DAMA Collaboration (spokesperson: prof. R. Bernabei):
Roma2, Roma1, LNGS-INFN, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev and others
+ neutron meas.: ENEA-Frascati e ENEA-Casaccia
+ in some studies on $\beta\beta$ decays (DST-MAE project): IIT Kharagpur/Ropar, India

DAMA Experimental Activities

DAMA: an observatory for rare processes @LNGS

http://people.roma2.infn.it/dama
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

---

**Composition?**
DM multicomponent also in the particle part?

**Right related nuclear and particle physics?**

**Right halo model and parameters?**
- Non thermalized components?
- Caustics?
- Clumpiness?

**etc... etc...**
Some Direct Detection Processes:

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

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

- Inelastic Dark Matter: $W + N \rightarrow W^* + N$

- Elastic scatterings on nuclei
  → detection of nuclear recoil energy

- 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

- Ionization:
  Ge, Si

- Bolometer:
  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

- e.g. sterile $\nu$

- ... also other ideas ...

- ... and more
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 June 2nd)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios.

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

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

the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

To mimic this signature, spurious effects and side reactions must not only - 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)

Permanences:

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
- Investigation on diurnal effect
- Exotic Dark Matter search
  PRL83(1999)4918
- Annual Modulation Signature

Data taking completed on July 2002, last data release 2003. Still producing results

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
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)

Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: D\textsuperscript{232}Th, D\textsuperscript{238}U and D\textsuperscript{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>30445</td>
<td>0.501</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>Sept. 9, 2003 - Sept. 8, 2010</td>
<td>379705</td>
<td>1.04 ton×yr</td>
</tr>
<tr>
<td>DAMA/NaI + DAMA/LIBRA-phase1</td>
<td>Sept. 9, 2003 - Sept. 8, 2010</td>
<td>379705</td>
<td>1.04 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
- EPJC56(2008)333
- EPJC67(2010)39
- EPJC73(2013)2648
- calibrations: $\approx$96 Mevents from sources
- acceptance window eff: 95 Mevents ($\approx$3.5 Mevents/keV)

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

a ton × yr experiment done
Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1  Total exposure: 1.33 ton\text{yr}

Residual rate of the 2-6 keV single-hit scintillation events vs time

Absence of modulation? No
\[ \chi^2/\text{dof} = 154/87 \]
\[ P(A=0) = 1.3 \times 10^{-5} \]

Fit with all the parameters free:
\[ A = (0.0112 \pm 0.0012) \text{ cpd/kg/keV} \]
\[ t_0 = (144 \pm 7) \text{ d} - T = (0.998 \pm 0.002) \text{ y} \]

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.3\sigma C.L.
Model Independent Annual Modulation Result

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

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

<table>
<thead>
<tr>
<th></th>
<th>A (cpd/kg/keV)</th>
<th>T = 2π/ω (yr)</th>
<th>t₀ (day)</th>
<th>C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/NaI + DAMA/LIBRA-phase1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2-4) keV</td>
<td>0.0190 ± 0.0020</td>
<td>0.996 ± 0.002</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 ± 0.002</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 ± 0.002</td>
<td>144 ± 7</td>
<td>9.3σ</td>
</tr>
</tbody>
</table>

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

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 residual rates of the single-hit events measured over the 7 DAMA/LIBRA annual cycles are reported as collected in a single cycle.

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.3σ C.L.
Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1

Total exposure: 487526 kg×day = 1.33 ton×yr

Maximum likelihood analysis of single hit events

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

\[ R(t) = S_0 + S_m \cos \left( \frac{2\pi}{\omega} (t - t_0) \right) \]

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

Energy distribution of the \( S_m \) variable for the total exposure. A clear modulation is present in the lowest energy region, while \( S_m \) values compatible with zero are present just above. In fact, 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.

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.
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: $(0.0029 \pm 0.0025)$
  - DAMA/LIBRA-7: $(0.0023 \pm 0.0024)$

→ 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:

<table>
<thead>
<tr>
<th>Period</th>
<th>Mod. Ampl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA-1</td>
<td>$-0.05 \pm 0.19$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>$-0.12 \pm 0.19$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>$-0.13 \pm 0.18$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>$0.15 \pm 0.17$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-5</td>
<td>$0.20 \pm 0.18$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-6</td>
<td>$0.20 \pm 0.16$ cpd/kg</td>
</tr>
<tr>
<td>DAMA/LIBRA-7</td>
<td>$0.28 \pm 0.18$ cpd/kg</td>
</tr>
</tbody>
</table>

$\sigma \approx 1\%$, fully accounted by statistical considerations

- 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 $\approx 0.13 \text{ m}^2$
  - $m$ 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 $\mu$:**
  - $\Phi_\mu @ LNSG \approx 20 \, \mu \text{ m}^{-2}\text{d}^{-1}$ (±1.5% modulated)
  - Annual modulation amplitude at low energy due to $\mu$ modulation:
    \[
    S_{m(\mu)} = R_n \, g \, e \, f_{DE} \, f_{\text{single}} \, 2\% \, / (M_{\text{setup}} \, \text{DE})
    \]

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

The DAMA phase: May 26 ± 7 days (stable over 14 years)

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

... many others arguments EPJC72(2012)2064, EPJC74(2014)3196
No role for $n/\mu/\nu$ in DAMA annual modulation result

- Contributions to the total neutron flux at LNGS;
- Counting rate in DAMA/LIBRA for single-hit events, in the (2–6) keV energy region induced by:
  - neutrons,
  - muons,
  - solar neutrinos.

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

(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} ) (neutrons cm(^{-2}) s(^{-1}))</th>
<th>( \eta_k )</th>
<th>( t_k )</th>
<th>( R_{0,k} ) (cpd/kg/keV)</th>
<th>( A_k = R_{0,k} \eta_k ) (cpd/kg/keV)</th>
<th>( A_k/S_{\text{exp}} )</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 ) however ( \ll 0.1 ) [2, 7, 8]</td>
<td>-</td>
<td>&lt; 8 \times 10(^{-6})</td>
<td>( \ll 8 \times 10(^{-7})</td>
<td>( \ll 7 \times 10(^{-5})</td>
</tr>
<tr>
<td>epithermal n (eV-keV)</td>
<td>2 \times 10(^{-6}) [15]</td>
<td>( \simeq 0 ) however ( \ll 0.1 ) [2, 7, 8]</td>
<td>-</td>
<td>&lt; 3 \times 10(^{-3})</td>
<td>( \ll 3 \times 10(^{-4})</td>
<td>( \ll 0.03 )</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 ) however ( \ll 0.1 ) [2, 7, 8]</td>
<td>-</td>
<td>&lt; 6 \times 10(^{-4})</td>
<td>( \ll 6 \times 10(^{-5})</td>
<td>( \ll 5 \times 10(^{-3})</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 [23, 7, 8]</td>
<td>&lt; 7 \times 10(^{-4}) (see text and ref. [2, 7, 8])</td>
<td>( \ll 9 \times 10(^{-6})</td>
<td>( \ll 8 \times 10(^{-4})</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 [23, 7, 8]</td>
<td>&lt; 1.4 \times 10(^{-3}) (see text and footnote 3)</td>
<td>( \ll 2 \times 10(^{-5})</td>
<td>( \ll 1.6 \times 10(^{-3})</td>
</tr>
<tr>
<td>( \nu \rightarrow n ) (few MeV)</td>
<td>( \simeq 3 \times 10(^{-10}) ) (see text)</td>
<td>0.03342* Jan. 4th*</td>
<td>-</td>
<td>&lt; 7 \times 10(^{-5}) (see text)</td>
<td>( \ll 2 \times 10(^{-6})</td>
<td>( \ll 2 \times 10(^{-4})</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 [23, 7, 8]</td>
<td>( \simeq 10^{-7})</td>
<td>( \simeq 10^{-9})</td>
<td>( \simeq 10^{-7})</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* Jan. 4th*</td>
<td>-</td>
<td>( \simeq 10^{-5})</td>
<td>( \simeq 3 \times 10^{-7})</td>
<td>( \simeq 3 \times 10^{-5})</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><strong>RADON</strong></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><strong>TEMPERATURE</strong></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><strong>NOISE</strong></td>
<td>Effective full noise rejection near threshold</td>
<td>$&lt;10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td><strong>ENERGY SCALE</strong></td>
<td>Routine + intrinsic calibrations</td>
<td>$&lt;1-2 \times 10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td><strong>EFFICIENCIES</strong></td>
<td>Regularly measured by dedicated calibrations</td>
<td>$&lt;10^{-4}$ cpd/kg/keV</td>
</tr>
<tr>
<td><strong>BACKGROUND</strong></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><strong>SIDE REACTIONS</strong></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**

Diurnal effects with DAMA/LIBRA–phase1

Velocity of the detector in the terrestrial laboratory:

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

Since:

\[ |\vec{v}_s| = |\vec{v}_{\text{LSR}} + \vec{v}_{\odot}| \approx 232 \pm 50 \text{ km/s}, \]
\[ |\vec{v}_{\text{rev}}(t)| \approx 30 \text{ km/s} \]
\[ |\vec{v}_{\text{rot}}(t)| \approx 0.34 \text{ km/s} \]

at LNGS

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

\[ S_k[\vec{v}_{\text{lab}}(t)] \simeq S_k[\vec{v}_s] + \left[ \frac{\partial S_k}{\partial \vec{v}_{\text{lab}}} \right]_{\vec{v}_s} [V_{\text{Earth}}B_m \cos(\omega(t - t_0)) + V_r B_d \cos \omega_{\text{rot}}(t - t_d)] \]

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

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

at LNGS latitude

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval: \( 0.0097 \pm 0.0013 \) cpd/kg/keV
- Thus, the expected value of the diurnal modulation amplitude is \( \simeq 1.5 \times 10^{-4} \) 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.

\( A_d (2-6 \text{ keV}) < 1.2 \times 10^{-3} \) 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 $m_{DM}$. 
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 × 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.
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 - at least in principle - be directly compared in a model independent way with DAMA.
... an example in literature...

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

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

PRD84(2011)055014, IJMPA28(2013)1330022

Including the Migdal effect ➔ Towards lower mass/higher σ

Co-rotating halo, Non thermalized component ➔ Enlarge allowed region towards larger mass
DAMA annual modulation effect and Symmetric mirror matter

Symmetric mirror matter:
- halo composed by a bubble of Mirror particles of different species; Sun is travelling across the bubble which is moving in the Galactic Frame (GF);
- the mirror particles in the bubble have Maxwellian velocity distribution in a frame where the bubble is at rest; cold and hot bubble with temp from $10^4$ K to $10^8$ K
- interaction via photon - mirror photon kinetic mixing

Examples of expected phase of the annual modulation signal

The blue regions correspond to directions of the halo velocities in GC ($\theta$, $\phi$) giving a phase compatible at $3\sigma$ with DAMA phase.
DAMA annual modulation effect and Symmetric mirror matter

Symmetric mirror matter:

- Results refers to halo velocities parallel or anti-parallel to the Sun ($\alpha = 0, \pi$). For these configurations the expected phase is June 2
- The only parameter whose value will be varied in the analysis is the $V_{\text{halo}}$ module (positive velocity will correspond to halo moving in the same direction of the Sun while negative velocity will correspond to opposite direction)

<table>
<thead>
<tr>
<th>Mirror matter composition</th>
<th>H (%)</th>
<th>He (%)</th>
<th>C (%)</th>
<th>O (%)</th>
<th>Fe (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}', \text{He}'$</td>
<td>25</td>
<td>75</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\text{H}', \text{He}', \text{C}', \text{O}'$</td>
<td>12.5</td>
<td>75.</td>
<td>7.</td>
<td>5.5</td>
<td>-</td>
</tr>
<tr>
<td>$\text{H}', \text{He}', \text{C}', \text{O}', \text{Fe}'$</td>
<td>20</td>
<td>74</td>
<td>0.9</td>
<td>5.</td>
<td>0.1</td>
</tr>
</tbody>
</table>

DAMA/LIBRA allowed values for $\sqrt{f \epsilon}$ in different scenarios

where $f$ is the fraction of DM in the Galaxy in form of mirror atoms and $\epsilon$ is the coupling constant

Many configurations and halo models favoured by the DAMA annual modulation effect corresponds to couplings values well compatible with cosmological bounds.
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
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, 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 phase 2 – data taking

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

- Fall 2012: new preamplifiers installed + special trigger modules.
- Calibrations 5 a.c.: ~1.03 x 10^8 events from sources
- Acceptance window eff. 5 a.c.: ~7 x 10^7 events (~2.8 x 10^6 events/keV)
- Exposure collected in the first 5 a.c. of DAMA/LIBRA-phase2: 0.92 ton x yr

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

<table>
<thead>
<tr>
<th>Annual Cycle (a.c.)</th>
<th>Period</th>
<th>Mass (kg)</th>
<th>Exposure (kg · day)</th>
<th>(α-β^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Dec 2010 – Sept. 2011</td>
<td>242.5</td>
<td>62917</td>
<td>0.519</td>
</tr>
<tr>
<td>II</td>
<td>Nov. 2, 2011 – Sept. 11, 2012</td>
<td>242.5</td>
<td>60586</td>
<td>0.534</td>
</tr>
<tr>
<td>III</td>
<td>Oct. 8, 2012 – Sept. 2, 2013</td>
<td>242.5</td>
<td>73792</td>
<td>0.479</td>
</tr>
<tr>
<td>IV</td>
<td>Sept. 8, 2013 – Sept. 1, 2014</td>
<td>242.5</td>
<td>71180</td>
<td>0.486</td>
</tr>
<tr>
<td>V</td>
<td>Sept. 1, 2014 – Sept. 9, 2015</td>
<td>242.5</td>
<td>67527</td>
<td>0.522</td>
</tr>
<tr>
<td>VI</td>
<td>Sept. 10, 2015 – Aug. 24, 2016</td>
<td>242.5</td>
<td>75135</td>
<td>0.480</td>
</tr>
</tbody>
</table>

New Data Release...

Exposure expected for the first data release of DAMA/LIBRA-phase2, 6 a.c.: ≈ 1.13 ton x yr
Towards future DAMA/LIBRA-phase3

DAMA/LIBRA-phase3 (enhancing sensitivities for corollary aspects, other DM features, second order effects and other rare processes):

• R&D studies towards the possible DAMA/LIBRA-phase3 are continuing in particular as regards new protocols for possible modifications of the detectors; moreover, four new PMT prototypes from a dedicated R&D with HAMAMATSU are already at hand.
• Improving the light collection of the detectors (and accordingly the light yields and the energy thresholds). Improving the electronics.
• Other possible option: new ULB crystal scintillators (e.g. ZnWO₄) placed among the DAMA/LIBRA detectors to add also a high sensitivity directionality measurements.

The presently-reached metallic PMTs features:
• Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
• radiopurity at level of 5 mBq/PMT (⁴⁰K), 3-4 mBq/PMT (²³²Th), 3-4 mBq/PMT (²³⁸U), 1 mBq/PMT (²²⁶Ra), 2 mBq/PMT (⁶⁰Co).

4 prototypes at hand
Anisotropic detectors are of great interest for many applicative fields, e.g.: they can offer a unique way to study directionality for Dark Matter candidates that induce just nuclear recoils.

Taking into account:
- the correlation between the direction of the nuclear recoils and the Earth motion in the galactic rest frame;
- the peculiar features of anisotropic detectors;

The detector response is expected to vary as a function of the sidereal time.

### Development of ZnWO₄ scintillators

- Both light output and pulse shape have anisotropic behavior and can provide two independent ways to study directionality.
- Very high reachable radio-purity;
- Threshold at keV feasible;

<table>
<thead>
<tr>
<th>Angle n-scat.</th>
<th>Axis</th>
<th>E_{\text{peak}} (keVee)</th>
<th>E_{\text{recoil,O}} (keV)</th>
<th>Q</th>
<th>Q_I / Q_{III}</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>I</td>
<td>157.5±3.0</td>
<td>856</td>
<td>0.184±0.004</td>
<td>1.26±0.05</td>
</tr>
<tr>
<td>60</td>
<td>III</td>
<td>124.9±4.1</td>
<td>856</td>
<td>0.146±0.005</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>I</td>
<td>170.5±2.2</td>
<td>1116</td>
<td>0.153±0.002</td>
<td>1.37±0.08</td>
</tr>
<tr>
<td>70</td>
<td>III</td>
<td>125.5±6.8</td>
<td>1116</td>
<td>0.112±0.006</td>
<td></td>
</tr>
</tbody>
</table>

O → light masses
Zn, W → high masses

Presently running at ENEA-Casaccia with neutron generator to measure anisotropy in keV range.
ZnWO₄ – work in progress…

- Cryostat for low temperature measurement with scintillation detectors realized
- Test of the Cryostat in progress
- Lowering the energy threshold (new PMT with higher QE, SiPM, APD, SDD, …)
- New purification techniques under study

- Measurements of anisotropy at low energy with MP320 Neutron Generator ($E_n = 14$ MeV) in progress at Casaccia ENEA lab
- Development of electronics

*Exp @ ENEA-Casaccia lab*

Diagram:
- ZnWO₄
- Paraffine
- Neutron Generator
- Scattered Neutron
- Nuclear Recoil
- PMT
- PSD capability of the EJ-309 Liquid Scintillator Detector Used
Conclusions

- Positive evidence for the presence of DM particles in the galactic halo at $9.3\sigma$ C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: 1.33 ton × yr)
- Modulation parameters determined with higher precision
- New investigations 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)
- Continuing investigations of rare processes other than DM
- **DAMA/LIBRA – phase3 R&D in progress**
- R&D for a possible DAMA/1ton set-up, proposed by DAMA since 1996, continuing as well as some other R&Ds
Thank you for the attention