Dark Matter signal in DAMA/LIBRA

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INFN-LNGS
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](http://people.roma2.infn.it/dama)
Some direct detection processes:

- **Scatterings on nuclei**
  → detection of nuclear recoil energy

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

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

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

- ** Ionization:**
  Ge, Si

- **Bolomter:**
  TeO$_2$, Ge, CaWO$_4$, ...

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

- **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 ...
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 of the 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

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

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

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.
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 PLB460(1999)235
  in iodine atoms (by L-shell) PLB515(2001)6
• Search for solar axions EPJdirect C14(2002)1
• Exotic Matter search EPJA23(2005)7
• Search for superdense nuclear matter EPJA24(2005)51
• Search for heavy clusters decays

Results on DM particles:
• PSD PLB389(1996)757
• Investigation on diurnal effect N.Cim.A112(1999)1541
• Exotic Dark Matter search 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×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

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving - including photos - in HP Nitrogen atmosphere)

Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
...calibration procedures
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc. NIMA592(2008)297, JINST 7(2012)03009

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold

Installation

- Glove-box for calibration
- Electronics + DAQ
- 5.5-7.5 phe/keV
- ~ 1m concrete from GS rock

- Dismounting/Installing protocol (with “Scuba” system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waveform Analyzer Acqiris DC270 (2chs per detector), 1 Gsample/s, 8 bit, bandwidth 250 MHz
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy
Residual contaminants in new ULB NaI(Tl) detectors

- $\alpha/e$ pulse shape discrimination has practically 100% effectiveness in the MeV range
- The measured $\alpha$ yield in the new DAMA/LIBRA detectors ranges from 7 to some tens $\alpha$/kg/day

$^{232}\text{Th}$ residual contamination: time-amplitude method. If $^{232}\text{Th}$ chain at equilibrium: from 0.5 ppt to 7.5 ppt

$^{238}\text{U}$ chain split into 5 subchains:

$^{238}\text{U} \rightarrow ^{234}\text{U} \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \rightarrow ^{210}\text{Pb} \rightarrow ^{206}\text{Pb}$

Thus, in this case: (2.1±0.1) ppt of $^{232}\text{Th}$; (0.35 ±0.06) ppt of $^{238}\text{U}$

and: (15.8±1.6) $\mu$Bq/kg for $^{234}\text{U} + ^{230}\text{Th}$; (21.7±1.1) $\mu$Bq/kg for $^{226}\text{Ra}$;

(24.2±1.6) $\mu$Bq/kg for $^{210}\text{Pb}$.

$^{nat}\text{K}$ residual contamination

The analysis has given for the $^{nat}\text{K}$ content in the crystals values not exceeding ~20 ppb

$^{129}\text{I}$ and $^{210}\text{Pb}$:

- $^{129}\text{I}/^{nat}\text{I} \approx 1.7 \times 10^{-13}$ for all the new detectors
- $^{210}\text{Pb}$ in the new detectors: (5 – 30) $\mu$Bq/kg

No sizable surface pollution by Radon daughters, thanks to the new handling protocols

... more on NIMA592 (2008)297
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.

$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

**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.

$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23) \cdot 10^{-4}$$

Thus, here and hereafter keV means keV electron equivalent.
Infos about DAMA/LIBRA data taking

<table>
<thead>
<tr>
<th>Period</th>
<th>Mass (kg)</th>
<th>Exposure (kg x day)</th>
<th>(\alpha/\beta)</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-1 to -6</td>
<td>317697</td>
<td>= 0.87 ton(\times)yr</td>
<td></td>
</tr>
</tbody>
</table>

DAMA/Nal (7 years) + DAMA/LIBRA (6 years)

Total exposure: 425428 kg\(\times\)day = 1.17 ton\(\times\)yr

- First upgrade on Sept 2008:
  - replacement of some PMTs in HP \(N_2\) atmosphere
  - restore 1 detector to operation
  - new Digitizers (U1063A Acqiris 1GS/s 8-bit High-Speed cPCI)
  - new DAQ system with optical read-out installed

- Second upgrade on Oct./Nov. 2010
  - replacement of all the PMTs with higher Q.E. ones

... continuously running.
Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)  
Total exposure: 425428 kg×day = 1.17 ton×yr

Experimental single-hit residuals rate vs time and energy

2-4 keV

\[ A = (0.0183 \pm 0.0022) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 75.7/79 \quad 8.3 \sigma \text{ C.L.} \]
Absence of modulation? No
\[ \chi^2/\text{dof}=147/80 \Rightarrow P(A=0) = 7 \times 10^{-6} \]

2-5 keV

\[ A = (0.0144 \pm 0.0016) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 56.6/79 \quad 9.0 \sigma \text{ C.L.} \]
Absence of modulation? No
\[ \chi^2/\text{dof}=135/80 \Rightarrow P(A=0) = 1.1 \times 10^{-4} \]

2-6 keV

\[ A = (0.0114 \pm 0.0013) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 64.7/79 \quad 8.8 \sigma \text{ C.L.} \]
Absence of modulation? No
\[ \chi^2/\text{dof}=140/80 \Rightarrow P(A=0) = 4.3 \times 10^{-5} \]

The data favor the presence of a modulated behavior with proper features at 8.8σ C.L.
Modulation amplitudes (A), period (T) and phase (t₀) measured in DAMA/NaI and DAMA/LIBRA

DAMA/NaI (7 annual cycles: 0.29 ton x yr) + DAMA/LIBRA (6 annual cycles: 0.87 ton x yr)

Total exposure: 425428 kg×day = 1.17 ton×yr

<table>
<thead>
<tr>
<th>Energy Interval</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>0.0194 ± 0.0022</td>
<td>0.996 ± 0.002</td>
<td>136 ± 7</td>
<td>8.8σ</td>
</tr>
<tr>
<td>(2±5) keV</td>
<td>0.0149 ± 0.0016</td>
<td>0.997 ± 0.002</td>
<td>142 ± 7</td>
<td>9.3σ</td>
</tr>
<tr>
<td>(2±6) keV</td>
<td>0.0116 ± 0.0013</td>
<td>0.999 ± 0.002</td>
<td>146 ± 7</td>
<td>8.9σ</td>
</tr>
</tbody>
</table>

A, T, t₀ obtained by fitting the single-hit data with A\cos[ω(t-t₀)].

The $\chi^2$ test ($\chi^2 = 9.3, 12.2$ and $10.1$ over 12 d.o.f. for the three energy intervals, respectively) and the run test (lower tail probabilities of 57%, 47% and 35% for the three energy intervals, respectively) accept at 90% C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.

Compatibility among the annual cycles
Power spectrum of single-hit residuals

Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

**DAMA/NaI (7 years)**
- total exposure: 0.29 ton×yr

**DAMA/LIBRA (6 years)**
- total exposure: 0.87 ton×yr

**DAMA/NaI (7 years) + DAMA/LIBRA (6 years)**
- total exposure: 1.17 ton×yr

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Principal mode in the 2-6 keV region:

- **DAMA/NaI**: $2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$
- **DAMA/LIBRA**: $2.697 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$
- **DAMA/NaI+LIBRA**: $2.735 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$

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Not present in the 6-14 keV region (only aliasing peaks)

- Clear annual modulation is evident in (2-6) keV while it is absent just above 6 keV
Rate behaviour above 6 keV

No Modulation above 6 keV

Mod. Ampl. (6-10 keV): cpd/kg/keV

DAMA/LIBRA-1: $(0.0016 \pm 0.0031)$
DAMA/LIBRA-2: $-(0.0010 \pm 0.0034)$
DAMA/LIBRA-3: $-(0.0001 \pm 0.0031)$
DAMA/LIBRA-4: $-(0.0006 \pm 0.0029)$
DAMA/LIBRA-5: $-(0.0021 \pm 0.0026)$
DAMA/LIBRA-6: $(0.0029 \pm 0.0025)$

$\rightarrow$ statistically consistent with zero

DAMA/LIBRA-1 to -6

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 $\rightarrow R_{90} \sim \text{tens cpd/kg} \rightarrow \sim 100\sigma$ far away

No modulation above 6 keV

This accounts for all sources of bckg and is consistent with studies on the various components
Multiple-hits events in the region of the signal

- Each detector has its own TDs read-out → pulse profiles of multiple-hits events (multiplicity > 1) acquired (exposure: 0.87 ton×yr).

- The same hardware and software procedures as those followed for single-hit events

Signals by Dark Matter particles do not belong to multiple-hits events, that is:

\[
\text{multiple-hits events} = \text{Dark Matter particles events “switched off”}
\]

Evidence of annual modulation with proper features as required by the DM annual modulation signature:
- present in the single-hit residuals
- absent in the multiple-hits residual

This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo, further excluding any side effect either from hardware or from software procedures or from background.
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 27.5 for 28 degrees of freedom.
Statistical distributions of the modulation amplitudes, $S_m$

a) $S_m$ for each detector, each annual cycle and each considered energy bin (here 0.25 keV)
b) $<S_m>$ = mean values over the detectors and the annual cycles for each energy bin; $\sigma$ = error on $S_m$

Each panel refers to each detector separately; 96 entries = 16 energy bins in 2-6 keV energy interval $\times$ 6 DAMA/LIBRA annual cycles (for crys 16, 1 annual cycle, 16 entries)

**DAMA/LIBRA (6 years)**
total exposure: 0.87 ton$\times$yr

Individual $S_m$ values follow a normal distribution since $(S_m-<S_m>)/\sigma$ is distributed as a Gaussian with a unitary standard deviation (r.m.s.)

$$x=(S_m-<S_m>)/\sigma, \quad \chi^2=\sum x^2$$

$S_m$ statistically well distributed in all the detectors and annual cycles
The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about $S_m$ already exclude any sizable presence of systematical effects.

### Additional investigations on the stability parameters

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation.

Running conditions stable at a level better than 1% also in the two new running periods.

<table>
<thead>
<tr>
<th></th>
<th>DAMA/LIBRA-1</th>
<th>DAMA/LIBRA-2</th>
<th>DAMA/LIBRA-3</th>
<th>DAMA/LIBRA-4</th>
<th>DAMA/LIBRA-5</th>
<th>DAMA/LIBRA-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>- (0.0001 ± 0.0061) °C</td>
<td>(0.0026 ± 0.0086) °C</td>
<td>(0.001 ± 0.015) °C</td>
<td>(0.0004 ± 0.0047) °C</td>
<td>(0.0001 ± 0.0036) °C</td>
<td>(0.0007 ± 0.0059) °C</td>
</tr>
<tr>
<td>Flux $N_2$</td>
<td>(0.13 ± 0.22) l/h</td>
<td>(0.10 ± 0.25) l/h</td>
<td>- (0.07 ± 0.18) l/h</td>
<td>- (0.05 ± 0.24) l/h</td>
<td>- (0.01 ± 0.21) l/h</td>
<td>- (0.01 ± 0.15) l/h</td>
</tr>
<tr>
<td>Pressure</td>
<td>(0.015 ± 0.030) mbar</td>
<td>- (0.013 ± 0.025) mbar</td>
<td>(0.022 ± 0.027) mbar</td>
<td>(0.0018 ± 0.0074) mbar</td>
<td>- (0.08 ± 0.12) \times 10^{-2} mbar</td>
<td>(0.07 ± 0.13) \times 10^{-2} mbar</td>
</tr>
<tr>
<td>Radon</td>
<td>- (0.029 ± 0.029) Bq/m$^3$</td>
<td>- (0.030 ± 0.027) Bq/m$^3$</td>
<td>- (0.015 ± 0.029) Bq/m$^3$</td>
<td>- (0.052 ± 0.039) Bq/m$^3$</td>
<td>(0.021 ± 0.037) Bq/m$^3$</td>
<td>- (0.028 ± 0.036) Bq/m$^3$</td>
</tr>
<tr>
<td>Hardware rate above single photoelectron</td>
<td>- (0.20 ± 0.18) \times 10^{-2} Hz</td>
<td>(0.09 ± 0.17) \times 10^{-2} Hz</td>
<td>- (0.03 ± 0.20) \times 10^{-2} Hz</td>
<td>(0.15 ± 0.15) \times 10^{-2} Hz</td>
<td>(0.03 ± 0.14) \times 10^{-2} Hz</td>
<td>(0.08 ± 0.11) \times 10^{-2} Hz</td>
</tr>
</tbody>
</table>

All the measured amplitudes well compatible with zero + none can account for the observed effect

(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)
Summary of the results obtained in the additional investigations of possible systematics or side reactions


<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
  - MonteCarlo simulation:
    - muon intensity distribution
    - Gran Sasso rock overburden map
    - Single hit events
  - 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 $\mu$:**
  - $R_n = (\text{fast n by } \mu)/(\text{time unit}) = \Phi_\mu \cdot Y \cdot M_{\text{eff}}$
  - $\Phi_\mu @$ LNGS $\approx 20 \mu$ m$^{-2}$d$^{-1}$ ($\pm 1.5\%$ modulated)
  - Measured neutron Yield @ LNGS:
    - $Y = 1 \div 7 \times 10^{-4}$ n/$\mu$/g/cm$^2$
  - Annual modulation amplitude at low energy due to $\mu$ modulation:
    - $S_{m}^{(m)} = R_n \cdot g \cdot \varepsilon \cdot f_{DE} \cdot f_{\text{single}} \cdot 2\% / (M_{\text{setup}} \cdot \Delta E)$

- **Detector’s matrix:**

- **Hyp.:** $M_{\text{eff}} = 15$ tons; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{\text{single}} \approx 0.5$ (cautiously)
  - Knowing that: $M_{\text{setup}} \approx 250$ kg and $\Delta E = 4$ keV

- **$S_{m}^{(m)} < (0.3-2.4) \times 10^{-5} \text{ cpd/kg/keV}$**

- Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the multi-hits events.
- It cannot mimic the signature: already excluded by $R_{90}$, by multi-hits analysis + different phase, etc.
Inconsistency of the phase between DAMA signal and $\mu$ modulation

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

Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:

- only events at low energy,
- only single-hit events,
- no sizable effect in the multiple-hit counting rate
- pulses with time structure as scintillation light

But, its phase should be (much) larger than $\mu$ phase, $t_{\mu}$:

- if $\tau \ll T/2\pi$: $t_{\text{side}} = t_{\mu} + \tau$
- if $\tau \gg T/2\pi$: $t_{\text{side}} = t_{\mu} + T/4$

It cannot mimic the signature: different phase

$\mu$ 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 muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a “mean” of the muon phase of each year
- The DAMA: modulation amplitude $10^{-2}$ cpd/kg/keV, in 2-6 keV energy range for single hit events; phase:
  May 26 $\pm$ 7 days (stable over 13 years)

considering the seasonal weather al 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 more EPJC72(2012)2064

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

Sterile neutrino

Light Dark Matter

Self interacting Dark Matter

heavy exotic candeitatches, as “4th family atoms”, ...

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
Model-independent evidence by DAMA/NaI and DAMA/LIBRA well compatible with several candidates (in many possible astrophysical, nuclear and particle physics scenarios)

- Resonant DM (arXiv:0909.2900)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Cogent results (arXiv:1002.4703, 1106.0650)
- Composite DM (IJMPD19(2010)1385)
- iDM on Tl (arXiv:1007.2688)
- Specific two higgs doublet models (arXiv:1106.3368)
- exothermic DM (arXiv:1004.0937)
- Secluded WIMPs (PRD79(2009)115019)
- Asymmetric DM (arXiv:1105.5431)
- Leptophobic Z0 models (arXiv:1106.0885)
- SD Inelastic DM (arXiv:0912.4264)
- Complex Scalar Dark Matter (arXiv:1005.3328)
- Specific GU (arXiv:1106.3583)
- Long range forces (arXiv:1108.4661)

Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

**WIMP: SI**

\[ 15 \text{ GeV} \]

\[ 100-120 \text{ GeV} \]

\[ \text{Evans power law} \]

\[ \theta = 2.435 \]

**WIMP: SI & SD**

\[ 15 \text{ GeV} \]

\[ 100 \text{ GeV} \]

\[ \text{Evans power law} \]

**LDM, bosonic DM**

\[ \sigma^N \alpha \over A^2_{N\alpha} \approx \sigma^I \over A^2_I \]

\[ m_L = 0 \]

Compatibility with several candidates; other ones are open

• Not best fit
• About the same C.L.

EPJC56(2008)333
...models...
- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

...and experimental aspects...
- Exposures
- Energy threshold
- 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
**DAMA/NaI & DAMA/LIBRA vs recent possible positive hints 2010/2011**

**CoGeNT:**
low-energy rise in the spectrum (irreducible by the applied background reduction procedures) + annual modulation

**CDMS:**
after many data selections and cuts, 2 Ge candidate recoils survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)

**CRESST:**
after many data selections and cuts, 67 candidate recoils in the O/Ca bands survive in an exposure of 730 kg x day (expected residual background: 40-45 events, depending on minimization)

All those excesses are compatible with the DAMA 8.9σ C.L. annual modulation result in various scenarios
Interpretation of the model independent DAMA results in the case of a “WIMP” candidate with SI coupling

Regions allowed by DAMA experiments at 7.5σ from the null hypothesis (absence of modulation) in 3 instances for the Na and I q.f.:

1) without including the channeling effect (green vertically-hatched region)
2) by including the channeling effect (blue horizontally-hatched region)
3) without the channeling effect but using the energy-dependent Na and I q.f. as in AstrPhys33 (2010)40 (red cross-hatched region)

many of the possible astrophysical models (see PRD66 (2002)043503) + some particle and nuclear model uncertainties for a WIMP with a pure SI coupling considered

Allowed region obtained for the CoGeNT experiment, assuming for simplicity a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters. Region include configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation), i.e. roughly to 90% CL far from zero signal

It is worth noting that, depending on other possible uncertainties not included here, the channeled (blue) horizontally-hatched region could span the domain between the present channeled region and the unchanneled one

Region allowed by CRESST (when its result is interpreted in terms of “WIMP” signal with elastic scattering on nuclei) are also compatible with the DAMA regions when uncertainties in astrophysical, particle and nuclear physics models are considered (e.g. arXiv: 1112.5666)
The new PMTs

Quantum Efficiency features

α/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blu points) and with previous PMT EMI-Electron Tube (red points).

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

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Conclusions

- Positive evidence for the presence of DM particles in the galactic halo now supported at 8.9 $\sigma$ C.L. (cumulative exposure 1.17 ton x yr – 13 annual cycles DAMA/NaI and DAMA/LIBRA)

- No experiment exists whose result can be directly compared in a model independent way with those by DAMA/NaI & DAMA/LIBRA

- The modulation parameters determined with better precision

- Full sensitivity to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation. That is not restricted to DM candidate inducing only nuclear recoils

- Possible positive hints in direct searches – due to excesses above an evaluated background – are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties.

- Indirect model dependent searches not in conflict.

- Investigations other than DM

Since Dec 2010 data taking and optimizations in this new configuration started

Nobody was born not to set a good example (Vincente del Bosque, Spain soccer trainer)

DAMA/LIBRA still the highest radio-pure set-up in the field with the largest sensitive mass, full control of running conditions, the largest duty-cycle, exposure orders of magnitude larger than any other activity in the field, etc., and the only one which effectively exploits a model independent DM signature