Results from DAMA

DAMA coll.
Roma2, Roma, IHEP/Beijing

see also DAMA site on: www.lngs.infn.it

NDM03
Nara, Japan
June, 2003
Now the new ~ 250 kg more radiopure NaI(Tl) set-up named LIBRA running... and looking forward: a new R&D for further radiopurifications started toward 1 ton set-up we proposed in 1996.
DAMA: an observatory for rare processes @LNGS

low bckg Ge for sampling meas.

LXe

R&D

NaI(Tl) → LIBRA
DAMA/LXe experiment: results on rare processes
NIMA482(2002)728

DARK MATTER investigation...

- Limits on recoils investigating the WIMP-\(^{129}\)Xe elastic scattering by means of Pulse Shape Discrimination
  PLB436(1998)379
- Limits on WIMP-\(^{129}\)Xe inelastic scattering
- Neutron calibration
- \(^{129}\)Xe vs \(^{136}\)Xe by using PSD \(\rightarrow\) comparing SD vs SI signal to increase the sensitivity on the SD component
  data taking in progress

... other rare processes

- Nuclear level excitation of\(^{129}\)Xe during CNC processes
  PLB465(1999)315
  \(\tau > 1.1 \times 10^{24}\) y at 90% C.L.
- Nucleon and di-nucleon decay into invisible channels
  PLB493(2000)12
  \(\tau > 1.9 \times 10^{24}\) y 90% C.L. (p\(\rightarrow\)invisible channel),
  \(\tau > 5.5 \times 10^{23}\) y 90% C.L. (pp\(\rightarrow\)invisible channel),
  \(\tau > 1.2 \times 10^{25}\) y 90% C.L. (nn\(\rightarrow\)invisible channel)
- Electron decay e\(^-\) \(\rightarrow\) \(\nu_e\gamma\)
  PRD61(2000)117301
  \(\tau > 2.0 \times 10^{25}\) y at 90% C.L.
- \(2\beta\) decay in \(^{136}\)Xe
  Xenon01
  \(T_{1/2} > 7.0 \times 10^{23}\) y at 90% C.L.
- \(2\beta\) decay in \(^{134}\)Xe
  PLB527(2002)182
- Improved results on \(2\beta\) in \(^{134}\)Xe and \(^{136}\)Xe
  PLB546(2002)23
DAMA/R&D set-up: results on rare processes

WIMPs:
• WIMP search with CaF$_2$(Eu) Astrop.Phys.7(1999)73

Other rare process:
• $2\beta$ decay in $^{136}$Ce and in $^{142}$Ce Il Nuov.Cim.A110(1997)189
• $2$EC$2\nu$ $^{40}$Ca decay using CaF$_2$(Eu) scintillator Astrop.Phys.7(1999)73
• $2\beta$ decay in $^{46}$Ca and in $^{40}$Ca NPB563(1999)97
• $2\beta^+$ decay in $^{106}$Cd Astrop.Phys.10(1999)115
• $2\beta$ and $\beta$ decay in $^{48}$Ca NPA705(2002)29
• $2$EC$2\nu$ in $^{136}$Ce and in $^{138}$Ce and $\alpha$ decay in $^{142}$Ce NIMA498(2003)352

The R&D shield closed

The R&D shield open

Fulfilling the inner Cu box
The installation

Glove box for calibration

Experimental details on

The ~100 kg NaI(Tl) set-up

The detectors
Exotic Dark Matter PRL83(1999)4918 Neutral SIMPs: excluded $M_s$ up to $4 \times 10^{16}$ GeV;

Neutral nuclearities: $\Phi_{\text{nucl}} < 1.9 \times 10^{-11} \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ (90% CL)

Pauli exclusion principle violation PLB408(1997)439 Limits for spontaneous emission rate of protons in $^{23}$Na and $^{127}$I

Exotic Matter EPJdirect C14(2002)1: new limits for neutral and charged Q-balls

WIMPs:
- PSD: PLB389(1996)757

Other rare processes:
- Nuclear level excitation of $^{127}$I and $^{23}$Na during CNC processes PRC60(1999)065501 Limits (1.5-2.4) $\times 10^{23}$ y (up to two orders of magnitude higher than the ones previously available)
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) PLB460(1999)235 Limit: $\tau > 2.4 \times 10^{24}$ y at 90% C.L.

Search for solar axions by exploiting the Primakoff effect in NaI(Tl) crystals

The achieved limit is:

$$g_{\gamma \gamma} < 1.7 \times 10^{-9} \text{ GeV}^{-1} \text{ (90\% C.L.)}.$$  

In particular, the region $m_a > 0.03$ eV (not accessible by other direct methods) has been explored and KSVZ axions with $m_a > 4.6$ eV have been excluded (90% C.L.)
Identifying signal from the WIMP wind

Annual modulation of the rate

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

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

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

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 in a multi-detector set-up
6) With modulated amplitude in the region of maximal sensitivity < 7%

To mimic this signature, the spurious effects and side reactions must satisfy contemporaneously all these 6 requirements
### 100 kg DAMA/NaI data takings

<table>
<thead>
<tr>
<th>Running period</th>
<th>Exposure (kgd)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/NaI-0</td>
<td>4123</td>
<td>PSD</td>
</tr>
<tr>
<td>DAMA/NaI-1</td>
<td>4549</td>
<td>annual modulation</td>
</tr>
<tr>
<td>DAMA/NaI-2</td>
<td>14962</td>
<td>“ + diurnal</td>
</tr>
<tr>
<td>DAMA/NaI-3</td>
<td>22455</td>
<td>“</td>
</tr>
<tr>
<td>DAMA/NaI-4</td>
<td>16020</td>
<td>“</td>
</tr>
<tr>
<td>DAMA/NaI-5</td>
<td>15911</td>
<td>(electronics and DAQ fully renewed)</td>
</tr>
<tr>
<td>DAMA/NaI-6</td>
<td>16608</td>
<td></td>
</tr>
<tr>
<td>DAMA/NaI-7</td>
<td>17226</td>
<td></td>
</tr>
</tbody>
</table>

TOTAL -1 to -7 107731 kgd

Data taking ended during July 2002

Starting of DAMA/LIBRA installation
DAMA/NaI out of operation

The switching off of the ~100kg NaI(Tl) set-up at end of July 2002

Opening the shield

Dismounting the ~100kg NaI(Tl) set-up in August 2002
## The data released so far on the model independent annual modulation signature

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>STATISTICS (kg · day)</th>
<th>REFERENCES</th>
<th>Considered Examples of Model Dependent Scenarios in the additional quest for the candidate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DAMA/NaI-1</strong></td>
<td>3363.8 winter + 1185.2 summer</td>
<td>PLB424(1998)195</td>
<td>WIMP SI, isothermal spherical halo, $v_0=220$ km/s, Helm FF, $m_W&gt;25$ GeV, all parameters assumed at fixed values</td>
</tr>
<tr>
<td><strong>DAMA/NaI-2</strong></td>
<td>14962 ~ November to end of July</td>
<td>PLB450(1999)440</td>
<td>WIMP SI, isothermal spherical halo + rotation, $v_0=220$ km/s + uncertainties on $v_0$, Helm FF, $m_W&gt;25$ GeV, all parameters assumed at fixed values</td>
</tr>
<tr>
<td><strong>DAMA/NaI-3</strong></td>
<td>22455 ~ middle August to end September</td>
<td>PLB480(2000) 23</td>
<td>WIMP SI, isothermal spherical halo + rotation, $v_0=220$ km/s + uncertainties on $v_0$, restrictions from DAMA/NaI-0, $m_W&gt;30$ GeV, Helm FF, all parameters assumed at fixed values</td>
</tr>
<tr>
<td><strong>DAMA/NaI-4</strong></td>
<td>16020 ~ middle October to second half August</td>
<td><strong>idem</strong></td>
<td>WIMP SI, isothermal spherical halo + rotation, $v_0=220$ km/s + uncertainties on $v_0$, restrictions from DAMA/NaI-0, $m_W&gt;30$ GeV, Helm FF, all parameters assumed at fixed values</td>
</tr>
<tr>
<td><strong>TOTAL STATISTICS</strong></td>
<td><strong>idem +</strong></td>
<td></td>
<td>WIMP SI, SI&amp;SD and Inelastic; Isothermal spherical halo + rotation + other consistent halo models, $v_0=220$ km/s + uncertainties on $v_0$, restrictions from DAMA/NaI-0, $m_W&gt;30$ GeV, Helm FF SI and Ressell FF SD, only few of the many uncertainties on assumption and parameters considered</td>
</tr>
</tbody>
</table>

+ **DAMA/NaI-0** (properly included in the cumulative result) limits on recoil fraction by PSD PLB389(1996) 757

**Many other scenarios possible and under investigation for the model dependent quest for the candidate**
**The model independent result**

✓ The quest for model independent signature: evidence from WIMP annual modulation signal

--- expected minimum

... expected maximum

Experimental point

1) \( t_0 = 152.5 \) days (fixed)  
   \( A = (0.022 \pm 0.005) \text{ cpd/kg/keV} \)  
   \( T = 2\pi/\omega = (1.00 \pm 0.01) \) years  
   \( \chi^2/\text{dof} = 23/18 \)

2) \( T = 1 \) years (fixed)  
   \( A = (0.023 \pm 0.005) \text{ cpd/kg/keV} \)  
   \( t_0 = (144 \pm 13) \) days  
   \( \chi^2/\text{dof} = 23/18 \)

If all the 3 parameters kept free, similar values with slightly larger errors

Absence of modulation:  
\[ \chi^2_0 (A=0)/\text{dof} = 48/20 \]
\[ \Rightarrow P = 4 \cdot 10^{-4} \]

Presence of annual modulation with characteristics of a WIMP candidate

• All the peculiarities of the signature satisfied.
• Presence of the annual modulation signal with the proper distinctive features for a WIMP induced effect
• No systematic or side reaction able to mimic the signature found

**PLB424(1998)195**  
**PLB450(1999)44**  
**PRD61(1999)023512**  
**PLB480(2000)23**  
**PLB509(2001)197**  
**EPJ C18(2000)283**  
**EPJ C23 (2002)61**  
**PRD66(2002)043503**

**Presence of annual modulation with characteristics of a WIMP candidate**
Fourier spectrum of residuals

2-6 keV

dati.pyn
Lomb Periodogram

1 y^{-1}
## Investigation on possible SYSTEMATICS


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition/Measurement</th>
<th>Rejection</th>
<th>Observed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RADON</strong></td>
<td>Sealed Cu box in HP Nitrogen atmosphere</td>
<td></td>
<td>&lt;0.2% $S_m^{obs}$</td>
</tr>
<tr>
<td><strong>TEMPERATURE</strong></td>
<td>The installation is air-conditioned</td>
<td></td>
<td>&lt;0.5% $S_m^{obs}$</td>
</tr>
<tr>
<td><strong>NOISE</strong></td>
<td>Effective noise rejection</td>
<td></td>
<td>&lt;1% $S_m^{obs}$</td>
</tr>
<tr>
<td><strong>ENERGY SCALE</strong></td>
<td>Periodical calibrations continuous monitoring of $^{210}$Pb peak</td>
<td></td>
<td>&lt;1% $S_m^{obs}$</td>
</tr>
<tr>
<td><strong>EFFICIENCIES</strong></td>
<td>Regularly measured by dedicated calibrations</td>
<td></td>
<td>&lt;1% $S_m^{obs}$</td>
</tr>
<tr>
<td><strong>BACKGROUND</strong></td>
<td>No modulation found in energy regions above 6keV</td>
<td></td>
<td>&lt;0.5% $S_m^{obs}$</td>
</tr>
<tr>
<td><strong>SIDE REACTIONS</strong></td>
<td>Muon flux modulation by MACRO</td>
<td></td>
<td>&lt;0.3% $S_m^{obs}$</td>
</tr>
</tbody>
</table>

+ even if larger they cannot satisfy all the 6 requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect
To investigate the nature and coupling with ordinary matter of the possible WIMP candidate, an effective energy and time correlation analysis has to be performed within given model frameworks.

\[ \rho_w \]

**WIMP velocity distribution:** \( f(\vec{v}) \)

- Parameters of \( f(\vec{v}) \) (in the usual case: \( v_0 \) and \( v_{\text{esc}} \))
- Couplings: SI, SD, mixed, inelastic, ...
- Scaling laws on cross sections
- SI and SD form factors
- Parameters of the form factors (in the usual case: \( r,s,b \))
- Etc.

**BUT uncertainties on models and comparisons:**

They can affect *not only* the annual modulation region *but also* the exclusion plots.

**Experimental parameters (typical of each experiment):**

Comparison within particle models
Example

Effect on the exclusion plot when changing the value of a parameter (inside its allowed range) within the same model framework.

- Top curves: \( v_0 = 180 \text{ km/s}; \ v_{\text{esc}} = 500 \text{ km/s} \)
- Lower curves: \( v_0 = 250 \text{ km/s}; \ v_{\text{esc}} = 1000 \text{ km/s} \)
- \( v_0 \) affects mainly the overall rate
- \( v_{\text{esc}} \) affects mostly the lower mass region

Similar effect can be found for every nucleus and interaction type for some expt/theoretical parameters.

Astrop. Phys. 2 (1994) 117
The Form Factors

• Take into account the structure of target nuclei
• In SD form factor: no decoupling between nuclear and WIMP degrees of freedom; dependence on nuclear potential.
• Example on $^{127}$I nucleus:

![Graph of SI and SD form factors](image)

- **Standard:**
  - $s = 1$ fm
  - $r = 1.2 \text{ A}^{1/3}$ fm
  - $r_0 = (r^2 - 5s^2)^{1/2} = 5.602$ fm

<table>
<thead>
<tr>
<th>Target-nucleus</th>
<th>$\lambda^2 J(J+1)$ single particle</th>
<th>$\lambda^2 J(J+1)$ odd group</th>
<th>$\lambda^2 J(J+1)$ from Ressel et al.</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{29}$Si</td>
<td>0.750</td>
<td>0.063</td>
<td>0.103</td>
<td>Neutron is unpaired nucleon</td>
</tr>
<tr>
<td>$^{73}$Ge</td>
<td>0.306</td>
<td>0.065</td>
<td>0.229 or 0.177</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>0.750</td>
<td>0.124</td>
<td>0.089</td>
<td>Proton is unpaired nucleon</td>
</tr>
<tr>
<td>$^{131}$Xe</td>
<td>0.150</td>
<td>0.055</td>
<td>0.250</td>
<td></td>
</tr>
<tr>
<td>$^1$H</td>
<td>0.750</td>
<td>0.750</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>0.750</td>
<td>0.647</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>$^{23}$Na</td>
<td>0.350</td>
<td>0.041</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>0.350</td>
<td>0.087</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>$^{69}$Ga</td>
<td>0.417</td>
<td>0.021</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>$^{71}$Ga</td>
<td>0.417</td>
<td>0.089</td>
<td>0.089</td>
<td></td>
</tr>
<tr>
<td>$^{75}$As</td>
<td>0.417</td>
<td>0.000</td>
<td>0.084 or 0.126</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>0.250</td>
<td>0.023</td>
<td>0.084 or 0.126</td>
<td></td>
</tr>
</tbody>
</table>
1st Simple Model Framework (improved with time)

- $\xi = \rho W/(0.3 \text{ GeV cm}^{-3})$
- isothermal, maxwellian WIMP velocity distribution
- accounting for $v_0$ and $v_{\text{esc}}$ uncertainties (preliminarily only analysis $v_0 = 220 \text{ km/s}$ and $v_{\text{esc}} = 650 \text{ km/s}$)
- SI coupling
- $\sigma \propto \mu^2 \alpha^2$
- Helm SI form factor assuming $r = 1.2 \text{ A}^{1/3} \text{fm}$, $s = 1 \text{ fm}$
- experimental and theoretical parameters at given values
- exploring mass above 30 GeV (bound inspired to the lower bound on SUSY candidate as derived from LEP data in the usually adopted SUSY schemes based on GUT unification assumptions)
- accounting for limits on recoils measured by PSD

DAMA/NaI-0 to 4

\[ v_0 = (220 \pm 50) \text{ km/s} \quad (90\% \text{ C.L.}) \]
\[ (v_{\text{esc}} = (550 \pm 100) \text{ km/s} \quad (90\% \text{ C.L.}) \leftarrow \text{negligible effect} \]

\[ 30 \text{ GeV} \leq m_W \leq 105 \text{ GeV} \quad (1\sigma \text{ C.L.}) \]

including possible Dark halo rotation

\[ 30 \text{ GeV} \leq m_W \leq 132 \text{ GeV} \quad (1\sigma \text{ C.L.}) \]

\[
\begin{array}{c|c|c}
  v_0 (\text{km/s}) & m_W (\text{GeV}) & \xi \sigma_p (\text{pb}) \\
  \hline 
  170 & 72_{-15}^{+18} & (5.7 \pm 1.1) \cdot 10^{-6} \\
  220 & 43_{-9}^{+12} & (5.4 \pm 1.0) \cdot 10^{-6} \\
  270 & 32_{-7}^{+8} & (5.7 +1.2_{-1.1}) \cdot 10^{-6} \\
\end{array}
\]

If SD $\neq 0$ or more favorable FF, regions go down

The region accounts for a large set of best fit values

Investigation of the effect of halo models, WIMP velocity distributions, uncertainties associated to all experimental, theoretical parameters and others extends the allowed region and the set of best fit values as well

→ see later + comment on FF in PLB480(2000)23 + etc.
Halo modeling

- Needed quantities for Dark Matter direct searches:
  \[ \rho_0 = \rho_{DM}(R_0 = 8.5 \text{ kpc}) \]
  \[ v_0 = v_{\text{rot}}(R_0 = 8.5\text{kpc}) \]
  \[ f(\vec{v}) \]

**Isothermal sphere**: the most widely used (but not correct) model

- Density profile: \( \rho_{DM}(r) \propto r^{-2} \)
- Gravitational potential: \( \Psi_0 \propto \log(r^2) \)

\[ \rightarrow \text{Maxwellian velocity distribution} \]

**Spherical \( \rho_{DM} \)** isotropic velocity dispersion

Evans’ logarithmic

\[ \rho_{DM}(r) = \frac{v_0^2}{4\pi G} \frac{3R_c^2 + r^2}{(R_c^2 + r^2)^2} \quad \Psi_0(r) = -\frac{v_0^2}{2} \log(R_c^2 + r^2) \quad v^2_{\text{rot}}(r) = \frac{v_c^2}{(R_c^2 + r^2)} \]

Evans’ power-law

\[ \rho_{DM}(r) = \frac{\beta \Psi_0 R_c^2}{4\pi G} \frac{3R_c^2 + r^2(1-\beta)}{(R_c^2 + r^2)^{(\beta+4)/2}} \quad \Psi_0(r) = \frac{\Psi_0 R_c^2}{(R_c^2 + r^2)^{\beta/2}}, (\beta \neq 0) \quad v^2_{\text{rot}}(r) = \frac{\beta \Psi_0 R_c^2 r^2}{(R_c^2 + r^2)^{(\beta+2)/2}} \]

Others:

\[ \rho_{DM}(r) = \rho_0 \left( \frac{R_0}{r} \right)^\gamma \frac{1+(R_0/a)^\alpha}{1+(r/a)^\alpha} \]

\[ \beta_0 = \frac{\beta}{(\beta+2)/2} \]

**If spherical \( \rho_{DM} \) with non-isotropic velocity dispersion**

\[ \rightarrow \beta_0 = 1 - \frac{\rho_{\phi}}{\rho_{\Psi}} \]

**If Axisymmetric \( \rho_{DM} \) → \( q \)** flatness

\[ \Psi_0(r,z) = -\frac{v_0^2}{2} \log \left( R_c^2 + r^2 + \frac{z^2}{q^2} \right) \]

**Triaxial \( \rho_{DM} \) → \( p, q, \delta \)**

\[ \Psi_0(x,y,z) = -\frac{v_0^2}{2} \log \left( x^2 + \frac{y^2}{p^2} + \frac{z^2}{q^2} \right) \]

\( \delta = \text{free parameter} \rightarrow \text{in spherical limit (p=q=1) quantifies} \)

the anisotropy of the velocity dispersion tensor

\[ \frac{\bar{v}_\phi^2}{\bar{v}_r^2} = 2 + \delta \]

Constraining the models

\[ v_0 = (220 \pm 50) \text{ km} \cdot \text{s}^{-1} \]

\[ 1 \cdot 10^{10} M_\odot \leq M_{\text{vir}} \leq 6 \cdot 10^{10} M_\odot \]

\[ 0.8 \cdot v_0 \leq v_{\text{rot}}(r = 100 \text{ kpc}) \leq 1.2 \cdot v_0 \]
**Consistent halo models**


Quantitative approach on DAMA/NaI0-4 data:
- purely SI coupling
- for the other assumptions see before

Belli,Cerulli,Fornengo,Scopel PRD66(2002)043503

<table>
<thead>
<tr>
<th>Class A: Spherical $\rho_{DM}$, isotropic velocity dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
</tr>
<tr>
<td>A1</td>
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<tr>
<td>A2</td>
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<tr>
<td>A3</td>
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<tr>
<td>A4</td>
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<tr>
<td>A5</td>
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<td>A6</td>
</tr>
<tr>
<td>A7</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Class B: Spherical $\rho_{DM}$, non-isotropic velocity dispersion (Osipkov-Merritt, $\beta_0=0.4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
</tr>
<tr>
<td>B2</td>
</tr>
<tr>
<td>B3</td>
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<tr>
<td>B4</td>
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<td>B7</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Class C: Axisymmetric $\rho_{DM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
</tr>
<tr>
<td>C2</td>
</tr>
<tr>
<td>C3</td>
</tr>
<tr>
<td>C4</td>
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</table>

<table>
<thead>
<tr>
<th>Class D: Triaxial $\rho_{DM}$ [17] ($q=0.8, p=0.9$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
</tr>
<tr>
<td>D2</td>
</tr>
<tr>
<td>D3</td>
</tr>
<tr>
<td>D4</td>
</tr>
</tbody>
</table>
Summary of the results

only uncertainties on halo models considered according to PRD66(2002)043503

The analysis is not exhaustive at all of the existing possibilities because of the poor present knowledge on many astrophysical, nuclear and particle physics assumptions and related parameters

Different best fit values correspond to each model framework and to each set of parameters’ values

3-σ modulation regions of all the considered models plotted jointly

DAMA annual modulation region for an isothermal sphere halo with $v_0=220$ km/s

Superposition of all regions allowed for non-rotating models

Allowed region:

- up to $m_W \approx 270$ GeV
- few $\times 10^{-10}$ nbarn $< \xi\sigma_p < 2 \times 10^{-8}$ nbarn

If existing uncertainties on all the assumptions and parameters in the model-dependent analysis are considered, the allowed region is further enlarged
The result is an allowed volume in the space \((m_W, \xi, \sigma_{p-SI}, \xi, \sigma_{p-SD})\) for each possible \(\theta\) (\(\tan \theta = a_n/a_p\) with \(0 \leq \theta < \pi\)).

Example of slices for given \(m_W\) and \(\theta\) (3\(\sigma\) C.L.) in the simple isothermal spherical halo model including all the existing uncertainties much larger regions (and volumes) are obtained.

+ Several other possibilities for the SI &SD mixed model framework are open and to be investigated (different SD-FF \((a_p \& a_n), g_n = g_p\) \(?\), different halo models, etc.)
As seen before

- If $SD=0$, interval not compatible with zero for $\xi_{SI}$
- If $SI=0$, interval not compatible with zero for $\xi_{SD}$
- Large regions allowed for mixed configurations also for $\xi_{SI} < 10^{-5}$ pb and $\xi_{SD} < 1$ pb.

$v_0=220$ km/s, fixed params

Allowed region for $\xi_{SD}$ when $\xi_{SI} \approx 3 \cdot 10^{-6}$ pb (as in the region allowed in the pure SI scenario) (contour a)

Allowed region for $\xi_{SD}$ when $\xi_{SI}$ much lower than those allowed in the pure SI scenario (contours b: $\xi_{SI} \approx 1 \cdot 10^{-6}$ pb, c $\xi_{SI} \approx 5 \cdot 10^{-8}$ pb).

Best fit minima in the plane $(\xi_{SI}, \xi_{SD})$ for some $m_W$ and $\theta$ pairs (related C.L. ranges between 3 and 4 $\sigma$)
3rd Model Framework: WIMPs with “preferred” inelastic scattering

- Model suggested by D. Smith and N. Weiner, PRD64(2001)043502
- Two states $\chi^+, \chi^-$ with $\delta$ mass splitting WIMP
- Kinematical constraint for the inelastic scattering of $\chi^-$ on a nucleus with mass $m_N$ becomes increasingly severe for low $m_N$

$$\frac{1}{2} \mu v^2 \geq \delta \iff v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

Energy-Time correlation analysis of the DAMA events gives an allowed volume in the space $(m_W, \xi \sigma_p, \delta)$

**Model framework:** accounting for $v_0$ and $v_{esc}$ uncertainties ($v_0=170-270$ km/s; $v_{esc}=450-650$ km/s) and for limit on recoils from PSD (DAMA/NaI-0) + for uncertainty on FF parameters

**Example of slices for given $m_W$**

- best fit values for $m_W=70$ GeV
  - i) when $v_0=170$ km/s: $\xi \sigma_p=2.5 \times 10^{-2}$ pb and $\delta=115$ keV
  - ii) when $v_0=220$ km/s: $\xi \sigma_p=6.3 \times 10^{-4}$ pb and $\delta=122$ keV

+ proper inclusion of uncertainties will enlarge the allowed regions and move the best values

Large parts of these allowed regions are out of the sensitivity of low $m_N$ detector (e.g. Ge, Si)
## DAMA/NaI vs others

<table>
<thead>
<tr>
<th></th>
<th>DAMA/NaI</th>
<th>CDMS-I</th>
<th>Edelweiss-I</th>
<th>UKLXe (Zeplin-I)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signature</strong></td>
<td>annual modulation</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td><strong>Target</strong></td>
<td>$^{23}$Na, $^{127}$I</td>
<td>nat Ge</td>
<td>nat Ge</td>
<td>nat Xe</td>
</tr>
<tr>
<td><strong>Technique</strong></td>
<td>widely known</td>
<td>poorly experienced</td>
<td>poorly experienced</td>
<td>liq/gas optical interface (light collected from top)</td>
</tr>
<tr>
<td><strong>Target mass</strong></td>
<td>$\approx 100$ kg</td>
<td>1.0 kg</td>
<td>0.32 kg</td>
<td>$\approx 3$ kg</td>
</tr>
<tr>
<td><strong>Used statistics</strong></td>
<td>57986 kg $\times$ day (+ other 3 cycles at hand)</td>
<td>28.3 kg $\times$ day</td>
<td>8.2 kg $\times$ day</td>
<td>280 kg $\times$ day</td>
</tr>
<tr>
<td><strong>Expt. depth</strong></td>
<td>1400 m</td>
<td>10 m</td>
<td>1700 m</td>
<td>1100 m</td>
</tr>
<tr>
<td><strong>Energy threshold</strong></td>
<td>2 keVee</td>
<td>5 keVee</td>
<td>20 keVee</td>
<td>2 keVee (but: $\sigma/E=100%$ and 1 p.e./keVee!!!; IDM02) (2.5 p.e./keVee; Moriond03)</td>
</tr>
<tr>
<td><strong>Quenching factor</strong></td>
<td>measured</td>
<td>assumed 1</td>
<td>assumed 1</td>
<td>measured</td>
</tr>
<tr>
<td><strong>Measured evt rate</strong></td>
<td>$\sim$1 cpd/kg/keV</td>
<td>$\sim$60 cpd/kg/keV (4.6 $10^6$ events)</td>
<td>2500 events total</td>
<td>$\sim$100 cpd/kg/keV (IDM02)</td>
</tr>
<tr>
<td><strong>Claimed evts after rejection procedures</strong></td>
<td>20 in Ge, 2 in Si, 3 multiple-Ge + then MC on neutron flux</td>
<td>0</td>
<td>$\sim$20-50 cpd/kg/keV after filtering (?) and ?? after PSD (Moriond03, IDM02)</td>
<td></td>
</tr>
<tr>
<td><strong>Evts satisfying the signature in DAMA/NaI effect</strong></td>
<td>modulation amplitude integrated over the given exposure $= 2000$ evts</td>
<td>from few down to zero (and on quenching factor)</td>
<td>from few down to zero (and on quenching factor)</td>
<td>depends on the models (even zero)</td>
</tr>
<tr>
<td><strong>Expected number of evts from DAMA/NaI effect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Notes:**
- $\sigma/E=100\%$ and 1 p.e./keVee!!!; IDM02
- 2.5 p.e./keVee; Moriond03
- $\sim$100 cpd/kg/keV (IDM02)
- $\sim$20-50 cpd/kg/keV after filtering (?) and ?? after PSD (Moriond03, IDM02)
A. Morselli, VULCANO2002

Data set of 2000 (new and different instrument) confirms data set of 1994/95.

Some hints from indirect searches consistent with DAMA result.
As a result of a new R&D for radiopurer NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

The new **LIBRA set-up ~250 kg NaI(Tl)**

(Large sodium Iodide Bulk for RAre processes) in the DAMA experiment

Improving installation etching staff at work

Storing new crystals

Installing LIBRA detectors

PMT +HV divider
Further on LIBRA installation
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

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.

View at end of detectors installation in the Cu box.

closing the Cu box housing the detectors,
verifying Cd foils,
Installing LIBRA electronics,
view with shielding completed,
upper glove box for calibration; the same as for ~100kg set-up (old photo).
LIBRA is living:

first high energy scintillation pulse

(V)

(ns)
Summary

☑ Successfully running ~100kg NaI(Tl), 6.5 kg LXe and R&D set-ups over many years

☑ Many rare processes significantly investigated with all the set-ups

• LXe alternatively running with $^{129}$Xe and $^{136}$Xe
• R&D set-up running with small scale expts
• 100 kg NaI(Tl):
  → 4 annual cycles released (~ $6 \times 10^4$ kg day)
  → Model independent analysis: presence of annual modulation with the proper features; no known systematics nor side reactions were found - or suggested by anyone - able to mimic the signature
  → Model dependent analyses: pure SI coupling, pure SD, mixed SI/SD, WIMP with preferred inelastic scattering in some of the possible model frameworks + studies on the uncertainties of the parameters and on the assumptions + halo models + many other possibilities under study
  → 5th, 6th and 7th annual cycles in progress to be released (total stat 107731 kg·d)

• From an improved R&D for radiopurity

DAMA/LIBRA (~250 kg NaI(Tl)) running and looking forward:

a new R&D for further radiopurifications started toward 1 ton set-up proposed in 1996