DAMA/LIBRA results and perspectives

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DAMA set-ups

an observatory for rare processes @ LNGS

- DAMA/LIBRA (DAMA/NaI)
- DAMA/LXe
- DAMA/R&D
- DAMA/Crys
- DAMA/Ge

Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev + other institutions
+ neutron meas.: ENEA-Frascati
+ in some studies on $\beta\beta$ decays (DST-MAE and Inter-Universities project):
IIT Kharagpur and Ropar, India

web site: http://people.roma2.infn.it/dama
**Some direct detection processes:**

- **Scatterings on nuclei**
  - detection of nuclear recoil energy
  - [Diagram: DMp incident on nucleus N]

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

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

- **Interaction only on atomic electrons**
  - detection of e.m. radiation
  - [Diagram: DMp incident on electron]

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

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

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

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

- **Ionization:** Ge, Si

- **Sterile $\nu$**

- **DMp'**

- **... even WIMPs**

- **... also other ideas ...**

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

1) Modulated rate according cosine
2) In 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

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

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

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

- \( \nu_{\text{sun}} \sim 232 \text{ km/s} \) (Sun vel in the halo)
- \( \nu_{\text{orb}} = 30 \text{ km/s} \) (Earth vel around the Sun)
- \( \gamma = \pi/3, \omega = 2\pi/T \), \( T = 1 \text{ year} \)
- \( t_0 = 2^{nd} \text{ June} \) (when \( \nu_\oplus \) is maximum)
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**

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: $^{232}$Th, $^{238}$U and $^{40}$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


The DAMA/LIBRA set-up

Polyethylene/paraffin

- 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

- ~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
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

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

**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

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

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>232.8</td>
<td>51405</td>
<td>0.562</td>
</tr>
<tr>
<td>DAMA/LIBRA-2</td>
<td>232.8</td>
<td>52597</td>
<td>0.467</td>
</tr>
<tr>
<td>DAMA/LIBRA-3</td>
<td>232.8</td>
<td>39445</td>
<td>0.591</td>
</tr>
<tr>
<td>DAMA/LIBRA-4</td>
<td>232.8</td>
<td>49377</td>
<td>0.541</td>
</tr>
<tr>
<td>DAMA/LIBRA-5</td>
<td>232.8</td>
<td>66105</td>
<td>0.468</td>
</tr>
<tr>
<td>DAMA/LIBRA-6</td>
<td>242.5</td>
<td>58768</td>
<td>0.519</td>
</tr>
<tr>
<td>DAMA/LIBRA-7</td>
<td>242.5</td>
<td>62098</td>
<td>0.515</td>
</tr>
<tr>
<td>DAMA/LIBRA-phase1</td>
<td>379795</td>
<td>1.04 ton×yr</td>
<td>0.518</td>
</tr>
<tr>
<td>DAMA/NaI + DAMA/LIBRA-phase1</td>
<td>1.33 ton×yr</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DAMA/LIBRA-phase1:**
- First upgrade on Sept 2008: replacement of some PMTs in HP N$_2$ 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: $\approx$96 Mevents from sources
- Acceptance window eff: 95 Mevents ($\approx$3.5 Mevents/keV)
The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.
DAMA/NaI & DAMA/LIBRA experiments main upgrades and improvements

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

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:
1. one detector recovered by replacing a broken PMT
2. a new optimization of some PMTs and HVs performed
3. all the TD replaced with new ones (U1063A Acqiris 8-bit 1GS/s DC270 High-Speed cPCI Digitizers)
4. a new DAQ with optical read-out installed.

On 2003 DAMA/LIBRA has begun first operations

The second DAMA/LIBRA upgrade in Fall 2010:
Replacement of all the PMTs with higher Q.E. ones from dedicated developments
(+new preamp in Fall 2012 and 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)
    - DAMA/LIBRA-2: (0.0010 ± 0.0034)
    - DAMA/LIBRA-3: (0.0001 ± 0.0031)
    - DAMA/LIBRA-4: (0.0006 ± 0.0029)
    - DAMA/LIBRA-5: (0.0021 ± 0.0026)
    - DAMA/LIBRA-6: (0.0029 ± 0.0025)
    - DAMA/LIBRA-7: (0.0023 ± 0.0024)

  → statistically consistent with zero

- No modulation in the whole energy spectrum:
  studying integral rate at higher energy, R\textsubscript{90}

  - R\textsubscript{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:

    | Period     | Mod. Ampl.          |
    |------------|---------------------|
    | DAMA/LIBRA-1 | -0.05±0.19 cpd/kg   |
    | DAMA/LIBRA-2 | -0.12±0.19 cpd/kg   |
    | DAMA/LIBRA-3 | -0.13±0.18 cpd/kg   |
    | DAMA/LIBRA-4 | 0.15±0.17 cpd/kg    |
    | DAMA/LIBRA-5 | 0.20±0.18 cpd/kg    |
    | DAMA/LIBRA-6 | -0.20±0.16 cpd/kg   |
    | DAMA/LIBRA-7 | -0.28±0.18 cpd/kg   |

  σ ≈ 1%, fully accounted by statistical considerations

  + if a modulation present in the whole energy spectrum at the level found
  in the lowest energy region → R\textsubscript{90} ~ tens cpd/kg → ~ 100 σ far away

No modulation above 6 keV

This accounts for all sources of bckg and is consistent with the studies on the various components
The modulation amplitude, $S_m$, obtained by maximum likelihood method

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

DAMA/NaI + DAMA/LIBRA-phase1
total exposure: 487526 kg$\times$day $\approx$1.33 ton$\times$yr

$\Delta E = 0.5$ keV bins

$T = \frac{2\pi}{\omega} = 1$ yr

$t_0 = 152.5$ day

A clear modulation is present in the (2-6) keV energy interval, while $S_m$ values compatible with zero are present just above

The $S_m$ values in the (6–20) keV energy interval have random fluctuations around zero with $\chi^2$ equal to 35.8 for 28 degrees of freedom (upper tail probability 15%)
Is there a sinusoidal contribution in the signal? phase $\neq 152.5$ day?

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

**DAMA/NaI + DAMA/LIBRA-phase1**

total exposure: $487526 \text{ kg} \times \text{day} \approx 1.33 \text{ ton} \times \text{yr}$

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $t^* \approx t_0 = 152.5d$
- $\omega = 2\pi/T$
- $T = 1$ year

Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)
No role for $\mu$ in DAMA annual modulation result

- **Direct $\mu$ interaction in DAMA/LIBRA set-up:**
  - DAMA/LIBRA surface $\approx 0.13$ m$^2$
  - $\mu$ flux @ DAMA/LIBRA $\approx 2.5$ $\mu$/day
  - It cannot mimic the signature: already excluded by $R_{90}$, by multi-hits analysis + different phase, etc.

- **Rate, $R_n$, of fast neutrons produced by $\mu$:**
  - $\Phi_\mu$ @ LNGS $\approx 20 \mu$ m$^{-2}$d$^{-1}$ ($\pm 1.5\%$ modulated)
  - Annual modulation amplitude at low energy due to $\mu$ modulation:
    $$S_m(\mu) = R_n g \varepsilon f_{\Delta E} f_{\text{single}} 2\% / (M_{\text{setup}} \Delta E)$$
  - Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the multi-hits events

- **Inconsistency of the phase between DAMA signal and $\mu$ modulation**
  - $\mu$ flux @ LNGS (MACRO, LVD, BOREXINO) $\approx 3 \cdot 10^{-4}$ m$^2$s$^{-1}$; modulation amplitude $1.5\%$; **phase**: July 7 $\pm 6$ d, June 29 $\pm 6$ d (Borexino)
  - The DAMA phase: May 26 $\pm 7$ days (stable over 13 years)
  - The DAMA phase is $5.7\sigma$ far from the LVD/BOREXINO phases of muons ($7.1\sigma$ far from MACRO measured phase)

- 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.

\[ \Phi_k = \Phi_0,k \left(1 + \eta_k \cos \omega (t - t_k)\right) \]
\[ R_k = R_0,k \left(1 + \eta_k \cos \omega (t - t_k)\right) \]

The annual modulation of solar neutrinos 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) can mimic the DM annual modulation signature since some of the peculiar requirements of the signature would fail, such as the neutrons would induce e.g. variations in all the energy spectrum, variation in the multiple hit events,... which were not observed.
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
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

Neutralino as LSP in various SUSY theories

Various kinds of WIMP candidates with several different kinds of interactions
Pure SI, pure SD, mixed + Migdal effect +channeling,... (from low to high mass)

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

Self-interacting Dark Matter

Pseudoscalar, scalar or mixed light bosons with axion-like interactions

a heavy \( \nu \) of the 4-th family

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

Sterile neutrino

Elementary Black holes such as the Daemons

Kaluza Klein particles

... and more
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

Well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

Compatibility with several candidates; other ones are open

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

- Not best fit
- About the same C.L.

WIMP: SI

WIMP: SI & SD $\theta = 2.435$

LDM, bosonic DM

\[ \frac{\sigma^{N,\alpha}}{A_{N,\alpha}} \sim \frac{\sigma^{I}}{A_{I}} \]

$\sigma^{N,\alpha}$

$\sigma^{I}$

$A_{N,\alpha}$

$A_{I}$

$m_L = 0$

EPJC56(2008)333
IJMPA28(2013)1330022
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 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
Case of DM particles inducing elastic scatterings on target-nuclei, SI case

Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ 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 a particular set of astrophysical, nuclear and particle Physics assumptions 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.

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
Scratching Below the Surface of the Most General Parameter Space (S. Scopel arXiv:1505.01926)

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

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~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 \( \frac{\epsilon}{2} F^\mu\nu F^\nu_\mu \)
- 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

DAMA/LIBRA allowed values for \( \sqrt{f} \cdot \epsilon \) in the case of mirror hydrogen atom, \( Z' = 1 \)
Perspectives for the future

Other signatures?
- Diurnal effects
- Second order 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: 

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

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

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

**Annual modulation term:**

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

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

**Diurnal modulation term:**

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

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

Expected signal counting rate in a k–th energy bin:

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

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

\[ R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{\text{Earth}} B_m} \approx 0.016 \text{ at LNGS latitude} \]
• Experimental *single-hit* residuals rate vs either sidereal and solar time.

• These residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part 

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

no diurnal variation with a significance of 95% C.L. + run test. The lower tail probabilities (in the four energy regions) are: 43, 18, 7, 26% for the solar case and 54, 84, 78, 16% for the sidereal case.

Thus, the presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity.

• 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 $\approx 1.5 \times 10^{-4}$ cpd/kg/keV.

• When fitting the *single-hit* residuals with a cosine function with period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes $A_d$ are compatible with zero at the present level of sensitivity.

Present experimental sensitivity is not yet enough for the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect.

larger exposure DAMA/LIBRA–phase2 (+lower energy threshold) offers increased sensitivity to such an effect.
Other signatures?

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

Earth shadowing effect with DAMA/LIBRA–phase1

- **Earth Shadow Effect** could be expected for DM candidate particles inducing 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 $m_{DM}$. 
DAMA/LIBRA phase 2 - running

Quantum Efficiency features

- Second upgrade on end of 2010: all PMTs replaced with new ones of higher Q.E.
- Mean value:
  - 7.5% (0.6% RMS)
  - 6.7% (0.5% RMS)
- Previous PMTs: 5.5-7.5 ph.e./keV
- New PMTs: up to 10 ph.e./keV

Quantum Efficiency features chart

Residual Contamination

Energy resolution

- σ/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).

The light responses

- Previous PMTs: 5.5-7.5 ph.e./keV
- New PMTs: up to 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
The importance of studying second order effects and the annual modulation phase

High exposure and lower energy threshold can allow further investigation on:

- the nature of the DM candidates
- possible diurnal effects on the sidereal time
- astrophysical models

The annual modulation phase depends on:

- Presence of streams (as SagDEG and Canis Major) in the Galaxy
- Presence of caustics
- Effects of gravitational focusing of the Sun

A step towards such investigations:

DAMA/LIBRA-phase2 running with lower energy threshold + further possible improvements (DAMA/LIBRA-phase3) and DAMA/1ton
Possible DAMA/LIBRA-phase3

• The light collection of the detectors can further be improved
• Light yields and the energy thresholds will improve accordingly

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

The presently-reached PMTs features, but not for the same PMT mod.:

• Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
• radiopurity at level of 5 mBq/PMT ($^{40}$K), 3-4 mBq/PMT ($^{232}$Th), 3-4 mBq/PMT ($^{238}$U), 1 mBq/PMT ($^{226}$Ra), 2 mBq/PMT ($^{60}$Co).

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

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

- Diurnal effects
- Second order effects
- Shadow effects
- Directionality
- …
Directionality technique with crystals

- Only for candidates inducing just recoils
- Identification of the Dark Matter particles by exploiting the non-isotropic recoil distribution correlated to the Earth velocity

The ADAMO project: Study of the directionality approach with ZnWO$_4$ anisotropic detectors

Nuclear recoils are expected to be strongly correlated with the DM impinging direction. 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 ZnWO$_4$ detectors depend on the direction of the impinging particles with respect to the crystal axes. Both these anisotropic features can provide two independent ways to exploit the directionality approach.

These and others competitive characteristics of ZnWO$_4$ detectors could permit to reach sensitivity comparable with that of the DAMA/LIBRA positive result.
Conclusions

- Positive evidence for the presence of DM particles in the galactic halo supported at $9.3\sigma$ C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: $1.33 \text{ ton} \times \text{yr}$)
- Modulation parameters determined with high precision
- New investigation on different peculiarities of the DM signal exploited (Diurnal Modulation and Earth Shadow Effect)
- Full sensitivity to many kinds of DM candidates and interactions types (both inducing recoils and/or e.m. radiation), full sensitivity to low and high mass candidates

- DAMA/LIBRA – phase2 in data taking at lower software energy threshold (below 2 keV) to investigate further features of DM signals and second order effects
- Continuing investigations of rare processes other than DM as well as further developments
- DAMA/LIBRA – phase3 R&D in progress
- R&D for a possible DAMA/1ton set-up, proposed by DAMA since 1996, continuing
- Study of ZnWO$_4$ scintillator for exploiting directionality technique in progress