First Model Independent Results from DAMA/LIBRA–phase2
DAMA set-ups

an observatory for rare processes @ LNGS

Collaboration:

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 $\beta\beta$ decays (DST-MAE and Inter-Universities 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

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

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

- Interaction only on atomic electrons
  → detection of 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

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

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

- ... also other ideas ...
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

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

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

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 be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements.
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 2nd order effects
- special data taking for other rare processes

PMTs’ 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</td>
<td>0.43</td>
<td>47</td>
<td>0.12</td>
<td>83</td>
<td>0.54</td>
</tr>
<tr>
<td>Contamination</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.

<table>
<thead>
<tr>
<th>Annual Cycles</th>
<th>Period</th>
<th>Mass (kg)</th>
<th>Exposure (kg×day)</th>
<th>$(\alpha-\beta^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Dec 23, 2010 – Sept. 9, 2011</td>
<td>242.5</td>
<td>commissioning</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>

- **Energy resolution @ 60 keV**
  - mean value:
    - prev. PMTs 7.5% (0.6% RMS)
    - new HQE PMTs 6.7% (0.5% RMS)

- **Fall 2012:** new preamplifiers installed + special trigger modules
- **Calibrations 6 a. c.:** $\approx 1.3 \times 10^8$ events from sources
- **Acceptance window eff. 6 a. c.:** $\approx 3.4 \times 10^6$ events ($\approx 1.4 \times 10^5$ events/keV)

**Exposure first data release of DAMA/LIBRA-phase2:** 1.13 ton x yr

**Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2:** 2.46 ton x yr
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 9.5σ C.L.
Absence of modulation? No

- 2-6 keV: $\chi^2/dof=199.3/102 \Rightarrow P(A=0) = 2.9 \times 10^{-8}$

The data of DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.9 $\sigma$ C.L.
### Releasing period (T) and phase (t₀) in the fit

<table>
<thead>
<tr>
<th></th>
<th>ΔE</th>
<th>A(cpd/kg/keV)</th>
<th>T=2π/ω (yr)</th>
<th>t₀ (day)</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-ph2</td>
<td>(1-3) keV</td>
<td>0.0184±0.0023</td>
<td>1.0000±0.0010</td>
<td>153±7</td>
<td>8.0σ</td>
</tr>
<tr>
<td></td>
<td>(1-6) keV</td>
<td>0.0106±0.0011</td>
<td>0.9993±0.0008</td>
<td>148±6</td>
<td>9.6σ</td>
</tr>
<tr>
<td></td>
<td>(2-6) keV</td>
<td>0.0096±0.0011</td>
<td>0.9989±0.0010</td>
<td>145±7</td>
<td>8.7σ</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph1 +</td>
<td>(2-6) keV</td>
<td>0.0096±0.0008</td>
<td>0.9987±0.0008</td>
<td>145±5</td>
<td>12.0σ</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAMA/NaI +</td>
<td>(2-6) keV</td>
<td>0.0103±0.0008</td>
<td>0.9987±0.0008</td>
<td>145±5</td>
<td>12.9σ</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph1 +</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Acos[ω(t-t₀)]**

DAMA/NaI (0.29 ton x yr)
DAMA/LIBRA-ph1 (1.04 ton x yr)
DAMA/LIBRA-ph2 (1.13 ton x yr)

total exposure = 2.46 ton×yr
Rate behaviour above 6 keV

• No Modulation above 6 keV

<table>
<thead>
<tr>
<th>Period</th>
<th>Mod. Ampl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-ph2_2</td>
<td>(0.12±0.14) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_3</td>
<td>-0.08±0.14) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_4</td>
<td>(0.07±0.15) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_5</td>
<td>-0.05±0.14) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_6</td>
<td>(0.03±0.13) cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-ph2_7</td>
<td>-0.09±0.14) cpd/kg</td>
</tr>
</tbody>
</table>

σ ≈ 1%, fully accounted by statistical considerations

• 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

• 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 background 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”

Single hit residual rate (red) vs Multiple hit residual rate (green)

- Clear modulation in the single hit events;
- No modulation in the residual rate of the multiple hit events

This result furthermore rules out 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

![Power spectra graph]

DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (20 yr)
total exposure: 2.46 ton×yr

Zoom around the 1 y⁻¹ peak

Principale 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

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

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

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

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

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

<table>
<thead>
<tr>
<th>Source</th>
<th>(\Phi_{0,k}^{(n)}) (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 = R_{0,k} \eta_k) (cpd/kg/keV)</th>
<th>(A_k / S_m^{exp})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLOW neutrons</td>
<td>thermal n ((10^{-2} - 10^{-1} \text{ eV}))</td>
<td>(1.08 \times 10^{-6}) [15]</td>
<td>(\simeq 0) however (\ll 0.1) [2, 7, 8]</td>
<td>(-)</td>
<td>(&lt; 8 \times 10^{-6}) [2, 7, 8]</td>
<td>(&lt; 8 \times 10^{-7})</td>
</tr>
<tr>
<td></td>
<td>epithermal n ((\text{eV-keV}))</td>
<td>(2 \times 10^{-6})</td>
<td>(\simeq 0) however (\ll 0.1) [2, 7, 8]</td>
<td>(-)</td>
<td>(&lt; 3 \times 10^{-3}) [2, 7, 8]</td>
<td>(&lt; 3 \times 10^{-4})</td>
</tr>
<tr>
<td>FAST neutrons</td>
<td>fission, ((\alpha, n) \rightarrow n) ((1-10 \text{ MeV}))</td>
<td>(\simeq 0.9 \times 10^{-7}) [17]</td>
<td>(\simeq 0) however (\ll 0.1) [2, 7, 8]</td>
<td>(-)</td>
<td>(&lt; 6 \times 10^{-4}) [2, 7, 8]</td>
<td>(&lt; 6 \times 10^{-5})</td>
</tr>
<tr>
<td></td>
<td>(\mu \rightarrow n) from rock ((&gt; 10 \text{ MeV}))</td>
<td>(\simeq 3 \times 10^{-9})</td>
<td>(0.0129) [23] end of June [23, 7, 8]</td>
<td>(-)</td>
<td>(&lt; 7 \times 10^{-4}) (see text and ref. [12])</td>
<td>(&lt; 9 \times 10^{-6})</td>
</tr>
<tr>
<td></td>
<td>(\mu \rightarrow n) from Pb shield ((&gt; 10 \text{ MeV}))</td>
<td>(\simeq 6 \times 10^{-9}) (see footnote 3)</td>
<td>(0.0129) [23] end of June [23, 7, 8]</td>
<td>(-)</td>
<td>(&lt; 1.4 \times 10^{-3}) (see text and footnote 3)</td>
<td>(&lt; 2 \times 10^{-5})</td>
</tr>
<tr>
<td></td>
<td>(\nu \rightarrow n) ((\text{few MeV}))</td>
<td>(\simeq 3 \times 10^{-10}) (see text)</td>
<td>(0.03342) * Jan. 4th *</td>
<td>(-)</td>
<td>(&lt; 7 \times 10^{-5}) (see text)</td>
<td>(&lt; 2 \times 10^{-6})</td>
</tr>
<tr>
<td></td>
<td>direct (\mu)</td>
<td>(\Phi_0^{(\mu)} \simeq 20 \mu \text{ m}^{-2} \text{d}^{-1}) [20]</td>
<td>(0.0129) [23] end of June [23, 7, 8]</td>
<td>(-)</td>
<td>(\simeq 10^{-7}) [2, 7, 8]</td>
<td>(\simeq 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>direct (\nu)</td>
<td>(\Phi_0^{(\nu)} \simeq 6 \times 10^{10} \nu \text{ cm}^{-2} \text{s}^{-1}) [26]</td>
<td>(0.03342) * Jan. 4th *</td>
<td>(-)</td>
<td>(\simeq 10^{-5}) [31]</td>
<td>(3 \times 10^{-7})</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 $\rightarrow$ 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>
Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

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

... PAPER IN PREPARATION...
...and experimental aspects...

- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling, ...
- ...
Running phase2 and towards DAMA/LIBRA–phase3 with software energy threshold below 1 keV

Enhancing sensitivities for DM corollary aspects, other DM features, second order effects and other rare processes:

• The light collection of the detectors can further be improved
• Light yields and the energy thresholds will improve accordingly
• The electronics can be improved too

Chosen strategy:
① new development of high Q.E. PMTs with increased radio-purity.
② new miniaturized low background pre-amps directly mounted on the low background voltage dividers.
③ S/N increase by decreasing noise.

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).
Conclusions

• Model-independent positive evidence for the presence of DM particles in the galactic halo at $12.9\sigma$ C.L. (20 independent annual cycles with 3 different set-ups: 2.46 ton $\times$ yr)

• Modulation parameters determined with increasing precision

• New investigations on different peculiarities of the DM signal exploited 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

• DAMA/LIBRA–phase2 continuing data taking

• DAMA/LIBRA–phase3 R&D in progress

• R&D for a possible DAMA/1ton - full sensitive mass - set-up, proposed to INFN by DAMA since 1996, continuing at some extent as well as some other R&Ds

• New corollary analyses in progress

• Continuing investigations of rare processes other than DM