Direct detection of Dark Matter particles
Relic DM particles from primordial Universe

- SUSY (as neutralino or sneutrino in various scenarios)
  - the sneutrino in the Smith and Weiner scenario
  - a heavy ν of the 4-th family
  - even a suitable particle not yet foreseen by theories

- electron interacting dark matter

- sterile ν

- axion-like (light pseudoscalar and scalar candidate)

- self-interacting dark matter

- mirror dark matter

- Kaluza-Klein particles (LKK)

- heavy exotic candidates, as "4th family atoms", ...

- Elementary Black holes, Planckian objects, Daemons

- (& invisible axions, ν's)

- Right halo model and parameters?

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

  - Right related nuclear and particle physics?

  - Non thermalized components?

  - Caustics?

  - clumpiness?

- etc... etc...
What accelerators can do:

to demonstrate the existence of some of the possible DM candidates

What accelerators cannot do:

to credit that a certain particle is the Dark Matter solution or the “single” Dark Matter particle solution…

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

DM direct detection method using a model independent approach and a low-background widely-sensitive target material
Some direct detection processes:

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

  ![Diagram of scatterings on nuclei]

  **Ionization:** Ge, Si
  **Bolometer:** TeO₂, Ge, CaWO₄, ...
  **Scintillation:** NaI(Tl), LXe, CaF₂(Eu), ...

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

- **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 of interaction with atomic electrons]

  ![Diagram of X-ray detection]

  ![Diagram of e.g. sterile $\nu$]

- **Interaction of light DMp (LDM)** on $e^-$ or nucleus with production of a lighter particle
  → detection of electron/nucleus recoil energy

  ![Diagram of interaction with DMp and light particle]

- **Ionization:** Ge, Si
  **Scintillation:** NaI(Tl), LXe, CaF₂(Eu), ...
  **Bolometer:** TeO₂, Ge, CaWO₄, ...

- **... even WIMPs**

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

- **... and more**

E.g. signals from these candidates are completely lost in experiments based on “rejection procedures” of the e.m. component of their rate.
The direct detection experiments can be classified in two classes, depending on what they are based:

1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a “model-independent” signature

2. on the use of uncertain techniques of rejection of electromagnetic background (adding systematical effects and lost of candidates with pure electromagnetic productions)
Dark Matter direct detection activities in underground labs

- Various approaches and techniques (many still at R&D stage)
- Various different target materials
- Various different experimental site depths
- Different radiopurity levels, etc.

- Gran Sasso (depth ~ 3600 m.w.e.): DAMA/Nal, DAMA/LIBRA, DAMA/LXe, HDMS, WARP, CRESST, Xenon10
- Boulby (depth ~ 3000 m.w.e.): Drift, Zeplin, NAIAID
- Modane (depth ~ 4800 m.w.e.): Edelweiss
- Canfranc (depth ~ 2500 m.w.e.): ANAIS, Rosebud, ArDM

- Snolab (depth ~ 6000 m.w.e.): Picasso, DEAP, CLEAN
- Stanford (depth ~10 m): CDMS I
- Soudan (depth ~ 2000 m.w.e.): CDMS II
- FNAL: COUPP

- Y2L (depth ~ 700 m): KIMS
- Oto (depth ~ 1400 m.w.e.): PICO-LON
- Kamioka (depth ~2700 m.w.e.): XMASS
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target</th>
<th>Type</th>
<th>Status</th>
<th>Site</th>
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<tr>
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<td>NaI</td>
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<td>construction</td>
<td>Canfranc</td>
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<td>concluded</td>
<td>LNGS</td>
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<td>DAMA/LIBRA</td>
<td>NaI</td>
<td>annual modulation</td>
<td>running</td>
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<td>R&amp;D</td>
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<td>HDMS</td>
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<td>KIMS</td>
<td>CsI</td>
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<td>Y2L(Korea)</td>
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<tr>
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<td>running</td>
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<td>Frejus</td>
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<td>F</td>
<td>SH droplet</td>
<td>R&amp;D</td>
<td>Fermilab</td>
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<tr>
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<td>F</td>
<td>SH droplet</td>
<td>running + R&amp;D</td>
<td>SNOLAB</td>
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<tr>
<td>SIMPLE</td>
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<td>CS₂ gas</td>
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<td>Bas Bruit</td>
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<tr>
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<td>³He gas</td>
<td>TPC</td>
<td>R&amp;D</td>
<td>LPSC Grenoble</td>
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</table>
The annual modulation: a model independent signature for the investigation of Dark Matter 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 would point out its presence.

Drukier, Freese, Spergel PRD86
Freese et al. PRD88

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

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

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

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

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) 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

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
+ neutron meas.: ENEA-Frascati
+ in some studies on $^7$Li decays (DST-MAE project): IIT Kharagpur, India

DAMA: an observatory for rare processes @LNGS

DAMA/LXe  DAMA/R&D  low bckg DAMA/Ge for sampling meas.

DAMA/NaI  meas. with $^{100}$Mo

DAMA/LIBRA

http://people.roma2.infn.it/dama
Results on rare processes:

- Possible Pauli exclusion principle violation
  - Reference: PLB408(1997)439

- CNC processes
  - Reference: PRC60(1999)065501

- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
  - Reference: PLB460(1999)235

- Search for solar axions
  - Reference: PLB515(2001)6

- Exotic Matter search
  - Reference: EPJ direct C14(2002)1

- Search for superdense nuclear matter
  - Reference: EPJ A23(2005)7

- Search for heavy clusters decays
  - Reference: EPJ A24(2005)51

Results on DM particles:

- PSD
  - Reference: PLB389(1996)757

- Investigation on diurnal effect

- Exotic Dark Matter search
  - Reference: PRL83(1999)4918

- Annual Modulation Signature

**Model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.**

total exposure (7 annual cycles) 0.29 ton x yr
detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

The new 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)

installing DAMA/LIBRA detectors

assembling a DAMA/ LIBRA detector

filling the inner Cu box with further shield

closing the Cu box housing the detectors

view at end of detectors’ installation in the Cu box
Some on residual contaminants in new NaI(Tl) detectors

α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/day

232Th residual contamination
From time-amplitude method. If 232Th chain at equilibrium: it ranges from 0.5 ppt to 7.5 ppt

238U residual contamination
First estimate: considering the measured α and 232Th activity, if 238U chain at equilibrium \(\Rightarrow\) 238U contents in new detectors typically range from 0.7 to 10 ppt

238U chain splitted 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 for \(^{238}\text{U} \)
and: (15.8±1.6) μBq/kg for \(^{234}\text{U} + ^{230}\text{Th} \); (21.7±1.1) μBq/kg for \(^{226}\text{Ra} \); (24.2±1.6) μBq/kg for \(^{210}\text{Pb} \).

natK residual contamination
The analysis has given for the natK content in the crystals values not exceeding about 20 ppb

129I and 210Pb
\( ^{129}\text{I} \text{/natI} \approx 1.7 \times 10^{-13} \) for all the new detectors
\( ^{210}\text{Pb} \text{ in the new detectors: (5 – 30) μBq/kg.} \)

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

... more on
NIMA592(2008)297
Noise rejection near the energy threshold

Typical pulse profiles of PMT noise and of scintillation event with the same area, just above the energy threshold of 2 keV

The different time characteristics of PMT noise (decay time of order of tens of ns) and of scintillation event (decay time about 240 ns) can be investigated building several variables

From the Waveform Analyser
2048 ns time window:

\[ X_1 = \frac{\text{Area (from 0 ns to 600 ns)}}{\text{Area (from 0 ns to 600 ns)}} \]

\[ X_2 = \frac{\text{Area (from 0 ns to 50 ns)}}{\text{Area (from 0 ns to 600 ns)}} \]

- The separation between noise and scintillation pulses is very good.
- Very clean samples of scintillation events selected by stringent acceptance windows.
- The related efficiencies evaluated by calibrations with \(^{241}\)Am sources of suitable activity in the same experimental conditions and energy range as the production data (efficiency measurements performed each ~10 days; typically \(10^4\text{–}10^5\) events per keV collected)

This is the only procedure applied to the analysed data
Cumulative low-energy distribution of the *single-hit* scintillation events

Single-hit events = each detector has all the others as anticoincidence

(Obviously differences among detectors are present depending e.g. on each specific level and location of residual contaminants, on the detector's location in the 5x5 matrix, etc.)

Efficiencies already accounted for

**About the energy threshold:**

- The DAMA/LIBRA detectors have been calibrated down to the keV region. This assures a clear knowledge of the "physical" energy threshold of the experiment.
- It obviously profits of the relatively high number of available photoelectrons/keV (from 5.5 to 7.5).
- The two PMTs of each detector in DAMA/LIBRA work in coincidence with hardware threshold at single photoelectron level.
- Effective near-threshold-noise full rejection.
- The software energy threshold used by the experiment is 2 keV.

DAMA/LIBRA (4 years)
total exposure: 0.53 ton\(\times\)yr
Model independent annual modulation result

DAMA/Nal (7 years) + DAMA/LIBRA (4 years) Total exposure: 300555 kg×day = 0.82 ton×yr

Experimental single-hit residuals rate vs time and energy in 2-6 keV over 11 annual cycles

Acos[ω(t-t₀)]
continuous lines: t₀ = 152.5 d, T = 1.00 y

A = (0.0129 ± 0.0016) cpd/kg/keV

χ²/dof = 54.3/66 8.2σ C.L.
Absence of modulation? No

χ²/dof = 116.4/67 ⇒ P(A=0) = 1.8 × 10⁻⁴
from the fit with all the parameters free:
A = (0.0131 ± 0.0016) cpd/kg/keV
t₀ = (144 ± 8) d
T = (0.998 ± 0.003) y

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

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Principal model

2.737 · 10⁻³ d⁻¹ ≈ 1 y⁻¹

Model independent evidence of a particle Dark Matter component in the galactic halo at 8.2σ C.L.
Energy distribution of the modulation amplitudes, $S_m$, for the total exposure

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

DAMA/Nal (7 years) + DAMA/LIBRA (4 years) total exposure: 300555 kg×day = 0.82 ton×yr

here $T = 2\pi / \omega = 1 \text{yr}$ and $t_0 = 152.5 \text{day}$

A clear modulation is present in the (2-6) keV energy interval, 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 24.4 for 28 degrees of freedom
**Is there a sinusoidal contribution in the signal?**

Phase $\neq 152.5$ day?

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

For Dark Matter signals:

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

Slight differences from 2$^{nd}$ June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)

<table>
<thead>
<tr>
<th>$E$ (keV)</th>
<th>$S_m$ (cpd/kg/keV)</th>
<th>$Z_m$ (cpd/kg/keV)</th>
<th>$Y_m$ (cpd/kg/keV)</th>
<th>$t^*$ (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-6</td>
<td>0.0122 ± 0.0016</td>
<td>-0.0019 ± 0.0017</td>
<td>0.0123 ± 0.0016</td>
<td>144.0 ± 7.5</td>
</tr>
<tr>
<td>6-14</td>
<td>0.0005 ± 0.0010</td>
<td>0.0011 ± 0.0012</td>
<td>0.0012 ± 0.0011</td>
<td>--</td>
</tr>
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</table>
The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about $S_m$ already exclude any sizeable 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%

<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>
</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>
</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>
</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>
</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>
</tr>
<tr>
<td>Hardware rate above single photoelectron</td>
<td>-(0.20 ± 0.18) × 10$^{-2}$ Hz</td>
<td>(0.09 ± 0.17) × 10$^{-2}$ Hz</td>
<td>-(0.03 ± 0.20) × 10$^{-2}$ Hz</td>
<td>(0.15 ± 0.15) × 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 \times 10^{-6} \text{ cpd/kg/keV})</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield (\rightarrow) huge heat capacity + T continuously recorded</td>
<td>(&lt;10^{-4} \text{ cpd/kg/keV})</td>
</tr>
<tr>
<td>NOISE</td>
<td>Effective full noise rejection near threshold</td>
<td>(&lt;10^{-4} \text{ cpd/kg/keV})</td>
</tr>
<tr>
<td>ENERGY SCALE</td>
<td>Routine + intrinsic calibrations</td>
<td>(&lt;1 - 2 \times 10^{-4} \text{ cpd/kg/keV})</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>(&lt;10^{-4} \text{ 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} \text{ cpd/kg/keV})</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured by MACRO</td>
<td>(&lt;3 \times 10^{-5} \text{ cpd/kg/keV})</td>
</tr>
</tbody>
</table>

+ even if larger they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect
Model-independent evidence by DAMA/NaI and DAMA/LIBRA well compatible with several candidates (in several of the many astrophysical, nuclear and particle physics scenarios); other ones are open

Neutralino as LSP in 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)

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

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

Sterile neutrino

Kaluza Klein particles

Elementary Black holes such as the Daemons

… and more

Self interacting Dark Matter

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

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

a heavy $\nu$ of the 4-th family

Available results from direct searches using different target materials and approaches do not give any robust conflict

Possible model dependent positive hints from indirect searches not in conflict with DAMA results (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.)
Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes \( S_{m,k} \)

- **15 GeV N.F.W.**
- **60 GeV N.F.W.**
- **100-120 GeV Evans power law**

**WIMP DM candidate** (as in [4])

considering elastic scattering on nuclei

**SI dominant coupling**

\( \nu_0 = 170 \text{ km/s} \)

About the same C.L.

...scaling from NaI

### Table

<table>
<thead>
<tr>
<th>Curve label</th>
<th>Halo model (see ref. [4, 34])</th>
<th>Local density (GeV/cm(^3))</th>
<th>Set as in [4]</th>
<th>DM particle mass</th>
<th>( \xi \sigma_{SI} ) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>( 3.1 \times 10^{-4} )</td>
</tr>
<tr>
<td>b</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>( 1.3 \times 10^{-5} )</td>
</tr>
<tr>
<td>c</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>( 5.5 \times 10^{-6} )</td>
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<tr>
<td>d</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>B</td>
<td>100 GeV</td>
<td>( 6.5 \times 10^{-6} )</td>
</tr>
<tr>
<td>e</td>
<td>B3 (Evans power law)</td>
<td>0.17</td>
<td>A</td>
<td>120 GeV</td>
<td>( 1.3 \times 10^{-5} )</td>
</tr>
</tbody>
</table>


channeling contribution as in EPJC53(2008)205 considered for curve b
Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$.

WIMP DM candidate (as in [4])
Elastic scattering on nuclei
SI & SD mixed coupling
$v_0 = 170$ km/s

About the same C.L.
...scaling from NaI

<table>
<thead>
<tr>
<th>Curve label</th>
<th>Halo model (see ref. [4, 34])</th>
<th>Local density (GeV/cm$^3$)</th>
<th>Set as in [4]</th>
<th>DM particle mass</th>
<th>$\xi\sigma_{SI}$ (pb)</th>
<th>$\xi\sigma_{SD}$ (pb)</th>
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<tr>
<td>f</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>$10^{-7}$</td>
<td>2.6</td>
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<tr>
<td>g</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>A</td>
<td>15 GeV</td>
<td>$1.4 \times 10^{-4}$</td>
<td>1.4</td>
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<tr>
<td>h</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>$10^{-7}$</td>
<td>1.4</td>
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<tr>
<td>i</td>
<td>A5 (NFW)</td>
<td>0.2</td>
<td>B</td>
<td>60 GeV</td>
<td>$8.7 \times 10^{-6}$</td>
<td>1.7</td>
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<td>j</td>
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<td>A</td>
<td>100 GeV</td>
<td>$10^{-7}$</td>
<td>1.7</td>
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<td>k</td>
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<td>A</td>
<td>100 GeV</td>
<td>$1.1 \times 10^{-5}$</td>
<td>0.11</td>
</tr>
</tbody>
</table>

$\theta = 2.435$

Examples for few of the many possible scenarios superimposed to the measured modulation amplitudes $S_{m,k}$

**LDM candidate**
(as in MPLA23(2008)2125):
inelastic interaction with electron or nucleus targets

**Light bosonic candidate**
(as in IJMPA21(2006)1445):
axion-like particles totally absorbed by target material

About the same C.L.

<table>
<thead>
<tr>
<th>Curve label</th>
<th>DM particle</th>
<th>Interaction</th>
<th>Set as in [4]</th>
<th>$m_a$</th>
<th>$\Delta$</th>
<th>Cross section (pb)</th>
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</thead>
<tbody>
<tr>
<td>$l$</td>
<td>LDM</td>
<td>coherent on nuclei</td>
<td>A</td>
<td>30 MeV</td>
<td>18 MeV</td>
<td>$\sigma_m^{coh} = 1.8 \times 10^{-6}$</td>
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<tr>
<td>$m$</td>
<td>LDM</td>
<td>coherent on nuclei</td>
<td>A</td>
<td>100 MeV</td>
<td>55 MeV</td>
<td>$\sigma_m^{coh} = 9.8 \times 10^{-6}$</td>
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<tr>
<td>$n$</td>
<td>LDM</td>
<td>incoherent on nuclei</td>
<td>A</td>
<td>30 MeV</td>
<td>3 MeV</td>
<td>$\sigma_m^{inc} = 2.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>$o$</td>
<td>LDM</td>
<td>incoherent on nuclei</td>
<td>A</td>
<td>100 MeV</td>
<td>55 MeV</td>
<td>$\sigma_m^{inc} = 4.6 \times 10^{-2}$</td>
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<tr>
<td>$p$</td>
<td>LDM</td>
<td>coherent on nuclei</td>
<td>A</td>
<td>28 MeV</td>
<td>28 MeV</td>
<td>$\sigma_m^{coh} = 1.6 \times 10^{-6}$</td>
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<tr>
<td>$q$</td>
<td>LDM</td>
<td>incoherent on nuclei</td>
<td>A</td>
<td>88 MeV</td>
<td>88 MeV</td>
<td>$\sigma_m^{inc} = 4.1 \times 10^{-2}$</td>
</tr>
<tr>
<td>$r$</td>
<td>LDM</td>
<td>on electrons</td>
<td>–</td>
<td>60 keV</td>
<td>60 keV</td>
<td>$\sigma_m = 0.3 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

$\sigma N = \alpha A^2 \sigma_0 = \alpha A^2 \sigma_0^i$

$m_L = 0$

curve $r$: also pseudoscalar axion-like candidates (e.g. majoron)
$m_a = 3.2 \text{ keV} \ q_{ae} = 3.9 \times 10^{-11}$

where DAMA is and is going to

• DAMA/LIBRA over 4 annual cycles (0.53 ton × yr) confirms the results of DAMA/NaI (0.29 ton × yr)

• The cumulative confidence level for the model independent evidence for presence of DM particle in the galactic halo is 8.2 σ (total exposure 0.82 ton × yr)
  
  • First upgrading of the experimental set-up in Sept. 2008
    • Mounting of the “clean room” in order to operate in HP N₂ atmosphere
    • Opening of the shield of DAMA/LIBRA set-up in HP N₂ atmosphere
    • Replacement of some PMTs in HP N₂ atmosphere
    • Dismounting of the Tektronix TDs (Digitizers + Crates)
    • Mounting of the new Acqiris TD (Digitizers + Crate) and of the new DAQ system with optical read-out

• Since Oct. 2008 again in data taking
  • Continuing the data taking
  • Update corollary analyses in some possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc.

• Next upgrading: replacement of all the PMTs with higher Q.E. ones
  • Production of new high Q.E. PMTs in progress
  • Goal: lowering the energy thresholds of the detectors

• Analyses/data taking to investigate also other rare processes in progress/foreseen

• Long term data taking to improve the investigation, to disentangle at least some of the many possibilities, to investigate other features of DM particle component(s) and second order effects, etc.

A possible highly radiopure NaI(Tl) multi-purpose set-up DAMA/1 ton (proposed by DAMA in 1996) at R&D phase

• to deep investigate Dark Matter phenomenology at galactic scale
Conclusions

- Different techniques can give complementary results
- Further efforts to demonstrate the solidity of some techniques are desirable
- The model independent signature is the definite strategy to investigate the Dark Matter particles
- Solid experimental results obtained by considering different detectors, target materials, techniques, etc., can – at least at some extent – constrain the dark matter particle nature and disentangle among the different astrophysical scenarios, nuclear and particle physics models

*Felix qui potuit rerum cognoscere causas* (Virgilio, Georgiche, II, 489)