Particle Dark Matter in the galactic halo
The Dark Matter in the Universe

- A large part of the Universe is made of Dark Matter and Dark Energy
- The so-called “baryonic” matter is only $\approx 5\%$ of the total budget
- (Concordance) $\Lambda$CDM model and precision cosmology
- The Dark Matter is fundamental for the formation of the structures and galaxies in the Universe
- Non-baryonic Dark Matter is the dominant component ($\approx 27\%$) among the matter.
They hypothesize that the theory of gravity is incomplete and that a new gravitational theory might explain the experimental observations:

- MOND modifies the law of motion for very small accelerations
- MOG modifies the Einstein’s theory of gravitation to account for an hypothetical fifth fundamental force in addition to the gravitational, electromagnetic, strong and weak ones.

Efforts to find alternative explanations to DM proposed e.g.:

- Modified Gravity Theory (MOG)
- Modified Newtonian Dynamics (MOND) theory

BUT

- no general underlying principle;
- generally unable to account for all small and large scale observations;
- fail to reproduce accurately the Bullet Cluster;
- generally require some amount of DM particles as seeds for the structure formation.
Relic DM particles from primordial Universe

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

What accelerators cannot do: to credit that a certain particle is a DM solution or the "only" DM particle solution...

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

DM direct detection using a model independent approach and a very low-background widely-sensitive target material

Right halo model and parameters?

- DM multicomponent also in the particle part?
- Right related nuclear and particle physics?
- Non thermalized components?
- Caustics?
- Clumpiness?
- etc
2 different questions:

✓ Are there Dark Matter particles in the galactic halo?
  
  e.g.: The exploitation of the DM annual modulation signature with highly radiopure NaI(Tl) as target material can permit to answer to this question by direct detection and in a way largely independent on the nature of the candidate and on the astrophysical, nuclear and particle Physics assumptions → DAMA/NaI and DAMA/LIBRA

✓ Which is exactly the nature of the DM particle(s) and the related astrophysical, nuclear and particle Physics scenarios?
  
  Always model-dependent corollary analyses required

REMARK: It does not exist any approach to investigate the nature of the candidate in the direct and indirect DM searches, which can offer this latter information independently on assumed astrophysical, nuclear and particle Physics scenarios...
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 background by using a **model-independent signature**

2. assuming a priori a particular nature for DM candidate and interaction type and using multiple uncertain techniques of huge data selections and subtractions in marginal exposure to statistically discriminate mostly the electromagnetic component of the counting rate (adding systematical effects and lost of candidates)

**Direct detection experiments**

- **Ionization:** Ge, Si
- **Scintillation:** NaI(Tl), LXe, CaF$_2$(Eu), ...
- **Bolometer:** TeO$_2$, Ge, CaWO$_4$, ...
- **Scintillation:** NaI(Tl), LXe, CaF$_2$(Eu), ...

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[Image of a cartoon representing a decision point with one way and two ways.]
Some direct detection processes:

- **Inelastic Dark Matter**: $W + N \rightarrow W^* + N$
  - $W$ has 2 mass states $\chi^+, \chi^-$ with $\delta$ mass splitting
  - Kinematic constraint for the inelastic scattering of $\chi^-$ on a nucleus
    \[
    \frac{1}{2} \mu v^2 \geq \delta \iff v \geq v_{\text{thr}} = \sqrt{\frac{2\delta}{\mu}}
    \]
  - $\chi^+$ has 2 mass states $\chi^+, \chi^-$ with $\delta$ mass splitting
- **Excitation of bound electrons in scatterings on nuclei**
  - $\rightarrow$ detection of recoil nuclei + e.m. radiation
- **Elastic scatterings on nuclei**
  - $\rightarrow$ detection of nuclear recoil energy
- **Conversion of particle into e.m. radiation**
  - $\rightarrow$ detection of $\gamma$, X-rays, $e^-$
- **Interaction only on atomic electrons**
  - $\rightarrow$ detection of e.m. radiation
  - $\cdots$ even WIMPs
- **Interaction of light DMp (LDM) on e- or nucleus with production of a lighter particle**
  - $\rightarrow$ detection of electron/nucleus recoil energy
    - e.g. sterile $\nu$
  - $\cdots$ and more

Example signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate.
The DM annual modulation: a model independent signature to investigate the DM particles component in the galactic halo

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

Requirements of the DM annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

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

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

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

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements.
The relevance of ULB NaI(Tl) as target-material

- 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, …)
- $\lambda$ of the NaI(Tl) scintillation light well directly match PMTs sensitivity
- Uniform response in the realized detectors
- High light response (5.5 - 7.5 ph.e./keV in DAMA/LIBRA-phase1)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold ($\tau$ of NaI(Tl) pulses hundreds ns, while $\tau$ 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.

To develop ULB NaI(Tl): many years of work, specific experience in the specific detector, suitable raw materials availability/selections, developments of purification strategies, additives, growing/handling protocols, selective cuts, abrasives, etc. etc. → long dedicated time and efforts.

The developments themselves are difficult and uncertain experiments.

ULB NaI(Tl) - as whatever ULB detector - cannot be simply bought or made by another researcher for you …
Roma2, Roma1, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev and others (as NIIC+ITEP-Moscow+ JSC NeoChem )
+ some studies on $\beta\beta$ decays (DST-MAE, inter-univ. agreem.): IIT Kharagpur/Ropar, India
The pioneer DAMA/Nal: ≈100 kg highly radiopure NaI(Tl)

Performances:

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

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


PLB408(1997)439
PRC60(1999)065501
PLB460(1999)235
PLB515(2001)6
EPJdirect C14(2002)1
EPJA23(2005)7
EPJA24(2005)51

PLB389(1996)757
PRL83(1999)4918

data taking completed on July 2002, last data release 2003. Still producing results


model independent evidence of a particle DM component in the galactic halo at 6.3 σ C.L.
total exposure (7 annual cycles) 0.29 ton × yr
Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: $^{232}$Th, $^{238}$U and $^{40}$K at level of $10^{-12}$ g/g

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)

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
  *IPP in $^{241}$Am*: EPJA49(2013)64
For details, radiopurity, performances, procedures, etc.

- **Polyethylene/paraffin**
- **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**

**Glove-box for calibration**

**Electronics + DAQ**

- **1m concrete from GS rock**
- **Dismounting/Installing protocol in HPN₂**
- **All the materials selected for low radioactivity**
- **Multicomponent passive shield** (>10 cm of OFHC Cu, 15 cm of boliden 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 both for single-hit and multiple-hit events
- **Data collected from low energy up to MeV region**, despite the hardware optimization was done for the low energy
### Complete DAMA/LIBRA-phase1: a ton x yr experiment? done


<table>
<thead>
<tr>
<th>DAMA/LIBRA phase</th>
<th>Period</th>
<th>Mass (kg)</th>
<th>Exposure (kg×day)</th>
<th>$(\alpha - \beta^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-1</td>
<td>Sept. 9, 2003 - July 21, 2004</td>
<td>232.8</td>
<td>51405</td>
<td>0.562</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>July 21, 2004 - Oct. 28, 2005</td>
<td>232.8</td>
<td>52597</td>
<td>0.467</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>Oct. 28, 2005 - July 18, 2006</td>
<td>232.8</td>
<td>39445</td>
<td>0.591</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>July 19, 2006 - July 17, 2007</td>
<td>232.8</td>
<td>49377</td>
<td>0.541</td>
</tr>
<tr>
<td>DAMA/LIBRA-5</td>
<td>July 17, 2007 - Aug. 29, 2008</td>
<td>232.8</td>
<td>66105</td>
<td>0.468</td>
</tr>
<tr>
<td>DAMA/LIBRA-6</td>
<td>Nov. 12, 2008 - Sept. 1, 2009</td>
<td>242.5</td>
<td>58768</td>
<td>0.519</td>
</tr>
<tr>
<td>DAMA/LIBRA-7</td>
<td>Sep. 1, 2009 - Sept. 8, 2010</td>
<td>242.5</td>
<td>62098</td>
<td>0.515</td>
</tr>
<tr>
<td>DAMA/LIBRA-phase1</td>
<td>Sept. 9, 2003 - Sept. 8, 2010</td>
<td>242.5</td>
<td>379795 $\sim$ 1.04 ton×yr</td>
<td>0.518</td>
</tr>
<tr>
<td>DAMA/NaI + DAMA/LIBRA-phase1</td>
<td></td>
<td></td>
<td>1.33 ton×yr</td>
<td></td>
</tr>
</tbody>
</table>

- **calibrations:** $\approx 9.6 \times 10^7$ events from sources
- **acceptance window eff:**

  95 M events ($\approx 3.5$ M events/keV)
Model Independent DM Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1

Experimental residuals of the single-hit scintillation events rate vs time and energy

\[ A = (0.0179 \pm 0.0020) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 87.1/86 \quad 9.0 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof} = 169/87 \Rightarrow P(A=0) = 3.7 \times 10^{-7} \]

\[ A = (0.0135 \pm 0.0015) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 68.2/86 \quad 9.0 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof} = 152/87 \Rightarrow P(A=0) = 2.2 \times 10^{-5} \]

\[ A = (0.0110 \pm 0.0012) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 70.4/86 \quad 9.2 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof} = 154/87 \Rightarrow P(A=0) = 1.3 \times 10^{-5} \]

The data favor the presence of a modulated behavior with proper features at $9.2\sigma$ C.L.
Modulation amplitudes (A), period (T) and phase ($t_0$) measured in DAMA/NaI and DAMA/LIBRA-phase1

<table>
<thead>
<tr>
<th></th>
<th>A (cpd/kg/keV)</th>
<th>$T = 2\pi/\omega$ (yr)</th>
<th>$t_0$ (day)</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DAMA/NaI</strong></td>
<td></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>
<td>5.0σ</td>
</tr>
<tr>
<td>(2-5) keV</td>
<td>0.0215 ± 0.0039</td>
<td>1.01 ± 0.02</td>
<td>140 ± 30</td>
<td>5.5σ</td>
</tr>
<tr>
<td>(2-6) keV</td>
<td>0.0200 ± 0.0032</td>
<td>1.00 ± 0.01</td>
<td>140 ± 22</td>
<td>6.3σ</td>
</tr>
<tr>
<td><strong>DAMA/LIBRA-phase1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2-4) keV</td>
<td>0.0178 ± 0.0022</td>
<td>0.996 ± 0.02</td>
<td>134 ± 7</td>
<td>8.1σ</td>
</tr>
<tr>
<td>(2-5) keV</td>
<td>0.0127 ± 0.0016</td>
<td>0.996 ± 0.02</td>
<td>137 ± 8</td>
<td>7.9σ</td>
</tr>
<tr>
<td>(2-6) keV</td>
<td>0.0097 ± 0.0013</td>
<td>0.998 ± 0.02</td>
<td>144 ± 8</td>
<td>7.5σ</td>
</tr>
<tr>
<td><strong>DAMA/NaI + DAMA/LIBRA-phase1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2-4) keV</td>
<td>0.0190 ± 0.0020</td>
<td>0.996 ± 0.0002</td>
<td>134 ± 6</td>
<td>9.5σ</td>
</tr>
<tr>
<td>(2-5) keV</td>
<td>0.0140 ± 0.0015</td>
<td>0.996 ± 0.0002</td>
<td>140 ± 6</td>
<td>9.3σ</td>
</tr>
<tr>
<td>(2-6) keV</td>
<td>0.0112 ± 0.0012</td>
<td>0.998 ± 0.0002</td>
<td>144 ± 7</td>
<td>9.3σ</td>
</tr>
</tbody>
</table>

χ² test ($\chi^2 = 9.5, 13.8$ and $10.8$ over $13$ d.o.f. for the three energy intervals, respectively; upper tail probability $73\%, 39\%, 63\%$) and run test (lower tail probabilities of $41\%, 29\%$ and $23\%$ for the three energy intervals, respectively) accept at $90\%$ C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.

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

**DAMA/NaI (7 years) + DAMA/LIBRA-phase1 (7 years)**

**total exposure:** 1.33 ton×yr

Principal mode in the 2-6 keV region:

\[ 2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1} \]

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


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

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

where:

\[
\bar{r} = \frac{1}{N} \sum_i r_i \quad \sigma^2 = \frac{1}{N-1} \sum_i (r_i - \bar{r})^2
\]

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

\[
\tan(2\omega \tau) = \frac{1}{2 \sigma^2} \sum_i \sin(2\omega t_i) \sum_i \cos(2\omega t_i)
\]

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.

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

- **No Modulation above 6 keV**
  
  Mod. Ampl. (6-10 keV): cpd/kg/keV
  
  (0.0016 ± 0.0031) DAMA/LIBRA-1
  
  -(0.0010 ± 0.0034) DAMA/LIBRA-2
  
  -(0.0001 ± 0.0031) DAMA/LIBRA-3
  
  -(0.0006 ± 0.0029) DAMA/LIBRA-4
  
  -(0.0021 ± 0.0026) DAMA/LIBRA-5
  
  (0.0029 ± 0.0025) DAMA/LIBRA-6
  
  -(0.0023 ± 0.0024) DAMA/LIBRA-7
  
  → statistically consistent with zero

- **No modulation in the whole energy spectrum:**
  studying integral rate at higher energy, R₉₀
  
  R₉₀ percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods

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

  consistent with zero

  + if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R₉₀ ~ tens cpd/kg → ~ 100 σ far away

  **No modulation above 6 keV**

  This accounts for all sources of bckg and is consistent with the studies on the various components
signals by Dark Matter particles do not belong to *multiple-hits* events, that is:

\[
\text{multiple-hits events} = \text{Dark Matter particles events “switched off”}
\]

Evidence of annual modulation with proper features as required by the DM annual modulation signature:
- present in the *single-hit* residuals
- absent in the *multiple-hits* residual

This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo, further excluding any side effect either from hardware or from software procedures or from background.
Energy distribution of the modulation amplitudes

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

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

DAMA/NaI + DAMA/LIBRA-phase1

total exposure: $487526 \text{ kg} \times \text{day} \approx 1.33 \text{ ton} \times \text{yr}$

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 35.8 for 28 degrees of freedom (upper tail probability 15%)
Is there a sinusoidal contribution in the signal? Phase $\neq 152.5$ 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\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>0.0106 ± 0.0012</td>
<td>-0.0006 ± 0.0012</td>
<td>0.0107 ± 0.0012</td>
<td>149.5 ± 7.0</td>
</tr>
<tr>
<td>6-14</td>
<td>0.0001 ± 0.0007</td>
<td>0.0000 ± 0.0005</td>
<td>0.0001 ± 0.0008</td>
<td>--</td>
</tr>
</tbody>
</table>
• Contributions to the total neutron flux at LNGS;
• Counting rate in DAMA/LIBRA for single-hit events, in the (2 – 6) keV energy region induced by:
  - neutrons,
  - muons,
  - solar neutrinos.

\( \Phi_k = \Phi_{0,k} (1 + \eta_k \cos \omega (t - t_k)) \)
\( R_k = R_{0,k} (1 + \eta_k \cos \omega (t - t_k)) \)

(See e.g. also EPJC 56 (2008) 333, EPJC 72 (2012) 2064, IJMPA 28 (2013) 1330022)

<table>
<thead>
<tr>
<th>Source</th>
<th>( \Phi_{0,k} ) (neutrons cm(^{-2}) s(^{-1}))</th>
<th>( \eta_k )</th>
<th>( t_k )</th>
<th>( R_{0,k} ) (cpd/kg/keV)</th>
<th>( A_k ) (cpd/kg/keV)</th>
<th>( A_k / S_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal n (10(^{-5}) – 10(^{-1}) eV)</td>
<td>( 1.08 \times 10^{-1} ) [19]</td>
<td>&lt; 0</td>
<td>–</td>
<td>&lt; 8 \times 10(^{-3}) [21, 23]</td>
<td>&lt; 8 \times 10(^{-3}) [21, 23]</td>
<td>&lt; 8 \times 10(^{-3}) [21, 23]</td>
</tr>
<tr>
<td>SLOW neutrons</td>
<td>( 2 \times 10^{-6} ) [15]</td>
<td>&gt; 0</td>
<td>–</td>
<td>&lt; 3 \times 10^{-3} [21, 23]</td>
<td>&lt; 3 \times 10^{-3} [21, 23]</td>
<td>&lt; 3 \times 10^{-3} [21, 23]</td>
</tr>
<tr>
<td>epithermal n (eV, keV)</td>
<td>( 0.9 \times 10^{-7} ) [12]</td>
<td>&gt; 0</td>
<td>–</td>
<td>&lt; 6 \times 10^{-4} [21, 23]</td>
<td>&lt; 6 \times 10^{-4} [21, 23]</td>
<td>&lt; 6 \times 10^{-4} [21, 23]</td>
</tr>
<tr>
<td>fusion, (( a, n )) ( n ) (1–10 MeV)</td>
<td>( 3 \times 10^{-9} ) (see text and ref [12])</td>
<td>&gt; 0</td>
<td>–</td>
<td>&lt; 7 \times 10^{-4} (see text and ref [12])</td>
<td>&lt; 7 \times 10^{-4} (see text and ref [12])</td>
<td>&lt; 7 \times 10^{-4} (see text and ref [12])</td>
</tr>
<tr>
<td>FAST neutrons</td>
<td>( 6 \times 10^{-9} ) (see footnote [3])</td>
<td>&gt; 0</td>
<td>–</td>
<td>&lt; 1.5 \times 10^{-4} (see footnote [3])</td>
<td>&lt; 1.5 \times 10^{-4} (see footnote [3])</td>
<td>&lt; 1.5 \times 10^{-4} (see footnote [3])</td>
</tr>
<tr>
<td>( \nu + n ) (few MeV)</td>
<td>( 3 \times 10^{-10} ) (see text)</td>
<td>&gt; 0</td>
<td>–</td>
<td>&lt; 7 \times 10^{-5} (see text)</td>
<td>&lt; 7 \times 10^{-5} (see text)</td>
<td>&lt; 7 \times 10^{-5} (see text)</td>
</tr>
<tr>
<td>( \mu + n ) from rock (&gt; 10 MeV)</td>
<td>( 0.0129 ) [72]</td>
<td>&lt; 0.1</td>
<td>Jan. 4th*</td>
<td>&lt; 2 \times 10^{-3} (see text and ref [12])</td>
<td>&lt; 2 \times 10^{-3} (see text and ref [12])</td>
<td>&lt; 2 \times 10^{-3} (see text and ref [12])</td>
</tr>
<tr>
<td>( \mu + n ) from Pb shield (&gt; 10 MeV)</td>
<td>( 0.0129 ) [72]</td>
<td>&lt; 0.1</td>
<td>Jan. 4th*</td>
<td>&lt; 2 \times 10^{-3} (see text and ref [12])</td>
<td>&lt; 2 \times 10^{-3} (see text and ref [12])</td>
<td>&lt; 2 \times 10^{-3} (see text and ref [12])</td>
</tr>
<tr>
<td>( \nu + p )</td>
<td>( 0.0334 ) [72]</td>
<td>–</td>
<td>Jan. 4th*</td>
<td>&lt; 2 \times 10^{-4} (see text)</td>
<td>&lt; 2 \times 10^{-4} (see text)</td>
<td>&lt; 2 \times 10^{-4} (see text)</td>
</tr>
<tr>
<td>direct ( \mu )</td>
<td>( 20 \mu m^2 d^{-1} )</td>
<td>&gt; 0.12</td>
<td>–</td>
<td>3 \times 10^{-4} [23, 24]</td>
<td>3 \times 10^{-4} [23, 24]</td>
<td>3 \times 10^{-4} [23, 24]</td>
</tr>
<tr>
<td>direct ( \nu )</td>
<td>( 6 \times 10^{-10} ) [26]</td>
<td>&gt; 0.03</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year, so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

\(+\) In no case neutrons (of whatever origin) can mimic the DM annual modulation signature since some of the peculiar requirements of the signature would fail, such as the neutrons would induce e.g. variations in all the energy spectrum, variation in the multiple hit events,... which were not observed.

\(+\) In no case muon or muons induced effects can mimic the signature (see e.g. EPJC 72 (2012) 2064)

\(+\) etc.
Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

<table>
<thead>
<tr>
<th>Source</th>
<th>Main comment</th>
<th>Cautious upper limit (90%C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RADON</strong></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><strong>TEMPERATURE</strong></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><strong>NOISE</strong></td>
<td>Effective full noise rejection near threshold</td>
<td>&lt;10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td><strong>ENERGY SCALE</strong></td>
<td>Routine + instrinsic calibrations</td>
<td>&lt;1-2×10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td><strong>EFFICIENCIES</strong></td>
<td>Regularly measured by dedicated calibrations</td>
<td>&lt;10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td><strong>BACKGROUND</strong></td>
<td>No modulation above 6 keV; no modulation in the (2-6) keV</td>
<td>&lt;10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td></td>
<td><em>multiple-hits</em> events; this limit includes all possible sources of background</td>
<td></td>
</tr>
<tr>
<td><strong>SIDE REACTIONS</strong></td>
<td>Muon flux variation measured at LNGS</td>
<td>&lt;3×10⁻⁵ cpd/kg/keV</td>
</tr>
</tbody>
</table>

Thus, they cannot mimic the observed annual modulation effect.
Final model independent result
DAMA/NaI+DAMA/LIBRA-phase1

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

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

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

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

2) Measured period is equal to $(0.998 \pm 0.002) \text{ yr}$, well compatible with the 1 yr period, as expected for the DM signal.

3) Measured phase $(144 \pm 7)$ days is well compatible with the roughly about 152.5 days, as expected for the DM signal.

4) The modulation is present only in the low energy (2–6) keV energy 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-hit ones, as expected for the DM signal.

6) The measured modulation amplitude in NaI(Tl) of the single-hit events in the (2–6) keV energy interval is: $(0.0112 \pm 0.0012)$ cpd/kg/keV ($9.3\sigma$ C.L.).

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available.
Model-independent evidence by DAMA/NaI and DAMA/LIBRA well compatible with several candidates (in many possible astrophysical, nuclear and particle physics scenarios)

Neutralino as LSP in various SUSY theories

Various kinds of WIMP candidates with several different 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

Elementary Black holes such as the Daemons

Sterile neutrino

a heavy ν 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

Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with possible positive hints in various scenarios

Possible model dependent positive hints from indirect searches (but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.) as well null results not in conflict with DAMA results;
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

10 GeV  WIMP: SI  N.F.W.
15 GeV  WIMP: SI  N.F.W.
60 GeV  WIMP: SI  N.F.W.
100-120 GeV WIMP: SI  Evans power law
15 GeV  WIMP: SI&SD  N.F.W.
60 GeV  WIMP: SI&SD  N.F.W.
100 GeV WIMP: SI&SD  Evans power law
10 GeV  LDM
60 GeV  LDM
100 GeV WIMP: SI&SD

Compatibility with several candidates; other ones are open

\theta = 2.435

Not best fit
About the same C.L.

EPJC56(2008)333,
IJMPA28(2013)1330022
About model dependent exclusion plots

Selecting just one simplified model framework, making lots of assumptions, fixing large numbers of parameters ... but...

• which particle?
• which couplings? which model for the coupling?
• which form factors for each target material and related parameters?
• which nuclear model framework for each target material?
• Which spin factor for each case?
• which scaling laws?
• which halo profile?
• which halo parameters?
• which velocity distribution?
• which parameters for velocity distribution?
• which \( v_0 \)?
• which \( v_{\text{esc}} \)?
• ...etc. etc.

and experimental aspects...

• marginal and “selected” exposures
• Threshold, energy scale and energy resolution when calibration in other energy region (& few phe/keV)? Stability? Too few calibration procedures and often not in the same running conditions
• Selections of detectors and of data
• handling of (many) “subtraction” procedures and stability in time of all the cuts windows and related quantities, etc.? Efficiencies?
• fiducial volume vs disuniformity of detector response in liquids?
• Used values in the calculation
• Used approximations etc., etc.

Exclusion plots have no “universal validity” and cannot disproof a model independent result in any given general model framework (they depend not only on the general assumptions largely unknown at present stage of knowledge, but on the details of their cooking) + generally overestimated + methodological robustness (see R. Hudson, Found. Phys. 39 (2009) 174) + etc.

On the other hand, possible positive hints should be interpreted. Large space for compatibility.
... an example ...

**DM particles inducing elastic scatterings on target-nuclei, SI case**

Regions in the nucleon cross section vs DM particle mass plane

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

- Compatibility also with CRESST and CDMS, if the two CDMS-Ge recoil-like events, the three CDMS-Si and the CRESST ones surviving the many applied cuts in marginal exposures are assumed as nuclear recoils induced by DM interactions.

**Compatibility**

- 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. (Astrophys33 (2010) 40)
  ➔ Towards lower σ
DM particle with preferred inelastic interaction

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

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

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

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

- Kinematical constraint for iDM

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

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

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

iDM interaction on Iodine nuclei


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

- For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with \(A\sim205\), which are present as a dopant at the \(10^{-3}\) level in NaI(Tl) crystals.

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

\[\arXiv:1007.2688\]

... and much more considering experimental and theoretical uncertainties
Model independent result on possible diurnal effect in DAMA/LIBRA–phase1

- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.
- These residual rates are calculated from the measured rate of the single-hit events after subtracting the constant part.

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

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

*Thus, the presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity.*
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

Velocity of the detector in the terrestrial laboratory:

\[ \vec{v}_{\text{lab}}(t) = \vec{v}_{\text{LSR}} + \vec{v}_\odot + \vec{v}_{\text{rev}}(t) + \vec{v}_{\text{rot}}(t), \]

Since:
- \( |\vec{v}_s| = |\vec{v}_{\text{LSR}} + \vec{v}_\odot| \approx 232 \pm 50 \text{ km/s} \)
- \( |\vec{v}_{\text{rev}}(t)| \approx 30 \text{ km/s} \)
- \( |\vec{v}_{\text{rot}}(t)| \approx 0.34 \text{ km/s} \)

\( v_{\text{lab}}(t) \approx v_s + \hat{v}_s \cdot \vec{v}_{\text{rev}}(t) + \hat{v}_s \cdot \vec{v}_{\text{rot}}(t). \)

**Annual modulation term:**

\[ \hat{v}_s \cdot \vec{v}_{\text{rev}}(t) = V_{\text{Earth}} B_m \cos(\omega(t - t_0)) \]
- \( V_{\text{Earth}} \) is the orbital velocity of the Earth \( \approx 30 \text{ km/s} \)
- \( B_m \approx 0.489 \)
- \( t_0 \approx t_{\text{equinox}} + 73.25 \text{ days} \approx \text{June 2} \)

**Diurnal modulation term:**

\[ \hat{v}_s \cdot \vec{v}_{\text{rot}}(t) = V_r B_d \cos[\omega_{\text{rot}}(t - t_d)] \]
- \( V_r \) is the rotational velocity of the Earth at the given latitude (for LNGS \( \approx 0.3435 \text{ km/s} \))
- \( B_d \approx 0.671 \)
- \( t_d \approx 14.02 \text{ h} \) (at LNGS)

Velocity of the Earth in the galactic frame as a function of the sidereal time, with starting point March 21 (around spring equinox). The contribution of diurnal rotation has been dropped off. The maximum of the velocity (vertical line) is about 73 days after the spring equinox.

Sum of the Sun velocity in the galactic frame \( (v_{\odot}) \) and of the rotation velocity of a detector at LNGS \( (\hat{v}_s \cdot \vec{v}_{\text{rot}}(t)) \) as a function of the sidereal time. The maximum of the velocity is about at 14 h (vertical line).
The time dependence of the counting rate

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

\[ S_k [v_{lab}(t)] \approx S_k [v_s] + \left[ \frac{\partial S_k}{\partial v_{lab}} \right] v_s \cos \omega (t-t_0) + v_s B_{d} \cos \omega \text{rot} (t-t_d) \]

- Annual modulation amplitude:
  \[ S_m = \left[ \frac{\partial S_k}{\partial v_{lab}} \right] v_s \cos \omega \text{Earth} B_m \]

- Diurnal modulation amplitude:
  \[ S_d = \left[ \frac{\partial S_k}{\partial v_{lab}} \right] v_s B_d \]

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

\[ \frac{S_d}{S_m} = \frac{V_r B_d}{V\text{Earth} B_m} \approx 0.016 \]

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval:
  \( (0.0097 \pm 0.0013) \text{ cpd/kg/keV} \)
- Thus, the expected value of the diurnal modulation amplitude is \( < 1.5 \times 10^{-4} \text{ cpd/kg/keV} \).
- When fitting the single-hit residuals with a cosine function with amplitude \( A_d \) as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.

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

DAMA/LIBRA-phase1

The \( A_d \) values are compatible with zero, having random fluctuations around zero with \( \chi^2 \) equal to 19.5 for 18 dof.

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

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

larger exposure DAMA/LIBRA–phase2 & lower energy threshold offers increased sensitivity to such an effect.
Investigation of Earth Shadow Effect with DAMA/LIBRA-phase1

- Earth Shadow Effect could be expected for DM candidate particles inducing nuclear recoils
- Can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- Would be induced by the variation during the day of the Earth thickness crossed by the DM particle in order to reach the experimental set-up

\[ \theta(t) \] is the angle between \( \mathbf{v}_{\text{lab}} \) and the zenith; determined by astrophysical considerations

DM particles crossing Earth lose their energy

DM velocity distribution observed in the laboratory frame is modified as function of time

At LNGS:
- 20:00 GMST minimum thickness crossed -> Maximum counting rate
- 08:00 GMST maximum thickness crossed -> Minimum counting rate

Arxiv:1505.05336 in press on EPJC
Study of the Earth Shadow Effect in DAMA/LIBRA-phase1

By MC code, the expected counting rate for a given mass, cross section and scenario has been estimated:

\[ S_{d,sh}(t) = \xi \sigma_n S'_{d,sh}(t) \]

Expectations are compared with the experimental diurnal residual rate of the single-hit scintillation events measured by DAMA/LIBRA-phase1 in the (2-4) keV energy interval.

Minimizing \( \chi^2 \), upper limits on \( \xi \) can be evaluated.

Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the \( \xi \) vs \( \sigma_n \) plane for each \( m_{DM} \).

In these examples:
Isothermal halo model with \( v_0 = 220 \) km/s and \( v_{esc} = 650 \) km/s
  a) QF const. without channeling
  b) QF const. including channeling
  c) QF depending on energy
  d) QF depending on energy renormalized to DAMA/LIBRA values

Red surface: 95% C.L. allowed mean value (uncertainties ± 30%)
DAMA/LIBRA phase 2 - running

Quantum Efficiency features

Energy resolution

 mean value:
 7.5% (0.6% RMS)
 6.7% (0.5% RMS)

σ/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blue points) and with previous PMT EMI-Electron Tube (red points).

The light responses

Previous PMTs: 5.5-7.5 ph.e./keV
New PMTs: up to 10 ph.e./keV

- 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
The sensitivity of the DM annual modulation signature depends – apart from the counting rate – on the product:

$$\varepsilon \times \Delta E \times M \times T \times (\alpha \cdot \beta^2)$$

Increased in DAMA/LIBRA-phase2

Increased with DAMA/LIBRA-phase2

Increased in DAMA/LIBRA-phase2

DM annual modulation signature also equivalent to have enlarged the exposed mass

DM annual modulation signature acts itself as a strong bckg reduction strategy as already pointed out in the original paper by Freese et al.

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 about the discrimination power of DAMA/LIBRA-phase2, 2-annual cycles under some given set of astrophysical, nuclear and particle physics assumptions.

Not best fit cases, same C.L., see table above for cross sections and other assumptions in their expectations (i.e. labels).

- discrimination among with channeling
- discrimination among WIMP's masses
- discrimination among DM models

here g.f. vs E assumed constant

(a) Assuming MT= 464000 kg day

\[ \sigma(S_m) = \sqrt{\frac{\langle R \rangle}{M \cdot T \cdot \Delta E \cdot \epsilon \cdot (\alpha - \beta^2)}} \]
The importance of studying second order effects and the annual modulation phase

Higher exposure and lower threshold can allow further investigation on:

- **the nature of the DMp**
  - to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, form factors, spin-factors ...)
  - scaling laws and cross sections
  - multi-component DMp halo?

- **possible diurnal effects in sidereal time**
  - expected in case of high cross section DM candidates (shadow of the Earth)
  - due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates)
  - due to the channeling in case of DM candidates inducing nuclear recoils.

- **astrophysical models**
  - velocity and position distribution of DMp in the galactic halo, possibly due to:
    - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal “streams”;
    - caustics in the halo;
    - gravitational focusing effect of the Sun enhancing the DM flow (“spike” and “skirt”);
    - possible structures as clumpiness with small scale size
    - Effects of gravitational focusing of the Sun

**DAMA/LIBRA-phase2: Features of the DM signal**

A step towards such investigations:

⇒**DAMA/LIBRA-phase2**

The effect of the streams on the phase depends on the galactic halo model

The annual modulation phase depends on:

- Presence of streams (as SagDEG and Canis Major) in the Galaxy
- Presence of caustics
- Effects of gravitational focusing of the Sun

PRL112(2014)011301
• Positive evidence for the presence of DM particles in the galactic halo now supported at 9.3σ C.L. (cumulative exposure 1.33 ton × yr − 14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1)

• The modulation parameters determined with increased precision

• Full sensitivity to many kinds of DM candidates and interactions types (both inducing recoils and/or e.m. radiation), full sensitivity to low and high mass candidates.

• No experiment exists whose result can be directly compared in a model independent way with those by DAMA/NaI and DAMA/LIBRA (in general: no direct model independent comparison is possible in the field among activities using e.g. different target-materials and/or approaches)

DAMA/LIBRA-phase 2

✓ In data taking in the new configuration with lower software energy threshold

... and more
DAMA/LIBRA still the highest radiopure set-up in the field with the largest full sensitive mass, full control of running conditions, the largest duty-cycle, exposure orders of magnitude larger than any other activity in the field, etc.

... and many further perspectives