DAMA/LIBRA-phase1 results, perspectives of phase-2 and beyond

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DAMA set-ups
an observatory for rare processes @ LNGS

- DAMA/LIBRA (DAMA/NaI)
- 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
+ in some studies on $\beta\beta$ decays (DST-MAE project): IIT Kharagpur, 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 recoiled 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

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

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

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

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

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

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

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 be able to account for the whole observed modulation amplitude, and also to satisfy simultaneously all the requirements
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 PLB515(2001)6
- Exotic Matter search EPJdirect C14(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
- Exotic Dark Matter search PRL83(1999)4918

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
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)

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

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
Complete DAMA/LIBRA-phase1

<table>
<thead>
<tr>
<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>232.8</td>
<td>51405</td>
<td>0.562</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>232.8</td>
<td>52597</td>
<td>0.467</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>232.8</td>
<td>39445</td>
<td>0.591</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>232.8</td>
<td>49377</td>
<td>0.541</td>
</tr>
<tr>
<td>DAMA/LIBRA-5</td>
<td>232.8</td>
<td>66105</td>
<td>0.468</td>
</tr>
<tr>
<td>DAMA/LIBRA-6</td>
<td>242.5</td>
<td>58768</td>
<td>0.519</td>
</tr>
<tr>
<td>DAMA/LIBRA-7</td>
<td>242.5</td>
<td>62098</td>
<td>0.515</td>
</tr>
<tr>
<td>DAMA/LIBRA-phase1</td>
<td>232.8</td>
<td>379795</td>
<td>approx. 1.04 ton×yr</td>
</tr>
<tr>
<td>DAMA/NaI + DAMA/LIBRA-phase1</td>
<td>242.5</td>
<td>379795</td>
<td>approx. 1.33 ton×yr</td>
</tr>
</tbody>
</table>

DAMA/LIBRA-phase1:
- First upgrade on Sept 2008: replacement of some PMTs in HP N₂ atmosphere, new Digitizers (U1063A Acqiris 1GS/s 8-bit High-speed cPCI), new DAQ system with optical read-out installed

DAMA/LIBRA-phase2 (running):
- Second upgrade on Oct./Nov. 2010: replacement of all the PMTs with higher Q.E. ones from dedicated developments
  Goal: lowering the software energy threshold
- Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

• EPJC56(2008)333
• EPJC67(2010)39
• EPJC73(2013)2648
• calibrations: ≈96 M events from sources
• acceptance window eff: 95 M events (≈3.5 M events/keV)
No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature.

Power spectrum

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature.

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.
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%).
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>RADON</td>
<td>Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.</td>
<td>&lt;2.5×10⁻⁶ cpd/kg/keV</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield → huge heat capacity + T continuously recorded</td>
<td>&lt;10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td>NOISE</td>
<td>Effective full noise rejection near threshold</td>
<td>&lt;10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td>ENERGY SCALE</td>
<td>Routine + intrinsic calibrations</td>
<td>&lt;1⁻²×10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>&lt;10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>No modulation above 6 keV; no modulation in the (2-6) keV multiple-hits events; this limit includes all possible sources of background</td>
<td>&lt;10⁻⁴ cpd/kg/keV</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured at LNGS</td>
<td>&lt;3×10⁻⁵ 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
No role for $\mu$ in DAMA annual modulation result

**Direct $\mu$ interaction in DAMA/LIBRA set-up:**

DAMA/LIBRA surface $\approx 0.13$ m$^2$

$\mu$ flux @ DAMA/LIBRA $\approx 2.5$ $\mu$/day

It cannot mimic the signature: already excluded by $R_{90}$, by multi-hits analysis + different phase, etc.

**Rate, $R_n$, of fast neutrons produced by $\mu$:**

- $\Phi_\mu$ @ LNGS $\approx 20$ $\mu$ m$^{-2}$d$^{-1}$ ($\pm 1.5\%$ modulated)
- Annual modulation amplitude at low energy due to $\mu$ modulation:

  $$S_m(\mu) = R_n \ g \ \epsilon \ f_{\Delta E} f_{\text{single}} \ 2\% / (M_{\text{setup}} \ \Delta E)$$

Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the multi-hits events

**Inconsistency of the phase between DAMA signal and $\mu$ modulation**

$\mu$ flux @ LNGS (MACRO, LVD, BOREXINO) $\approx 3 \cdot 10^{-4}$ m$^{-2}$s$^{-1}$; modulation amplitude $1.5\%$; phase: July $7 \pm 6$ d, June $29 \pm 6$ d (BOREXINO)

The DAMA phase: May $26 \pm 7$ days (stable over 13 years)

The DAMA phase is $5.7 \sigma$ far from the LVD/BOREXINO phases of muons ($7.1 \sigma$ far from MACRO measured phase)

Considering the seasonal weather at LNGS, quite impossible that the max. temperature of the outer atmosphere (on which $\mu$ flux variation is dependent) is observed e.g. in June 15 which is $3 \sigma$ from DAMA

For many others arguments EPJC72(2012)2064
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

well compatible with several candidates (in several of the many possible astrophysical, nuclear and particle physics scenarios); other ones are open

- Neutralino as LSP in various SUSY theories
- A heavy n of the 4-th family
- Various kinds of WIMP candidates with several different kind of interactions
  - Pure SI, pure SD, mixed + Migdal effect + channeling,… (from low to high mass)
- Pseudoscalar, scalar or mixed light bosons with axion-like interactions
- Sterile neutrino
- WIMP with preferred inelastic scattering
- Light Dark Matter
- Mirror Dark Matter
- Self interacting Dark Matter
- Dark Matter (including some scenarios for WIMP) electron-interacting
- Heavy exotic candidates, as “4th family atoms”, …
- Elementary Black holes such as the Daemons
- Kaluza Klein particles
- … and more

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.) not in conflict with DAMA results; null results not in conflict as well

Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility of possible positive hints
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios.

- WIMP: SI
  - 10 GeV
  - 60 GeV
  - 15 GeV

- WIMP: SI & SD
  - 100-120 GeV
  - 60 GeV
  - 100 GeV

- LDM
  - m_L = 0

Not best fit
About the same C.L.

θ = 2.435

Compatibility with several candidates; other ones are open.

EPJC56(2008)333
IJMPA28(2013)1330022
Uncertainty in experimental parameters, as well as 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 experiment can be directly compared in model independent way with DAMA.
Case of DM particles inducing elastic scatterings on target-nuclei

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 $7.5\sigma$ 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 $1.64\sigma$ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent Quenching Factors (red)

Co-rotating halo, Non thermalized component: Enlarge allowed region towards larger mass

Including the Migdal effect: Towards lower mass/higher $\sigma$

Compatibility also with CRESST and CDMS, if the two CDMS-Ge events, the three CDMS-Si events and the CRESST events are interpreted as relic DM interactions

... many other interpretations available in literature
A diurnal modulation with sidereal time is expected because of Earth rotation.

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

detector velocity

It can be written:

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

Annual modulation term:

\[ \hat{v}_s \cdot \vec{v}_{rev}(t) = V_{Earth} B_m \cos(\omega(t - t_0)) \]

- \( V_{Earth} \) is the orbital velocity of the Earth \( \approx 30 \text{ km/s} \)
- \( B_m \approx 0.489 \)
- \( t_0 \approx t_{equinox} + 73.25 \text{ days} \approx \text{June 2} \)

Diurnal modulation term:

\[ \hat{v}_s \cdot \vec{v}_{rot}(t) = V_r B_d \cos[\omega_{rot}(t - t_d)] \]

- \( V_r \) is the rotational velocity of the Earth at the given latitude (for LNGS \( \approx 0.3435 \text{ km/s} \))
- \( B_d \approx 0.671 \)
- \( t_d \approx 14.02 \text{ h (at LNGS)} \)
• 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.

Run-Test gives similar results.

Diurnal variation (sidereal and solar) excluded at 95% C.L.
The ratio $R_{dy}$ of the diurnal over annual modulation amplitudes is a model independent constant.

- Annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV: $(0.0097 \pm 0.0013)$ cpd/kg/keV
- Expected value of diurnal modulation amplitude: $\simeq 1.5 \times 10^{-4}$ cpd/kg/keV.
- Fitting the single-hit residuals with a cosine function with amplitude $A_d$ as free parameter, period 24 h and phase 14 h

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

DAMA/LIBRA–phase2 will offer increased sensitivity.
**Investigation of Earth Shadow Effect**

- **Earth Shadow Effect** expected for DM candidate particles inducing nuclear recoils
- Only for candidates with **high cross-section** with ordinary matter (low DM local density)
- Induced by the **variation** during the day of the Earth **thickness crossed by the DM particle** reaching the experimental set-up

DM particles crossing Earth lose their energy → DM velocity distribution observed in the laboratory frame is distorted as function of time

**At LNGS:**
- 20:00 GMST → Minimum thickness crossed → Maximum counting rate
- 08:00 GMST → maximum thickness crossed → Minimum counting rate
Investigation of Earth Shadow Effect

Expected counting rate for a given mass, cross section and scenario by MC:

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

Expectations compared with diurnal residual rate of the single-hit events of DAMA/LIBRA-phase1 in (2-4) keV

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

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

In these examples:

- Isothermal halo model with \( v_0 = 220 \text{ km/s} \) and \( v_{\text{esc}} = 650 \text{ km/s} \)
  - 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

Second upgrade on end of 2010: all PMTs replaced with new ones of higher Q.E.

Energy resolution

Mean value:
prev. PMTs 7.5%(0.6% RMS)
new HQE PMTs 6.7%(0.5% RMS)

Energy resolution

Residual Contamination

<table>
<thead>
<tr>
<th></th>
<th>$^{226}$Ra (Bq/kg)</th>
<th>$^{235}$U (Bq/kg)</th>
<th>$^{228}$Ra (Bq/kg)</th>
<th>$^{228}$Th (Bq/kg)</th>
<th>$^{40}$K (Bq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>0.43</td>
<td>0.047</td>
<td>0.12</td>
<td>0.083</td>
<td>0.54</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.06</td>
<td>0.010</td>
<td>0.02</td>
<td>0.017</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The light responses

Previous PMTs: 5.5-7.5 ph.e./keV
New PMTs: up to 10 ph.e./keV
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**
  - to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, form factors, spin-factors …)
  - scaling laws and cross sections
  - multi-component DM particles halo?

- **possible diurnal effects on the 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 DM particles 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

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

A step towards such investigations:

**DAMA/LIBRA-phase2**

with lower energy threshold and larger exposure
• The light collection of the detectors can further be improved
• Light yields and the energy thresholds will improve accordingly

The strong interest in the low energy range suggests the possibility of a new development of high Q.E. PMTs with increased radiopurity to directly couple them to the DAMA/LIBRA crystals, removing the special radio-pure quartz (Suprasil B) light guides (10 cm long), which act also as optical window.

The presently-reached PMTs features, but not for the same PMT mod.:
• Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
• radiopurity 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).

R&D efforts to obtain PMTs matching the best performances... feasible

No longer need for light guides (a 30-40% improvement in the light collection is expected)
Conclusions

- Positive evidence for the presence of DM particles in the galactic halo supported at \(9.3\sigma\) C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: 1.33 ton \(\times\) yr)
- Modulation parameters determined with better precision
- New investigation on different peculiarities of the DM signal exploited
- 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 in data taking** at lower software energy threshold (below 2 keV) to investigate further features of DM signals and second order effects
- Continuing investigations of rare processes other than DM as well as further developments
- DAMA/LIBRA – phase3 under study
- R&D for a possible DAMA/1ton set-up in progress