Annual Modulation Results from DAMA/LIBRA
DAMA set-ups

an observatory for rare processes @ LNGS

- DAMA/LIBRA (DAMA/Nal)
- DAMA/LXe
- DAMA/R&D
- DAMA/Crys
- DAMA/Ge

Collaboration:
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur and Ropar, India

Web Site: http://people.roma2.infn.it/dama
Some direct detection processes:

- **Scatterings on nuclei**
  - detection of nuclear recoil energy

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

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

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

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

- **Inelastic Dark Matter: \( W + N \rightarrow W^* + N \)**
  - \( W \) has 2 mass states \( \chi^+ , \chi^- \) with \( \delta \) mass splitting
  - Kinematical constraint for the inelastic scattering of \( \chi^- \) on a nucleus

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

- **Ionization:** Ge, Si
- **Bolomter:** TeO₂, Ge, CaWO₄, ...
- **Scintillation:** NaI(Tl), LXe, CaF₂(Eu), …

- **DMp**

- ... even WIMPs...

- **e.g. signals from these candidates are completely lost in experiments based on “rejection procedures” of the e.m. component of their rate**...
The annual modulation: a model independent signature for the investigation of DM particles

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:

1) Cosine-like modulation of the rate
2) In low energy range
3) Period of 1 year
4) Phase at about June 2\textsuperscript{nd}
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

\begin{align*}
\mathbf{v}_\odot(t) &= \mathbf{v}_{\text{sun}} + \mathbf{v}_{\text{orb}} \cos \gamma \cos[\omega(t-t_0)] \\
S_k[\eta(t)] &= \int \frac{dR}{\Delta E_k} dE_R \approx S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]
\end{align*}

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 be able to account for the whole observed modulation amplitude, and also to satisfy simultaneously all the requirements

Drukier, Freese, Spergel PRD86; Freese et al. PRD88
Highly radiopure NaI(Tl) experiment in DAMA

**DAMA/Nal**
- Concluded on July 2002; 7 annual cycles collected;
- Exposure: 0.29 ton × yr

**DAMA/LIBRA**
- New NaI(Tl) detectors with better radiopurity features
- Residual contaminations: $^{232}\text{Th}$, $^{238}\text{U}$ and $^{40}\text{K}$ at level of $10^{-12}$ g/g

- DAMA/LIBRA-phase 1: 7 annual cycles, 1.04 ton × yr
- Model independent evidence of a particle DM component in the galactic halo at 9.3σ C.L.
- DAMA/LIBRA-phase 2: lowering software energy threshold below 2 keV; 8 annual cycles released so far (1.53 ton × yr)

Model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.
+ many results on other rare processes
The pioneer DAMA/NaI:
≈100 kg highly radiopure NaI(Tl)

Performances:


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
• Exotic Matter search
• Search for superdense nuclear matter
• Search for heavy clusters decays

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 6.3σ 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

As a result of a 2$^{nd}$ generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving - including photos - in HP Nitrogen atmosphere)

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles,
- Results on rare processes:
  - CNC: EPJC72(2012)1920;
  - IPP in $^{241}$Am: EPJA49(2013)64

DAMA/LIBRA–phase1 (7 annual cycles, 1.04 ton$\times$yr) confirmed the model-independent evidence of DM: reaching 9.3$\sigma$ C.L.
Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

Q.E. of the new PMTs:
- 33 – 39% @ 420 nm
- 36 – 44% @ peak
Lowering software energy threshold below 2 keV:

- to study the nature of the particles and features of astrophysical, nuclear and particle physics aspects, and to investigate 2\textsuperscript{nd} order effects
- special data taking for other rare processes

The light responses:

<table>
<thead>
<tr>
<th>Detector number</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_m$ (cpd/kg/keV)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Energy (keV)</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

The contaminations:

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>$^{226}$Ra (Bq/kg)</th>
<th>$^{235}$U (mBq/kg)</th>
<th>$^{228}$Ra (Bq/kg)</th>
<th>$^{228}$Th (mBq/kg)</th>
<th>$^{40}$K (Bq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Contamination</td>
<td>0.43</td>
<td>47</td>
<td>0.12</td>
<td>83</td>
<td>0.54</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.06</td>
<td>10</td>
<td>0.02</td>
<td>17</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The light responses:

- DAMA/LIBRA-phase1: 5.5 – 7.5 ph.e./keV
- DAMA/LIBRA-phase2: 6-10 ph.e./keV

Mean value

Phase1: 7.5\%(0.6\% RMS)
Phase2: 6.7\%(0.5\% RMS)
DAMA/LIBRA-phase2 data taking

Upgrade at end of 2010: all PMTs replaced with new ones of higher Q.E.

Energy resolution @ 60 keV mean value:

| prev. PMTs | 7.5%  (0.6% RMS) |
| new HQE PMTs | 6.7%  (0.5% RMS) |

<table>
<thead>
<tr>
<th>Annual Cycles</th>
<th>Period</th>
<th>Mass (kg)</th>
<th>Exposure (kg x d)</th>
<th>(\left(\alpha-\beta^2\right))</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Dec 23, 2010 – Sept. 9, 2011</td>
<td>commissioning</td>
<td></td>
<td>0.519</td>
</tr>
<tr>
<td>II</td>
<td>Nov. 2, 2011 – Sept. 11, 2012</td>
<td>242.5</td>
<td>62917</td>
<td>0.534</td>
</tr>
<tr>
<td>III</td>
<td>Oct. 8, 2012 – Sept. 2, 2013</td>
<td>242.5</td>
<td>60586</td>
<td>0.479</td>
</tr>
<tr>
<td>IV</td>
<td>Sept. 8, 2013 – Sept. 1, 2014</td>
<td>242.5</td>
<td>73792</td>
<td>0.486</td>
</tr>
<tr>
<td>V</td>
<td>Sept. 1, 2014 – Sept. 9, 2015</td>
<td>242.5</td>
<td>71180</td>
<td>0.522</td>
</tr>
<tr>
<td>VI</td>
<td>Sept. 10, 2015 – Aug. 24, 2016</td>
<td>242.5</td>
<td>67527</td>
<td>0.480</td>
</tr>
<tr>
<td>VII</td>
<td>Sept. 7, 2016 – Sept. 25, 2017</td>
<td>242.5</td>
<td>75135</td>
<td>0.557</td>
</tr>
<tr>
<td>VIII</td>
<td>Sept. 25, 2017 – Aug. 20, 2018</td>
<td>242.5</td>
<td>68759</td>
<td>0.446</td>
</tr>
<tr>
<td>IX</td>
<td>Aug. 24, 2018 – Oct. 3, 2019</td>
<td>242.5</td>
<td>77213</td>
<td>0.557</td>
</tr>
</tbody>
</table>

Fall 2012: new preamplifiers installed + special trigger modules.

Calibrations 8 a.c.: \(\approx 1.6 \times 10^8\) events from sources

Acceptance window eff. 8 a.c.: \(\approx 4.2 \times 10^6\) events (\(\approx 1.7 \times 10^5\) events/keV)

New data release July 2021

Exposure with this data release of DAMA/LIBRA-phase2:

Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2:

1.53 ton \(\times\) yr

2.86 ton \(\times\) yr
Model Independent Annual Modulation Result

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

Absence of modulation? No

χ²/dof = 130/69 (1-2 keV); 176/69 (1-3 keV); 202/69 (1-6 keV); 157/69 (2-6 keV)

Fit on DAMA/LIBRA-phase2

Acos[ω(t-t₀)] ; t₀ = 152.5 d, T = 1.00 y

1-2 keV

A=(0.0224±0.0030) cpd/kg/keV

χ²/dof = 75.8/68 7.4 σ C.L.

1-3 keV

A=(0.0191±0.0020) cpd/kg/keV

χ²/dof = 81.6/68 9.7 σ C.L.

1-6 keV

A=(0.01048±0.00090) cpd/kg/keV

χ²/dof = 66.2/68 11.6 σ C.L.

2-6 keV

A=(0.00933±0.00094) cpd/kg/keV

χ²/dof = 58.2/68 9.9 σ C.L.

The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6σ C.L.
Rate behaviour above 6 keV

- No Modulation above 6 keV
- No modulation in the whole energy spectrum: studying integral rate at higher energy, $R_{90}$
- $R_{90}$ percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods
- Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles: consistent with zero

<table>
<thead>
<tr>
<th>Period</th>
<th>Mod. Ampl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-ph2_2</td>
<td>$(0.12\pm0.14)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_3</td>
<td>$-(0.08\pm0.14)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_4</td>
<td>$(0.07\pm0.15)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_5</td>
<td>$-(0.05\pm0.14)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_6</td>
<td>$(0.03\pm0.13)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_7</td>
<td>$-(0.09\pm0.14)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_8</td>
<td>$(0.18\pm0.13)$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_9</td>
<td>$(0.08\pm0.14)$ cpd/kg</td>
</tr>
</tbody>
</table>

$\sigma \approx 1\%$, fully accounted by statistical considerations

No modulation above 6 keV
This accounts for all sources of bckg and is consistent with the studies on the various components
DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (8 a.c., 1.53 ton × yr)

Multiple hits events = Dark Matter particle “switched off”

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

To perform the Fourier analysis of the data in a wide region of frequency, the single-hit scintillation events have been grouped in 1 day bins.

The whole power spectra up to the Nyquist frequency

DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (22 yr)
total exposure: 2.86 ton×yr

Zoom around the 1 y\(^{-1}\) peak

Principal mode:
2.74\times10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}

Green area: 90\% C.L. region calculated taking into account the signal in (2-6) keV

Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region
A clear modulation is present in the (1-6) keV energy interval, while $S_m$ values compatible with zero are present just above

- The $S_m$ values in the (6–14) keV energy interval have random fluctuations around zero with $\chi^2$ equal to 20.3 for 16 degrees of freedom (upper tail probability 21%).
- In (6–20) keV $\chi^2$/dof = 42.2/28 (upper tail probability 4%). The obtained $\chi^2$ value is rather large due mainly to two data points, whose centroids are at 16.75 and 18.25 keV, far away from the (1–6) keV energy interval. The P-values obtained by excluding only the first and either the points are 14% and 23%.
The signal is well distributed over all the annual cycles in each energy bin.
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:
- $|Z_m| \ll |S_m| \approx |Y_m|$
- $t^* \approx t_0 = 152.5d$
- $\omega = 2\pi/T$
- $T = 1 \text{ year}$

Slight differences from 2$^{\text{nd}}$ 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>DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-6</td>
<td>$0.0097 \pm 0.0007$</td>
<td>$-0.0003 \pm 0.0007$</td>
<td>$0.0097 \pm 0.0007$</td>
<td>$150.5 \pm 4.0$</td>
</tr>
<tr>
<td>6-14</td>
<td>$0.0003 \pm 0.0005$</td>
<td>$-0.0006 \pm 0.0005$</td>
<td>$0.0007 \pm 0.0010$</td>
<td>undefined</td>
</tr>
<tr>
<td>1-6</td>
<td>$0.0104 \pm 0.0007$</td>
<td>$0.0002 \pm 0.0007$</td>
<td>$0.0104 \pm 0.0007$</td>
<td>$153.5 \pm 4.0$</td>
</tr>
</tbody>
</table>
A new data point with the 8 a.c. of DAMA/LIBRA-phase2 (1.53 ton·yr)

- Efforts towards lower software energy threshold
  - decreasing the software energy threshold down to 0.75 keV
  - using the same technique to remove the noise pulses
  - evaluating the efficiency by dedicated studies

- A clear modulation is also present below 1 keV, from 0.75 keV, while $S_m$ values compatible with zero are present just above 6 keV

- This preliminary result suggests the necessity to lower the software energy threshold and to improve the experimental error on the first energy bin
**Stability parameters of DAMA/LIBRA–phase2**

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

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

<table>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature (°C)</strong></td>
<td>(0.0012 ± 0.0051)</td>
<td>-(0.0002 ± 0.0049)</td>
<td>-(0.0003 ± 0.0031)</td>
<td>(0.0009 ± 0.0050)</td>
<td>(0.0018 ± 0.0036)</td>
<td>-(0.0006 ± 0.0035)</td>
<td>-(0.0029 ± 0.0039)</td>
<td>(0.0014 ± 0.0033)</td>
</tr>
<tr>
<td><strong>Flux N₂ (l/h)</strong></td>
<td>-(0.15 ± 0.18)</td>
<td>-(0.02 ± 0.22)</td>
<td>-(0.02 ± 0.12)</td>
<td>-(0.02 ± 0.14)</td>
<td>-(0.01 ± 0.10)</td>
<td>-(0.01 ± 0.16)</td>
<td>(0.05 ± 0.25)</td>
<td>(0.014 ± 0.092)</td>
</tr>
<tr>
<td><strong>Pressure (mbar)</strong></td>
<td>(1.1 ± 0.9) × 10⁻³</td>
<td>(0.2 ± 1.1) × 10⁻³</td>
<td>(2.4 ± 5.4) × 10⁻³</td>
<td>(0.6 ± 6.2) × 10⁻³</td>
<td>(1.5 ± 6.3) × 10⁻³</td>
<td>(7.2 ± 8.6) × 10⁻³</td>
<td>(3 ± 12) × 10⁻³</td>
<td>(3.5 ± 4.9) × 10⁻³</td>
</tr>
<tr>
<td><strong>Radon (Bq/m³)</strong></td>
<td>(0.015 ± 0.034)</td>
<td>-(0.002 ± 0.050)</td>
<td>-(0.009 ± 0.028)</td>
<td>-(0.044 ± 0.050)</td>
<td>(0.082 ± 0.086)</td>
<td>(0.06 ± 0.11)</td>
<td>-(0.046 ± 0.076)</td>
<td>(0.002 ± 0.035)</td>
</tr>
<tr>
<td><strong>Hardware rate above single ph.e. (Hz)</strong></td>
<td>-(0.12 ± 0.16) × 10⁻²</td>
<td>(0.00 ± 0.12) × 10⁻²</td>
<td>-(0.14 ± 0.22) × 10⁻²</td>
<td>-(0.05 ± 0.22) × 10⁻²</td>
<td>-(0.06 ± 0.16) × 10⁻²</td>
<td>-(0.08 ± 0.17) × 10⁻²</td>
<td>(0.04 ± 0.20) × 10⁻²</td>
<td>-(0.19 ± 0.18) × 10⁻²</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

<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>$&lt;2.5 \times 10^{-6}$ 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 $\rightarrow$ 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>$&lt;1-2 \times 10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>$&lt;10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>No modulation above 6 keV; no modulation in the (2-6) keV multiple-hits events; this limit includes all possible sources of background</td>
<td>$&lt;10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured at LNGS</td>
<td>$&lt;3 \times 10^{-5}$ cpd/kg/keV</td>
</tr>
</tbody>
</table>

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect
About ANAIS result

• ANAIS has ≈ 5 times larger counting rate in [1,2] keV than DAMA/LIBRA-phase2
• High counting rate in ROI explained as populations, other than bckg, “which could be leaking at the lowest energies in the ROI” being the trigger rate “dominated by other events, some of them with origin in the PMTs, others still unexplained”

• Even a 0.3% instability of the ANAIS counting rate in the [1-6] keV region is enough to hide the annual modulation signal detected by DAMA: A ≈ 0.01 cpd/kg/keV (green line in the plot)

• In ANAIS the detection efficiencies of the applied cuts are not periodically evaluated with dedicated calibrations at very low energy as in DAMA/LIBRA

• The only check on stability of the cut-efficiencies is a fit on the counting rate of low energy events induced by the $^{22}$Na or $^{40}$K contaminations, selected in double coincidences, and with cuts applied

• But statistics is low: ≈ 100 events in bin of 10 days, i.e. a 10% error/bin

• A fit of these data including a modulated components shows that they cannot exclude an effect at the level of 2-3%, much higher than the needed stability

• while the searched effect requires a stability of the efficiency at the level of 0.4% in [1,2] keV

• Similar result can be obtained for the [2-5] keV region (studying $^{40}$K double) the sensitivity is ≈ 1% (needed: <0.4%)

Moreover:

• Different quenching factors are expected and measured for different NaI(Tl) crystals (they depends, e.g., on the used growing technique, on the different thallium doping concentration, …)

• A clear evidence is offered by the different $\alpha/\beta$ light ratio measured with DAMA and COSINE crystals

• As mentioned also in the ANAIS paper, this effect introduce a systematic uncertainty in the comparison with DAMA/LIBRA
About Interpretation: is an “universal” and “correct” way to approach the problem of DM and comparisons?

No, it isn’t. This is just a largely arbitrary/partial/incorrect exercise

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

...and experimental aspects...
- Exposures
- Energy threshold
- Calibrations
- Stability of all the operating conditions.
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Detector response (phe/keV)
- Energy scale and energy resolution
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Quenching factors, channeling, ...
- ...

Uncertainty in experimental parameters, and necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters’ values are intrinsically strongly uncertain.

No direct model-independent comparison among expts with different target-detectors and different approaches

well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

• Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

• $E_{\text{th}} = 1$ keV; old data release
Examples of model-dependent analyses

A large (but not exhaustive) class of halo models and uncertainties are considered

\[ \sigma_{SI}(A,Z) \propto m_{red}^2(A,DM) \left[ f_p Z + f_n (A-Z) \right]^2 \]

Case of isospin violating SI coupling: \( f_p \neq f_n \)

- Two bands at low mass and at higher mass;
- Good fit for low mass DM candidates at \( f_n/f_p \approx -53/74 = -0.72 \) (signal mostly due to \(^{23}\)Na recoils);
- The inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support for \( f_n/f_p=1 \) low mass DM candidates either including or not the channeling effect.
- The case of isospin-conserving \( f_n/f_p=1 \) is well supported at different extent both at lower and larger mass.

1. Constants q.f.
2. Varying q.f. \( E_R \)
3. With channeling effect

Even a relatively small SD (SI) contribution can drastically change the allowed region in the \((m_{DM}, \xi\sigma_{SI(SD)})\) plane
Running phase2 with lower software energy threshold below 1 keV with high efficiency

Enhancing experimental sensitivities and improving DM corollary aspects, other DM features, second order effects and other rare processes

• After a dedicated R&D on new high Q.E. PMTs with increased radio-purity
• After the study of possible new protocols for possible modifications of the detectors

Alternative strategy has been chosen, upgrading the hardware:

• new miniaturized low background pre-amps directly installed on the low-background supports of the voltage dividers of the low background high Q.E. PMTs of phase2
• higher vertical resolution 14bit digitizers

The features of the voltage divider+preamp system:

• S/N improvement ≈3.0-9.0;
• discrimination of the single ph.el. from electronic noise: 3 - 8;
• the Peak/Valley ratio: 4.7 - 11.6;
• residual radioactivity lower than that of single PMT
Conclusions

- Model-independent evidence for a signal that satisfies all the requirements of the DM annual modulation signature at 13.7σ C.L. (22 independent annual cycles with 3 different set-ups: 2.86 ton × yr)
- Modulation parameters determined with increasing precision
- New investigations on different peculiarities of the DM signal in progress
- 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
- Model-dependent analyses improve the C.L. and restrict the allowed parameters’ space for the various scenarios
- DAMA/LIBRA–phase2 continuing data taking
- Preliminary efforts towards 0.75 keV software energy threshold done
- DAMA/LIBRA–phase2 towards lower software energy threshold of 0.5 keV. New divider/amp systems and new 14bit digitizers
- Continuing investigations of rare processes other than DM
- Other pursued ideas: ZnWO₄ anisotropic scintillator for DM directionality. Response to nuclear recoils measured.