Recent analyses on the DAMA/LIBRA-phase1 data

http://www.mauriziopignotti.com
DAMA set-ups
an observatory for rare processes @ LNGS

- DAMA/LIBRA
  (former expt. 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
+ collaborators from several foreigner institution depending on the measurement
+ in some studies on ββ decays (DST-MAE project): IIT 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
  e.g. sterile $\nu$

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

- Ionization:
  Ge, Si

- Bolomoter:
  TeO$_2$, Ge, CaWO$_4$, ...

- Scintillation:
  NaI(Tl), LXe, CaF$_2$(Eu), ...

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

... even WIMPs

... also other ideas ...
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 2nd
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

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

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

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

As a result of a 2\textsuperscript{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)

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
### 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 and optimization tests 2011: 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

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<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>379795</td>
<td>1.04 ton×yr</td>
<td>0.518</td>
</tr>
<tr>
<td>DAMA/NaI + DAMA/LIBRA-phase1</td>
<td>1.33 ton×yr</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Calibrations:** ≈96 M events from sources

**Acceptance window eff:** 95 M events (≈3.5 M events/keV)

a ton × yr experiment? done

- EPJC56(2008)333
- EPJC67(2010)39
- EPJC73(2013)2648
The data favor the presence of a modulated behavior 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>$&lt;2.5 \times 10^{-6}$ 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>$&lt;3 \times 10^{-6}$ 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 $\approx 0.13 \text{ m}^2$
  - $\mu$ 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 $\approx 20 \mu \text{ m}^{-2}\text{d}^{-1}$ ($\pm 1.5\%$ modulated)
  - Annual modulation amplitude at low energy due to $\mu$ modulation:
    \[
    S_m(\mu) = R_n \ g \ \varepsilon \ f_{\Delta E} \ f_{\text{single}} \ 2\% / (M_{\text{setup}} \Delta E)
    \]
  - 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) $\approx 3 \cdot 10^{-4} \text{ m}^{-2}\text{s}^{-1}$; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)
  - The DAMA phase: May 26 ± 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

... many other arguments EPJC72(2012)2064, EPJC74(2014)3196
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

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

WIMP with preferred inelastic scattering

Light Dark Matter

Mirror Dark Matter

Self interacting Dark Matter

Dark Matter (including some scenarios for WIMP) electron-interacting

Elementary Black holes such as the Daemons

k Heavy n of the 4-th family

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

Elementary Black holes such as the Daemons

Neutralino as LSP in various SUSY theories

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
...models...
• Which particle?
• Which interaction coupling?
• Which EFT operators contribute?
• 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
• 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
• ...

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

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

Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than $7.5\,\sigma$ 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 the considered scenario without (green), with (blue) channeling, with energy-dependent Quenching Factors (red);

- $7.5\,\sigma$ C.L.
- $1.64\,\sigma$ C.L.

CoGeNT: q.f. at a fixed assumed value

Including the Migdal effect

- Towards lower mass/higher $\sigma$

Co-rotating halo, Non thermalized component

- Enlarge allowed region towards larger mass

Combining channeling and q.f.energy dependence (AstrPhys33(2010)40)

- Towards lower $\sigma$
Asymmetric mirror matter: mirror parity spontaneously broken at the level of electroweak interactions $\Rightarrow$ mirror sector heavier and deformed copy of ordinary sector; mirror hydrogen can be stable and a good DM candidate

- Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2} F^{\mu \nu} F'^{\mu \nu}$
- mirror atom scattering off the ordinary target nuclei with Rutherford-like cross sections.

Examples of expected $S_m$ for the Mirror DM candidate for different values of quenching factor, $M=5m_p$ ($\approx 5 \text{ GeV}$)

The allowed values for $\sqrt{f \cdot \epsilon}$ in the case of mirror hydrogen atom, $Z' = 1$, ranges between $7.7 \times 10^{-10}$ to $1.1 \times 10^{-7}$. The values within this overall range are well compatible with cosmological bounds. In particular, the best fit values among all the considered scenarios gives $\sqrt{f \cdot \epsilon}_{b.f.} = 2.4 \times 10^{-9}$
A diurnal modulation with sidereal time is expected because of Earth rotation

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

**Model Independent result on Diurnal Modulation**

- 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

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

**Diurnal variation (sidereal and solar) not observed at 95% C.L. at the reached level of sensitivity**

\( R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \approx 0.016 \)

- 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:
  \( = 1.5 \times 10^{-4} \) cpd/kg/keV

- Fitting the *single-hit* residuals as function of sidereal time with a cosine function with amplitude \( A_d \) as free parameter, period 24 h and phase 14 h:
  \( A_{d(2-6\text{ keV})} < 1.2 \times 10^{-3} \) cpd/kg/keV (90%CL)

\( \Rightarrow \) experimental sensitivity more modest than the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 annual modulation observed effect.

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

- **Earth Shadow Effect** expected for DM candidate particles inducing just 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

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

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

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

Constrain (red line) on DAMA/LIBRA DM annual modulation result from Earth Shadow Effect in the \( \xi \) vs \( \sigma_n \) plane for some \( m_{DM} \) (left: 10 GeV, right: 60 GeV) for the considered model framework

\[ v_0 = 220 \text{ km/s}; m_{DM} = 30 \text{ GeV}; QF const.; \xi \sigma_n = 1.1 \times 10^7 \text{ pb} \]
DAMA/LIBRA phase 2 - running

Second upgrade on end of 2010:

all PMTs replaced with new ones of higher Q.E.

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

• The sensitivity of the DM annual modulation signature depends – apart from the counting rate – on:
  
  $\epsilon \times \Delta E \times M \times T \times (\alpha - \beta^2)$

  Increased in DAMA/LIBRA-phase2; equivalent to have enlarged the exposed mass

• First data release after 6 annual cycles

• Further annual cycles to collect exposure to investigate other peculiarities and second order effect

JINST 7(2012)03009
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
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 × yr)

• Modulation parameters determined with high precision

• New investigation on different peculiarities of the DM signal exploited (Diurnal Modulation and Earth Shadow Effect)

• New corollary analysis on Mirror Dark Matter

• 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 full sensitive mass DAMA/1ton, DAMA proposed already in 1996, in progress