Annual Modulation with DAMA/LIBRA–phase2

P. Belli
INFN – Roma Tor Vergata

CNNP2020
Arabella Hotel in the Kogelberg Biosphere near Cape Town, South Africa
February 24-28, 2020
DAMA set-ups
an observatory for rare processes @ LNGS

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

DAMA/Nal
DAMA/LIBRA-phase1
DAMA/LIBRA-phase2
towards DAMA/LIBRA-phase3

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

web site: http://people.roma2.infn.it/dama
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

Multi-component non-baryonic DM?

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

Accelerators:
- can demonstrate the existence of some possible DM candidates
- cannot credit that a certain particle is the Dark Matter solution or the “single” Dark Matter particle solution...

The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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
  $$\frac{1}{2} m^2 \geq \delta \Leftrightarrow \nu \geq \nu_{min} = \sqrt{\frac{2\delta}{\mu}}$$

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

Conversion of particle into e.m. radiation
- detection of $\gamma$, X-rays, $e^-$

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

... also other ideas ...

Interaction of light DMp (LDM) on $e^-$ or nucleus with production of a lighter particle
- detection of electron/nucleus recoil energy
  e.g. sterile $\nu$

Scattering:
- NeUTRino, LNO, CaF$_2$(Eu), ...

Self-interacting dark matter
Mirror dark matter
Kaluza-Klein particles (LKK)
Heavy exotic candidates, as “4th family atoms”, ...
Elementary Black holes, Planckian objects, Daemons

DM candidates and scenarios exist on which accelerators cannot give any information

Scattering on nuclei
- detection of nuclear recoil energy

Excitation of bound electrons in scatterings on nuclei
- detection of recoil nuclei + e.m. radiation
The annual modulation: a model independent signature for the investigation of 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:

1) Modulated rate according cosine
2) In 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

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

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

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.

- \( v_{\text{sun}} \approx 232 \text{ km/s} \) (Sun vel in the halo)
- \( v_{\text{orb}} = 30 \text{ km/s} \) (Earth vel around the Sun)
- \( \gamma = \pi/3, \omega = 2\pi/T, T = 1 \text{ year} \)
- \( t_0 = 2^{nd} \text{ June (when } v_\oplus \text{ is maximum)} \)
The pioneer DAMA/Nal: 
\( \approx 100 \) 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  
  PLB515(2001)6
- Exotic Matter search  
  EPJd14(2002)1
- Search for superdense nuclear matter  
  EPJA23(2005)7
- Search for heavy clusters decays  
  EPJA24(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 ton\( \times \)yr
The pioneer DAMA/Nal: ~100 kg highly radiopure NaI(Tl)

The DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RARe processes)

As a result of a 2nd 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 $^{241}\text{Am}$: EPJA49(2013)64

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

DAMA/LIBRA-phase1 (7 annual cycles, 1.04 ton×yr) confirmed the model-independent evidence of DM: reaching 9.3σ C.L.
DAMA/LIBRA–phase2

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

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

The contaminations:

<table>
<thead>
<tr>
<th></th>
<th>$^{226}\text{Ra}$ (Bq/kg)</th>
<th>$^{235}\text{U}$ (mBq/kg)</th>
<th>$^{228}\text{Ra}$ (Bq/kg)</th>
<th>$^{228}\text{Th}$ (mBq/kg)</th>
<th>$^{40}\text{K}$ (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
DAMA/LIBRA-phase2 data taking

Second 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 × d)</th>
<th>(α-β²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Dec 23, 2010 – Sept. 9, 2011</td>
<td>commissioning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Nov. 2, 2011 – Sept. 11, 2012</td>
<td>242.5</td>
<td>62917</td>
<td>0.519</td>
</tr>
<tr>
<td>III</td>
<td>Oct. 8, 2012 – Sept. 2, 2013</td>
<td>242.5</td>
<td>60586</td>
<td>0.534</td>
</tr>
<tr>
<td>IV</td>
<td>Sept. 8, 2013 – Sept. 1, 2014</td>
<td>242.5</td>
<td>73792</td>
<td>0.479</td>
</tr>
<tr>
<td>V</td>
<td>Sept. 1, 2014 – Sept. 9, 2015</td>
<td>242.5</td>
<td>71180</td>
<td>0.486</td>
</tr>
<tr>
<td>VI</td>
<td>Sept. 10, 2015 – Aug. 24, 2016</td>
<td>242.5</td>
<td>67527</td>
<td>0.522</td>
</tr>
<tr>
<td>VII</td>
<td>Sept. 7, 2016 – Sept. 25, 2017</td>
<td>242.5</td>
<td>75135</td>
<td>0.480</td>
</tr>
</tbody>
</table>

Fall 2012: new preamplifiers installed + special trigger modules.

Calibrations 6 a.c.: ≈ 1.3 × 10^8 events from sources

Acceptance window eff. 6 a.c.: ≈ 3.4 × 10^6 events (≈ 1.4 × 10^5 events/keV)

Exposure first data release of DAMA/LIBRA-phase2: 1.13 ton × yr
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: 2.46 ton × yr
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 9.5σ C.L.
DM model-independent Annual Modulation Result

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

DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.46 ton × yr)

\[ \chi^2/\text{dof} = 113.8/138 \quad \text{12.8 } \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof} = 272.3/142 \Rightarrow P(A=0) = 3.0 \times 10^{-10} \]

Continuous lines: \( t_0 = 152.5 \text{ d}, \ T = 1.00 \text{ y} \)
A=(0.0102±0.0008) cpd/kg/keV

Releasing period \( (T) \) and phase \( (t_0) \) in the fit

The data of DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 12.9 \( \sigma \) C.L.
Rate behaviour above 6 keV

- No Modulation above 6 keV

  Mod. Ampl. (6-14 keV): cpd/kg/keV
  
<table>
<thead>
<tr>
<th>Component</th>
<th>Mod. Ampl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-ph2_2</td>
<td>(0.0032 ± 0.0017)</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_3</td>
<td>(0.0016 ± 0.0017)</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_4</td>
<td>(0.0024 ± 0.0015)</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_5</td>
<td>(-0.0004 ± 0.0015)</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_6</td>
<td>(0.0001 ± 0.0015)</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_7</td>
<td>(0.0015 ± 0.0014)</td>
</tr>
</tbody>
</table>

  → statistically consistent with zero

- 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
    $+_{0.0004}$ 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

  $\sigma \approx 1\%$, 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 (1.13 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.
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.

**DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (20 yr)**

**total exposure: 2.46 ton×yr**

**Zoom around the 1 y⁻¹ peak**

**Principal mode:**

\[2.74 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}\]

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 19.0 for 16 degrees of freedom (upper tail probability 27%).

- In (6–20) keV $\chi^2$/dof = 42.6/28 (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 11% and 25%.
$S_m$ for each detector

DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: 2.17 ton\(\times\)yr

$S_m$ integrated in the range (2 - 6) keV for each of the 25 detectors
(1\(\sigma\) error)

Shaded band = weighted averaged $S_m \pm 1\sigma$

$\chi^2$/d.o.f = 23.9/24 d.o.f.

The signal is well distributed over all the 25 detectors.
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:

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

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

### DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2

$[2.46 \text{ ton} \times \text{ yr}]$

<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>0.0100 $\pm$ 0.0008</td>
<td>-0.0003 $\pm$ 0.0008</td>
<td>0.0100 $\pm$ 0.0008</td>
<td>150.5 $\pm$ 5.0</td>
</tr>
<tr>
<td>6-14</td>
<td>0.0003 $\pm$ 0.0005</td>
<td>-0.0009 $\pm$ 0.0006</td>
<td>0.0010 $\pm$ 0.0013</td>
<td>undefined</td>
</tr>
</tbody>
</table>

### DAMA/LIBRA-phase2

<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>1-6</td>
<td>0.0105 $\pm$ 0.0011</td>
<td>0.0009 $\pm$ 0.0010</td>
<td>0.0105 $\pm$ 0.0011</td>
<td>157.5 $\pm$ 5.0</td>
</tr>
</tbody>
</table>
Any effect from long-term decay in DAMA/LIBRA?

- Adopted cautious procedure: each annual cycle starts from Sept./Autumn (when $\cos \omega (t-t_0) \approx 0$) towards Summer $\rightarrow$ during the annual cycle the **minimum** (December) of the DM signal **occurs before** of the **maximum** (June).

- Any possible decay of **long–term–living isotopes** cannot simulate the observed positive signal.

- Assuming a constant background within each annual cycle, it may only lead to an **underestimate** of the observed $S_m$.

- arXiv:2002.00459 claims that the DAMA annual modulation signal may be biased by a slow variation only in the (2-6) keV **single-hit** rate, possibly due to some background, even that the total rate at low energy in DAMA/LIBRA can have a odd behaviour, increasing with time.

- By the fact, this odd time behaviour of the counting rate was already **excluded**: the contaminants of the DAMA set-ups are reported in several papers; none of them increases with time. The stability with time of the running parameters is well verified. The assumptions in arXiv:2002.00459 are **untenable** and the conclusions are **valueless**.

1) The case of (2–6) keV **single-hit residual rates**.

- We recalculate the (2–6) keV **single-hit residual rates** by considering a possible time behaviour given by the signal searched for and by **different straight lines**, one for each annual cycle, simulating the time–varying background (hereafter, **hypothesis B**).

- The residuals, once subtracting the so-obtained background, are reported in figure.

<table>
<thead>
<tr>
<th>Period and phase fixed in the fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference case: $A = (0.0095 \pm 0.0008)$ cpd/kg/keV ($\chi^2$/dof = 71.8/101)</td>
</tr>
<tr>
<td>Hypothesis B: $A = (0.0093 \pm 0.0008)$ cpd/kg/keV ($\chi^2$/dof = 60.4/75)</td>
</tr>
<tr>
<td>$\Delta \chi^2$/dof = 11.4/26 $\rightarrow$ the hypothesis B is not favoured at 90% C.L. wrt the reference case: $P(\Delta \chi^2 &lt; 11.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Period and phase released in the fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference case: $A = (0.0096 \pm 0.0008)$ cpd/kg/keV $T = (0.9987 \pm 0.0008)$ yr $t_0 = (145 \pm 5)$ days</td>
</tr>
<tr>
<td>Hypothesis B: $A = (0.0094 \pm 0.0008)$ cpd/kg/keV $T = (0.9985 \pm 0.0009)$ yr $t_0 = (143 \pm 5)$ days</td>
</tr>
</tbody>
</table>

The effect of long–term time–varying background – if any – is negligible.
2) The tail of the $S_m$ distribution case.

- A possible long–term time–varying background can also induce a (either positive or negative) **fake modulation amplitudes** ($\Sigma$) on the tail of the $S_m$ distribution above the energy region where the signal has been observed.

- For example, taking as reference the (6–14) keV energy interval:

  $$\langle S_m \rangle_{(6-14)} = (0.00028 \pm 0.00075) \text{ cpd/kg/keV, for DAMA/LIBRA–phase1}$$
  $$\langle S_m \rangle_{(6-14)} = (0.0006 \pm 0.0006) \text{ cpd/kg/keV for DAMA/LIBRA–phase2}$$

- They are both **compatible with zero** → one can obtain an upper limit on the absolute value of $\Sigma$:

  $$|\Sigma| < 1.5 \times 10^{-3} \text{ cpd/kg/keV (90% C.L.) for DAMA/LIBRA–phase1}$$
  $$|\Sigma| < 1.6 \times 10^{-3} \text{ cpd/kg/keV (90% C.L.) for DAMA/LIBRA–phase2}$$

- The observed $S_m \sim 10^{-2} \text{ cpd/kg/keV}$ → the possible effect of long–term time–varying background – if any – is negligible.

3) The maximum likelihood analysis.

- The maximum likelihood analysis has been repeated by replacing the $b_{jk}$ constant in each annual cycle with a **linear behaviour decreasing with time** (hypothesis B).

<table>
<thead>
<tr>
<th></th>
<th>$S_m$ (cpd/kg/keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference case</td>
<td>Hypothesis B</td>
</tr>
<tr>
<td>DAMA/LIBRA–phase1</td>
<td></td>
</tr>
<tr>
<td>2–6 keV</td>
<td>0.0093±0.0013</td>
</tr>
<tr>
<td>DAMA/LIBRA–phase2</td>
<td></td>
</tr>
<tr>
<td>1–6 keV</td>
<td>0.0105±0.0011</td>
</tr>
<tr>
<td>2–6 keV</td>
<td>0.0095±0.0011</td>
</tr>
</tbody>
</table>

Possibly the systematic error on the determination of the previously-reported $S_m$ is marginal.
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.

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

<table>
<thead>
<tr>
<th>Source</th>
<th>(\Phi_{0,k}^{(n)}) (\text{neutrons cm}^{-2} \text{s}^{-1})</th>
<th>(\eta_k)</th>
<th>(t_k)</th>
<th>(R_{0,k}) (\text{cpd/kg/keV})</th>
<th>(A_k) (\text{cpd/kg/keV})</th>
<th>(A_k/S_{\text{m}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLOW neutrons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>thermal n ((10^{-2} - 10^{-1} \text{ eV}))</td>
<td>1.08 \times 10^{-8} [15]</td>
<td>(\approx 0) (\text{however} \ll 0.1 [2, 7, 8])</td>
<td>-</td>
<td>&lt; 8 \times 10^{-6} [2, 7, 8]</td>
<td>(\ll 8 \times 10^{-7})</td>
<td>(\ll 7 \times 10^{-5})</td>
</tr>
<tr>
<td>epithermal n ((\text{eV-keV}))</td>
<td>2 \times 10^{-6} [15]</td>
<td>(\approx 0) (\text{however} \ll 0.1 [2, 7, 8])</td>
<td>-</td>
<td>&lt; 3 \times 10^{-3} [2, 7, 8]</td>
<td>(\ll 3 \times 10^{-4})</td>
<td>(\ll 0.03)</td>
</tr>
<tr>
<td>FAST neutrons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fission, (\alpha, n) (\rightarrow n) ((1\text{-}10 \text{ MeV}))</td>
<td>(\approx 0.9 \times 10^{-7}) [17]</td>
<td>(\approx 0) (\text{however} \ll 0.1 [2, 7, 8])</td>
<td>-</td>
<td>&lt; 6 \times 10^{-4} [2, 7, 8]</td>
<td>(\ll 6 \times 10^{-5})</td>
<td>(\ll 5 \times 10^{-3})</td>
</tr>
<tr>
<td>(\mu \rightarrow n) from rock ((&gt; 10 \text{ MeV}))</td>
<td>(\approx 3 \times 10^{-9}) (\text{see text and ref. [12]})</td>
<td>0.0129 [23]</td>
<td>end of June [23, 7, 8]</td>
<td>(\ll 7 \times 10^{-4}) (\text{see text and ref. [12]})</td>
<td>(\ll 9 \times 10^{-6})</td>
<td>(\ll 8 \times 10^{-4})</td>
</tr>
<tr>
<td>(\mu \rightarrow n) from Pb shield ((&gt; 10 \text{ MeV}))</td>
<td>(\approx 6 \times 10^{-9}) (\text{see footnote 3})</td>
<td>0.0129 [23]</td>
<td>end of June [23, 7, 8]</td>
<td>(\ll 1.4 \times 10^{-3}) (\text{see text and footnote 3})</td>
<td>(\ll 2 \times 10^{-5})</td>
<td>(\ll 1.6 \times 10^{-3})</td>
</tr>
<tr>
<td>(\nu \rightarrow n) ((\text{few MeV}))</td>
<td>(\approx 3 \times 10^{-10}) (\text{see text})</td>
<td>0.03342 *</td>
<td>Jan. 4th *</td>
<td>(\ll 7 \times 10^{-5}) (\text{see text})</td>
<td>(\ll 2 \times 10^{-6})</td>
<td>(\ll 2 \times 10^{-4})</td>
</tr>
<tr>
<td>direct (\mu)</td>
<td>(\Phi_0^{(\mu)} \approx 20 \mu \text{ m}^{-2} \text{d}^{-1}) [20]</td>
<td>0.0129 [23]</td>
<td>end of June [23, 7, 8]</td>
<td>(\approx 10^{-7}) [2, 7, 8]</td>
<td>(\approx 10^{-9})</td>
<td>(\approx 10^{-7})</td>
</tr>
<tr>
<td>direct (\nu)</td>
<td>(\Phi_0^{(\nu)} \approx 6 \times 10^{10} \nu \text{ cm}^{-2} \text{s}^{-1}) [26]</td>
<td>0.03342 *</td>
<td>Jan. 4th *</td>
<td>(\approx 10^{-5}) [31]</td>
<td>(3 \times 10^{-7})</td>
<td>(3 \times 10^{-5})</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.

All are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude.

+ 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.
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 → 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
Other annual modulation results with NaI(Tl)

DAMA-LIBRA is still much better than any other NaI experiment for exposure time, for exposed mass, for background, and for energy threshold and control of all the experimental parameters.

### Energy interval

<table>
<thead>
<tr>
<th>Energy interval</th>
<th>Experiment</th>
<th>Exposure (ton x yr)</th>
<th>Rate (cpd/kg/keV)</th>
<th>Amplitude (cpd/kg/keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2,6) keV</td>
<td>DAMA/LIBRA (ph1 + ph2)</td>
<td>2.17</td>
<td>0.8</td>
<td>0.0095 ± 0.0008</td>
</tr>
<tr>
<td></td>
<td>COSINE-100</td>
<td>0.098</td>
<td>3.0</td>
<td>0.0083 ± 0.0068</td>
</tr>
<tr>
<td></td>
<td>ANAIS-112</td>
<td>0.16</td>
<td>3.2</td>
<td>-0.0044 ± 0.0058</td>
</tr>
<tr>
<td>(1,6) keV</td>
<td>DAMA/LIBRA-phase2</td>
<td>1.13</td>
<td>0.7</td>
<td>0.0105 ± 0.0011</td>
</tr>
<tr>
<td></td>
<td>ANAIS-112</td>
<td>0.16</td>
<td>3.6</td>
<td>-0.0015 ± 0.0063</td>
</tr>
</tbody>
</table>

COSINE & ANAIS have not sufficient sensitivity to DAMA signal.
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

The case of the NaI(Tl) quenching factors (QF)

- The QFs are a property of the specific detector and not a general property, particularly in the very low energy range.
- For example in NaI(Tl), QFs depend on the adopted growing procedures, on Tl concentration and uniformity in the detector, on the specific materials added in the growth, on the mono-crystalline or poly-crystalline nature of the detector, etc.
- Their measurements are difficult and always affected by significant experimental uncertainties.
- All these aspects are always relevant sources of uncertainties when comparing whatever results in terms of DM candidates inducing nuclear recoils.

• A wide spread existing in literature for different NaI(Tl) productions
• This is also confirmed by the different $\alpha/\beta$ light ratio measured with DAMA and COSINE crystals. This implies much lower QFs at keV region for COSINE than DAMA.

CURIOSITY: Recent productions (generally by Bridgman growth) yields low QF...

The model dependent analyses and comparisons must be performed using the QF measured for each detector.

Example: 2 keVee of DAMA ≠2 keVee of COSINE-100 for nuclear recoils

Alphas from $^{238}\text{U}$ and $^{232}\text{Th}$ chains span from 2.6 to 4.5 MeVee in DAMA, while from 2.3 to 3.0 MeVee in COSINE
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
Examples of model-dependent analyses

DM particles elastically interacting with target nuclei – SI interaction

- A large (but not exhaustive) class of halo models is considered;
- Local velocity $v_0$ in the range $[170, 270]$ km/s;
- Halo density $\rho$ depending on the halo model;
- $v_{\text{esc}} = 550$ km/s (no sizable differences if $v_{\text{esc}}$ in the range $[550, 650]$ km/s);
- For DM candidates inducing nuclear recoils: three different sets of values for the nuclear form factor and quenching factor parameters.

The point-like SI cross section of DM particles scattering off $(A,Z)$ nucleus:

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

where $f_p, f_n$ are the effective DM particle couplings to protons and neutrons.

If $f_p = f_n$:

$$\sigma_{SI}(A,Z) = \frac{m_{\text{red}}^2(A,DM)}{m_{\text{red}}^2(1,DM)} A^2 \sigma_{SI}$$

- $\xi \sigma_{SI}$ vs $m_{DM}$

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

Allowed DAMA regions: Domains where the likelihood-function values differ more than $10\sigma$ from absence of signal.
Model-dependent analyses

DM particles elastically interacting with target nuclei SI-IV interaction

Case of isospin violating SI coupling:

\[ f_p \neq f_n \]

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

\[ f_n/f_p \text{ vs } m_{DM} \]

marginalizing on \( \xi \sigma_{SI} \)

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

Allowed DAMA regions for A0 (isothermal sphere), B1, C1, D3 halo models (top to bottom)
Model-dependent analyses
DM particles elastically interacting with
target nuclei SI-IV interaction
NPAE 20(4) (2019) 317

DAMA/NaI, DAMA/LIBRA-ph1 and ph2

Case of isospin violating SI coupling:
\[ f_p \neq f_n \]

\[ \frac{f_n}{f_p} \text{ vs } m_{DM} \]
marginalizing on \( \xi \sigma_{SI} \)

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

Allowed DAMA regions for
A0 (isothermal sphere), B1, C1, D3 halo
models (top to bottom)

- 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 \( ^{23}\text{Na} \) recoils).
- Contrary to what was stated in Ref. [PLB789,262(2019), JCAP07,016(2018), JCAP05,074(2018)] where the low mass DM candidates were disfavored for \( f_n/f_p = 1 \) by
DAMA data, the inclusion of the uncertainties related to
halo models, quenching factors, channeling effect,
nuclear form factors, etc., can also support 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.
Model-dependent analyses: other examples

DM particles elastically interacting with target nuclei – purely SD interaction

Only possible for target nuclei with spin ≠ 0

\[ \theta = 0 \Rightarrow a_n = 0, a_p ≠ 0 \text{ or } |a_p| >> |a_n|; \]

\[ \theta = \pi/4 \Rightarrow a_n = a_p; \]

\[ \theta = \pi/2 \Rightarrow a_p = 0, a_n ≠ 0 \text{ or } |a_n| >> |a_p|; \]

\[ \theta = 2.435\text{rad} \Rightarrow a_r/a_p = -0.85, \text{ pure } Z_0 \text{ coupling} \]

\[ \xi \sigma_{SD} \text{ vs } m_{DM} \]

Effect induced by the inclusion of a SD component on allowed regions in the plane \( \xi \sigma_{SI} \text{ vs } m_{DM} \)

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;
- The model-dependent comparison plots between exclusion limits at a given C.L. and regions of allowed parameter space do not hold e.g. for mixed scenarios when comparing experiments with and without sensitivity to the SD component of the interaction.
- The same happens when comparing regions allowed by experiments whose target-nuclei have unpaired proton with exclusion plots quoted by experiments using target-nuclei with unpaired neutron when the SD component of the interaction would correspond either to \(\theta ≈ 0\) or \(\theta ≈ \pi\)
Model-dependent analyses: other examples

Inelastic DM in the scenario of Smith and Weiner [Phys. Rev. D 64, 043502 (2001)]

\[ \text{W + N} \rightarrow \text{W* + N} \]

→ W has 2 mass states \( \chi^+ , \chi^- \) with \( \delta \) mass splitting

→ Kinematical constraint for the inelastic scattering of \( \chi^- \) on a nucleus (\( \mu: \chi^-\text{-nucleus reduced mass} \))

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

- Higher mass target-nuclei are favourites
- Enhanced \( S_m \) with respect to \( S_0 \)

Slices of the 3-dim allowed volume
\( (\xi, \sigma_p, m_{DM}, \delta) \)

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

Including Thallium: new allowed regions

DAMA/NaI, DAMA/LIBRA-ph1 and ph2
Model-dependent analyses: other examples

Inelastic DM in the scenario of Smith and Weiner [Phys. Rev. D 64, 043502 (2001)]

$W + N \rightarrow W^* + N$

$W$ has 2 mass states $\chi^+, \chi^-$ with $\delta$ mass splitting

Kinematical constraint for the inelastic scattering of $\chi^-$ on a nucleus ($\mu$: $\chi$-nucleus reduced mass)

$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Higher mass target-nuclei are favourites
- Enhanced $S_m$ with respect to $S_0$

Slices of the 3-dim allowed volume $(\xi \sigma_p, m_{DM}, \delta)$

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

- New regions with $\xi \sigma_p > 1$ pb and $\delta > 100$ keV are allowed by DAMA after the inclusion of the inelastic scattering off Thallium nuclei.
- Such regions are not fully accessible to detectors with target nuclei having mass lower than Thallium.

Including Thallium: new allowed regions
Toward DAMA/LIBRA-phase3

- updating hardware to lower the software energy threshold below 1 keV
- new miniaturized low background pre-amps directly installed on the low-background supports of the voltage dividers of the new lower background high Q.E. PMTs

The presently-reached metallic PMTs features:

- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- Radio-purity at level of 5 mBq/PMT ($^{40}$K), 3-4 mBq/PMT ($^{232}$Th), 3-4 mBq/PMT ($^{238}$U), 1 mBq/PMT ($^{226}$Ra), 2 mBq/PMT ($^{60}$Co).
- Dark counts < 100 Hz

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 much lower than that of the single PMT

• several prototypes from a dedicated R&D with HAMAMATSU at hand
• 4 DAMA/LIBRA detectors already equipped with the new PMTs
The importance of studying second order effects and the annual modulation phase

High exposure and lower energy threshold can allow further investigation on:
- the nature of the DM candidates
- possible diurnal effects on the sidereal time
- astrophysical models

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

---

Features of the DM signal
Investigated by the different stages of DAMA; improvements foreseen with DAMA/LIBRA-phase3

DAMA/NaI+LIBRA-phase2

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

PRL112(2014)011301

DAMA: (2-6) keV - $t_0 = (146 \pm 7)$ d

Example, NaI: 10 tons$\times$yr

Evans’log axisymmetric non-rotating, $v_0=220$km/s, $R_0=5$kpc, $p_0$ max +4% Sgr

NFW spherical isotropic non-rotating, $v_0=220$km/s, $p_0$ max +4% Sgr

Expected phase in the absence of streams $t_0 \sim 152.5$ d (2$^{nd}$ June)
Conclusions

- **Model-independent** evidence for a signal that satisfies all the requirements of the DM annual modulation signature at $12.9\sigma$ C.L. (20 independent annual cycles with 3 different set-ups: $2.46 \text{ ton} \times \text{yr}$)

- 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 wrt previous DAMA results

- DAMA/LIBRA–phase2 **continuing data taking**

- DAMA/LIBRA–phase3 **R&D almost concluded**; 4 detectors already equipped with the new PMT/divider/amp systems

- Continuing investigations of **rare processes** other than DM

- Other pursued ideas: **ZnWO$_4$ anisotropic scintillator** for DM **directionality**. Response to nuclear recoils measured.