>
<th>t₀ (day)</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DAMA/NaI (7 years)</strong></td>
<td></td>
<td></td>
<td></td>
</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><strong>DAMA/LIBRA (4 years)</strong></td>
<td></td>
<td></td>
<td></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><strong>DAMA/NaI + DAMA/LIBRA</strong></td>
<td></td>
<td></td>
<td></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

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

2-6 keV vs 6-14 keV

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

DAMA/LIBRA
2.705 × 10⁻³ d⁻¹ ≈ 1 yr⁻¹

DAMA/NaI + LIBRA
2.737 × 10⁻³ d⁻¹ ≈ 1 yr⁻¹

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

Clear annual modulation is evident in (2-6) keV while it is 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): $\text{cpd/kg/keV}$
    - DAMA/LIBRA-1: $(0.0016 \pm 0.0031)$
    - DAMA/LIBRA-2: $-(0.0010 \pm 0.0034)$
    - DAMA/LIBRA-3: $-(0.0001 \pm 0.0031)$
    - DAMA/LIBRA-4: $-(0.0006 \pm 0.0029)$

  → statistically consistent with zero

- **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

<table>
<thead>
<tr>
<th>Period</th>
<th>Mod. Ampl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-1</td>
<td>$-(0.05\pm0.19)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>$-(0.12\pm0.19)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>$-(0.13\pm0.18)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>$(0.15\pm0.17)$ cpd/kg</td>
</tr>
</tbody>
</table>

- 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 → $\sim 100\,\sigma$ far away

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

---

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

total exposure: 300555 kg×day = 0.82 ton×yr

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

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) $S_m$ values for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

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

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

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

2-6 keV

Standard deviations of the variable

$$\frac{(S_m - \langle S_m \rangle)}{\sigma}$$

for the DAMA/LIBRA detectors

Individual $S_m$ values follow a normal distribution since

$$\frac{(S_m - \langle S_m \rangle)}{\sigma}$$

is distributed as a Gaussian with a unitary standard deviation ($r.m.s.$)

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

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

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

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 $\times$ 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.

DAMA/LIBRA (4 years)  
total exposure: 0.53 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:

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

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

<table>
<thead>
<tr>
<th>(E) (keV)</th>
<th>(S_m) (cpd/kg/keV)</th>
<th>(Z_m) (cpd/kg/keV)</th>
<th>(Y_m) (cpd/kg/keV)</th>
<th>(t^*) (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-6</td>
<td>0.0122 ± 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>$-(0.0001 \pm 0.0061) , ^\circ, C$</td>
<td>$(0.0026 \pm 0.0086) , ^\circ, C$</td>
<td>$(0.001 \pm 0.015) , ^\circ, C$</td>
<td>$(0.0004 \pm 0.0047) , ^\circ, C$</td>
</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>
</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>
</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>
</tr>
<tr>
<td>Hardware rate above single photoelectron</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>
</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)
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 and 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

Corollary quests for candidates
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 kinds 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

Dark Matter (including some scenarios for WIMP) electron-interacting

Sterile neutrino

Elementary Black holes such as the Daemons

... and more

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

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.
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 $\nu_0 = 170$ km/s

15 GeV N.F.W.

60 GeV N.F.W.

100-120 GeV Evans power law

About the same C.L. (no best fit values) ...scaling from NaI

channeling contribution as in EPJC53(2008)205 considered for curve $b$

<table>
<thead>
<tr>
<th>Curve label</th>
<th>Halo model (see ref. [4, 34])</th>
<th>Local density (GeV/cm$^3$)</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>

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

- **15 GeV**
  - N.F.W.
  - WIMP DM candidate (as in [4])
  - Elastic scattering on nuclei
  - SI & SD mixed coupling
  - $v_0 = 170$ km/s

- **60 GeV**
  - N.F.W.

- **100 GeV**
  - Evans power law

Table:

<table>
<thead>
<tr>
<th>Curve label</th>
<th>Halo model (see ref. [4, 34])</th>
<th>Local density (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>1.7</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>$8.7 \times 10^{-2}$</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>

$\theta = 2.435$

LDM candidate
(as in arXiv:0802.4336):
inelastic interaction with electron or nucleus targets

\[
LDM \quad (\text{as in arXiv:0802.4336)}: \quad \frac{\sigma_{N\alpha}}{A_{N\alpha}^2} \approx \frac{\sigma_{I}}{A_{I}^2}
\]

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

\[
\sigma_{N\alpha} \approx \sigma_{I}
\]

\( m_L = 0 \)

Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes \( S_{m,k} \)

About the same C.L. (no best fit values)

(NFW) halo model as in [4, 34], local density = 0.17 GeV/cm³, local velocity = 170 km/s

<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>

\[4\] RNC 26 (2003) 1; [34] PRD66 (2002) 043503
• Assuming for the neutralino a dominant purely SI coupling
• when releasing the gaugino mass unification at GUT scale: $M_1/M_2 \neq 0.5$ (\(<\));
  (where $M_1$ and $M_2$ U(1) and SU(2) gaugino masses)

Inelastic DM

Light DM

Axion-like DM

Weiner & Tucker-Smith

MPLA23 (2008) 2125

... some examples appeared in literature...
where DAMA/LIBRA is ...

- 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
... where DAMA/LIBRA is going

- Continuing the data taking
- 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 thresholds of the detectors

- 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, (& results on other processes with higher sensitivity), etc..