Highlights on signals from the Dark Matter particles

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Relic DM particles from primordial Universe

What accelerators can do:

to demonstrate the existence of some of the DM candidates

What accelerators cannot do:

to credit that a certain particle is a DM solution or the “only” DM particle solution...

+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

Right halo model and parameters?

- DM multicomponent also in the particle part?
- Right related nuclear and particle physics?

Non thermalized components?
- Caustics?
- Clumpiness?

etc
Indirect detection: measurement of secondary particles ($\nu$'s, $\gamma$'s, antiparticles,...) occasionally produced by annihilation of some particular DM candidate in celestial bodies provided several assumptions are fulfilled (approach: continuous radiation damage + subtraction of unknown competing background + strongly model dependent + can require very high boost factor, ...)

No direct model independent comparison possible with direct detection and accelerators
Some direct detection processes:

- **Excitation of bound electrons in scatterings on nuclei**
  \[ W + N \rightarrow W^* + N \]
  \[ \rightarrow \text{detection of recoil nuclei + e.m. radiation} \]

- **Inelastic Dark Matter:**
  \[ W + N \rightarrow W^* + N \]
  \[ W \text{ has } 2 \text{ mass states } \chi^+ , \chi^- \text{ with } \delta \text{ mass splitting} \]
  \[ \rightarrow \text{Kinematic constraint for the inelastic scattering of } \chi^- \text{ on a nucleus} \]
  \[ \frac{1}{2} \mu v^2 \geq \delta \iff v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}} \]

- **Elastic scatterings on nuclei**
  \[ \rightarrow \text{detection of nuclear recoil energy} \]

- **Interaction of light DMp (LDM) on e- or nucleus with production of a lighter particle**
  \[ \rightarrow \text{detection of electron/nucleus recoil energy} \]
  \[ e.g. \text{sterile } \nu \]

- **Conversion of particle into e.m. radiation**
  \[ \rightarrow \text{detection of } \gamma, \text{X-rays, e}^- \]

- **Interaction only on atomic electrons**
  \[ \rightarrow \text{detection of e.m. radiation} \]

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  \[ e.g. \text{sterile } \nu \]

- **... and more**
Is it 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?
- 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?
- ...

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, etc., 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 possible among experiments using different target materials and/or approaches

...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, ...
- ...
- ...
The DM annual modulation: a model independent signature to investigate the 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 of the DM annual modulation**

1) Modulated rate according cosine
2) In a definite 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

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

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

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.
Roma2, Roma1, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev and others
+ neutron meas.: ENEA-Frascati
+ in some studies on $\beta\beta$ decays (DST-MAE project): IIT Kharagpur, India

DAMA: an observatory for rare processes @LNGS

DAMA/NaI
DAMA/LIBRA
DAMA/LXe
DAMA/R&D
DAMA/CRYS
DAMA/Ge

http://people.roma2.infn.it/dama
The relevance of ULB NaI(Tl) as target-material

- Well known technology
- High duty cycle
- Large mass possible
- “Ecological clean” set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- $\lambda$ of the NaI(Tl) scintillation light well directly match PMTs sensitivity
- Uniform response in the realized detectors
- High light response (5.5 – 7.5 ph.e./keV in DAMA/LIBRA-phase1)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold ($\tau$ of NaI(Tl) pulses hundreds ns, while $\tau$ of noise pulses tens ns)
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios on the contrary of other proposed target-materials (and approaches)
- Sensitive to both high (mainly by Iodine target) and low mass (mainly by Na target) candidates
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up
- etc.

ULB NaI(Tl) also allows the study of several rare processes

To develop ULB NaI(Tl): many years of work, specific experience in the specific detector, suitable raw materials availability/selections, developments of purification strategies, additives, growing/handling protocols, selective cuts, abrasives, etc. etc. $\rightarrow$ long dedicated time and efforts.

The developments themselves are difficult and uncertain experiments.

ULB NaI(Tl) – as whatever ULB detector – cannot be simply bought or made by another researcher for you …
The pioneer DAMA/NaI: $\approx 100$ kg highly radiopure NaI(Tl)

Performances:

Results on rare processes:
- Possible Pauli exclusion principle violation
- CNC processes
- Electron stability and non-paulian transitions in iodine atoms (by L-shell)
- Search for solar axions
- Exotic Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

Results on DM particles:
- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- Annual Modulation Signature

Results on rare processes:
- PLB408(1997)439
- PRC60(1999)065501
- PLB460(1999)235
- PLB515(2001)6
- EPJdirect C14(2002)1
- EPJA23(2005)7
- EPJA24(2005)51

Performances:
- PLB389(1996)757
- PRL83(1999)4918

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
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

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

As a result of a second generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

• Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
**DAMA/LIBRA calibrations**

**Low energy:** various external gamma sources ($^{241}$Am, $^{133}$Ba) and internal X-rays or gamma’s ($^{40}$K, $^{125}$I, $^{129}$I), routine calibrations with $^{241}$Am

\[
\sigma_{LE} = \left( \frac{0.448 \pm 0.035}{E} \right) + (9.1 \pm 5.1) \cdot 10^{-3}
\]

**High energy:** external sources of gamma rays (e.g. $^{137}$Cs, $^{60}$Co and $^{133}$Ba) and gamma rays of 1461 keV due to $^{40}$K decays in an adjacent detector, tagged by the 3.2 keV X-rays

\[
\sigma_{HE} = \left( \frac{1.12 \pm 0.06}{E} \right) + (17 \pm 23) \cdot 10^{-4}
\]

The signals (unlike low energy events) for high energy events are taken only from one PMT

Thus, here and hereafter keV means keV electron equivalent
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>Sept. 9, 2003 - July 21, 2004</td>
<td>232.8</td>
<td>51405</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>July 21, 2004 - Oct. 28, 2005</td>
<td>232.8</td>
<td>52597</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>Oct. 28, 2005 - July 18, 2006</td>
<td>232.8</td>
<td>39445</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>July 19, 2006 - July 17, 2007</td>
<td>232.8</td>
<td>49377</td>
</tr>
<tr>
<td>DAMA/LIBRA-5</td>
<td>July 17, 2007 - Aug. 29, 2008</td>
<td>232.8</td>
<td>66105</td>
</tr>
<tr>
<td>DAMA/LIBRA-6</td>
<td>Nov. 12, 2008 - Sept. 1, 2009</td>
<td>242.5</td>
<td>58768</td>
</tr>
<tr>
<td>DAMA/LIBRA-7</td>
<td>Sep. 1, 2009 - Sept. 8, 2010</td>
<td>242.5</td>
<td>62098</td>
</tr>
<tr>
<td>DAMA/LIBRA-phase1</td>
<td>Sept. 9, 2003 - Sept. 8, 2010</td>
<td>379795 × 1.04 ton×yr</td>
<td>1.3518</td>
</tr>
<tr>
<td>DAMA/Nal + DAMA/LIBRA-phase1:</td>
<td></td>
<td></td>
<td></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 at end 2010: replacement of all the PMTs with higher Q.E. ones from dedicated developments
- commissioning on 2011
  - 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 Mevents from sources
- acceptance window eff: 95 Mevents (~3.5 Mevents/keV)
Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = 1.33 ton×yr


Measured modulation amplitudes (A), period (T) and phase (t₀) from single-hit residual rate vs time

<table>
<thead>
<tr>
<th>DAMA/NaI+DAMA/LIBRA-phase1 (2-4) keV</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>(2-4) keV</td>
<td>0.0190 ± 0.0020</td>
<td>0.996 ± 0.0002</td>
<td>134 ± 6</td>
<td>9.5σ</td>
</tr>
<tr>
<td>(2-5) keV</td>
<td>0.0140 ± 0.0015</td>
<td>0.996 ± 0.0002</td>
<td>140 ± 6</td>
<td>9.3σ</td>
</tr>
<tr>
<td>(2-6) keV</td>
<td>0.0112 ± 0.0012</td>
<td>0.998 ± 0.0002</td>
<td>144 ± 7</td>
<td>9.3σ</td>
</tr>
</tbody>
</table>

Comparison between single hit residual rate (red points) and multiple hit residual rate (green points): Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events

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 data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at more than 9σ C.L.
Model Independent Annual Modulation Result

Max-lik analysis of single hit events

\[ R(t) = S_0 + S_m \cos[\omega(t-t_0)] \]

DAMA/NaI + DAMA/LIBRA-phase1
Total exposure: 487526 kg\texttimes day = 1.33 ton\texttimes yr

\[ R(t) = S_0 + S_m \cos[\omega(t-t_0)] + Z_m \sin[\omega(t-t_0)] = S_0 + Y_m \cos[\omega(t-t')] \]

\[ T = \frac{2\pi}{\omega} = 1 \text{ yr} \] and \( t_0 = 152.5 \text{ day} \)

\[ \Delta E = 0.5 \text{ keV bins} \]

No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy all the many peculiarities of the signature are available.
July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector):
(i) TD VXI Tektronix; (ii) Digital Unix DAQ system; (iii) GPIB-CAMAC.

July 2002 DAMA/NaI data taking completed

On 2003 DAMA/LIBRA has begun first operations (one TD channel for each PMT; two for each detector)

Sept.-Oct. 2008 - DAMA/LIBRA upgrade:
(i) one detector has been recovered by replacing a broken PMT
(ii) new optimization of some PMTs and HVs performed
(iii) All TD replaced with new ones
(iv) new DAQ with optical read-out installed

The second DAMA/LIBRA upgrade in Fall 2010: replacement of all the PMTs with higher Q.E. ones (+ new preamplifiers in fall 2012 & other developments in progress)

DAMA/LIBRA-phase2 in data taking
Rate behaviour above 6 keV

- No Modulation above 6 keV
  
  Mod. Ampl. (6-10 keV): cpd/kg/keV  
  
  DAMA/LIBRA-1: (0.0016 ± 0.0031) cpd/kg/keV  
  DAMA/LIBRA-2: -(0.0010 ± 0.0034) cpd/kg/keV  
  DAMA/LIBRA-3: -(0.0001 ± 0.0031) cpd/kg/keV  
  DAMA/LIBRA-4: -(0.0006 ± 0.0029) cpd/kg/keV  
  DAMA/LIBRA-5: -(0.0021 ± 0.0026) cpd/kg/keV  
  DAMA/LIBRA-6: (0.0029 ± 0.0025) cpd/kg/keV  
  DAMA/LIBRA-7: -(0.0023 ± 0.0024) cpd/kg/keV  

→ 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

  + if a modulation present in the whole energy spectrum at the level found in the lowest energy region → $R_{90} \sim$ tens cpd/kg → ∼ 100 $\sigma$ far away

No modulation above 6 keV, no modulation in the whole energy spectrum, no modulation in the 2-6 keV multiple-hit events  

This accounts for all sources of bckg and is consistent with the studies on the various components
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

- **Rate, $R_\mu$, of fast neutrons produced by $\mu$:**
  - $\Phi_\mu$ @ LNGS $\approx$ 20 $\mu$ m$^{-2}$d$^{-1}$ (±1.5% modulated)
  - Annual modulation amplitude at low energy due to $\mu$ modulation:
    \[
    S_m(\mu) = R_n \cdot g \cdot f_{\Delta E} \cdot f_{\text{single}} \cdot 2\% / (M_{\text{setup}} \cdot \Delta E)
    \]
  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$3·10$^{-4}$ m$^{-2}$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)

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

\[ R_{k} = R_{0,k} \left( 1 + \eta_{k} \cos \omega (t - t_{k}) \right) \]

(See e.g. also EPJC 56 (2008) 333, EPJC 72(2012) 2064, IJMPA 28 (2013) 1330022)

<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}/A_{\text{cap}} )</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}) eV)</td>
<td>1.08 \times 10^{-6} [15]</td>
<td>( \simeq 0 )</td>
<td>however ( \ll 0.1 )</td>
<td>[2, 7, 8]</td>
<td>( &lt; 8 \times 10^{-6} )</td>
<td>( \ll 8 \times 10^{-7} )</td>
</tr>
<tr>
<td>epithermal n (eV-keV)</td>
<td>2 \times 10^{-6} [15]</td>
<td>( \simeq 0 )</td>
<td>however ( \ll 0.1 )</td>
<td>[2, 7, 8]</td>
<td>( &lt; 3 \times 10^{-3} )</td>
<td>( \ll 3 \times 10^{-4} )</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) (1-10 MeV)</td>
<td>( \simeq 0.9 \times 10^{-7} ) [17]</td>
<td>( \simeq 0 )</td>
<td>however ( \ll 0.1 )</td>
<td>[2, 7, 8]</td>
<td>( &lt; 6 \times 10^{-4} )</td>
<td>( \ll 6 \times 10^{-5} )</td>
</tr>
<tr>
<td>(\mu \rightarrow n) from rock (&gt; 10 MeV)</td>
<td>( \simeq 3 \times 10^{-9} ) (see text and ref. [12])</td>
<td>0.0129 [23]</td>
<td>end of June</td>
<td>[23, 7, 8]</td>
<td>( \ll 7 \times 10^{-4} ) (see text and ref. [2, 7, 8])</td>
<td>( \ll 9 \times 10^{-6} )</td>
</tr>
<tr>
<td>(\mu \rightarrow n) from Pb shield (&gt; 10 MeV)</td>
<td>( \simeq 6 \times 10^{-9} ) (see footnote 3)</td>
<td>0.0129 [23]</td>
<td>end of June</td>
<td>[23, 7, 8]</td>
<td>( \ll 1.4 \times 10^{-3} ) (see text and footnote 3)</td>
<td>( \ll 2 \times 10^{-5} )</td>
</tr>
<tr>
<td>(\nu \rightarrow n) (few MeV)</td>
<td>( \simeq 3 \times 10^{-10} ) (see text)</td>
<td>0.03342 *</td>
<td>Jan. 4th *</td>
<td></td>
<td>( \ll 7 \times 10^{-5} ) (see text)</td>
<td>( \ll 2 \times 10^{-6} )</td>
</tr>
<tr>
<td>direct (\mu)</td>
<td>( \Phi_{0}^{(\mu)} \simeq 20 \mu m^{-2}d^{-1} ) [20]</td>
<td>0.0129 [23]</td>
<td>end of June</td>
<td>[23, 7, 8]</td>
<td>( \simeq 10^{-7} )</td>
<td>( \simeq 10^{-9} )</td>
</tr>
<tr>
<td>direct (\nu)</td>
<td>( \Phi_{0}^{(\nu)} \simeq 6 \times 10^{10} \nu cm^{-2}s^{-1} ) [26]</td>
<td>0.03342 *</td>
<td>Jan. 4th *</td>
<td></td>
<td>( \simeq 10^{-6} )</td>
<td>( \simeq 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), muon or muon induced events, solar \(\nu\) can mimic the DM annual modulation signature since some of the peculiar requirements of the signature would fail (and – in addition quantitatively negligible amplitude with respect to the measured effect).
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→ 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
Final model independent result
DAMA/NaI+DAMA/LIBRA-phase1

Presence of modulation over 14 annual cycles at 9.3σ C.L. with the proper distinctive features of the DM signature: all the features satisfied by the data over 14 independent experiments of 1 year each one.

The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.33 ton x yr (14 annual cycles).

In fact, as required by the DM annual modulation signature:

1) The single-hit events show a clear cosine-like modulation, as expected for the DM signal.

2) Measured period is equal to (0.998±0.002) yr, well compatible with the 1 yr period, as expected for the DM signal.

3) Measured phase (144±7) days is well compatible with the roughly about 152.5 days, as expected for the DM signal.

4) The modulation is present only in the low energy (2–6) keV energy interval and not in other higher energy regions, consistently with expectation for the DM signal.

5) The modulation is present only in the single-hit events, while it is absent in the multiple-hit ones, as expected for the DM signal.

6) The measured modulation amplitude in NaI(Tl) of the single-hit events in the (2–6) keV energy interval is: (0.0112 ± 0.0012) cpd/kg/keV (9.3σ C.L.).

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available.
Final model independent result
DAMA/NaI+DAMA/LIBRA - phase I

Presence of modulation over 14 annual cycles at 9.3σ C.L. with the proper distinctive features of the DM signature: all the features satisfied by the data over 14 independent experiments of 1 year each one

The total exposure by former DAMA/NaI and present DAMA/LIBRA is $1.33 \text{ ton} \times \text{yr}$ (14 annual cycles)

In fact, as required by the DM annual modulation signature:

1) The single-hit events show a clear cosine-like modulation, as expected for the DM signal

2) Measured period is equal to (0.998±0.002) yr, well compatible with the 1 yr period, as expected for the DM signal

3) Measured phase (144±7) days is well compatible with the roughly about 152.5 days expected for the DM signal

4) The modulation energy (2-3 GeV) is observed in other higher energy experiments, as expected for the DM signal

5) The modulation is present only in the single-hit events, while it is absent in the multiple-hit events, as expected for the DM signal

No systematic or side process able to simultaneously produce the signature and to account for the whole measured modulation
Case of DM particles inducing elastic scatterings on target-nuclei, Spin-Independent 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 7.5σ 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 1.64σ 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 σ C.L.

CoGeNT; qf at fixed assumed value

1.64 σ C.L.

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

Including the Migdal effect

Towards lower mass/higher σ

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

Combining channeling and energy dependence of q.f. (AstrPhys33 (2010) 40)
Towards lower σ

PRD84(2011)055014, IJMPA28(2013)1330022
Scratching Below the Surface of the Most General Parameter Space
(S. Scopel talk in DM2 session at MG14)

Most general approach: consider ALL possible NR couplings, including those depending on velocity and momentum

• A much wider parameter space opens up
• First explorations show that indeed large rooms for compatibility can be achieved

... and much more considering experimental and theoretical uncertainties

Other examples

DMp with preferred inelastic interaction:
\[ \chi^- + N \rightarrow \chi^+ + N \]

• iDM mass states \( \chi^+ , \chi^- \) with \( \delta \) mass splitting
• Kinematic constraint for iDM:
\[ \frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{th} \approx \frac{2\delta}{\sqrt{\mu}} \]

DAMA slices from the 3D allowed volume in given scenario

iDM interaction on Tl nuclei of the NaI(Tl) dopant?

• For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with \( A \approx 205 \), which are present as a dopant at the \( 10^{-3} \) level in NaI(Tl) crystals.
• large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, ... nuclei.

Mirror Dark Matter

Asymmetric mirror matter: mirror parity spontaneously broken \( \Rightarrow \)
mirror sector becomes a heavier and deformed copy of ordinary sector
(See EPJC75(2015)400)

• Interaction portal: photon - mirror photon kinetic mixing \( \frac{\epsilon}{2} F^\mu\nu F^\mu_\nu \)
• mirror atom scattering of the ordinary target nuclei in the NaI(Tl) detectors of DAMA/LIBRA set-up with the Rutherford-like cross sections.

\[ \sqrt{f} \cdot \epsilon \] coupling const. and fraction of mirror atom
Positive hints from CoGeNT (ionization detector)

Experimental site: Soudan Underground Lab (2100 mwe)
Detector: 440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure: 146 kg x day (dec '09 - mar '11)

✓ Irreducible excess of bulk-like events below 3 keVee observed;
✓ annual modulation of the rate in 0.5-4.5 keVee at ~2.2σ C.L.

• 6 years of data at hand.
• CoGeNT upgrade: C-4 is coming up very soon
• C-4 aims at x4 total mass increase, bckg decrease, and substantial threshold reduction. Soudan is still the lab

arXiv:1401.3295

A straightforward analysis indicates a persistent annual modulation exclusively at low energy and for bulk events. Best-fit phase consistent with DAMA/LIBRA (small offset may be meaningful). Similar best-fit parameters to 15 mo dataset, but with much better bulk/surface separation (~90% SA for~90% BR)

Unoptimized frequentist analysis yields ~2.2σ preference over null hypothesis. This however does not take into account the possible relevance of the modulation amplitude found...
Double read-out bolometric technique (scintillation vs heat)?

CRESST at LNGS: 33 CaWO₄ crystals (10 kg mass) data from 8 detectors. Exposure: ≈ 730 kg x day

Data from one detector

67 total events observed in O-band; Data from one detector

Latest runs with lower energy threshold does not confirm the previous 4 σ excess?! → Large systematics can be present in this kind of approach

≈ 29 kg x day (exposure 25 times lower than the previous run).

background-only hypothesis rejected with high statistical significance → additional source of events needed (DM?)

crucial role: efficiencies + stability + calibrations
after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

A profile likelihood analysis favors a signal hypothesis at 99.81% CL (~3 σ, p-value: 0.19%).

Si excluded in previous analysis.
Results of CDMS-II with the Si detectors published in two close-in-time data releases:

in six detectors (55.9 kg x day)
in eight (over 11) detectors (140.2 kg x day)

• 1.2 kg Si (11 x 10^6g)
• July 2007 - September 2008
Second upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

After a period of tests and optimizations in data taking in this new configuration

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

- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes
- R&D in progress towards more future phase3
DAMA/LIBRA – phase2

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

After a period of tests and optimizations in data taking in this new configuration

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

- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes
- R&D in progress towards more future phase3
The sensitivity of the DM annual modulation signature depends – apart from the counting rate – on the product:

\[ \varepsilon \times \Delta E \times M \times T \times (\alpha - \beta^2) \]

increased in DAMA/LIBRA-phase2
increased with DAMA/LIBRA-phase2
increased in DAMA/LIBRA-phase2

DM annual modulation signature

\[ \Rightarrow \text{DAMA/LIBRA-phase2} \] also equivalent to have enlarged the exposed mass
The importance of studying second order effects and the annual modulation phase

Higher exposure and lower threshold can allow further investigation on:

- **the nature of the DMp**
  - to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, form factors, spin-factors ...)
  - scaling laws and cross sections
  - multi-component DMp halo?

possible diurnal effects in 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 DMp 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

A step towards such investigations: 

⇒ **DAMA/LIBRA-phase2 running with lower energy threshold**

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

Reference:

PRL112(2014)011301
Other signatures?

- Second order effects
- Diurnal effects
- Shadow effects
- Directionality
- ...

**Diurnal effects**

A diurnal effect with the sidereal time is expected for DM because of Earth rotation.

Velocity of the detector in the terrestrial laboratory:

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

where:

- \(|\vec{v}_s| = |\vec{v}_{LSR} + \vec{v}_\odot| \approx 232 \pm 50 \text{ km/s}
- |\vec{v}_{rev}(t)| \approx 30 \text{ km/s}
- |\vec{v}_{rot}(t)| \approx 0.34 \text{ km/s} \quad \text{at LNGS}

Expected signal counting rate in a given k-th energy bin:

\[
S_k[v_{lab}(t)] \approx \frac{S_k[v_s]}{\left| V_{Earth} B_m \cos \omega (t - t_0) + V_r B_d \cos \omega_{rot} (t - t_d) \right|}
\]

The ratio \(R_{dy}\) is a model independent constant:

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

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval: \((0.0097 \pm 0.0013) \text{ cpd/kg/keV}
- Thus, the expected value of the diurnal modulation amplitude is \(1.5 \times 10^{-4} \text{ cpd/kg/keV}
- When fitting the single-hit residuals with a cosine function with amplitude \(A_d\) as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.

\(A_d (2-6 \text{ keV}) < 1.2 \times 10^{-3} \text{ cpd/kg/keV (90\%CL)}

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

larger exposure DAMA/LIBRA–phase2 with lower energy threshold offers increased sensitivity to such an effect.
Earth shadowing effect with DAMA/LIBRA–phase1

- **Earth Shadow Effect** could be expected for DM candidate particles inducing just nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM particle in order to reach the experimental set-up

- DM particles crossing Earth lose their energy
- DM velocity distribution observed in the laboratory frame is modified as function of time (GMST 8:00 black; GMST 20:00 red)

Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the $\xi$ vs $\sigma_n$ plane for each $m_{DM}$.
Directionality technique

- Identification of the presence of DM candidates inducing just nuclear recoils by exploiting the non-isotropic nuclear recoil distribution correlated to the Earth velocity.

The ADAMO project: Study of the directionality approach with ZnWO₄ anisotropic detectors.

Nuclear recoils are expected to be strongly correlated with impinging direction of those DM candidates. This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day.

The light output and the pulse shape of ZnWO₄ detectors depend on the direction of those impinging candidates with respect to the crystal axes.

Both these anisotropic features can provide two independent ways to exploit the directionality approach.

No anisotropy for e.m. signals.

These and others competitive features of ZnWO₄ detectors could permit a first realistic attempt towards directionality.

Example (for a given model framework) of the expected counting rate as a function of the detector velocity direction.
Future/new laboratories?

Developments about new kinds of detectors and – if successful – a new kind of DM experimental activities and other applications as well.

Do need new ideas!

An intriguing one which could hold for low mass DM candidates inducing just nuclear recoils is the exploitation of a new class of nano-booms and biological DM detectors, taking advantage of new signatures with low atomic number targets.

✓ Nano-explosives detectors (nano-booms): each explosives grain is “independent” room-temperature bolometer.

   Advantages:
   • Use very low mass targets – Li, Be, B, C, N, O
   • Large choice of compounds to select from;
   • Each explosives grain is “independent” bolometer;
   • Amplification of signal from 0.1 keV to 1 MeV possible;
   • \( dE/dx \) (nuclei) \( > \) \( dE/dx \) (electrons)
   => expected advantages

✓ Two types of biological DM detectors: DNA-based detectors and enzymatic reactions (ER) based detectors.

See A.K. Drukier talk in DM2 session at MG14 and IJMPA 29 (2014) 1443008
Conclusions

• Different solid techniques can give complementary results

• Further efforts to demonstrate the solidity of some techniques and developments are needed

• Higher exposed mass not a synonymous of higher sensitivity

• DAMA model-independent positive evidence at 9.3 σ C.L. & full sensitivity to many kind of DM candidates, inducing both nuclear recoils and/or e.m. radiation, of astrophysical, nuclear and particle Physics scenarios as well as to low and large DM masses

• DAMA/LIBRA-phase2 running with the aim to disantangle at least among some of the many possible scenarios, to reach higher precision in modulation parameters (in particular on the phase), to investigate second order effects

• R&D towards possible future DAMA/LIBRA-phase3 in progress, and more

The model independent signature is the definite strategy to investigate the presence of Dark Matter particle component(s) in the Galactic halo, but with reliable set-ups, stability, calibrations, procedures, … as DAMA reached