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 can point out its presence.

Drukier, Freese, Spergel PRD86
Freese et al. PRD88
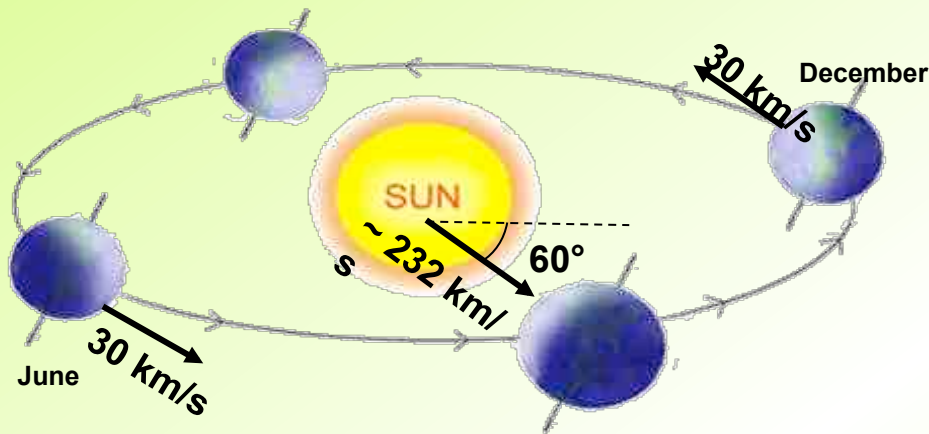
- $v_{sun} \sim 232$ km/s (Sun velocity in the halo)
- $v_{orb} = 30$ km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, $T = 1$ year
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

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

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

Expected rate in given energy bin changes because the revolution motion of the Earth around the Sun, which is 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) 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

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

The pioneer DAMA/NaI:
≈100 kg highly radiopure NaI(Tl)

**Performances**: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

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**

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

Results on DM particles:
- PSD   **PLB389(1996)757**
- Investigation on diurnal effect   **N.Cim.A112(1999)1541**
- Exotic Dark Matter search   **PRL83(1999)4918**
- Annual Modulation Signature

PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004) 2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008) 023506, MPLA23(2008)2125.
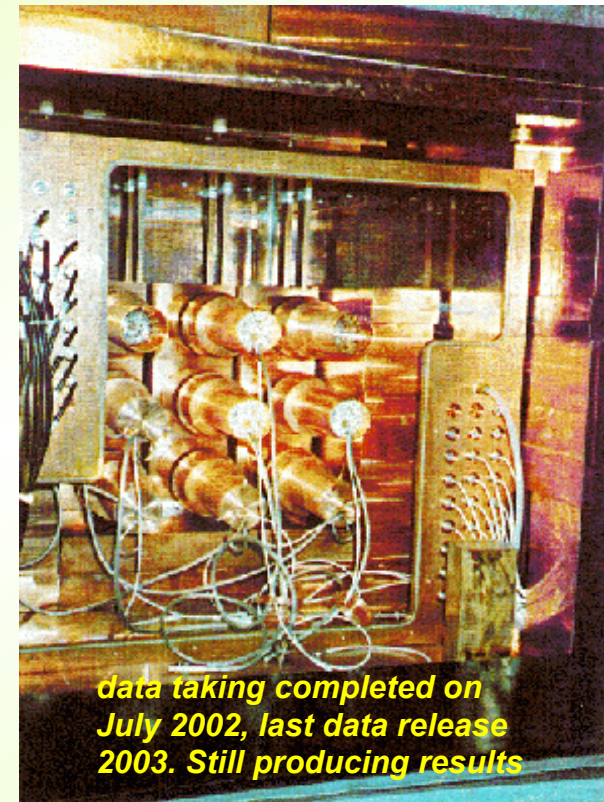
model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

total exposure (7 annual cycles) 0.29 ton×yr

The 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: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

- *Radiopurity, performances, procedures, etc.:* NIMA592(2008)297, JINST 7 (2012) 03009
- *Results on DM particles: Annual Modulation Signature:* EPJC56(2008)333, EPJC67(2010)39
- *Results on rare processes: PEP violation in Na, I:* EPJC62(2009)327, *CNC in I:* EPJC72(2012)1920, *IPP in ^{241}Am decay:* to appear on EPJA (arXiv:1305.2318)
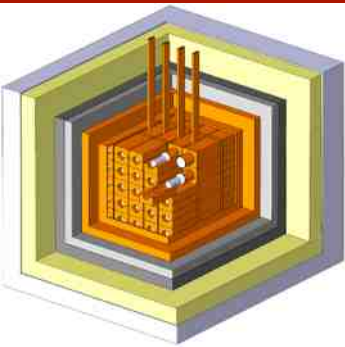
...calibration procedures

The DAMA/LIBRA set-up

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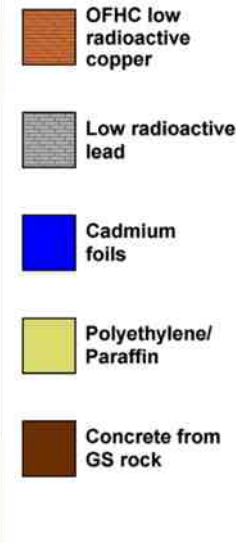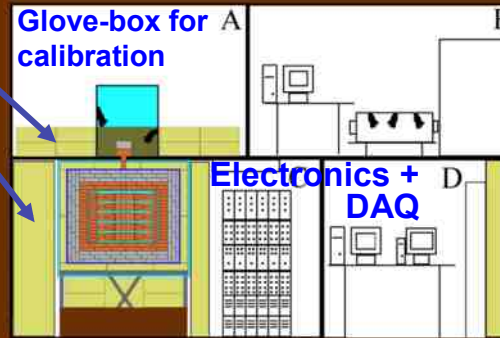
Polyethylene/paraffin

- 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

5.5-7.5 phe/keV

Installation

**Glove-box for
calibration**   A

B

**Electronics +
DAQ**   D

OFHC low
radioactive
copper

Low radioactive
lead

Cadmium
foils

Polyethylene/
Paraffin

Concrete from
GS rock

~ 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 Waweform 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

Some on residual contaminants in new ULB NaI(Tl) detectors
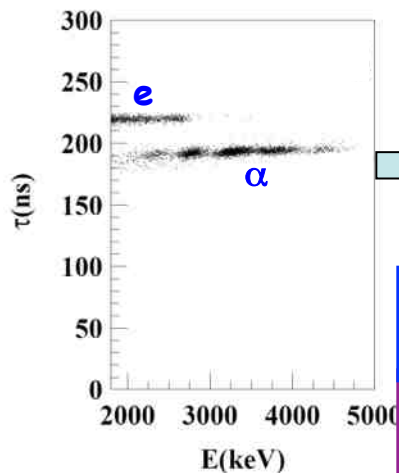
α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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

Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/ chemical radiopurification, new selection of overall materials, new protocol for growing and handling
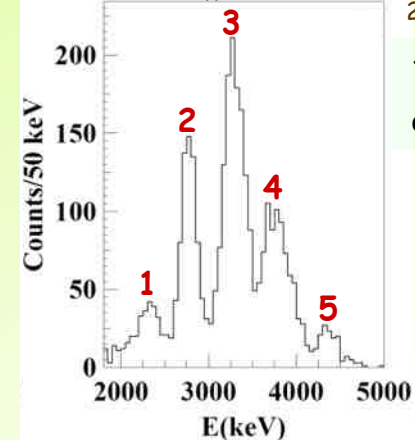
^{232}Th residual contamination — From time-amplitude method. If ^{232}Th chain at equilibrium: it ranges from 0.5 ppt to 7.5 ppt

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

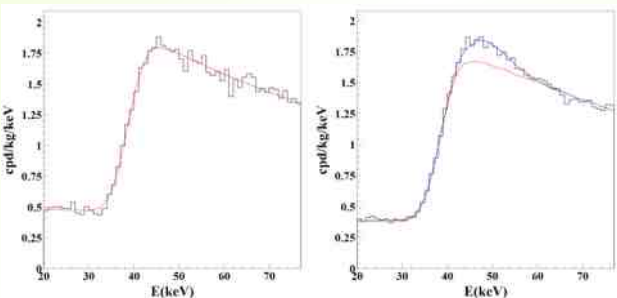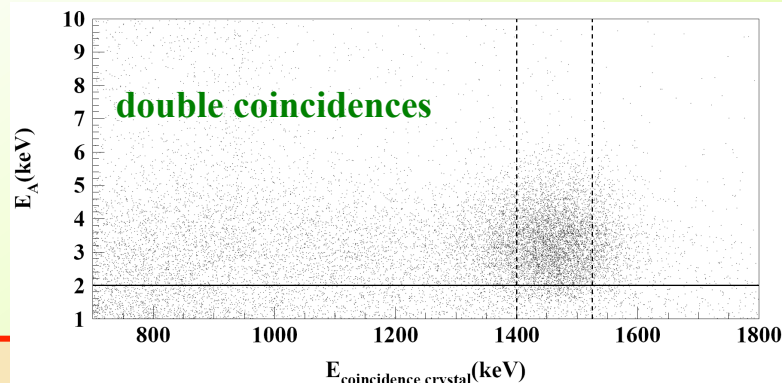^{238}U chain splitted into 5 subchains: ^{238}U $\rightarrow$ ^{234}U $\rightarrow$ ^{230}Th $\rightarrow$ ^{226}Ra $\rightarrow$ ^{210}Pb $\rightarrow$ ^{206}Pb

Thus, in this case: (2.1 ± 0.1) ppt of ^{232}Th; (0.35 ± 0.06) ppt for ^{238}U and: (15.8 ± 1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7 ± 1.1) μBq/kg for ^{226}Ra; (24.2 ± 1.6) μBq/kg for ^{210}Pb.

live time = 570 h

^{nat}K residual contamination

The analysis has given for the ^{nat}K content in the crystals values not exceeding about 20 ppb

double coincidences

^{129}I and ^{210}Pb

^{129}I/^{nat}I $\approx 1.7\times10^{-13}$ for all the new detectors

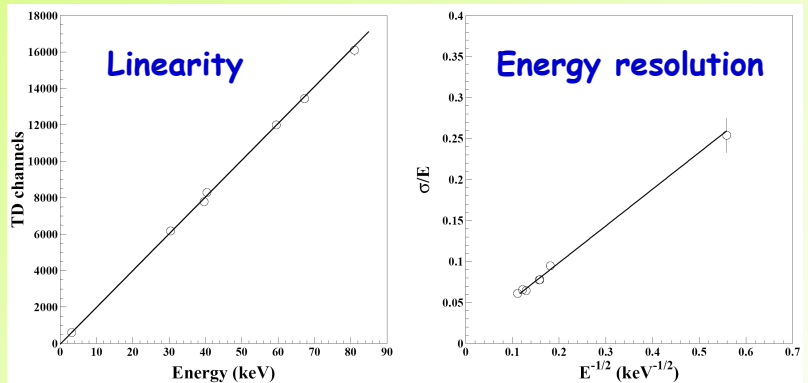^{210}Pb in the new detectors: $(5 - 30)$ μBq/kg.

No sizable surface pollution by Radon daugthers, thanks to the new handling protocols
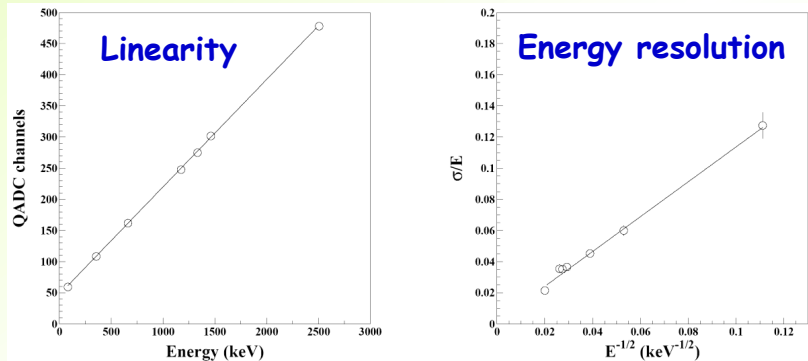
... more on NIMA592 (2008)297

DAMA/LIBRA calibrations

<u>Low energy</u>: various external gamma sources (^{241}Am, ^{133}Ba) and internal X-rays or gamma's (^{40}K, ^{125}I, ^{129}I), routine calibrations with ^{241}Am
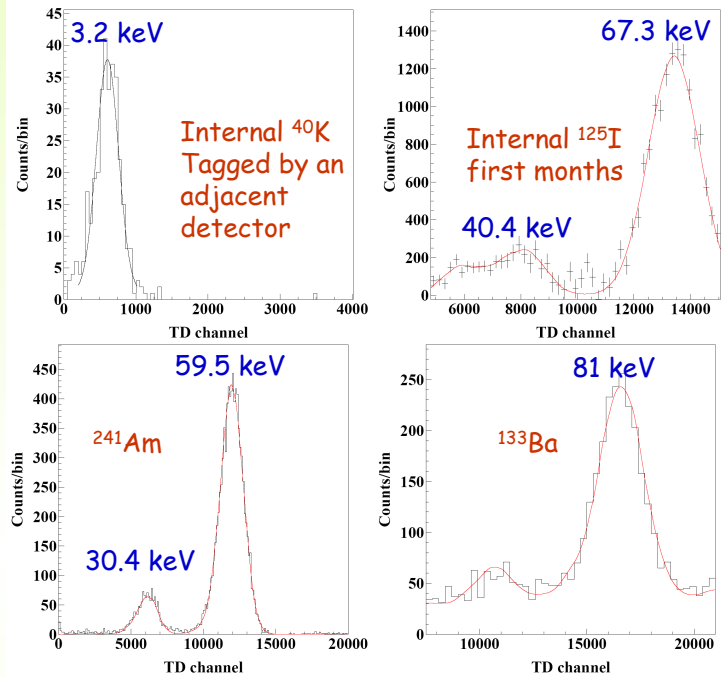

$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

<u>High energy</u>: 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

The signals (unlike low energy events) for high energy events are taken only from one PMT

The curves superimposed to the experimental data have been obtained by simulations

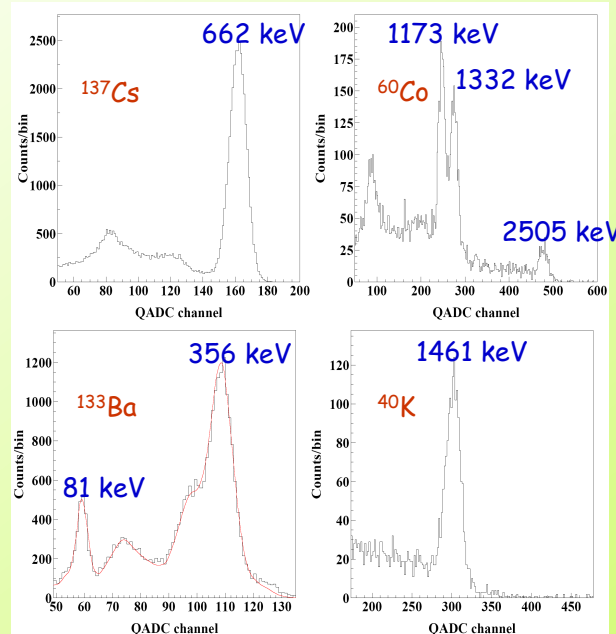$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23) \cdot 10^{-4}$$

Thus, here and hereafter keV means keV electron equivalent

DAMA/LIBRA data taking

Period		Mass (kg)	Exposure (kg × day)	α-β²
DAMA/LIBRA-1	Sep. 9, 2003 – July 21, 2004	232.8	51405	0.562
DAMA/LIBRA-2	July 21, 2004 – Oct. 28, 2005	232.8	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 – July 18, 2006	232.8	39445	0.591
DAMA/LIBRA-4	July 19, 2006 – July 17, 2007	232.8	49377	0.541
DAMA/LIBRA-5	July 17, 2007 – Aug. 29, 2008	232.8	66105	0.468
DAMA/LIBRA-6	Nov. 12, 2008 – Sep. 1, 2009	242.5	58768	0.519
DAMA/LIBRA-1 to -6	Sep. 9, 2003 – Sep. 1, 2009		**317697** = 0.87 ton×yr	**0.519**

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

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

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

The annual cycle 2009/10 will be released soon – End of the DAMA/LIBRA – phase 1

- **calibrations: ≈72 M events from sources**

- **acceptance window eff: 82 M events (≈3M events/keV)**

- **EPJC56(2008)333**

- **EPJC67(2010)39**

START of DAMA/LIBRA – phase 2

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

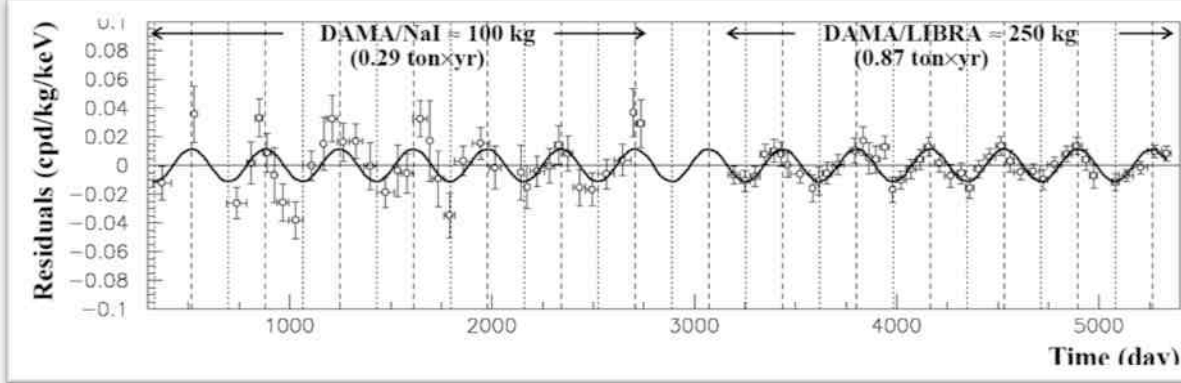Two annual cycles at lower energy threshold at hand...

... continuously running

Model Independent Annual Modulation Result

DAMA/NaI (7 years) + **DAMA/LIBRA** (6 years)   Total exposure: 425428 kg×day = **1.17 ton×yr**
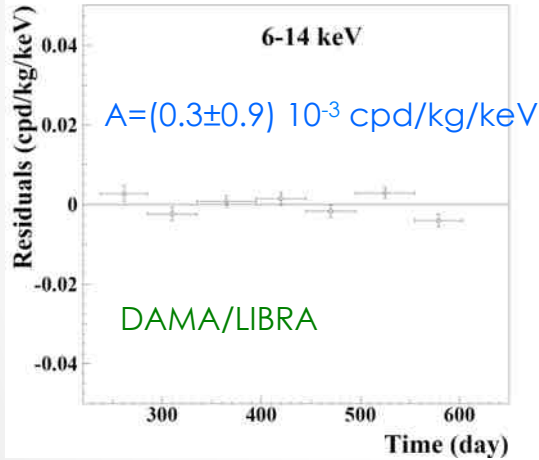
Single-hit residuals rate *vs* time in 2-6 keV

EPJC 56(2008)333, EPJC 67(2010)39

continuous line: t_0 = 152.5 d, T =1.0 y

A=(0.0114±0.0013) cpd/kg/keV
χ^2/dof = 64.7/79   8.8 σ C.L.

Absence of modulation? No
χ^2/dof=140/80 P(A=0) = 4.3×10^{-5}

fit with all the parameters free:
A = (0.0116 ± 0.0013) cpd/kg/keV
t_0 = (146±7) d - T = (0.999±0.002) y

A=(0.3±0.9) 10^{-3} cpd/kg/keV

6-14 keV

DAMA/LIBRA

+ No modulation in the whole energy spectrum

No modulation above 6 keV
This accounts for all sources of bckg

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**. Clear modulation in the single hit events. No modulation in the residual rate of the multiple hit events
A=-(0.0006±0.0004) cpd/kg/keV

*Multiple hits events =
Dark Matter particle "switched off"*

2-6 keV

DAMA/LIBRA
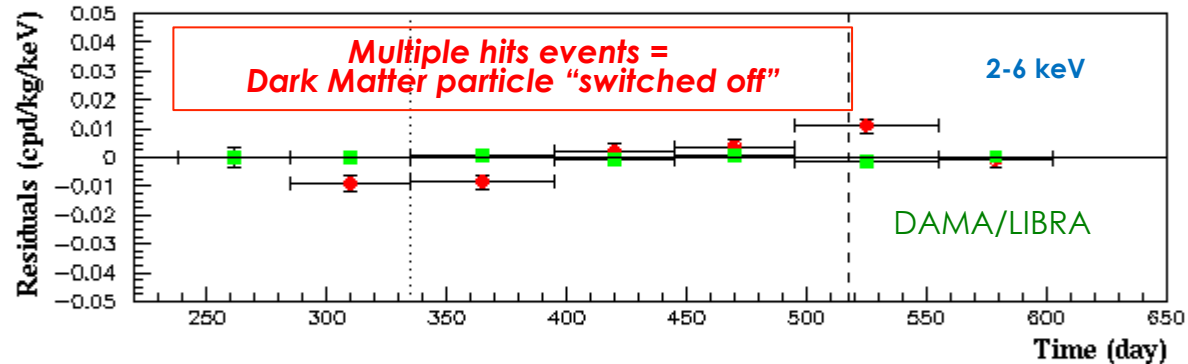
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9σ C.L.

Power spectrum of single-hit residuals

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)
total exposure: 1.17 ton×yr
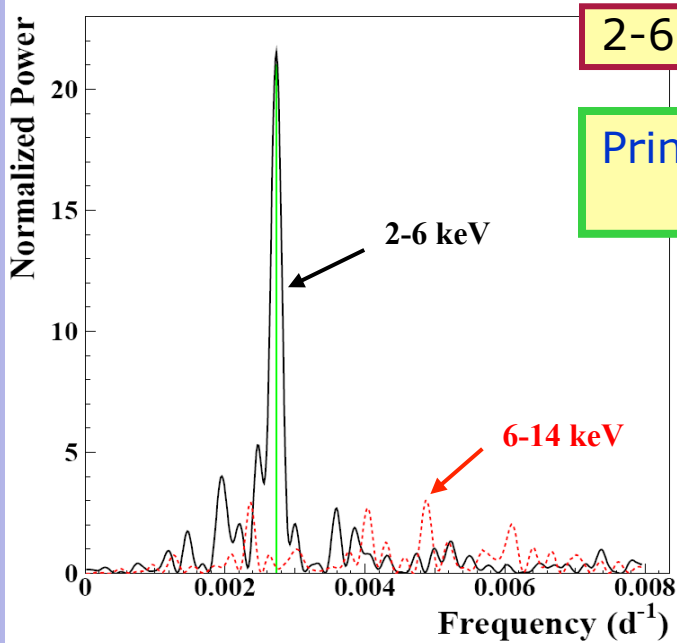
2-6 keV vs 6-14 keV

Principal mode in the 2-6 keV region:
$2.735 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$

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

The Lomb-Scargle periodogram, as reported in DAMA papers, always according to Ap.J. 263 (1982) 835, Ap.J. 338 (1989) 277; with the treatment of the experimental errors and of the time binning

Violet:
CL obtained with Montecarlo procedure for Lomb Scargle periodogram as in DAMA papers

From the formula: $CL = 1 - e^{-S}$
CL=99.7%   →   S = 5.8
CL=95.5%   →   S = 3.1
CL=90.0%   →   S = 2.3
CL=68.3%   →   S = 1.15

The Nyquist frequency is $\approx 3 \text{ y}^{-1}$ ($\approx 0.008 \text{ d}^{-1}$); meaningless higher frequencies, washed off by the integration over the time binning.

Frequency range: $[0, 0.06] \text{ d}^{-1}$ or $[0,22] \text{ y}^{-1}$
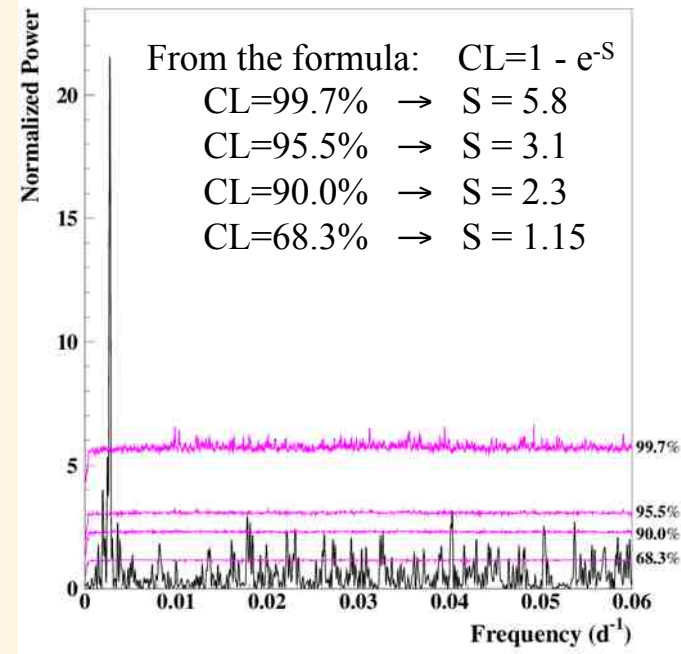
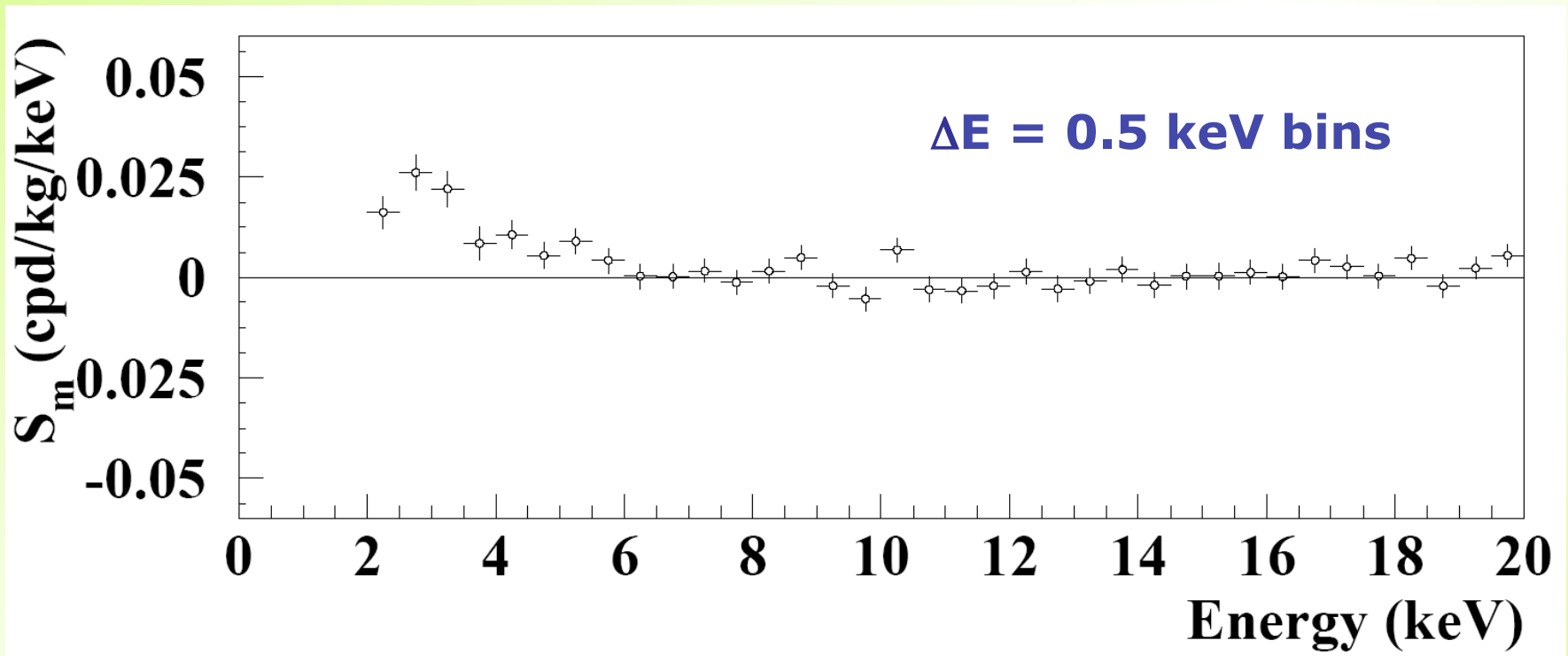Clear annual modulation is evident in (2-6) keV, while it is absent just above 6 keV

Energy distribution of the modulation amplitudes

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

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

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

total exposure: 425428 kg×day ≈1.17 ton×yr

ΔE = 0.5 keV bins

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 χ^2 equal to 27.5 for 28 degrees of freedom

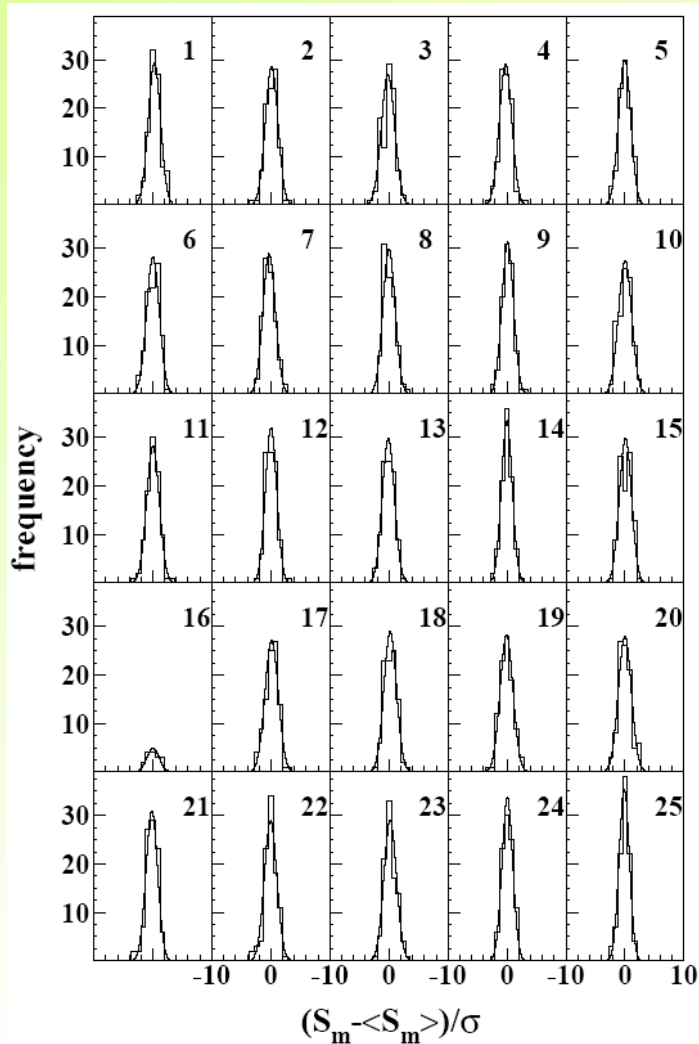# *Statistical distributions of the modulation amplitudes (S_m)*

a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

b) $<S_m>$ = mean values over the detectors and the annual cycles for each energy bin; σ = error on S_m
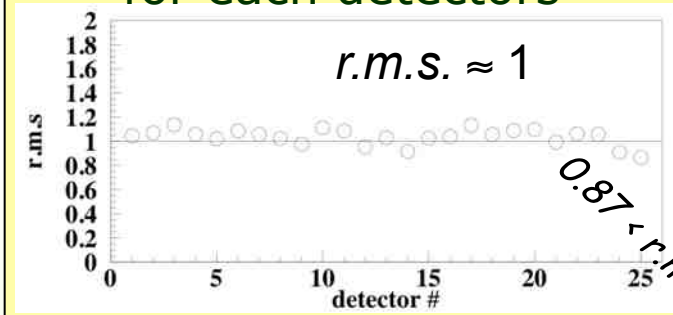
DAMA/LIBRA (6 years)
total exposure: 0.87 ton×yr

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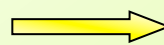

2-6 keV

Standard deviations of $(S_m-\langle S_m \rangle)/\sigma$ for each detectors

r.m.s. ≈ 1

$0.87 < r.m.s. < 1.14$

$x=(S_m-<S_m>)/\sigma,$

$\chi^2 = \Sigma\, x^2$

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

⟹ **S_m statistically well distributed in all the detectors and annual cycles**

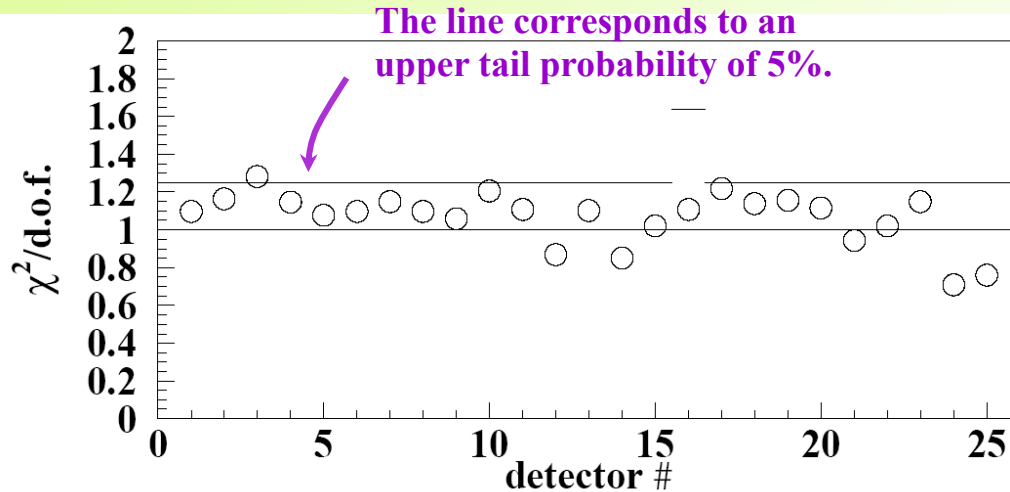# Statistical analyses about modulation amplitudes (S_m)

$x = (S_m - \langle S_m \rangle)/\sigma,$

$\chi^2 = \Sigma \, x^2$

$\chi^2/d.o.f.$ values of S_m distributions for each DAMA/LIBRA detector in the (2–6) keV energy interval for the six annual cycles.

DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr

The line corresponds to an upper tail probability of 5%.

The $\chi^2/d.o.f.$ values range from 0.7 to 1.22 (96 $d.o.f.$ = 16 energy bins × 6 annual cycles) for 24 detectors ⟹ at 95% C.L. the observed annual modulation effect is well distributed in all these detectors.

The remaining detector has $\chi^2/d.o.f.$ = 1.28 exceeding the value corresponding to that C.L.; this also is statistically consistent, considering that the expected number of detectors exceeding this value over 25 is 1.25.

- The mean value of the twenty-five points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.

- In this case, one would have an additional error of $\leq 4 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 5 \times 10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 − 6) keV energy interval.

- This possible additional error ($\leq 4\ \%$ or $\leq 0.5\%$, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

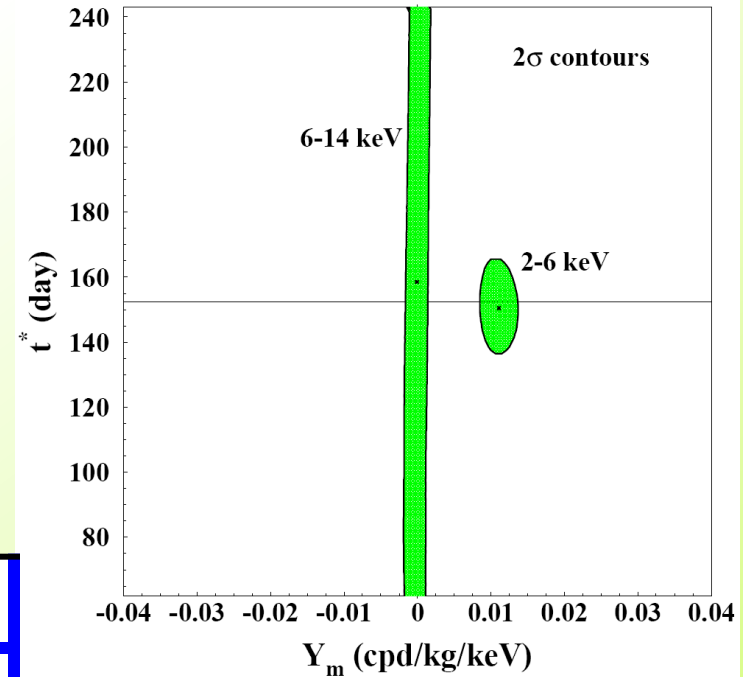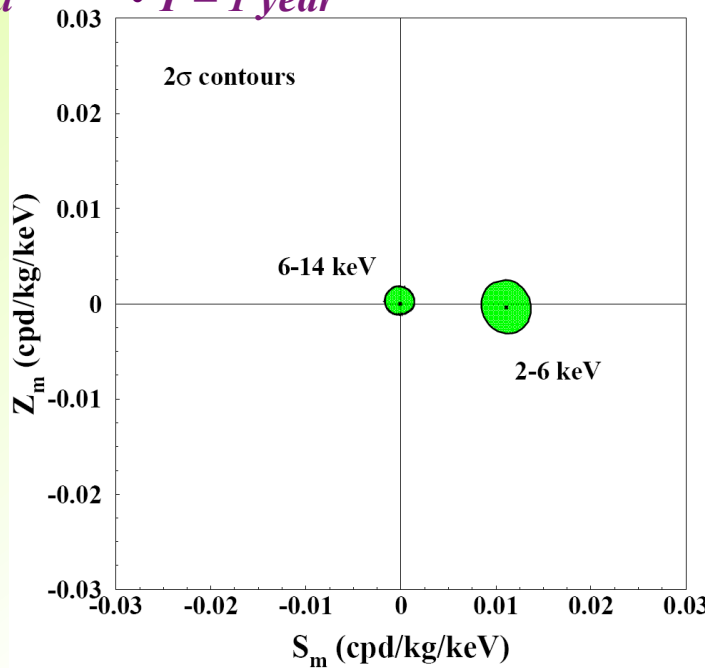**DAMA/NaI (7 years) + DAMA/LIBRA (6 years)**

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

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

For Dark Matter signals:

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

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

E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
2-6	0.0111 ± 0.0013	-0.0004 ± 0.0014	0.0111 ± 0.0013	150.5 ± 7.0
6-14	-0.0001 ± 0.0008	0.0002 ± 0.0005	-0.0001 ± 0.0008	--

The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about S_m already exclude any sizable presence of systematical effects

Additional investigations on the stability parameters

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

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

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

All the measured amplitudes well compatible with zero
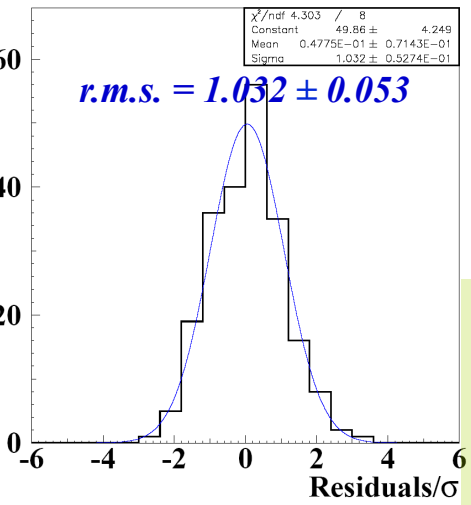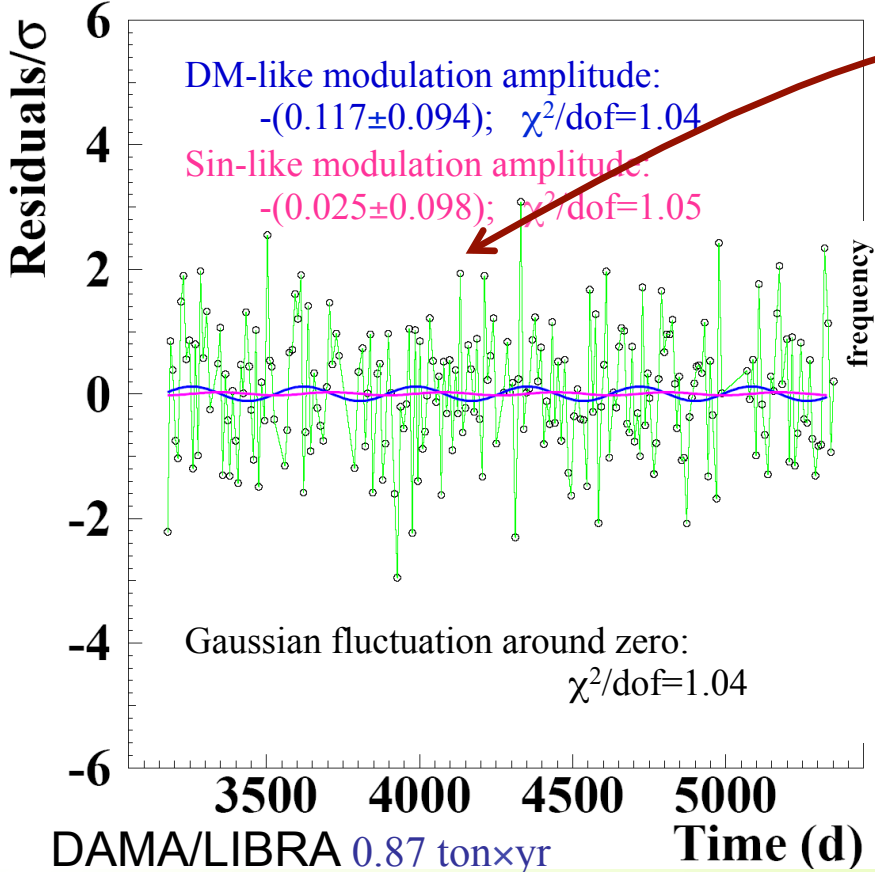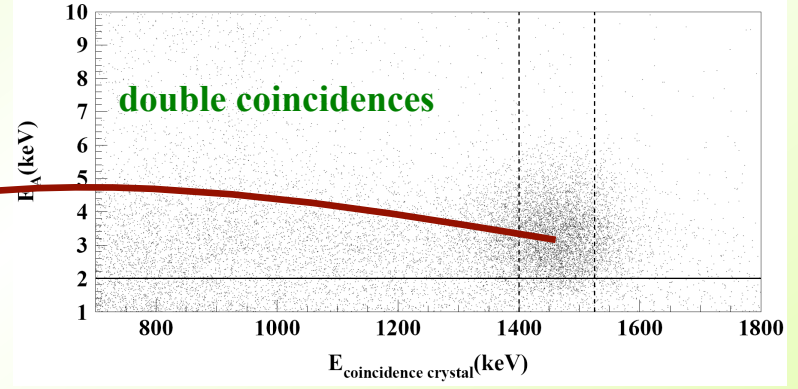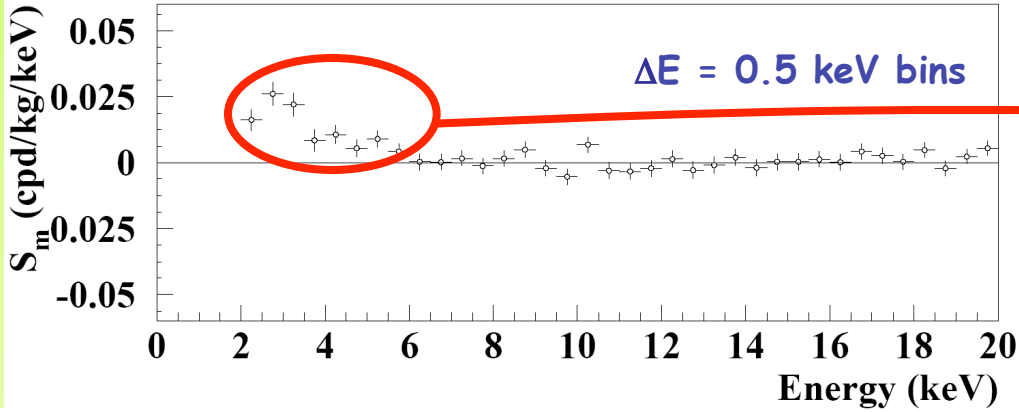+ none can account for the observed effect
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

No role for ^{40}K in the experimental S_m

$\Delta E = 0.5$ keV bins

also see arXiv:0912.0660

The experimental S_m cannot be due to ^{40}K for many reasons.

No modulation of the double coincidence events (1461 keV-3 keV).

double coincidences

DM-like modulation amplitude:
$-(0.117\pm0.094)$; $\chi^2/dof=1.04$
Sin-like modulation amplitude:
$-(0.025\pm0.098)$; $\chi^2/dof=1.05$

r.m.s. = 1.032 ± 0.053

Gaussian fluctuation around zero:
$\chi^2/dof=1.04$

DAMA/LIBRA 0.87 ton×yr

The ^{40}K double coincidence events are not modulated

Any modulation contribution around 3 keV in the single-hit events from the hypothetical cases of: i) ^{40}K "exotic" modulated decay; ii) spill-out effects from double to single events and viceversa, is ruled out at more than 10 σ

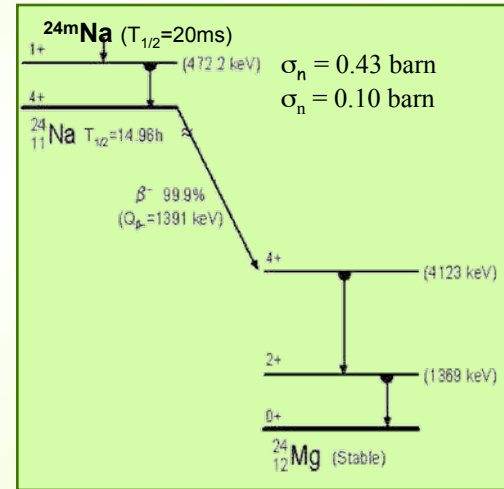# Can a possible **thermal neutron modulation** account for the observed effect?

NO

- Thermal neutrons flux measured at LNGS :

  $$\Phi_n = 1.08 \ 10^{-6} \ \text{n cm}^{-2} \ \text{s}^{-1} \ (\text{N.Cim.A101(1989)959})$$

- Experimental upper limit on the thermal neutrons flux "*surviving*" the neutron shield in DAMA/LIBRA:
  - studying triple coincidences able to give evidence for the possible presence of ^{24}Na from neutron activation:

    $$\Phi_n < 1.2 \times 10^{-7} \ \text{n cm}^{-2} \ \text{s}^{-1} \ (90\%\text{C.L.})$$

- Two consistent upper limits on thermal neutron flux have been obtained with DAMA/NaI considering the same capture reactions and using different approaches.

^{24m}**Na** ($T_{1/2}$=20ms)

1+ (472.2 keV) σ_n = 0.43 barn

4+ σ_n = 0.10 barn

$^{24}_{11}$Na $T_{1/2}$=14.96h

β^- 99.9%
(Q_β=1391 keV)

4+ (4123 keV)

2+ (1369 keV)

0+

$^{24}_{12}$Mg (Stable)

Evaluation of the expected effect:

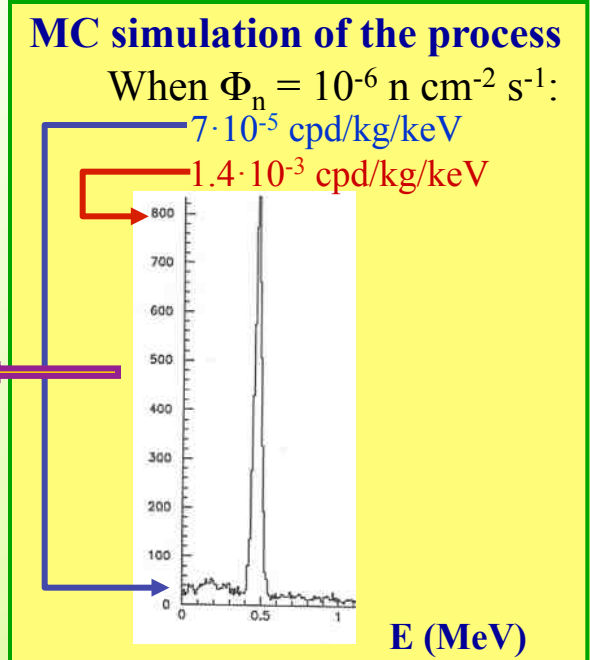▶ Capture rate = $\Phi_n \ \sigma_n \ N_T$ < 0.022 captures/day/kg

HYPOTHESIS: assuming very cautiously a 10% thermal neutron modulation:

➡ $S_m^{(\text{thermal n})} < 0.8 \times 10^{-6}$ cpd/kg/keV ($< 0.01\% \ S_m^{\text{observed}}$)

In all the cases of neutron captures (^{24}Na, ^{128}I, ...) a possible thermal n modulation induces a variation in all the energy spectrum

Already excluded also by R_{90} analysis

MC simulation of the process

When $\Phi_n = 10^{-6}$ n cm^{-2} s^{-1}:

$7 \cdot 10^{-5}$ cpd/kg/keV

$1.4 \cdot 10^{-3}$ cpd/kg/keV

E (MeV)

Can a possible fast neutron modulation account for the observed effect?

NO

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield

Measured fast neutron flux @ LNGS:
$\Phi_n = 0.9 \ 10^{-7}$ n cm^{-2} s^{-1} (Astropart.Phys.4 (1995)23)

By MC: differential counting rate above 2 keV $\approx 10^{-3}$ cpd/kg/keV

HYPOTHESIS: assuming - very cautiously - a 10% neutron modulation:

$S_m^{(fast\ n)} < 10^{-4}$ cpd/kg/keV ($< 0.5\%$ $S_m^{observed}$)

- Experimental upper limit on the fast neutrons flux "*surviving*" the neutron shield in DAMA/LIBRA:
  - ➤ through the study of the inelastic reaction ^{23}Na(n,n')^{23}Na*(2076 keV) which produces two γ's in coincidence (1636 keV and 440 keV):

    $\Phi_n < 2.2 \times 10^{-7}$ n cm^{-2} s^{-1} (90%C.L.)

  - ➤ well compatible with the measured values at LNGS. This further excludes any presence of a fast neutron flux in DAMA/LIBRA significantly larger than the measured ones.

Moreover, a possible fast n modulation would induce:
- ▶ a variation in all the energy spectrum (steady environmental fast neutrons always accompanied by thermalized component)

  already excluded also by R_{90}
- ▶ a modulation amplitude for multiple-hit events different from zero

  already excluded by the multiple-hit events

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

No role for μ in DAMA annual modulation result

✓ **Direct μ interaction in DAMA/LIBRA set-up:**

DAMA/LIBRA surface ≈0.13 m^2
μ flux @ DAMA/LIBRA ≈2.5 μ/day

MonteCarlo simulation:
- muon intensity distribution
- Gran Sasso rock overburden map
- Single hit events

It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.

Detector's matrix

✓ **Rate, R_n, of fast neutrons produced by μ:**

R_n = (fast n by μ)/(time unit) = Φ_μ Y M_{eff}

- Φ_μ @ LNGS ≈ 20 μ m^{-2}d^{-1} (±1.5% modulated)
- Measured neutron Yield @ LNGS:

  Y=1÷7 10^{-4} n/μ/(g/cm^2)

Annual modulation amplitude at low energy due to **μ modulation**:

$S_m^{(m)} = R_n$ **g ε** f_{DE} f_{single} **2%** /(M_{setup} ΔE)

g   = geometrical factor;
ε   = detection eff. by elastic scattering
f_{DE} = energy window (E>2keV) effic.;
f_{single} = single hit effic.

**Hyp.**: M_{eff} = 15 tons; g≈ε≈$f_{ΔE}$≈f_{single}≈0.5 (cautiously)
Knowing that: M_{setup} ≈ 250 kg and ΔE=4keV

$S_m^{(m)}$ < (0.3-2.4) × 10^{-5} cpd/kg/keV

Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events

It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.

Inconsistency of the phase between DAMA signal and μ modulation

For many others arguments
EPJC72(2012)2064
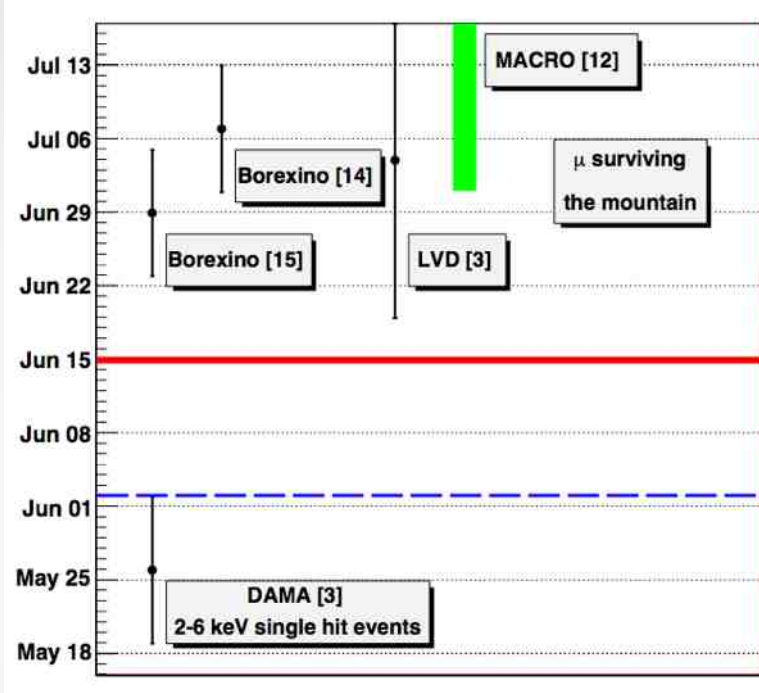
μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈3·10^{-4} m^{-2}s^{-1}; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)

but

- the muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a "mean" of the muon phase of each year

- The DAMA: modulation amplitude 10^{-2} cpd/kg/keV, in 2-6 keV energy range for single hit events; phase:

   May 26 ± 7 days (stable over 13 years)

considering the seasonal weather al LNGS, quite impossible that the max. temperature of the outer atmosphere (on which μ flux variation is dependent) is observed e.g. in June 15 which is 3 σ from DAMA

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

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

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

But, its phase should be (much) larger than μ phase, t_μ :

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

It cannot mimic the signature: different phase

Summary of the results obtained in the additional investigations of possible systematics or side reactions

DAMA/LIBRA 1-6

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5 \times 10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield $\rightarrow$ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + instrinsic calibrations	$<1-2 \times 10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured at LNGS	$<3 \times 10^{-5}$ cpd/kg/keV

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

Summarizing the model independent annual modulation result

- Presence of modulation for 13 annual cycles at 8.9σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 13 independent experiments of 1 year each one

- The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.17 ton × yr (13 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 (0.999 ± 0.002) yr, well compatible with the 1 yr period, as expected for the DM signal

3. Measured phase (146 ± 7) days is well compatible with 152.5 days, as expected for the DM signal

4. The modulation is present only in the low energy (2-6) keV 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-hits,* as expected for the DM signal
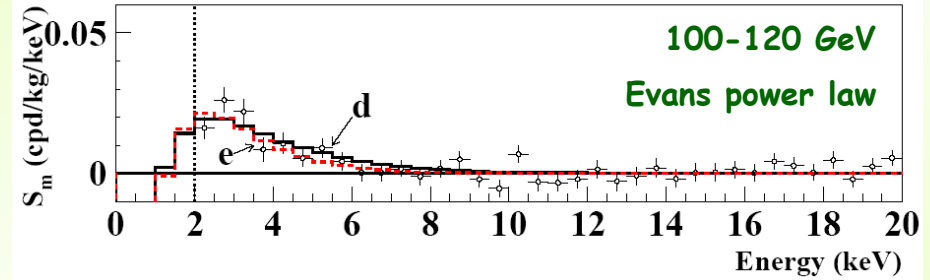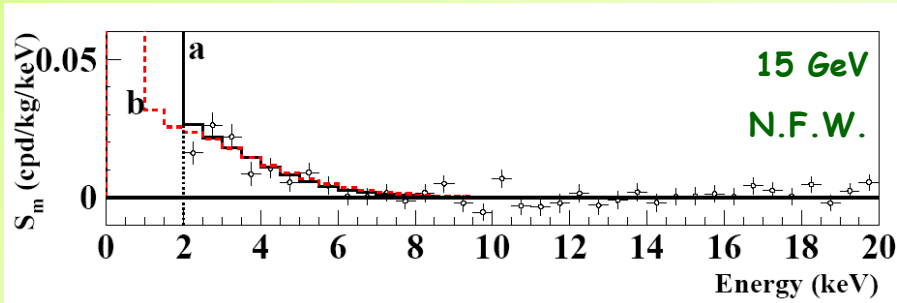
6. The measured modulation amplitude in NaI(Tl) of the *single-hit* events in (2-6) keV is: (0.0116 ± 0.0013) cpd/kg/keV $(8.9\sigma$ C.L.).

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
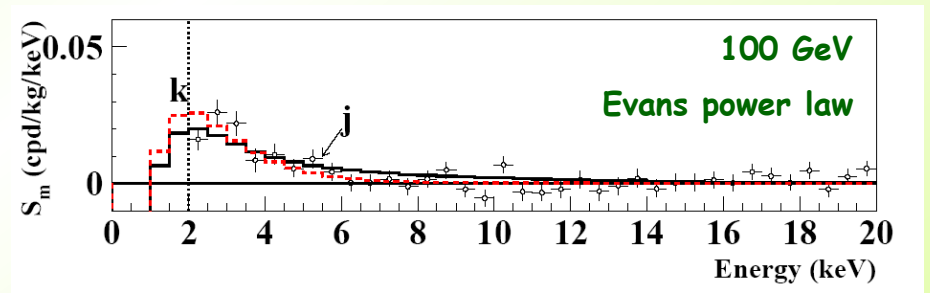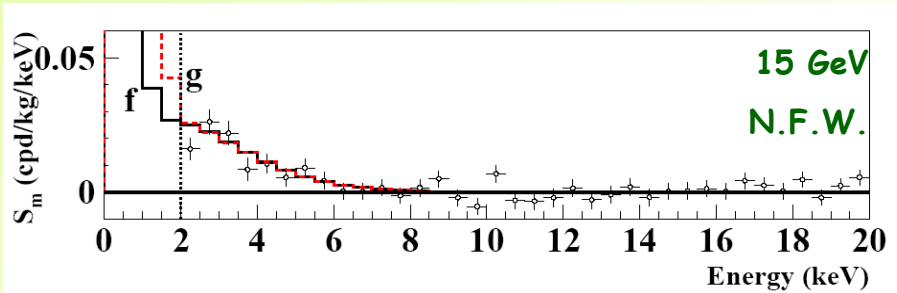
Just few _examples_ of interpretation of the annual modulation in terms of candidate particles in _some scenarios_
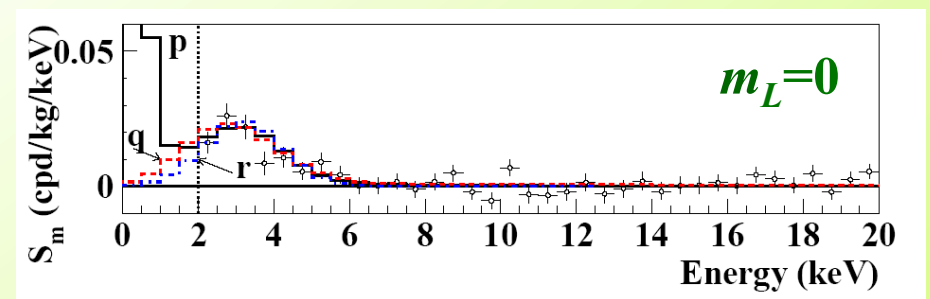
WIMP: SI

WIMP: SI & SD $\theta = 2.435$
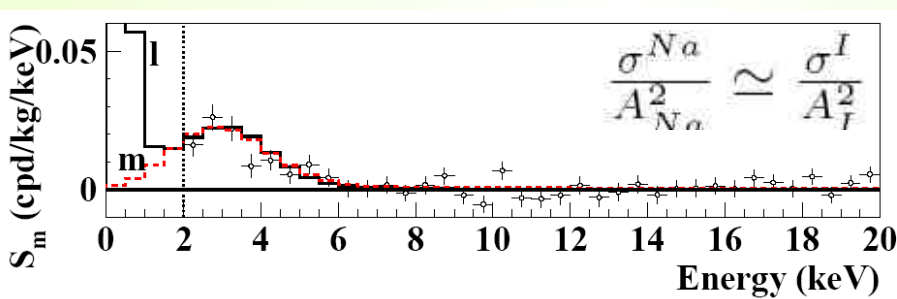
LDM, bosonic DM

•Not best fit
•About the same C.L.
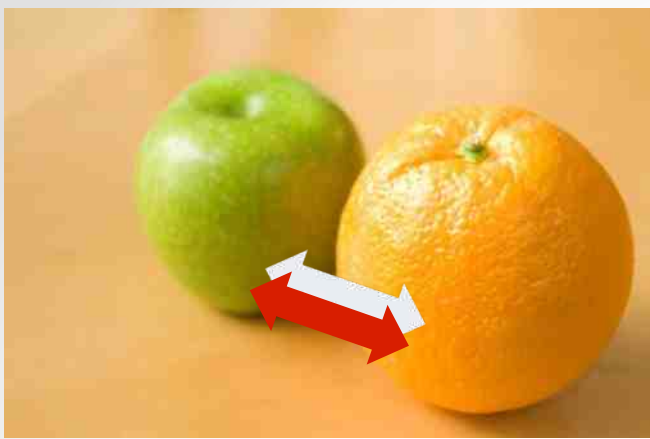
15 GeV N.F.W.

100-120 GeV Evans power law

15 GeV N.F.W.

100 GeV Evans power law

$\dfrac{\sigma^{Na}}{A^2_{Na}} \simeq \dfrac{\sigma^I}{A^2_I}$

$m_L = 0$

EPJC56(2008)333

Compatibility with several candidates; other ones are open

About interpretation

…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, …
- …

…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?
- …

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA

DAMA vs possible positive hints 2010-13

- ➢ **CoGeNT:** low-energy rise in the spectrum (irreducible by the applied background reduction procedures) + annual modulation
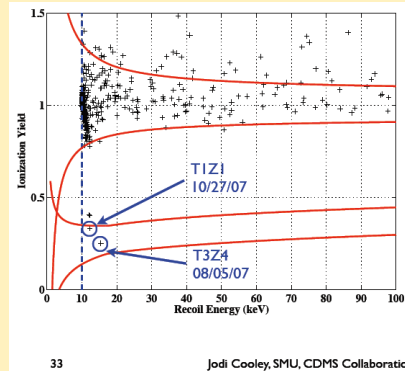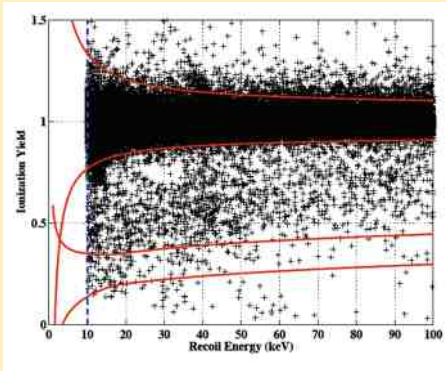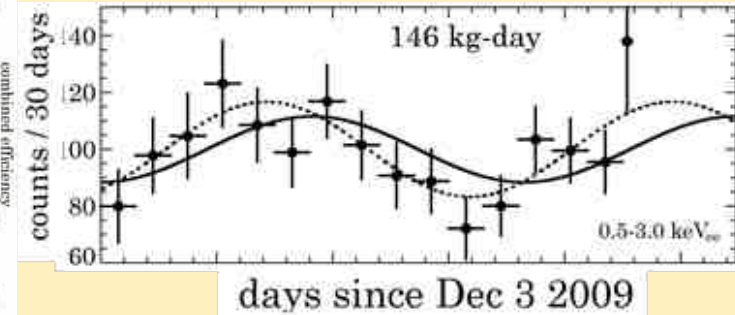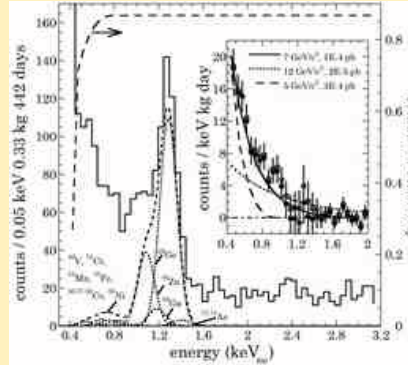
- ➢ **CDMS-Ge:** after many data selections and cuts, 2 Ge candidate recoils survive in an exposure of 194.1 kg x day. Estimated residual background 0.8
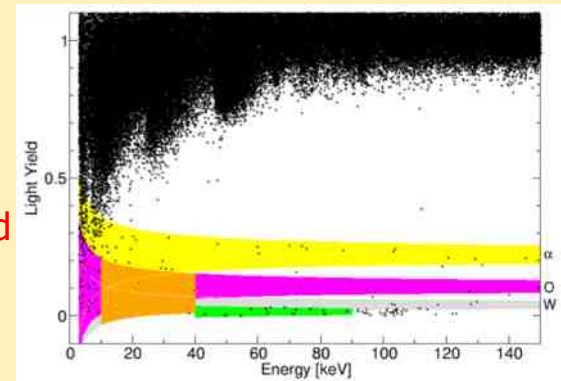
- ➢ **CRESST:** after many data selections and cuts, 67 candidate recoils in the O/Ca bands survive in an exposure of 730 kg x day (expected residual background: 40-45 events, depending on minimization)
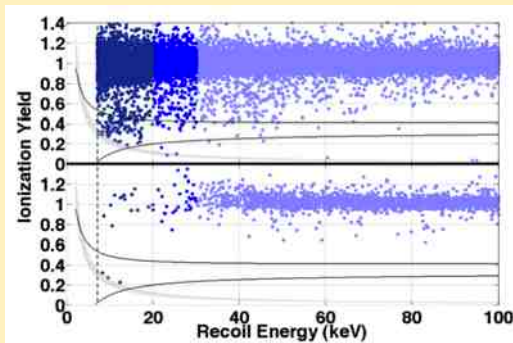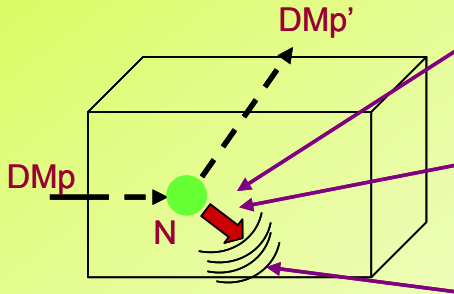
- ➢ **CDMS-Si:** after many data selections and cuts, 3 Si candidate recoils survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

All compatible with the DAMA 8.9 σ C.L. annual modulation result in various scenarios

... an example in literature...

Case of DM particles inducing elastic scatterings on target-nuclei

DMp'

DMp

N

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.

Including the Migdal effect
→Towards lower mass/higher σ

PRD84(2011)055014
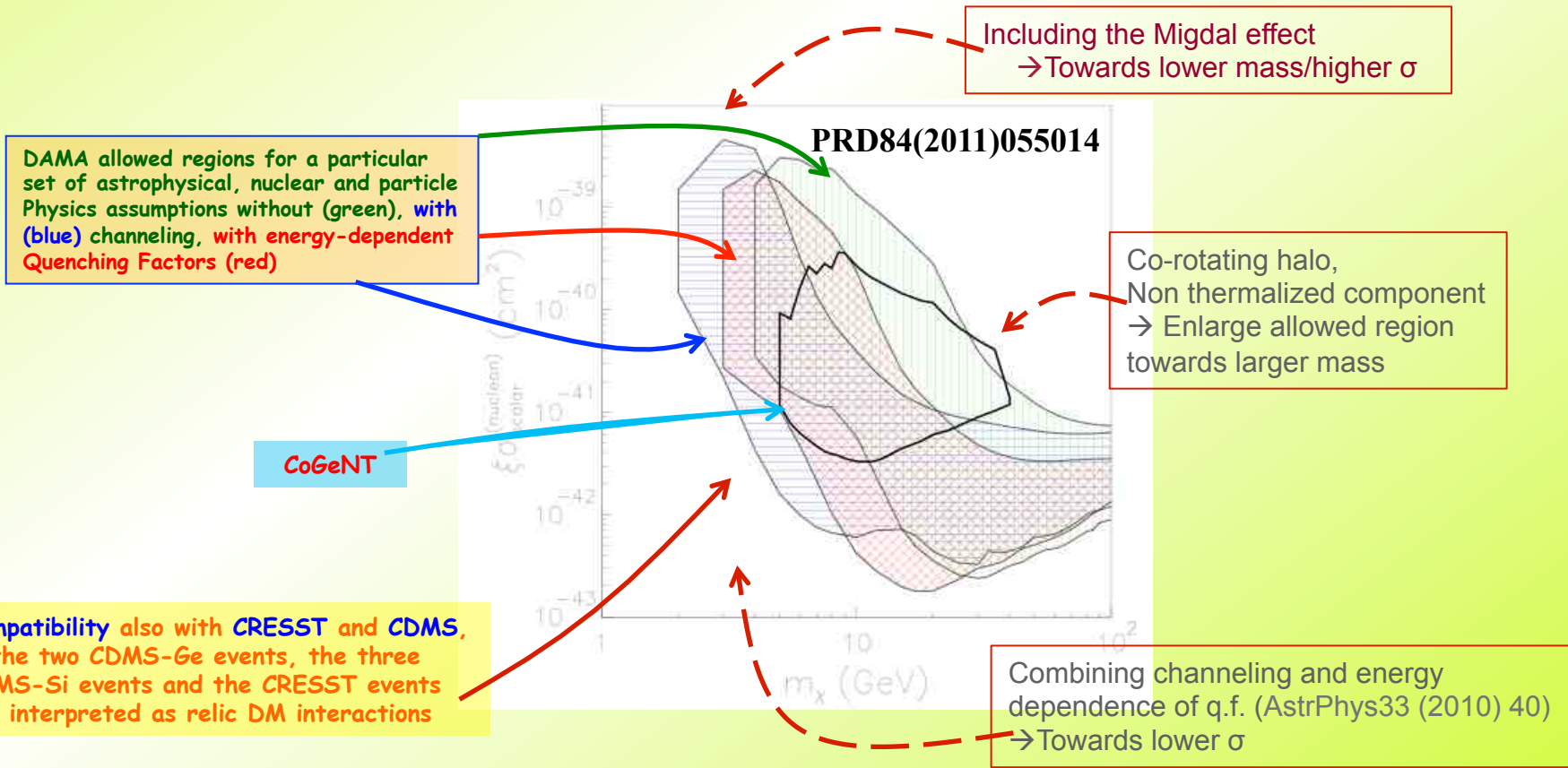
DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent Quenching Factors (red)

Co-rotating halo,
Non thermalized component
→ Enlarge allowed region towards larger mass

CoGeNT

$\xi \sigma_{SI}^{(nucleon)}$ (cm^2)

10^{-39}

10^{-40}

10^{-41}

10^{-42}

10^{-43}

1 10 10^2

m_x (GeV)

Compatibility also with CRESST and CDMS, if the two CDMS-Ge events, the three CDMS-Si events and the CRESST events are interpreted as relic DM interactions

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

... examples in some given frameworks

DM particle with preferred inelastic interaction

- In the Inelastic DM (iDM) scenario, WIMPs scatter into an excited state, split from the ground state by an energy comparable to the available kinetic energy of a Galactic WIMP.

$$\chi^- + N \rightarrow \chi^+ + N$$

→ W has two mass states χ^+, χ^- with δ mass splitting

→ Kinematical constraint for iDM

DAMA/NaI+DAMA/LIBRA
Slices from the 3-dimensional allowed volume

iDM interaction on Iodine nuclei

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

Fund. Phys. 40(2010)900

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.
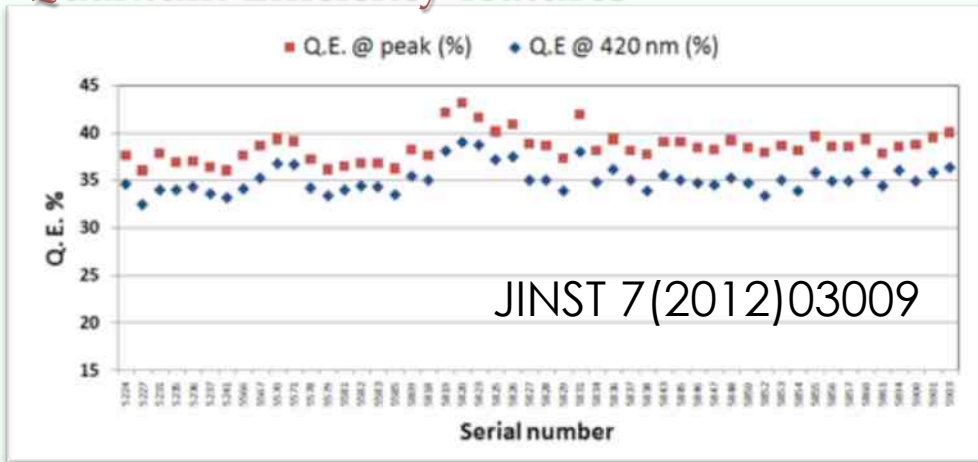
arXiv:1007.2688

- Inelastic scattering WIMPs with **large splittings** do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, ... nuclei.

... and more considering experimental and theoretical uncertainties
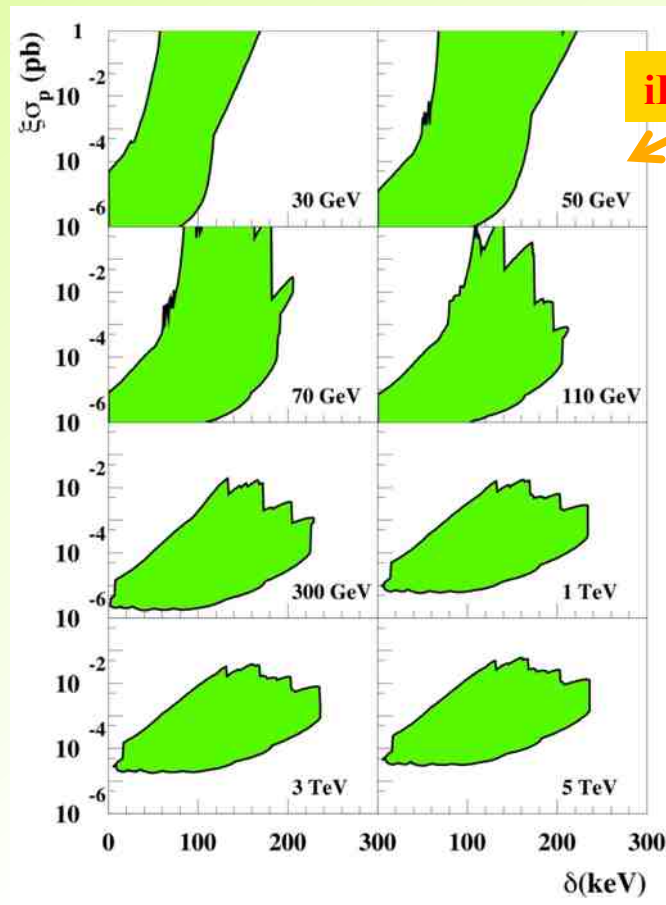
DAMA/LIBRA phase 2 - running
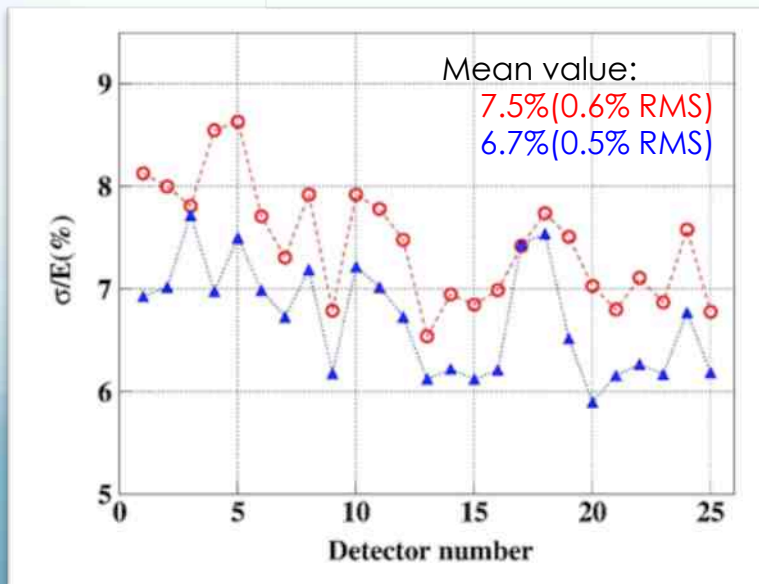
Quantum Efficiency features

Q.E. @ peak (%)   • Q.E @ 420 nm (%)

JINST 7(2012)03009

Residual Contamination

The limits are at 90% C.L.

PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
Average			0,43	-	47	0,12	83	0,54	-	-
Standard deviation			0,06	-	10	0,02	17	0,16	-	-

Energy resolution

Mean value:
7.5%(0.6% RMS)
6.7%(0.5% RMS)

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*

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo supported at 8.9 σ C.L. (13 annual cycles: 1.17 ton × yr)

- The modulation parameters determined with better precision

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

- Possible positive hints in direct searches are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties. Indirect model dependent searches not in conflict

A new annual cycle will be released soon – End of the DAMA/LIBRA – phase 1

- New PMTs with higher Q.E.: two annual cycles at hand…

DAMA/LIBRA – phase 2 perspectives

- *Continuing data taking* in the new configuration with lower software energy threshold (below 2 keV).

- New preamplifiers and trigger modules realized to further implement low energy studies.

- Suitable exposure planned in the new configuration to deeper study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects.

- Investigation on dark matter peculiarities and second order effect

- Special data taking for other rare processes.