DAMA/LIBRA results

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Relic DM particles from primordial Universe

SUSY
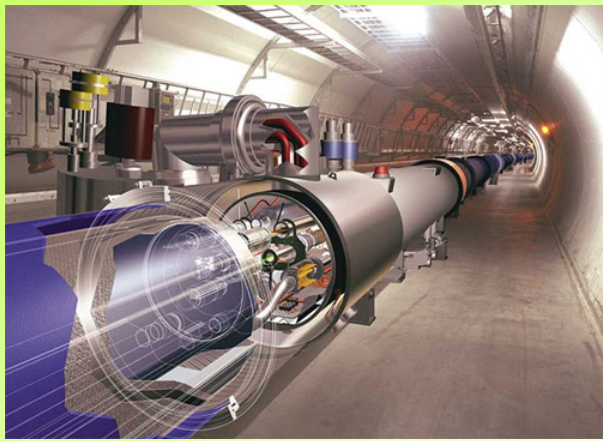(as neutralino or sneutrino
In various scenarios)

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

the sneutrino in the Smith
and Weiner scenario

mirror dark matter

sterile ν

Kaluza-Klein particles (LKK)

electron interacting dark matter

heavy exotic canditates, as
"4th family atoms", ...

a heavy ν of the 4-th family

Elementary Black holes,
Planckian objects,
Daemons

even a suitable particle not
yet foreseen by theories

etc…

(& invisible axions, ν's)

&

Right halo model and parameters?

• Composition?
DM multicomponent also
in the particle part?

Non thermalized components?

Caustics?

• Right related nuclear and
particle physics?

clumpiness?

etc… etc…

What accelerators can do:
to demostrate 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…

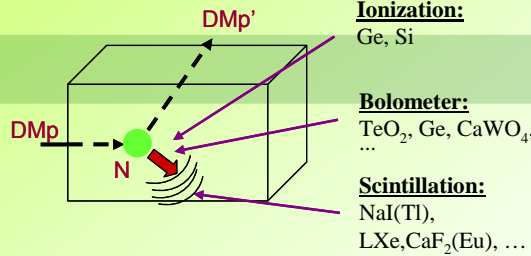+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

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

Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, ...

Scintillation:
NaI(Tl),
LXe,CaF_2(Eu), ...

- Inelastic Dark Matter: **W + N → W* + N**

  → W has Two mass states $\chi+$, $\chi-$ with δ mass splitting

  → Kinematical constraint for the inelastic scattering of $\chi-$ on a nucleus

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

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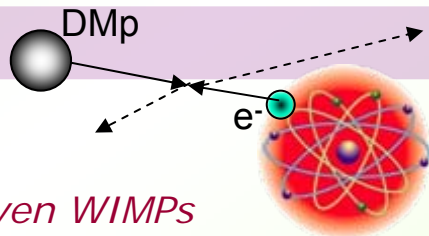
  → detection of recoil nuclei + e.m. radiation

- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e-

  a   **X-ray** γ **e-**
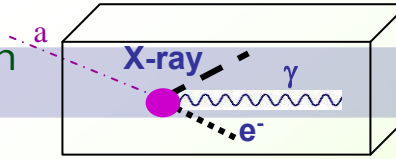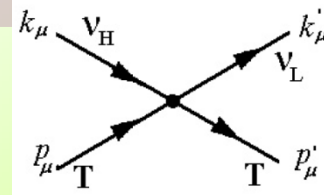
- Interaction only on atomic electrons

  → detection of e.m. radiation

  DMp

  e-

... even WIMPs

- Interaction of light DMp (LDM) on e- or nucleus with production of a lighter particle

  → detection of electron/nucleus recoil energy

  k_μ ν_H k'_μ
  ν_L
  p_μ T   T p'_μ
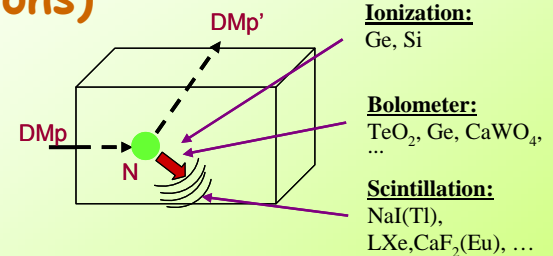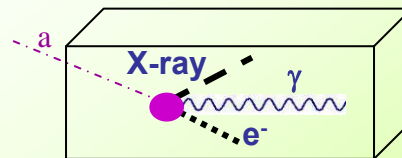
e.g. sterile ν

... also other ideas ...

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

- **... and more**

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)

DMp'

Ionization:
Ge, Si

DMp

Bolometer:
TeO_2, Ge, $CaWO_4$, ...

N

Scintillation:
NaI(Tl),
LXe, CaF_2(Eu), …

a

X-ray

γ

e^-

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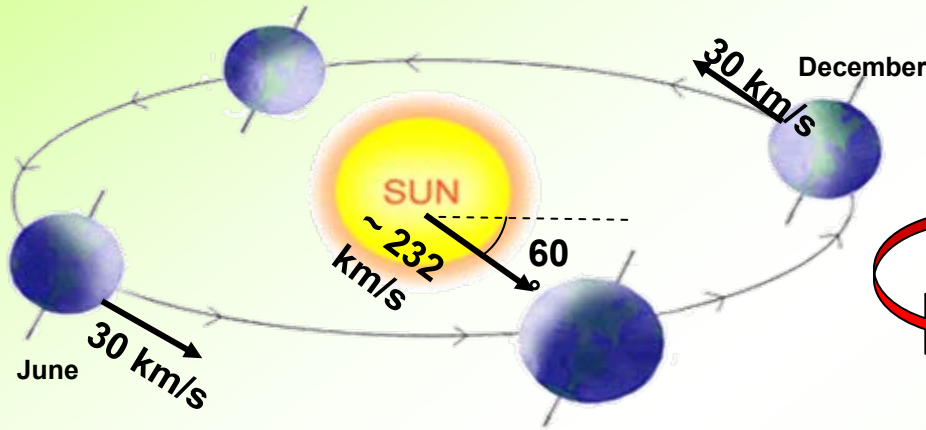
• v_{sun} ~ 232 km/s (Sun velocity in the halo)
• v_{orb} = 30 km/s (Earth velocity around the Sun)
• $\gamma = \pi/3$
• $\omega = 2\pi/T$ T = 1 year
• t_0 = 2nd June (when $v_{\oplus}$ is maximum)

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

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

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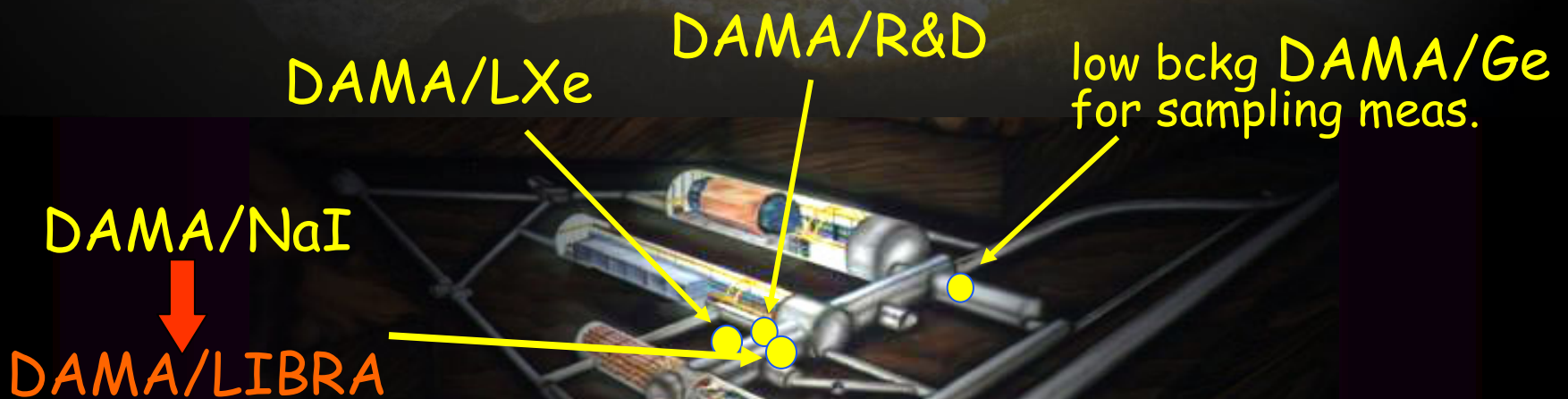
Requirements of the annual modulation

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) 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, thus, different peculiarities (e.g. the phase) with respect to those effects connected with the seasons instead

DAMA: an observatory for rare processes @LNGS

DAMA/R&D

DAMA/LXe

low bckg DAMA/Ge for sampling meas.

DAMA/NaI

DAMA/LIBRA

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

DAMA membership

Overall membership in the DAMA activities

Spokesperson: R. Bernabei

P. Belli, R. Bernabei, A. Bussolotti*, F. Montecchia, F. Nozzoli
Dip. di Fisica, Univ. Roma "Tor Vergata" and INFN, sez. Roma Tor Vergata, Italy

F. Cappella, A. d'Angelo, A. Incicchitti, A. Mattei*, D. Prosperi
Dip. di Fisica, Università di Roma "La Sapienza" and INFN, sez. Roma, Italy

R. Cerulli, V. Caracciolo, A. di Marco
INFN - Laboratori Nazionali del Gran Sasso, Italy

C.J. Dai, H.L. He, X.H. Ma, X.D. Sheng, R.G. Wang, Z.P. Ye**
IHEP, Chinese Academy, China;

+ in some by-product results and small scale experiments:

**F. Danevich, B.V. Grinyov, V.V. Kobychev,
V.M. Kudovbenko, S.S. Nagorny,
L.L. Nagornaya, D.V. Poda, R.B. Podviyanuk,
O.G. Polischuk, V.I. Tretyak, I. M. Vyshnevskyi,
S.S. Yurchenko and coll.**
Institute for Nuclear Research of Kiev, Ukraine

M. Laubenstein, S. Nisi
INFN - Laboratori Nazionali del Gran Sasso, Italy

S. d'Angelo
Dip. di Fisica and INFN, Università di Roma "Tor Vergata", Italy

+ in some studies on $\beta^+\beta^+$, EC/β^+, EC/EC decay modes (under the joint Indo-Italian DST-MAE project):

**P.K. Raina, A.K. Singh,
P.K. Rath, A. Shukla**
Indian Institute of Technology, Kharagpur, India.

+ in neutron measurements:

M. Angelone, P. Batistoni, M.Pillon
ENEA - C. R. Frascati, Italy

* Technical staff; ** also University of Jing Gangshan, Jiangxi, China.

LABORATORI NAZIONALI DEL GRAN SASSO - INFN

Largest underground laboratory for astroparticle physics

LNGS

ROME

Roma-L'Aquila-Teramo highway: tunnel under Gran Sasso mountain, 10.4 km long

In 1979 A. Zichichi proposed to the Parliament the project of a large underground laboratory close to the Gran Sasso highway tunnel, then under construction.

In 1982 the Parliament approved the construction, finished in 1987

In 1989 first experiments (GALLEX, MACRO, LVD, ...) started taking data

L'AQUILA

CERN

A   B

C

TERAMO
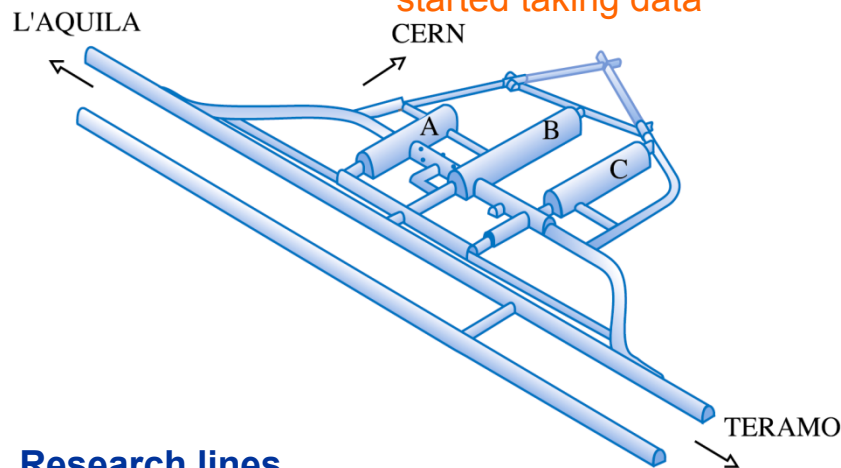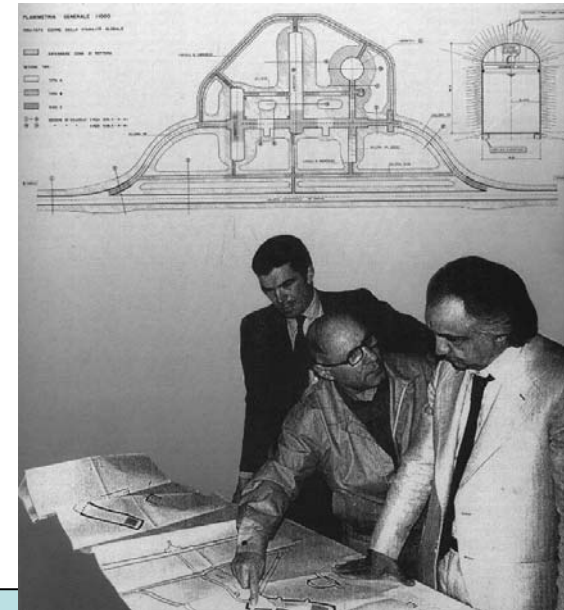
- 1400 m rock coverage
- cosmic μ reduction= 10^{-6} (i.e. ≈ 1 /m^2 h)
- underground area: 18 000 m^2
- external facilities
- easy access
- thoudand scientists from about 30 countries
- Permanent staff = hundred positions

Research lines

- **Neutrino physics** (mass, oscillations, stellar physics, solar ν's, ν's from beam, ν's from supernovae)
- **Dark matter**
- **Rare processes**

- **Nuclear reactions of astrophysics interest**
- **Geophysics**
- **Biology**
- **Gravitational waves (in future)**

DAMA/LXe: results on rare processes

NIMA482(2002)728

Dark Matter Investigation

- Limits on recoils investigating the DMp-^{129}Xe elastic scattering by means of PSD
- Limits on DMp-^{129}Xe inelastic scattering
- Neutron calibration
- ^{129}Xe vs ^{136}Xe by using PSD → SD vs SI signals to increase the sensitivity on the SD component

PLB436(1998)379
PLB387(1996)222, NJP2(2000)15.1
PLB436(1998)379, EPJdirectC11(2001)1

foreseen/in progress

Other rare processes:
- Electron decay into invisible channels
- Nuclear level excitation of ^{129}Xe during CNC processes
- N, NN decay into invisible channels in ^{129}Xe
- Electron decay: $e^- \rightarrow \nu_e \gamma$
- 2β decay in ^{136}Xe
- 2β decay in ^{134}Xe
- Improved results on 2β in ^{134}Xe, ^{136}Xe
- CNC decay ^{136}Xe → ^{136}Cs
- N, NN, NNN decay into invisible channels in ^{136}Xe

Astrop.P.5(1996)217
PLB465(1999)315
PLB493(2000)12
PRD61(2000)117301
Xenon01
PLB527(2002)182
PLB546(2002)23
Beyond the Desert (2003) 365
EPJA27 s01 (2006) 35

DAMA/R&D set-up: results on rare processes

- Particle Dark Matter search with CaF$_2$(Eu)

NPB563(1999)97,
Astrop.Phys.7(1997)73

- 2β decay in ^{136}Ce and in ^{142}Ce
- 2EC2ν ^{40}Ca decay
- 2β decay in ^{46}Ca and in ^{40}Ca
- 2β$^+$ decay in ^{106}Cd
- 2β and β decay in ^{48}Ca
- 2EC2ν in ^{136}Ce, in ^{138}Ce and α decay in ^{142}Ce
- 2β$^+$ 0ν, EC β$^+$ 0ν decay in ^{130}Ba
- Cluster decay in LaCl$_3$(Ce)
- CNC decay ^{139}La → ^{139}Ce

II N. Cim.A110(1997)189
Astrop. Phys. 7(1997)73
NPB563(1999)97
Astrop.Phys.10(1999)115
NPA705(2002)29
NIMA498(2003)352

NIMA525(2004)535
NIMA555(2005)270
UJP51(2006)1037

- α decay of natural Eu
- β decay of ^{113}Cd
- ββ decay of ^{64}Zn, ^{70}Zn, ^{180}W, ^{186}W
- ββ decay of ^{108}Cd and ^{114}Cd

NPA789(2007)15
PRC76(2007)064603
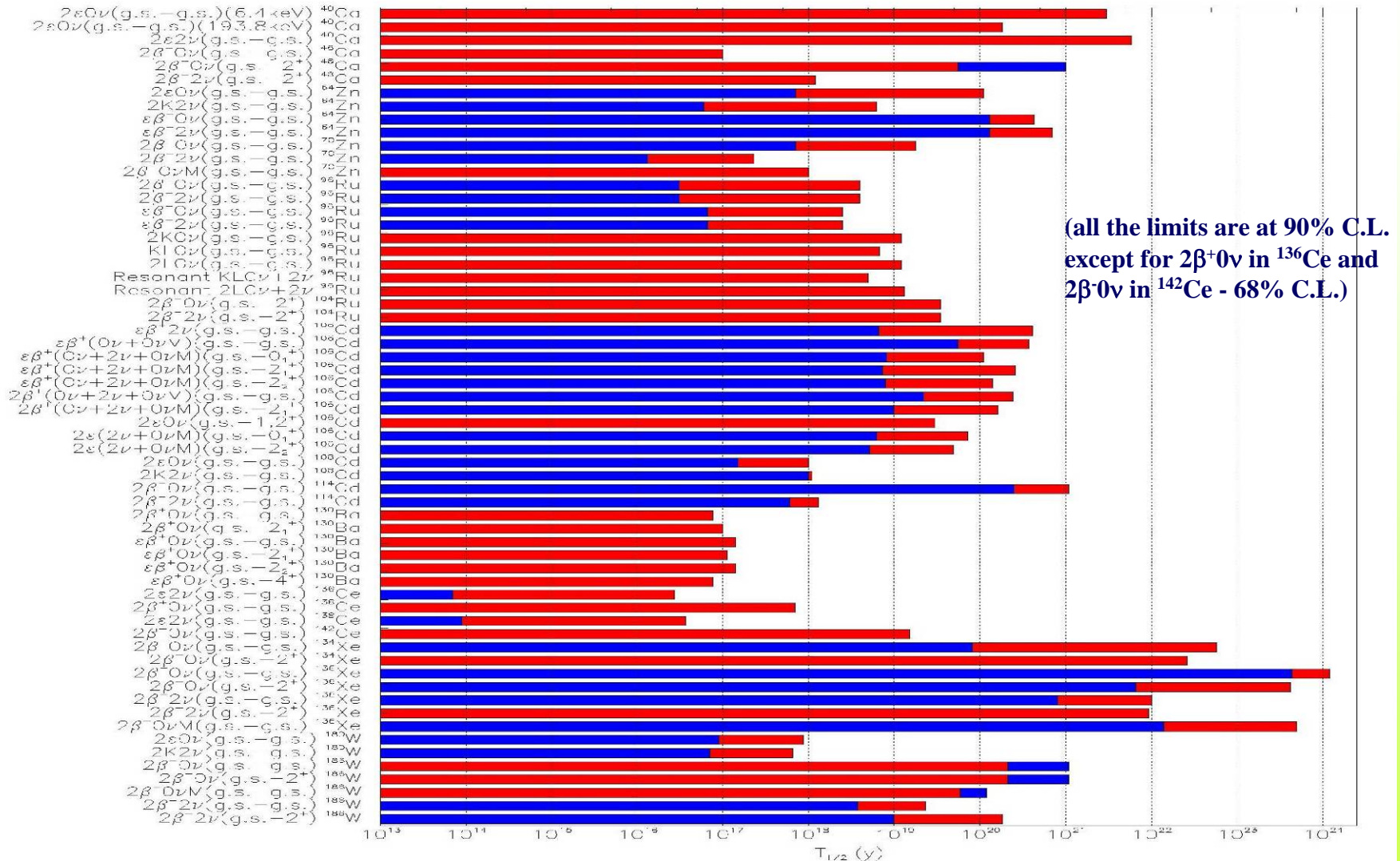PLB658(2008)193, NPA826(2009)256
EPJA36(2008)167

DAMA/Ge & LNGS Ge facility

- RDs on highly radiopure NaI(Tl) set-up;
- several RDs on low background PMTs;
- qualification of many materials
- measurements with a Li$_6$Eu(BO$_3$)$_3$ crystal (NIMA572(2007)734)
- measurements with ^{100}Mo sample investigating ββ decay in the 4π low-bckg HP Ge facility of LNGS (Proceed. of the Int. Conf. NPAE 2008, ed. INR-Kiev (2009) 473)
- search for ^{7}Li solar axions (NPA806(2008)388)
- ββ decay of ^{96}Ru and ^{104}Ru (EPJA42(2009)171)
- measurements with a Li$_2$MoO$_4$ (NIMA607(2009) 573)
- ββ decay of ^{136}Ce and ^{138}Ce (NPA824(2009)101)

+Many other meas. already scheduled for near future

DAMA set-ups also produce many results on rare processes.
An example: DAMA results on ββ decay

(all the limits are at 90% C.L. except for $2\beta^+0\nu$ in ^{136}Ce and $2\beta^-0\nu$ in ^{142}Ce - 68% C.L.)

Experimental limits on $T_{1/2}$ obtained by DAMA (red) and by previous experiments (blue)

DAMA/NaI: ≈100 kg 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 x yr
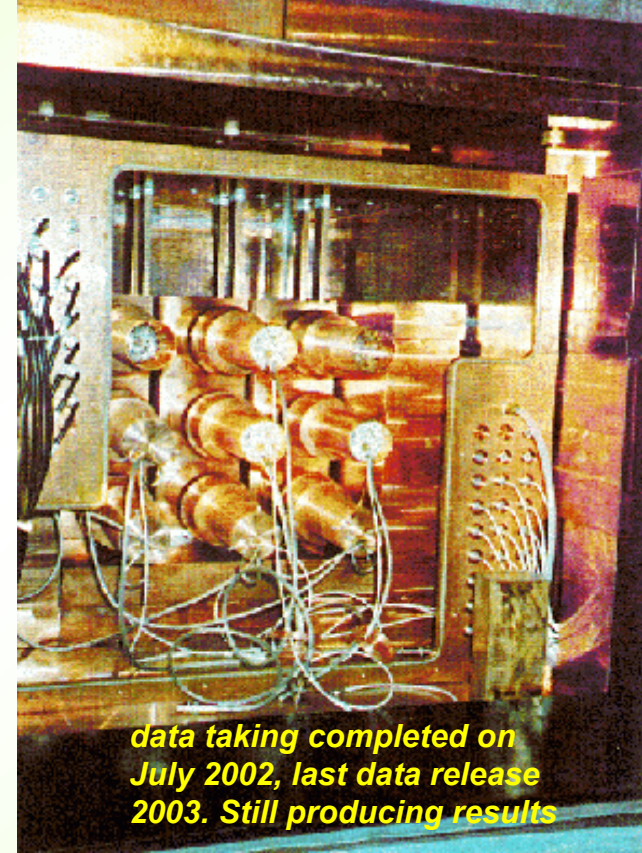
The new DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

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

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

filling the inner Cu box with further shield

- *Radiopurity, performances, procedures, etc.:* NIMA592(2008)297
- *Results on DM particles: Annual Modulation Signature:* EPJC56(2008)333, EPJC67(2010)39
- *Results on rare processes: PEP violation in Na and I:* EPJC62(2009)327
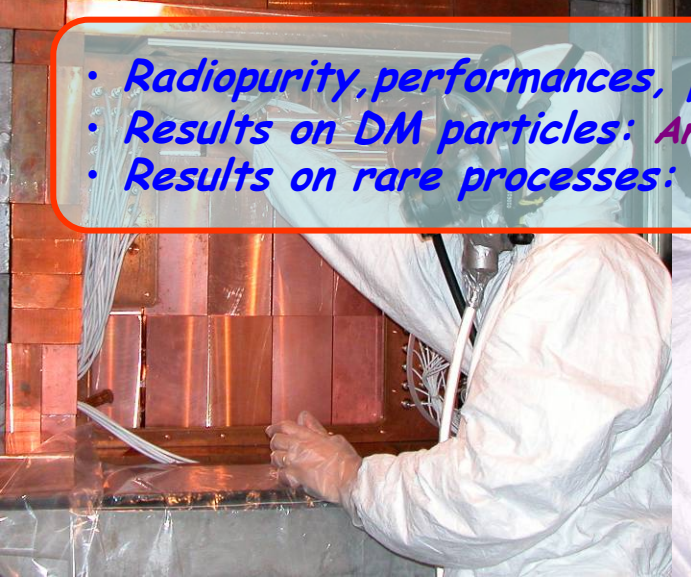
closing the Cu box housing the detectors

view at end of detectors' installation in the Cu box

The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.
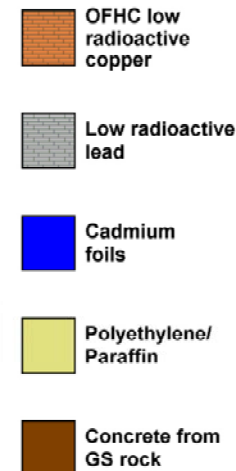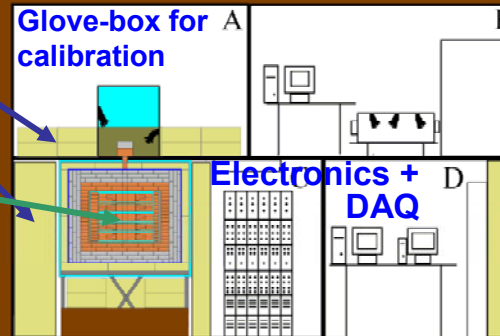NIMA592(2008)297

Polyethylene/paraffin

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix

- two Suprasil-B light guides directly coupled to each bare crystal

- two PMTs working in coincidence at the single ph. el. threshold

Installation

Glove-box for calibration

Electronics + DAQ

OFHC low radioactive copper

Low radioactive lead

Cadmium foils

Polyethylene/Paraffin
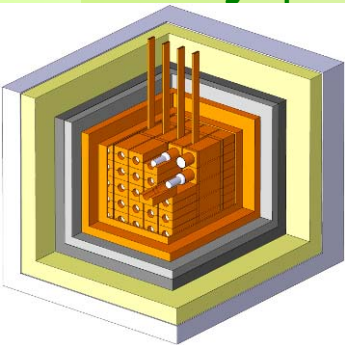
Concrete from GS rock

5.5-7.5 phe/keV

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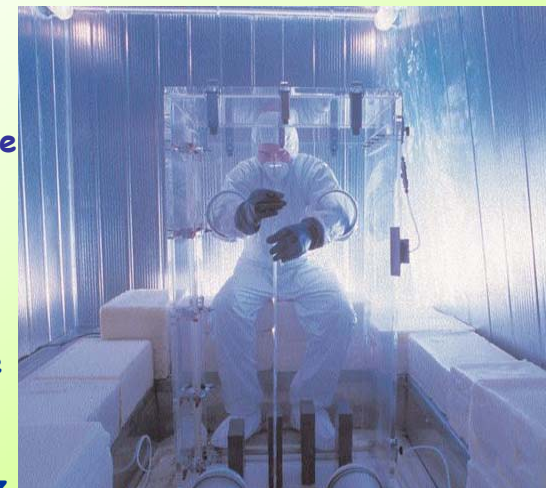
# Some on residual contaminants in new ULB NaI(Tl) detectors
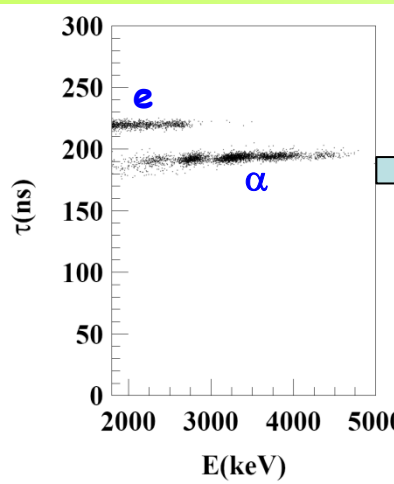
α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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

live time = 570 h
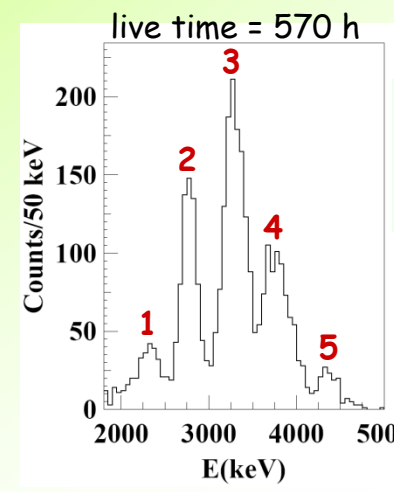
^{238}U chain splitted into 5 subchains: ^{238}U $\rightarrow$ ^{234}U $\rightarrow$ ^{230}Th $\rightarrow$ ^{226}Ra $\rightarrow$ ^{210}Pb $\rightarrow$ ^{206}Pb

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.

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

double coincidences
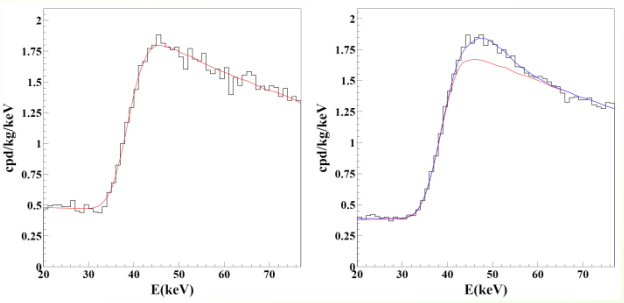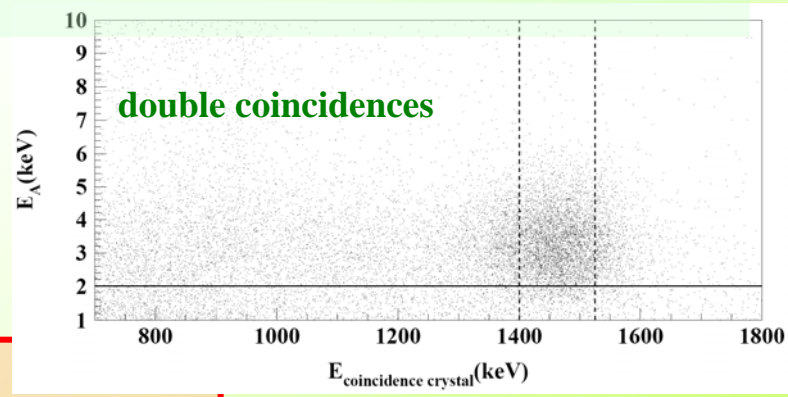
^{129}I and ^{210}Pb

^{129}I/^{nat}I ≈1.7×10^{-13} for all the new detectors

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

... more on
NIMA592(2008)297

No sizable surface pollution by Radon daugthers, thanks to the new handling protocols

Infos about DAMA/LIBRA data taking

Period		Mass (kg)	Exposure (kg × day)	α-β^2
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

- calibrations: ≈72 M events from sources

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

- EPJC56(2008)333

- arXiv:1002.1028 (in press on EPJC)

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

- **New upgrade foreseen on fall 2010**

... continuously running

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.)

DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr

experimental energy threshold
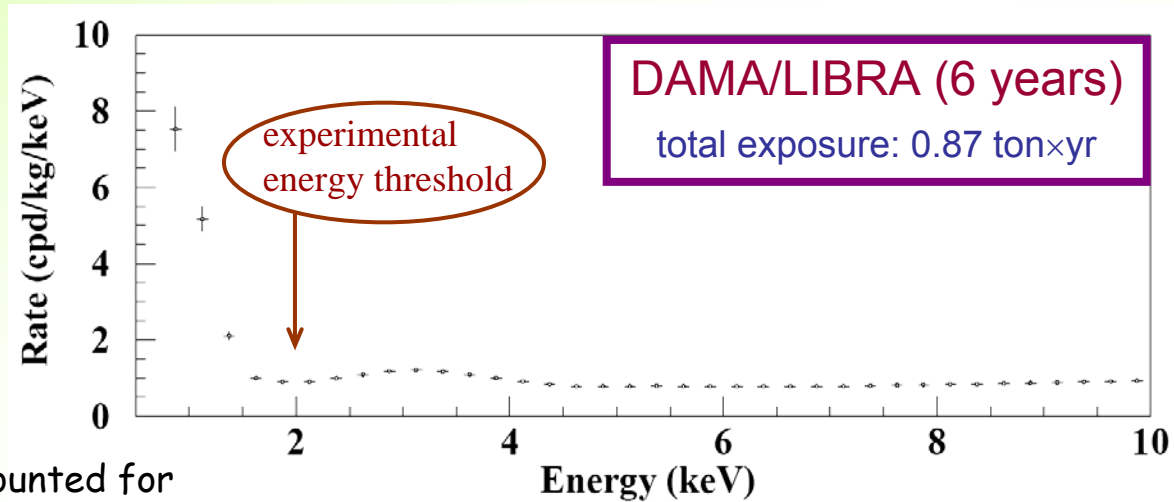
Efficiencies already accounted for

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.

3.2 keV, tagged by 1461 keV γ in an adjacent detector
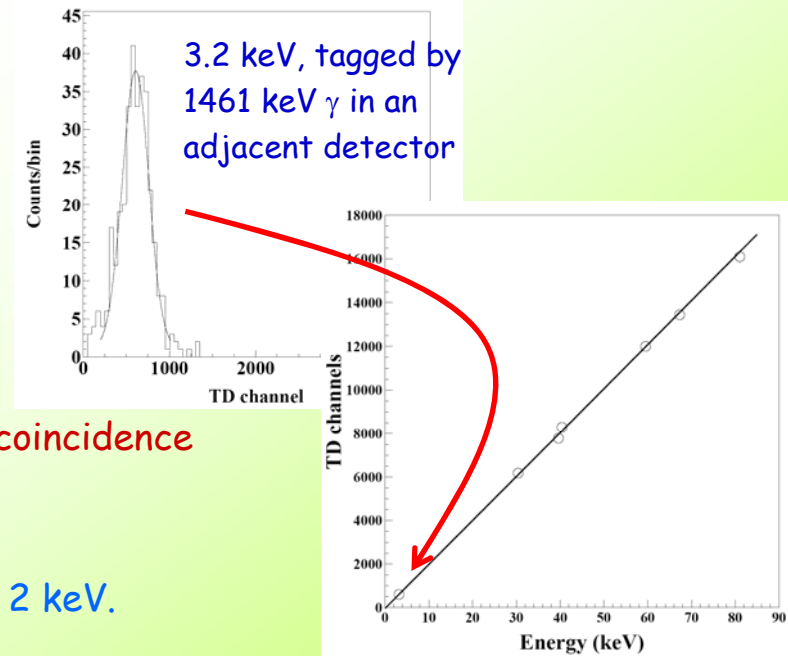
Experimental *single-hit* residuals rate vs time and energy

- Model-independent investigation of the annual modulation signature has been carried out by exploiting the time behaviour of the residual rates of the *single-hit* events in the lowest energy regions of the DAMA/LIBRA data.

- These residual rates are calculated from the measured rate of the *single-hit* events (obviously corrections for the overall efficiency and for the acquisition dead time are already applied) after subtracting the constant part:

$$\left\langle r_{ijk} - flat_{jk} \right\rangle_{jk}$$
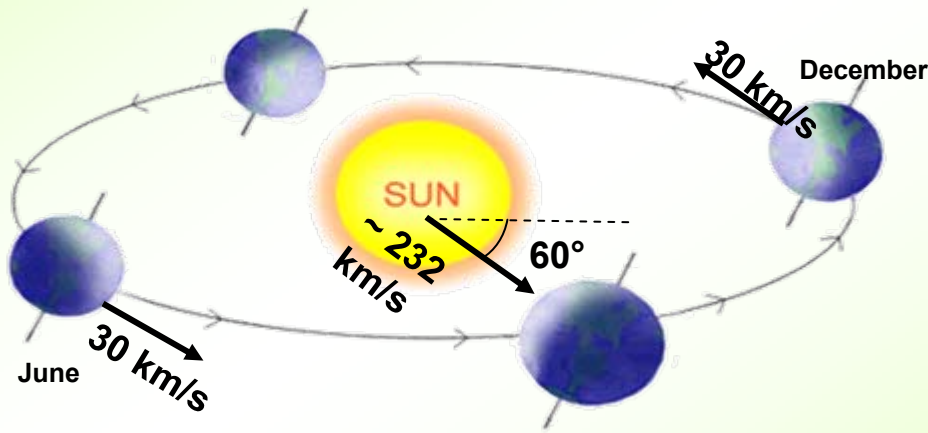
- r_{ijk} is the rate in the considered *i-th* time interval for the *j-th* detector in the *k-th* energy bin

- $flat_{jk}$ is the rate of the *j-th* detector in the *k-th* energy bin averaged over the cycles.

- The average is made on all the detectors (*j* index) and on all the energy bins (*k* index)

- The weighted mean of the residuals must obviously be zero over one cycle.

Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)   Total exposure: 425428 kg×day = 1.17 ton×yr

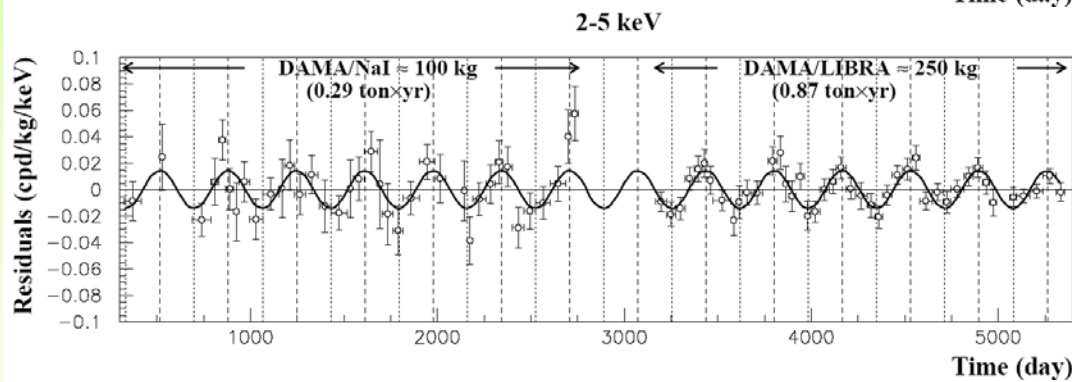experimental single-hit residuals rate vs time and energy

$A\cos[\omega(t-t_0)]$; continuous lines: $t_0 = 152.5$ d, $T = 1.00$ y
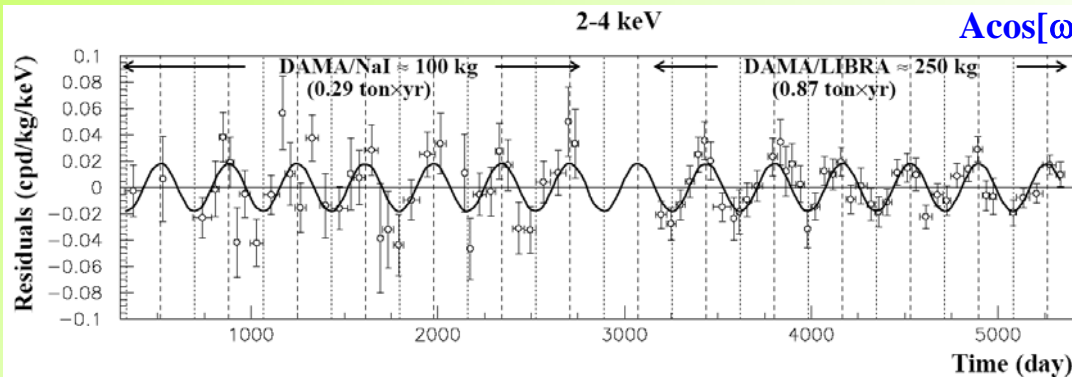
2-4 keV

A=(0.0183±0.0022) cpd/kg/keV

χ^2/dof = 75.7/79   **8.3 σ C.L.**

Absence of modulation? No
χ^2/dof=147/80 ⇒ P(A=0) = 7×10^{-6}

2-5 keV

A=(0.0144±0.0016) cpd/kg/keV

χ^2/dof = 56.6/79   **9.0 σ C.L.**

Absence of modulation? No
χ^2/dof=135/80 ⇒ P(A=0) = 1.1×10^{-4}
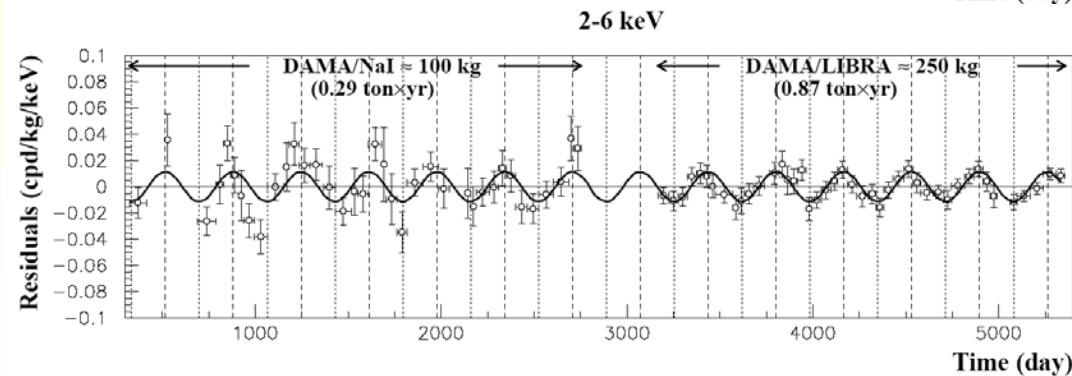
2-6 keV

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}

The data favor the presence of a modulated behavior with proper features at 8.8σ C.L.

Modulation amplitudes measured in each one of the 13 one-year experiments (DAMA/NaI and DAMA/LIBRA)

	A (cpd/kg/keV)	T= 2π/ω (yr)	t_0 (day)	C.L.
DAMA/NaI (7 years)				
(2÷4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2÷5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2÷6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA (6 years)				
(2÷4) keV	0.0180 ± 0.0025	0.996 ± 0.002	135 ± 8	7.2σ
(2÷5) keV	0.0134 ± 0.0018	0.997 ± 0.002	140 ± 8	7.4σ
(2÷6) keV	0.0098 ± 0.0015	0.999 ± 0.002	146 ± 9	6.5σ
DAMA/NaI + DAMA/LIBRA				
(2÷4) keV	0.0194 ± 0.0022	0.996 ± 0.002	136 ± 7	8.8σ
(2÷5) keV	0.0149 ± 0.0016	0.997 ± 0.002	142 ± 7	9.3σ
(2÷6) keV	0.0116 ± 0.0013	0.999 ± 0.002	146 ± 7	8.9σ

DAMA/NaI (7 annual cycles: 0.29 ton x yr) +
DAMA/LIBRA (6 annual cycles: 0.87 ton x yr)
total exposure: 425428 kg×day = 1.17 ton×yr

A, T, t_0 obtained by fitting the single-hit data with $\mathbf{A \cos[\omega(t-t_0)]}$

- The modulation amplitudes for the (2 – 6) keV energy interval, obtained when fixing the period at 1 yr and the phase at 152.5 days, are: (0.019±0.003) cpd/kg/keV for DAMA/NaI and (0.010±0.002) cpd/kg/keV for DAMA/LIBRA.
- Thus, their difference: (0.009±0.004) cpd/kg/keV is **≈2σ** which corresponds to a modest, but non negligible probability.

The χ^2 test (χ^2 = 9.3, 12.2 and 10.1 over 12 *d.o.f.* for the three energy intervals, respectively) and the *run test* (lower tail probabilities of 57%, 47% and 35% for the three energy intervals, respectively) accept at 90% C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.
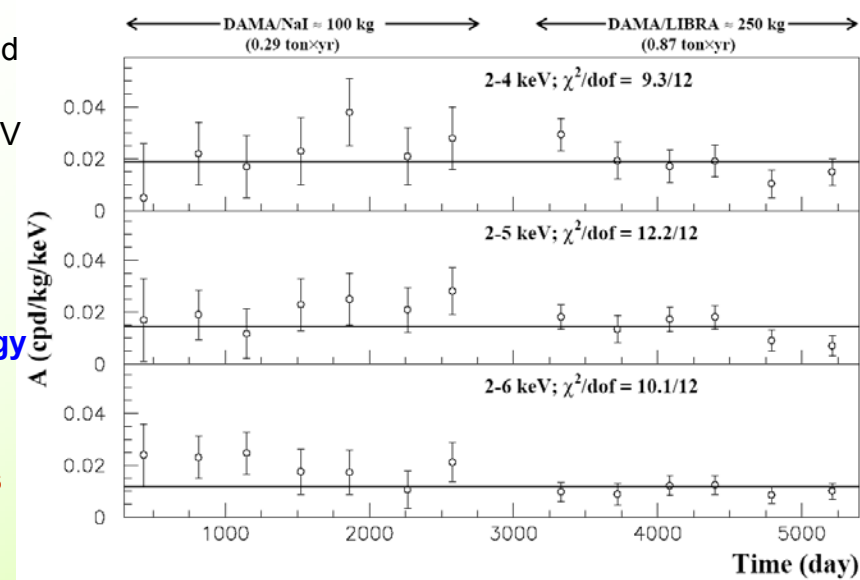
Compatibility among the annual cycles

Power spectrum of single-hit residuals

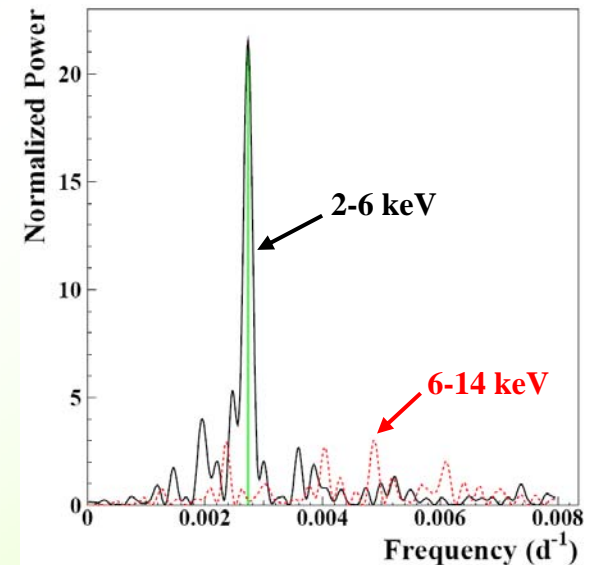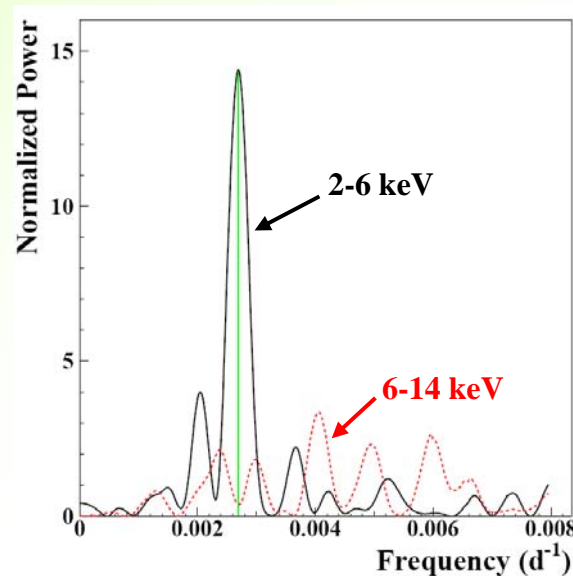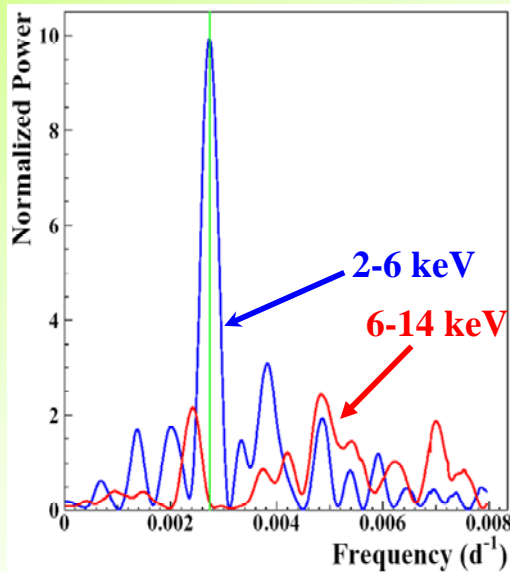(according to Ap.J.263(1982)835; Ap.J.338(1989)277)

Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

DAMA/NaI (7 years)
total exposure: 0.29 ton×yr

DAMA/LIBRA (6 years)
total exposure: 0.87 ton×yr

DAMA/NaI (7 years) +
DAMA/LIBRA (6 years)
total exposure: 1.17 ton×yr

Principal mode in the 2-6 keV region:

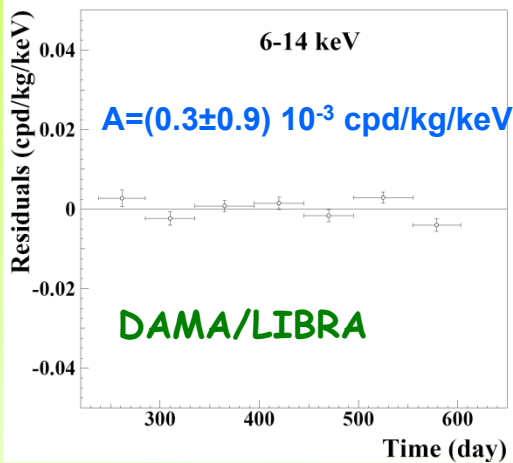| DAMA/NaI	DAMA/LIBRA	DAMA/NaI+LIBRA
$2.737 \cdot 10^{-3}$ d^{-1} ≈ 1 y^{-1}	2.697×10^{-3} d^{-1} ≈ 1 yr^{-1}	2.735×10^{-3} d^{-1} ≈ 1 yr^{-1}

+

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

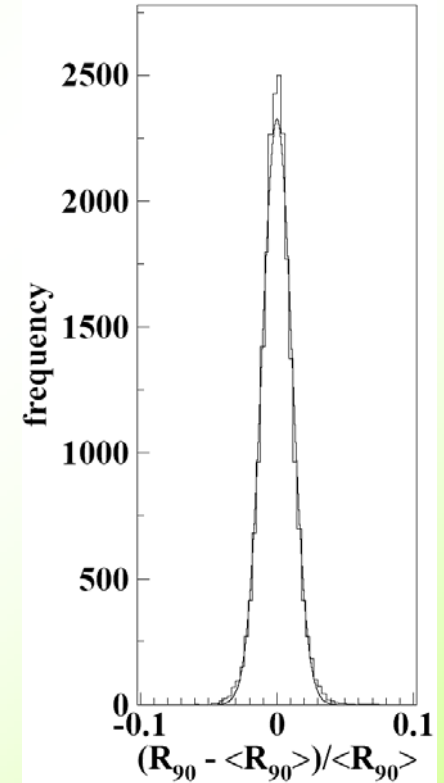**Clear annual modulation is evident in (2-6) keV while it is absent just above 6 keV**

Rate behaviour above 6 keV

- ## No Modulation above 6 keV

DAMALIBRA-1 to -6

6-14 keV

$A=(0.3\pm0.9)\ 10^{-3}$ cpd/kg/keV

DAMA/LIBRA

Residuals (cpd/kg/keV) — Time (day)

Mod. Ampl. (6-10 keV): cpd/kg/keV
 (0.0016 ± 0.0031) DAMA/LIBRA-1
-(0.0010 ± 0.0034) DAMA/LIBRA-2
-(0.0001 ± 0.0031) DAMA/LIBRA-3
-(0.0006 ± 0.0029) DAMA/LIBRA-4
-(0.0021 ± 0.0026) DAMA/LIBRA-5
 (0.0029 ± 0.0025) DAMA/LIBRA-6
$\rightarrow$ statistically consistent with zero

- ## No modulation in the whole energy spectrum:
  studying integral rate at higher energy, R_{90}

  - R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods

  - Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:

    consistent with zero

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

frequency — $(R_{90} - \langle R_{90}\rangle)/\langle R_{90}\rangle$

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

+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region $\rightarrow R_{90} \sim$ tens cpd/kg $\rightarrow \sim 100\ \sigma$ far away

No modulation above 6 keV
This accounts for all sources of bckg and is consistent with studies on the various components

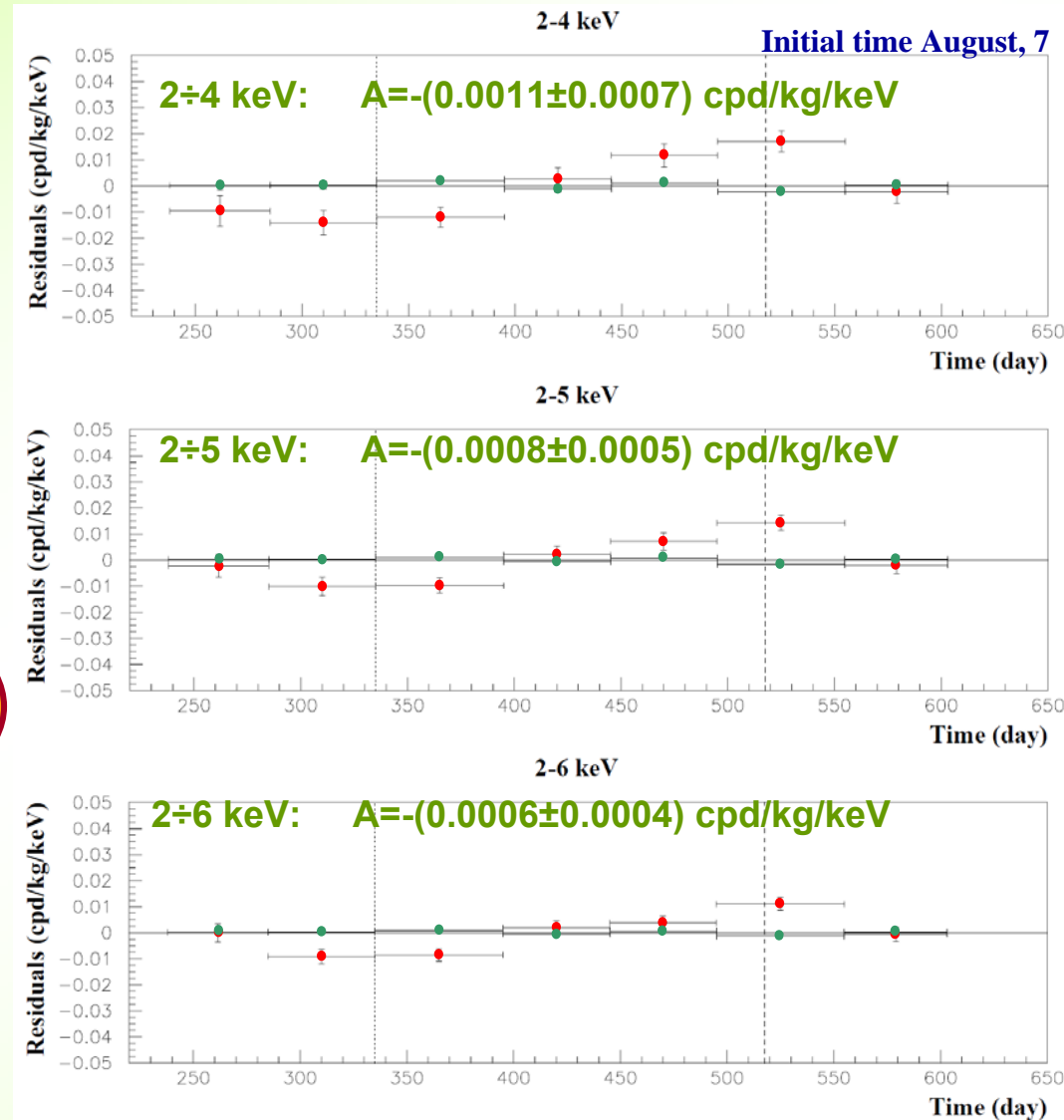# Multiple-hits events in the region of the signal, DAMA/LIBRA 1-6

- Each detector has its own TDs read-out → pulse profiles of multiple-hits events (multiplicity > 1) acquired (exposure: 0.87 ton×yr).

- The same hardware and software procedures as the ones followed for single-hit events

signals by Dark Matter particles do not belong to multiple-hits events, that is:

multiple-hits events = Dark Matter particles events "switched off"

Evidence of annual modulation with proper features as required by the DM annual modulation signature is present in the *single-hit* residuals, while it is absent in the *multiple-hits* residual rate.

Initial time August, 7

2-4 keV

2÷4 keV: A=-(0.0011±0.0007) cpd/kg/keV

2-5 keV

2÷5 keV: A=-(0.0008±0.0005) cpd/kg/keV

2-6 keV

2÷6 keV: A=-(0.0006±0.0004) cpd/kg/keV

This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo, further excluding any side effect either from hardware or from software procedures or from background

Modulation amplitudes, $S_{m,k}$, as function of the energy

The likelihood function of the *single-hit* experimental data in the *k-th* energy bin is defined as:

$$L_k = \prod_{ij} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!}$$

N_{ijk} is the number of events collected in the *i-th* time interval, by the *j-th* detector and in the *k-th* energy bin.

N_{ijk} follows a Poissonian distribution with expectation value:

$$\mu_{ijk} = \left[b_{jk} + R_k(t) \right] M_j \Delta t_i \Delta E \varepsilon_{jk} = \left[b_{jk} + S_{0,k} + S_{m,k} \cos \omega(t_i - t_0) \right] M_j \Delta t_i \Delta E \varepsilon_{jk}$$

The b_{jk} are the background contributions, M_j is the mass of the *j-th* detector, Δt_i is the detector running time during the *i-th* time interval, ΔE is the chosen energy bin, ε_{jk} is the overall efficiency.

The usual procedure is to minimize the function y_k=-2ln(L_k) - *const* for each energy bin; the free parameters of the fit are the (b_{jk} + $S_{0,k}$) contributions and the $S_{m,k}$ parameter.

The $S_{m,k}$ is the modulation amplitude of the modulated part of the signal obtained by maximum likelihood method over the data considering *T=2π/ω=1* yr and *t₀= 152.5* day.
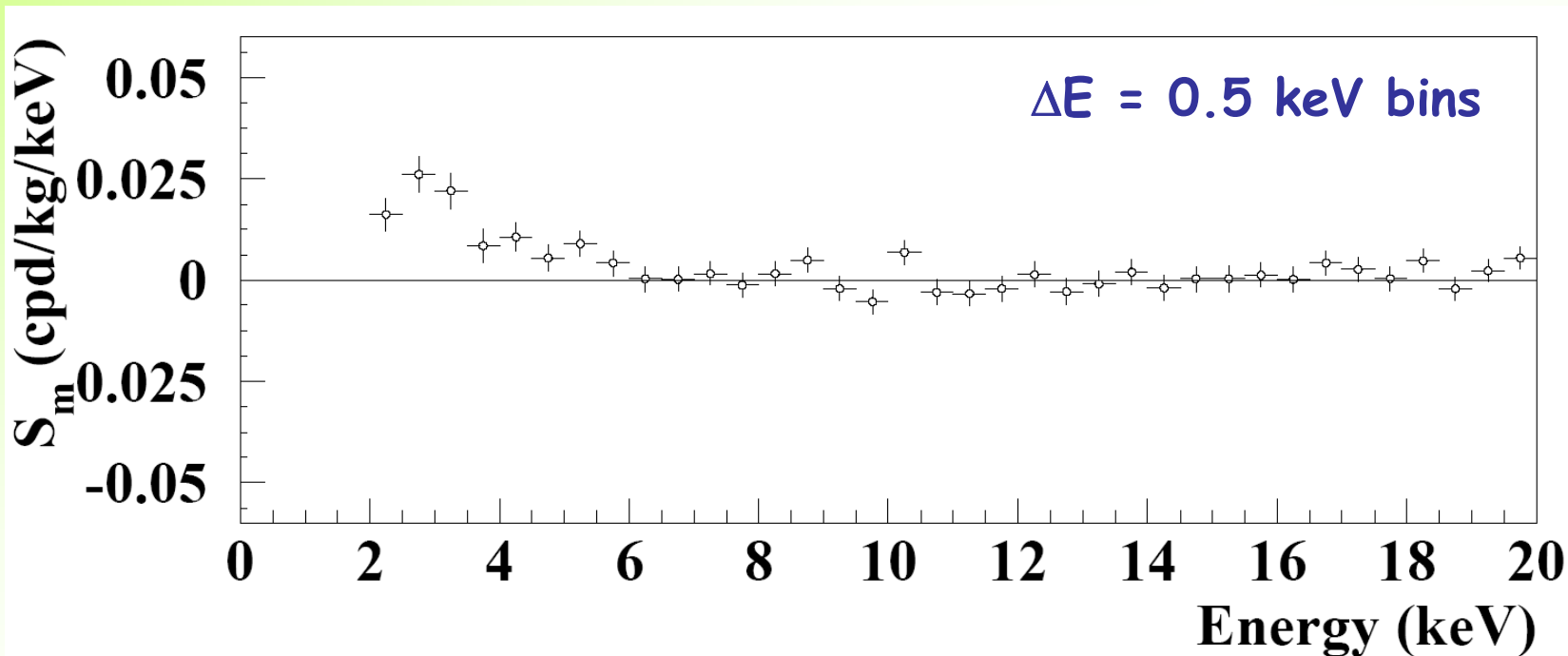
Energy distribution of the modulation amplitudes

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

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) $\langle S_m \rangle$ = mean values over the detectors and the annual cycles for each energy bin; σ = error associated to the S_m
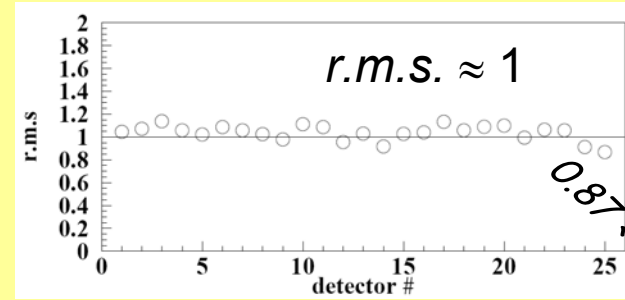
DAMA/LIBRA (6 years)

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)
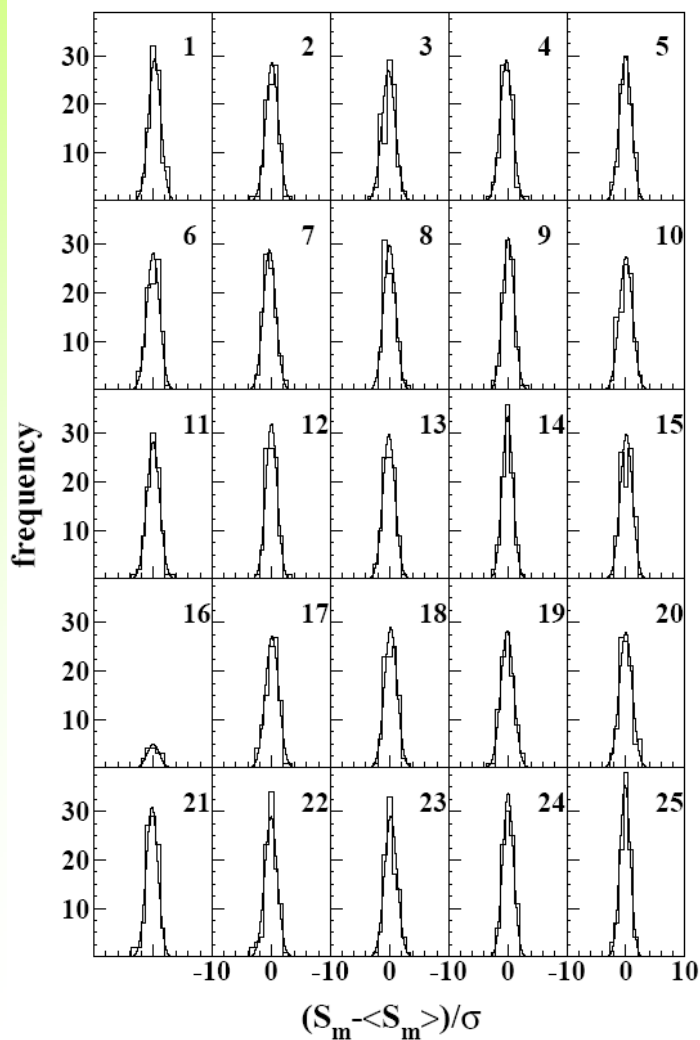
2-6 keV

Standard deviations of the variable

(Sm-⟨Sm⟩)/σ

for the DAMA/LIBRA detectors

r.m.s. ≈ 1

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

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

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

Individual S_m values follow a normal distribution since **$(S_m-\langle S_m\rangle)/\sigma$** 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
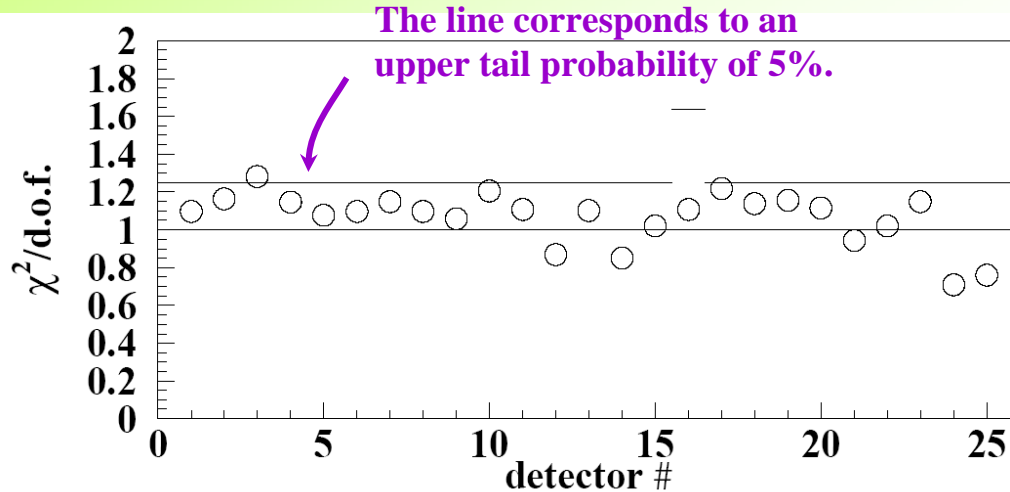
Statistical analyses about modulation amplitudes (S_m)

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

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

$\chi^2/d.o.f.$ 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 ≤ 4 × 10⁻⁴ cpd/kg/keV, if quadratically combined, or ≤ 5×10⁻⁵ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.

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

Energy distributions of cosine (S_m) and sine (Z_m) modulation amplitudes

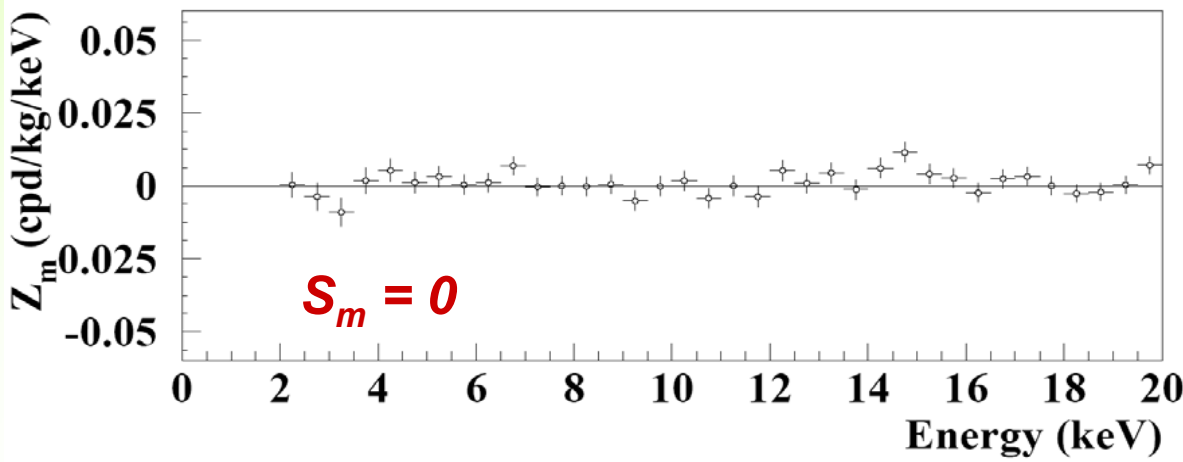$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)]$$

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

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

$\Delta E = 0.5$ keV bins

$Z_m = 0$

$S_m = 0$
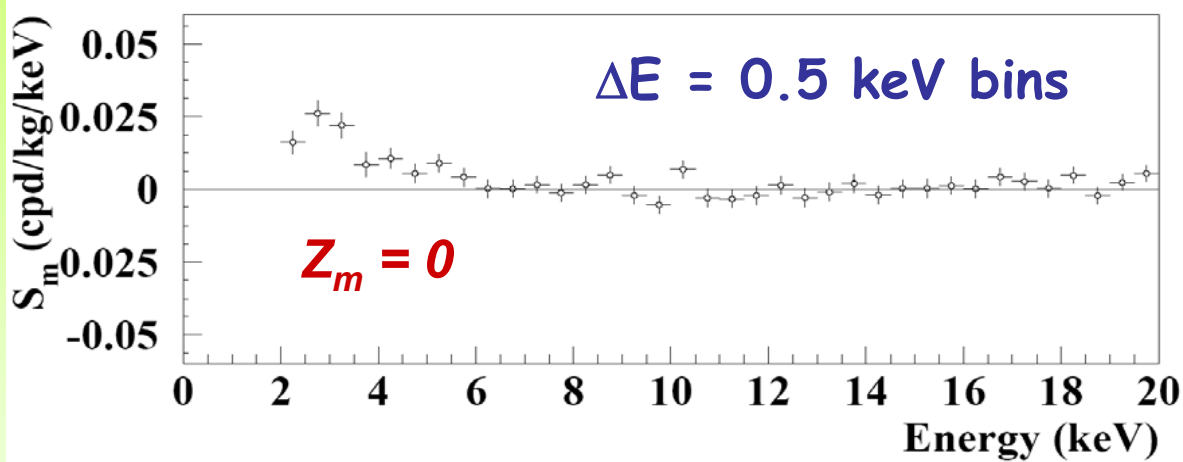
$t_0 = 152.5$ *day* (2° June)

maximum at 2° June

as for DM particles

maximum at 1° September

T/4 days after 2° June

The χ^2 test in the (2-14) keV and (2-20) keV energy regions (χ^2/dof = 21.6/24 and 47.1/36, probabilities of 60% and 10%, respectively) supports the hypothesis that the $Z_{m,k}$ values are simply fluctuating around zero.

Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?
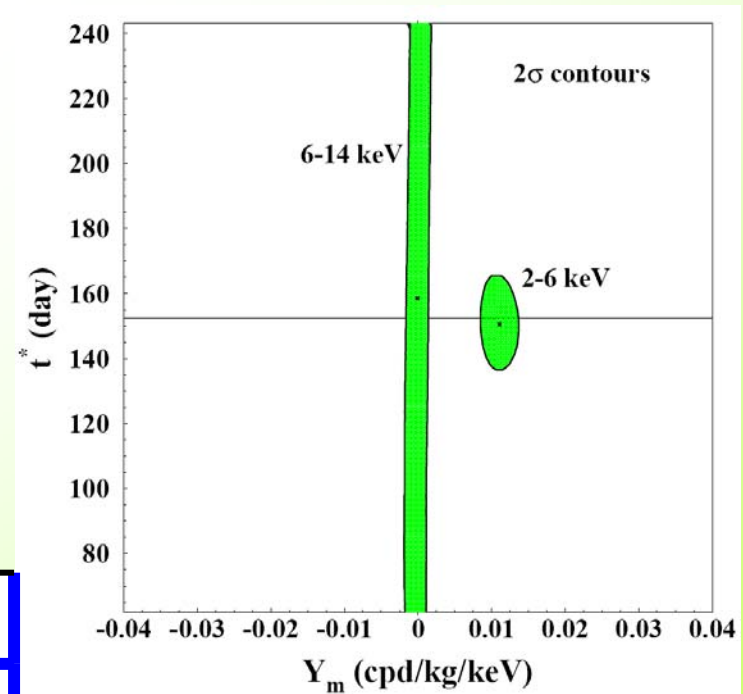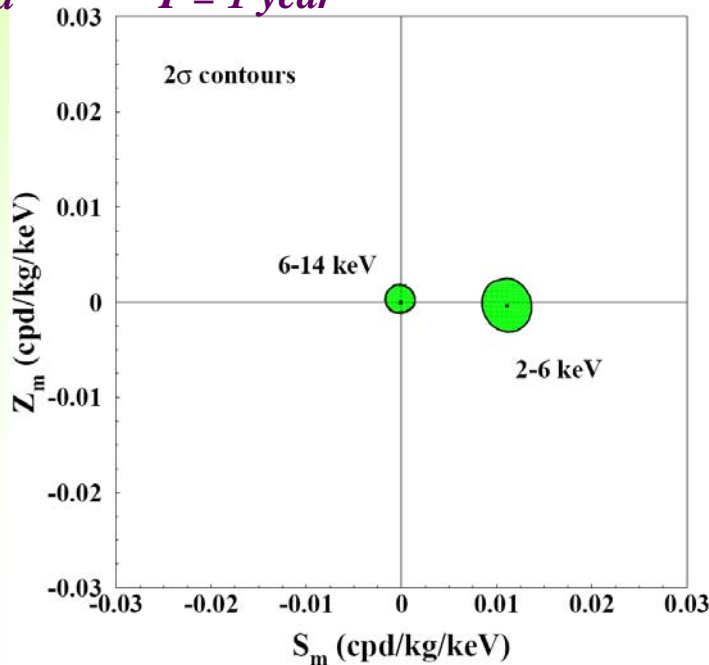
DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

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:

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

Phase as function of energy

$$R(t) = S_0 + Y_m \cos\left[\omega\left(t - t^*\right)\right]$$

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)
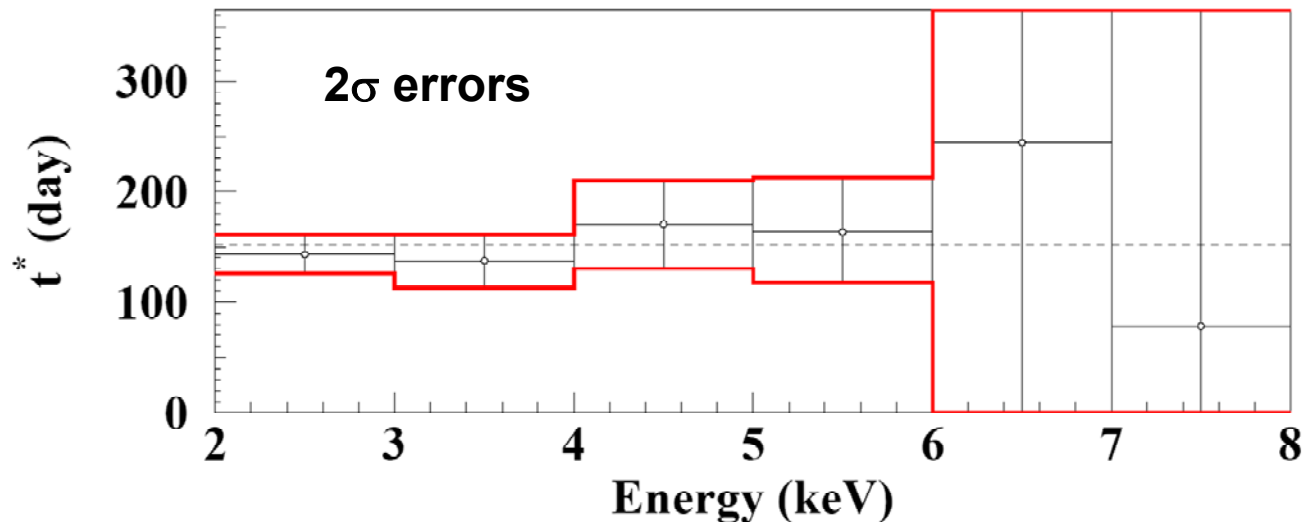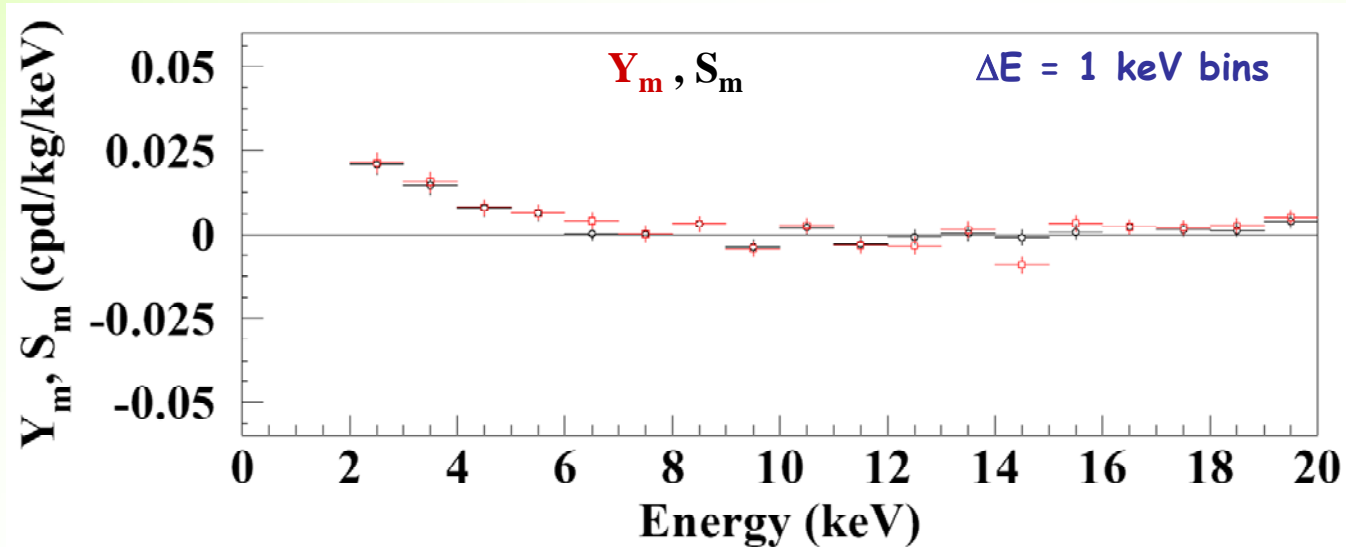total exposure: 425428 kg×day = 1.17 ton×yr

For DM signals:

$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

$\omega = 2\pi/T; \quad T = 1\ year$

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

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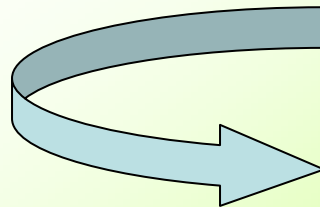
The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about S_m already exclude any sizable presence of systematical effects

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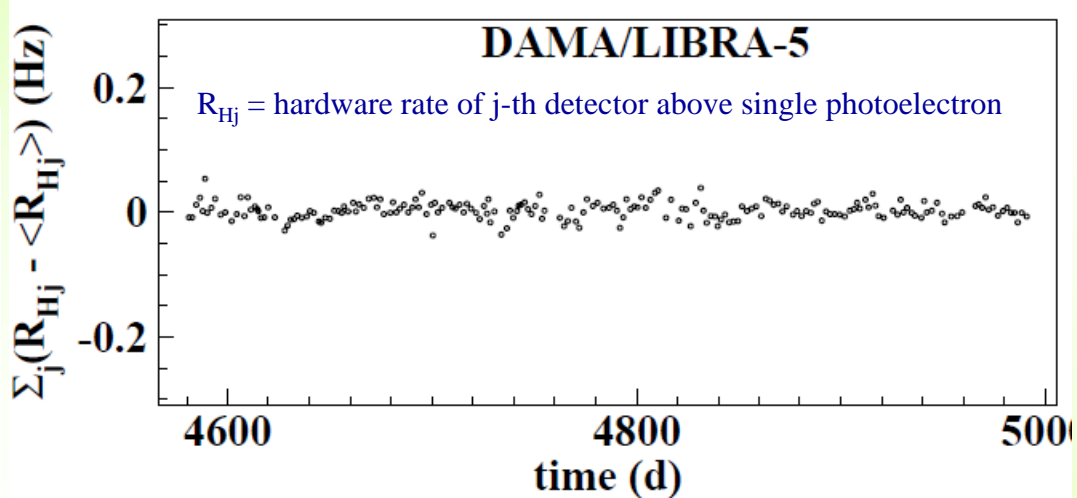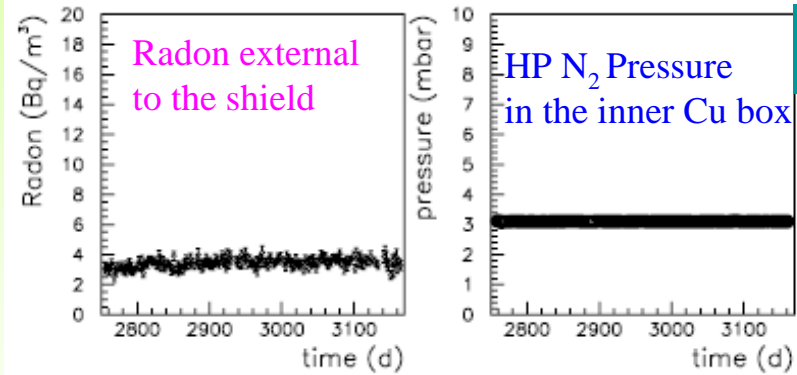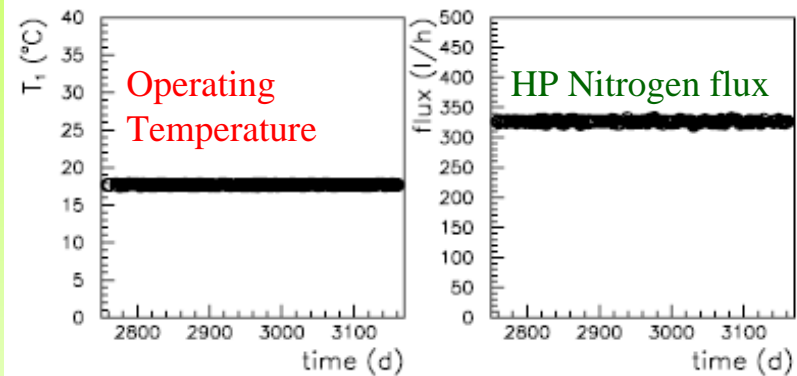
Running conditions stable at a level better than 1% also in the two new running periods

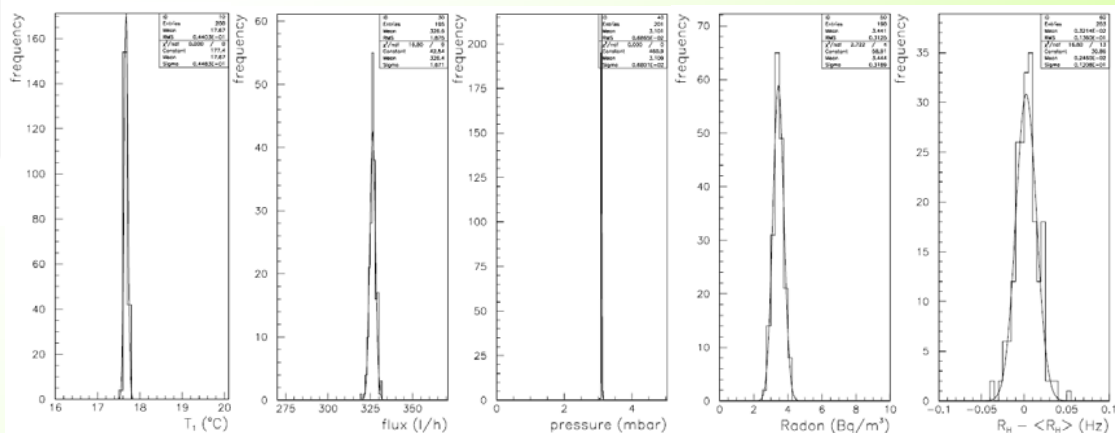|	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4	DAMA/LIBRA-5	DAMA/LIBRA-6
Temperature	-(0.0001 ± 0.0061) °C	(0.0026 ± 0.0086) °C	(0.001 ± 0.015) °C	(0.0004 ± 0.0047) °C	(0.0001 ± 0.0036) °C	(0.0007 ± 0.0059) °C
Flux N_2	(0.13 ± 0.22) l/h	(0.10 ± 0.25) l/h	-(0.07 ± 0.18) l/h	-(0.05 ± 0.24) l/h	-(0.01 ± 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)

Example of Stability Parameters: DAMA/LIBRA-5

Operating Temperature

HP Nitrogen flux

Radon external to the shield

HP N_2 Pressure in the inner Cu box

DAMA/LIBRA-5

R_{Hj} = hardware rate of j-th detector above single photoelectron

$\Sigma_j(R_{Hj} - \langle R_{Hj}\rangle)$ (Hz)

Running conditions stable at level < 1%

Parameters distributions

**All amplitudes well compatible with zero
+ no effect can mimic the annual modulation**

Temperature

- **Detectors in Cu housings directly in contact with multi-ton shield → huge heat capacity (≈10^6 cal/^{0}C)**

- **Experimental installation continuosly air conditioned (2 independent systems for redundancy)**

- **Operating T of the detectors continuously controlled**

	T (°C)
DAMA/LIBRA-1	-(0.0001 ± 0.0061)
DAMA/LIBRA-2	(0.0026 ± 0.0086)
DAMA/LIBRA-3	(0.001 ± 0.015)
DAMA/LIBRA-4	(0.0004 ± 0.0047)
DAMA/LIBRA-5	(0.0001 ± 0.0036)
DAMA/LIBRA-6	(0.0007 ± 0.0059)

Amplitudes for annual modulation in the operating T of the detectors **well compatible with zero**

σ=0.3%

Distribution of the relative variations of the operating T of the detectors

Distribution of the root mean square values of the operating T within periods with the same calibration factors (typically ≈7days):

mean value ≈ 0.04°C
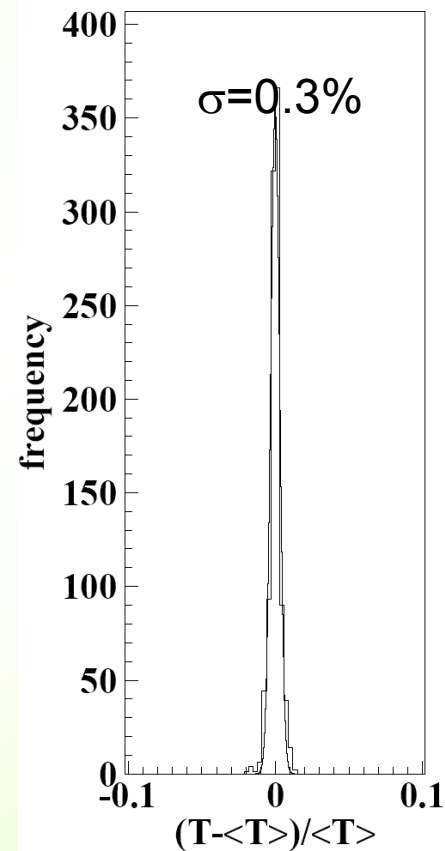
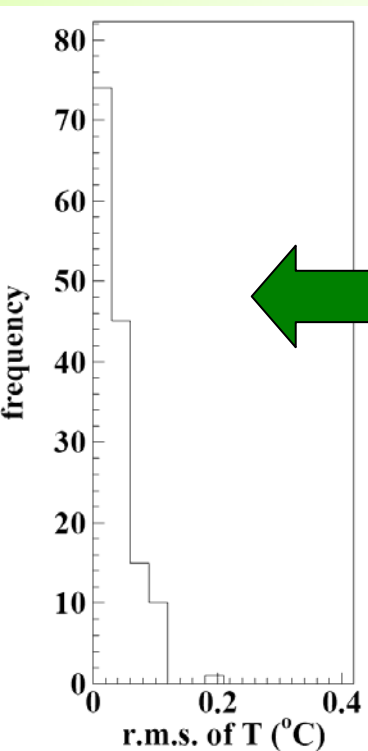Considering the slope of the light output ≈ -0.2%/ °C: relative light output variation < 10^{-4} :

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

An effect from temperature can be excluded

+ Any possible modulation due to temperature would always fail some of the peculiarities of the signature
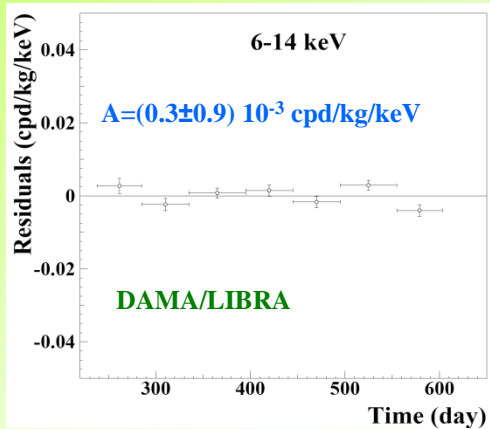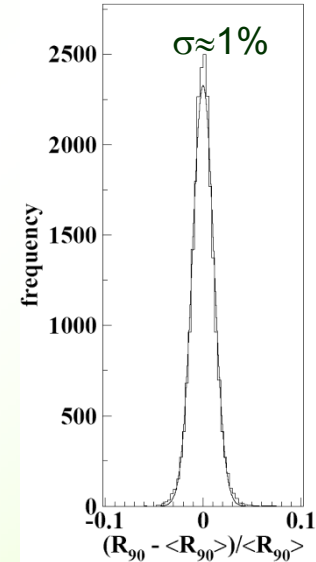
Summarizing on a hypothetical background modulation in DAMA/LIBRA 1-6

- **No Modulation above 6 keV**


- **No modulation in the whole energy spectrum**

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

- **No modulation in the 2-6 keV *multiple-hits* residual rate**

No background modulation (and cannot mimic the signature): all this accounts for the all possible sources of bckg

multiple-hits residual rate (green points) vs single-hit residual rate (red points)
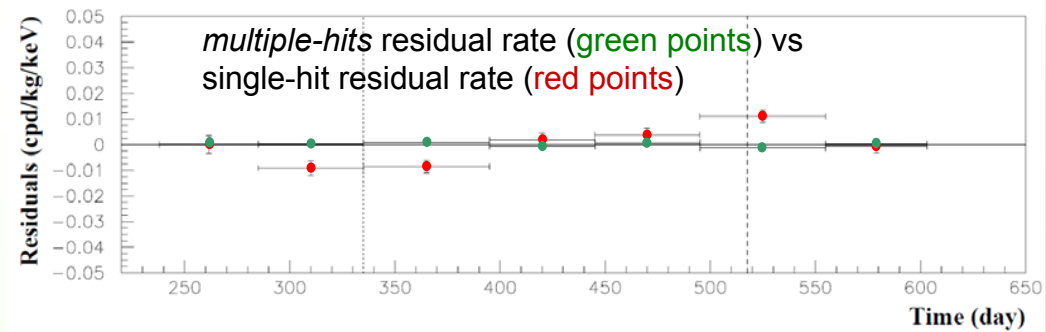
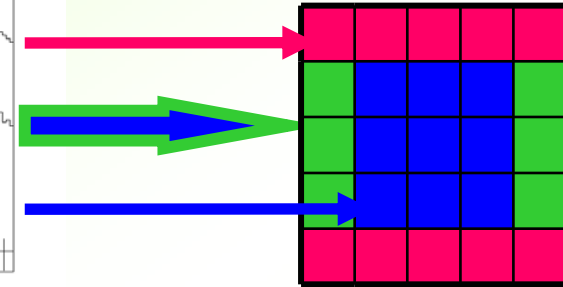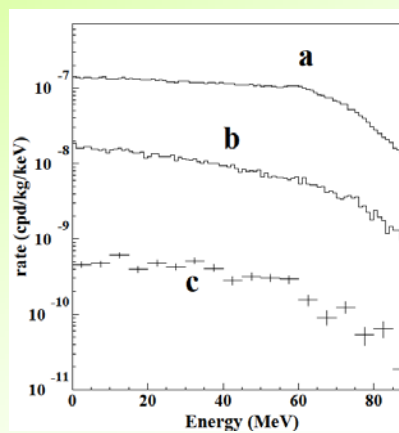**Nevertheless, additional investigations performed ...**

Three examples for specific cases in the following:

1. The muon case
2. The ^{40}K case
3. The neutron case

The μ case

MonteCarlo simulation
- muon intensity distribution
- Gran Sasso rock overburden map

events where just one detector fires

Case of fast neutrons produced by μ

Φ_μ @ LNGS ≈ 20 μ m^{-2}d^{-1} (±2% modulated)
Measured neutron Yield @ LNGS: Y=1÷7 10^{-4} n/μ/(g/cm^2)
R_n = (fast n by μ)/(time unit) = Φ_μ Y M_{eff}

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

Annual modulation amplitude at low energy due to μ modulation:

$$S_m^{(\mu)} = R_n \ g \ \varepsilon \ f_{\Delta E} \ f_{single} \ 2\% \ /(M_{setup} \ \Delta E)$$

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

$$S_m^{(\mu)} < (0.4÷3) \times 10^{-5} \text{ cpd/kg/keV}$$

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 also by R_{90}, by *multi-hits* analysis + different phase, etc.

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

?

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

- if τ≪T/2π: $t_{side} = t_\mu + \tau$
- if τ≫T/2π: $t_{side} = t_\mu + T/4$

It cannot mimic the signature: different phase

The phase of the muon flux at LNGS is roughly around middle of July and largely variable from year to year. Last meas. by LVD partially overlapped with DAMA/NaI and fully with DAMA/LIBRA: 1.5% modulation and phase=July 5th ± 15 d.

DAMA/NaI + DAMA/LIBRA
measured a stable phase: May, 26th ± 7 days

This phase is 7.3 σ far from July 15th and is 5.9 σ far from July 5th

R_{90}, multi-hits, phase, and other analyses ⟹ **NO**

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

see arXiv:0912.0660

not evidence for any 3 keV peak in the S_m distribution. Behaviour compatible with a **monotonic behaviour** and with a **"structure"** as expected for many Dark Matter candidates (also for WIMP)

The annual modulation signal is equally distributed over all the detectors

Stability of efficiency
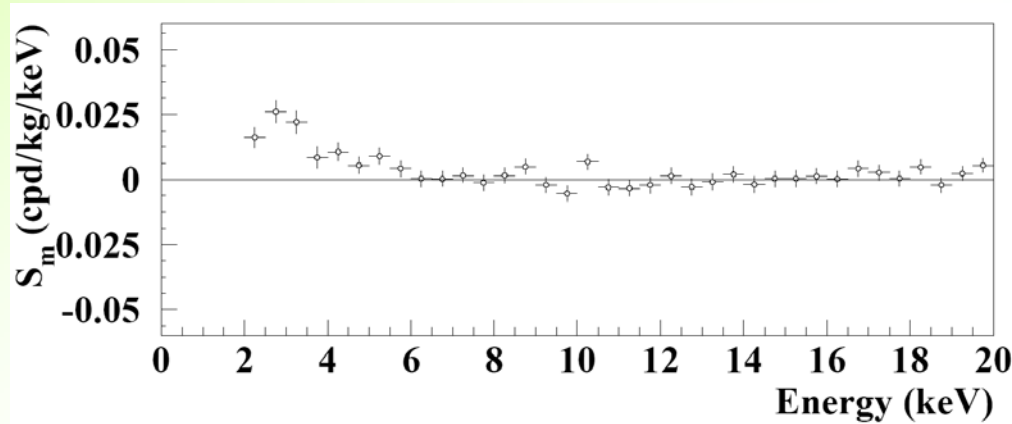
^{40}K decay cannot give any modulation, unless evoking new exotic physics.

No modulation has been observed in other energy regions where ^{40}K decay contributes

The annual modulation signal is present in the outer and in the inner detectors.

(no dependence on the veto capability, that is different – for geometrical reasons – among the detectors)

No modulation of the double coincidence events, 1461 keV-3 keV

No modulation in multiple-hit events in 2-6 keV (^{40}K can give double events in two adjacent detectors and multi-site events due to Compton scatterings)

The analysis of the double coincidences rules out at more than 10 σ any modulation around 3 keV in the *single-hit* events from the hypothetical cases of : i) ^{40}K "exotic" modulation decay; ii) spill-out from double to single events and viceversa.
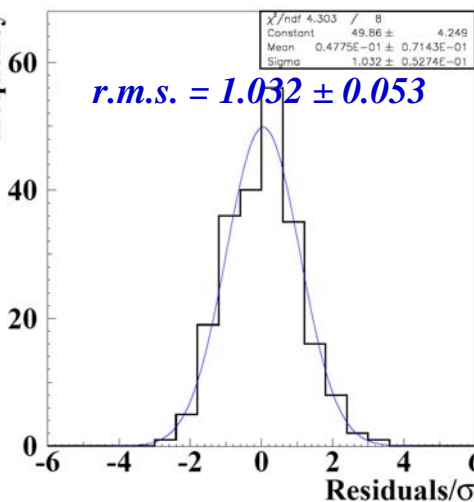
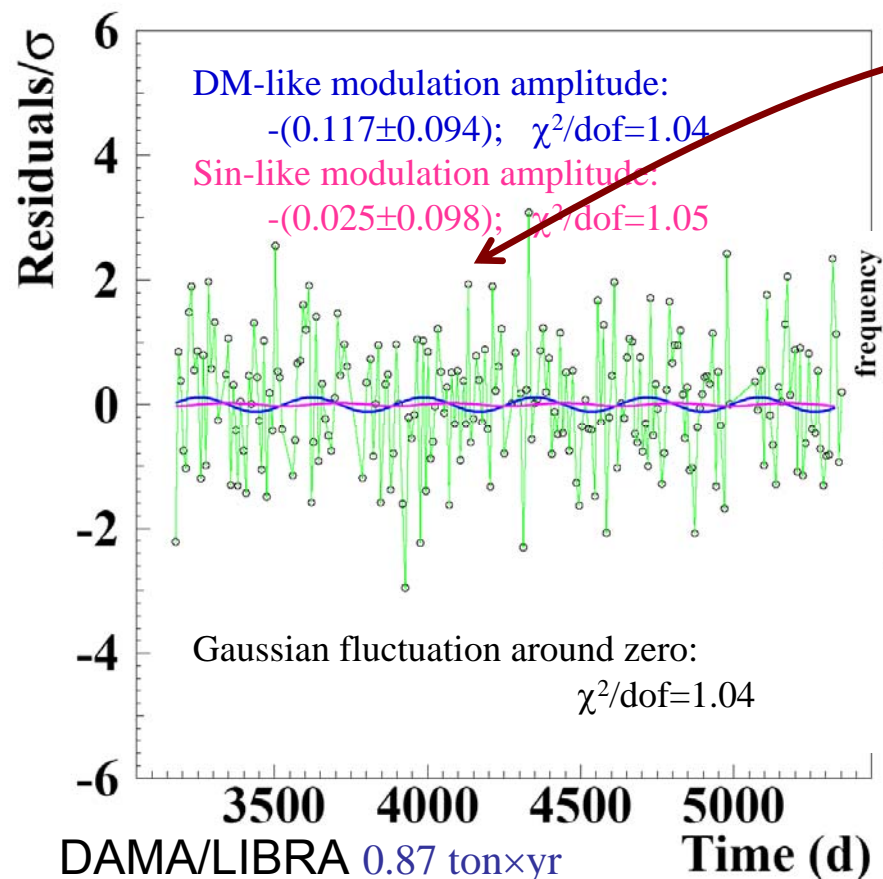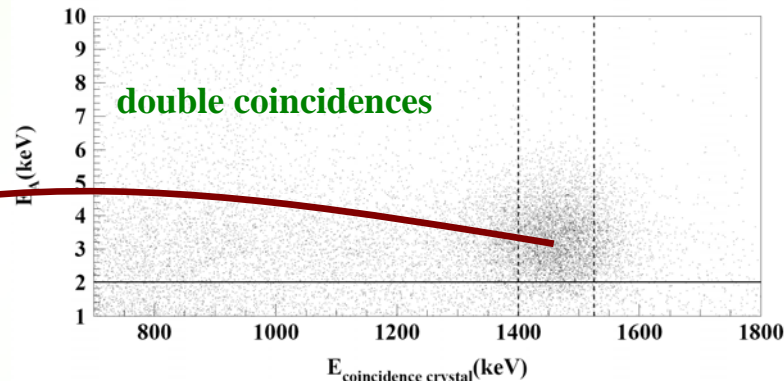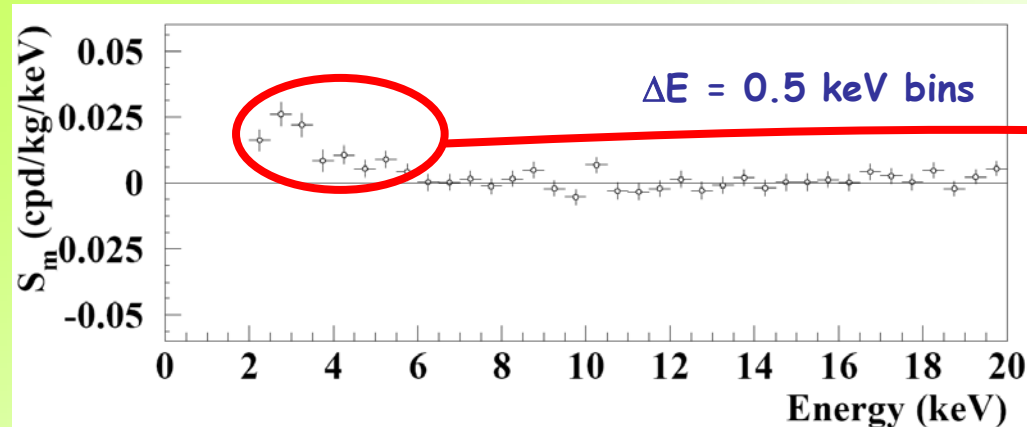Even assuming the arXiv:0808.3283 scenario:
- the expected single hit modulation amplitude would be much below the measured modulation amplitude
- the phase (3 jan) would be well different from the measured phase (26 may±7 day).

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

$\Delta E = 0.5$ keV bins

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±0.094); $\chi^2/dof=1.04$
Sin-like modulation amplitude:
-(0.025±0.098); $\chi^2/dof=1.05$

r.m.s. = 1.032 ± 0.053

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

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

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

DAMA/LIBRA 0.87 ton×yr

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

NO

- Thermal neutrons flux measured at LNGS :

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

^{24m}Na $(T_{1/2}=20ms)$
$1+$ (472.2 keV) $\sigma_n = 0.43$ barn
$4+$ $\sigma_n = 0.10$ barn
$^{24}_{11}$Na $T_{1/2}=14.96h$
β^- 99.9%
$(Q_{\beta^-}=1391 keV)$
$4+$ (4123 keV)
$2+$ (1369 keV)
$0+$
$^{24}_{12}$Mg (Stable)

- 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:

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

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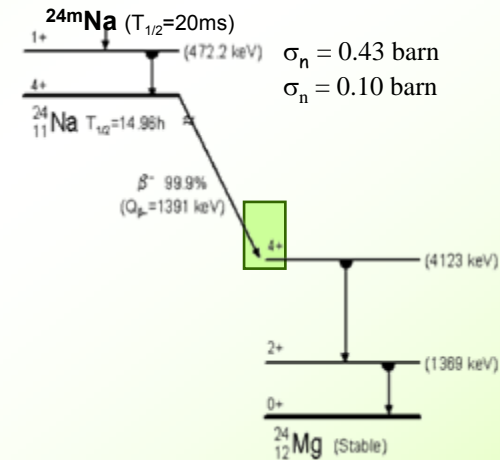
Evaluation of the expected effect:

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

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

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

In all the cases of neutron captures (^{24}Na, ^{128}I, ...) a possible thermal n modulation induces a variation in all the energy spectrum
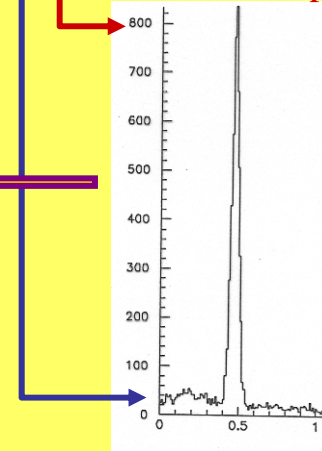Already excluded also by R_{90} analysis

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 ≈ 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):

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

  - 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 accompained 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

Summary of the results obtained in the additional investigations of possible systematics or side reactions: DAMA/LIBRA-1 to 6

(previous exposure and details see: NIMA592(2008)297, EPJC56(2008)333, arXiv:0912.4200)

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	$<1\text{-}2 \times 10^{-4}$ 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 can not mimic the observed annual modulation effect

Summarizing

- 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, <u>as expected for the DM signal</u>

2) Measured period is equal to (0.999±0.002) yr, well compatible with the 1 yr period, <u>as expected for the DM signal</u>

3) Measured phase (146±7) days is well compatible with the roughly about 152.5 days <u>as expected for the DM signal</u>

4) The modulation is present only in the low energy (2—6) keV energy interval and not in other higher energy regions, <u>consistently with expectation for the DM signal</u>

5) The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones <u>as expected for the DM signal</u>

6) The measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2-6) keV energy interval is: (0.0116±0.0013) cpd/kg/keV (8.9σ 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

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

well compatible with several candidates (in several of the many possible astrophysical, nuclear and particle physics scenarios)

Neutralino as LSP in various 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)

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

Self interacting Dark Matter

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

Sterile neutrino

heavy exotic canditates, as "4th family atoms", ...

Elementary Black holes such as the Daemons

... and more

Kaluza Klein particles

Possible model dependent positive hints from indirect searches (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.) **not in conflict with DAMA results**
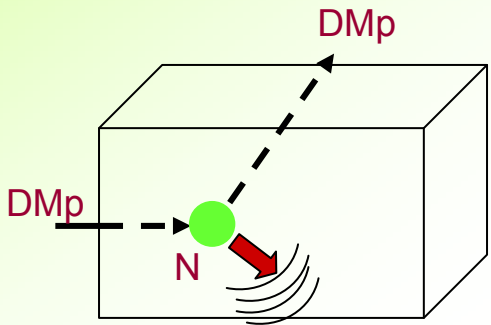
Available results from direct searches using different target materials and approaches do not give any robust conflict

Moreover, some possible hints from direct searches are not in conflict with DAMA results

No other experiment whose result can be directly compared in model independent way is available so far

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

WIMP DM candidate (as in [4])
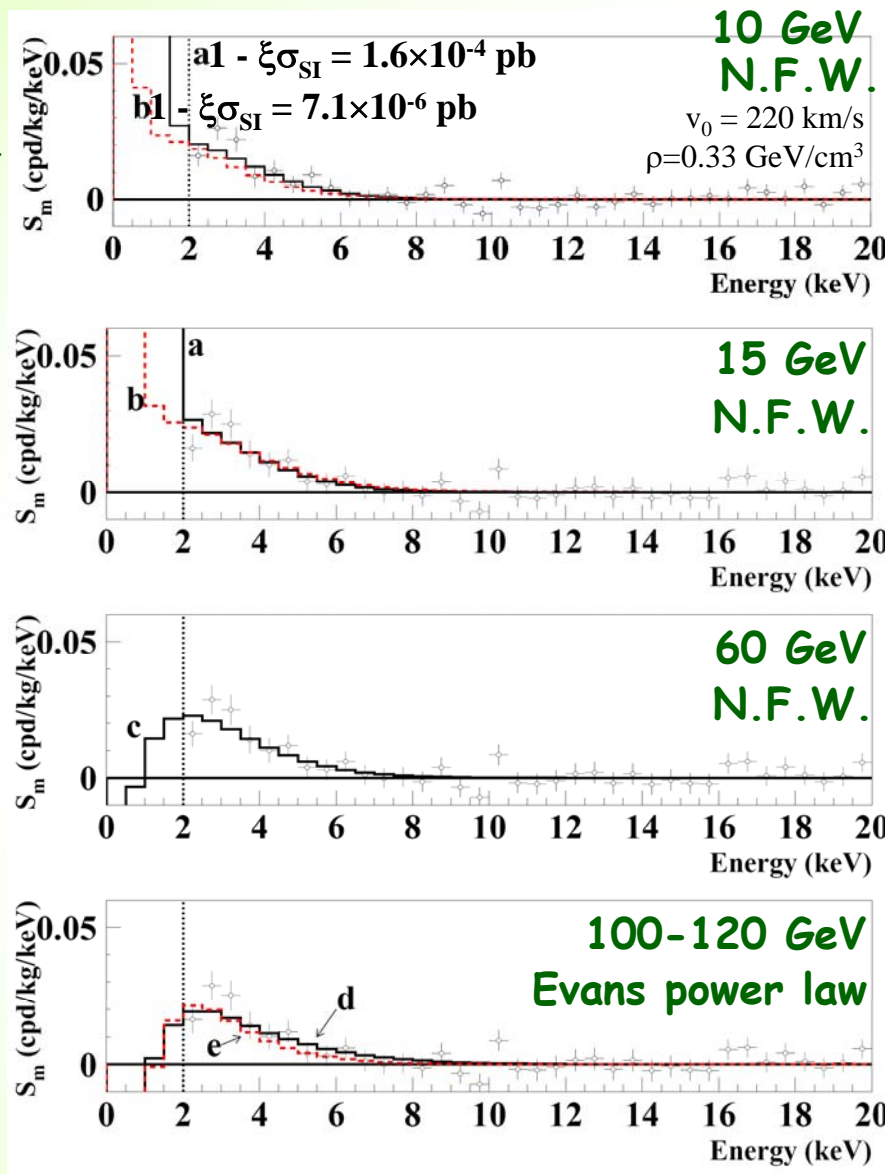considering elastic scattering on nuclei
SI dominant coupling
v_0 = 170 km/s

DMp

DMp

N

About the same C.L.

...scaling from NaI

Plot 1 (top):
S_m (cpd/kg/keV)
a1 - $\xi\sigma_{SI}$ = 1.6×10⁻⁴ pb
b1 - $\xi\sigma_{SI}$ = 7.1×10⁻⁶ pb
10 GeV N.F.W.
v_0 = 220 km/s
ρ=0.33 GeV/cm³
Energy (keV)

Plot 2:
S_m (cpd/kg/keV)
a
b
15 GeV N.F.W.
Energy (keV)

Plot 3:
S_m (cpd/kg/keV)
c
60 GeV N.F.W.
Energy (keV)

Plot 4 (bottom):
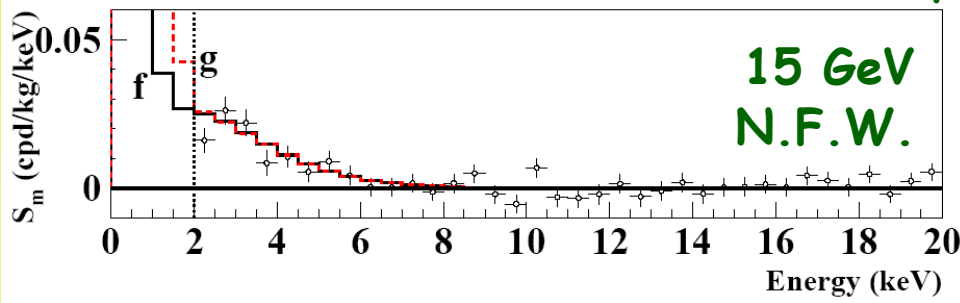S_m (cpd/kg/keV)
d
e
100-120 GeV Evans power law
Energy (keV)

Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm³)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)
a	A5 (NFW)	0.2	A	15 GeV	3.1×10^{-4}
b	A5 (NFW)	0.2	A	15 GeV	1.3×10^{-5}
c	A5 (NFW)	0.2	B	60 GeV	5.5×10^{-6}
d	B3 (Evans power law)	0.17	B	100 GeV	6.5×10^{-6}
e	B3 (Evans power law)	0.17	A	120 GeV	1.3×10^{-5}

channeling contribution as in EPJC53(2008)205 considered for curve *b*

[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

15 GeV
N.F.W.

60 GeV
N.F.W.

100 GeV
Evans power law
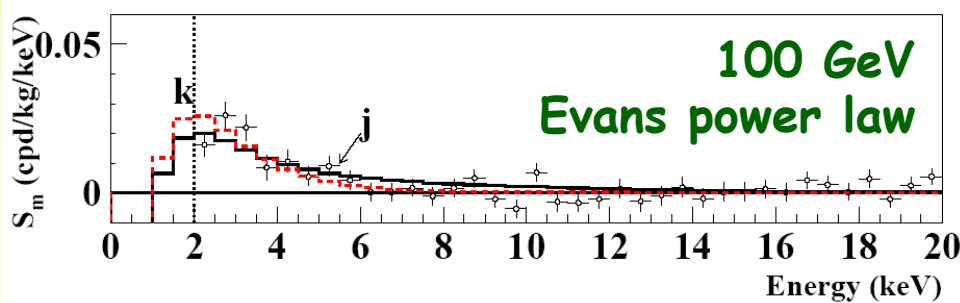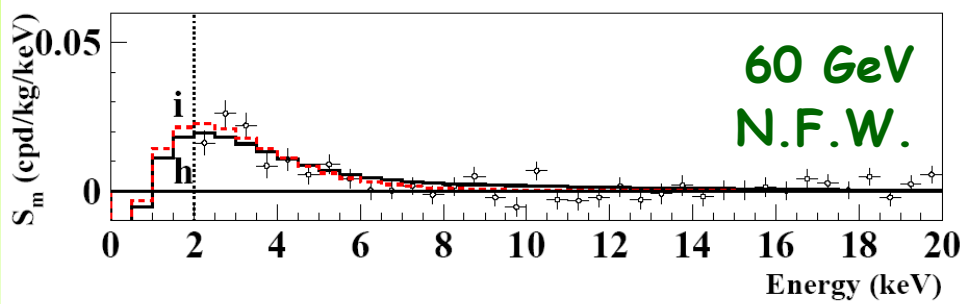
$\theta = 2.435$

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

DMp

DMp

N
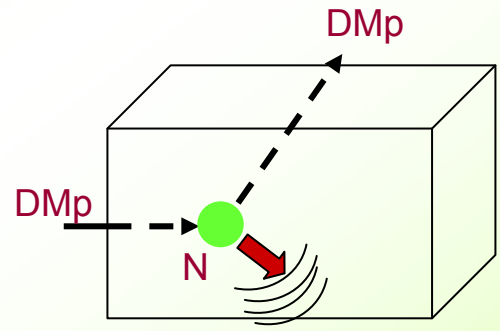
• Not best fit
• About the same C.L.

…scaling from NaI

Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)	$\xi\sigma_{SD}$ (pb)
f	A5 (NFW)	0.2	A	15 GeV	10^{-7}	2.6
g	A5 (NFW)	0.2	A	15 GeV	1.4×10^{-4}	1.4
h	A5 (NFW)	0.2	B	60 GeV	10^{-7}	1.4
i	A5 (NFW)	0.2	B	60 GeV	8.7×10^{-6}	8.7×10^{-2}
j	B3 (Evans power law)	0.17	A	100 GeV	10^{-7}	1.7
k	B3 (Evans power law)	0.17	A	100 GeV	1.1×10^{-5}	0.11

[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

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

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

$$\sigma^{Na} \simeq \sigma^I$$

$m_L = 0$
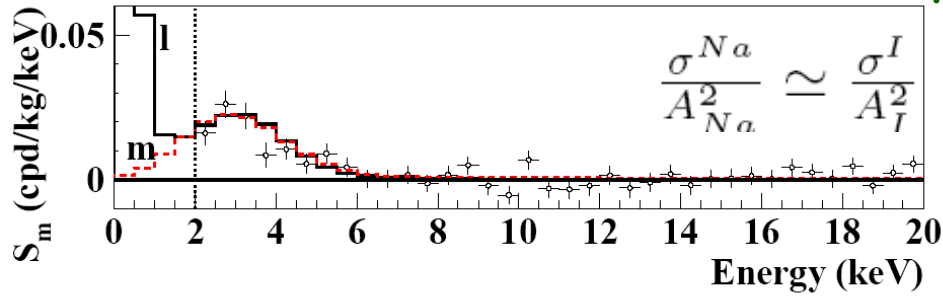
LDM candidate
(as in MPLA23(2008)2125): inelastic interaction with electron or nucleus targets
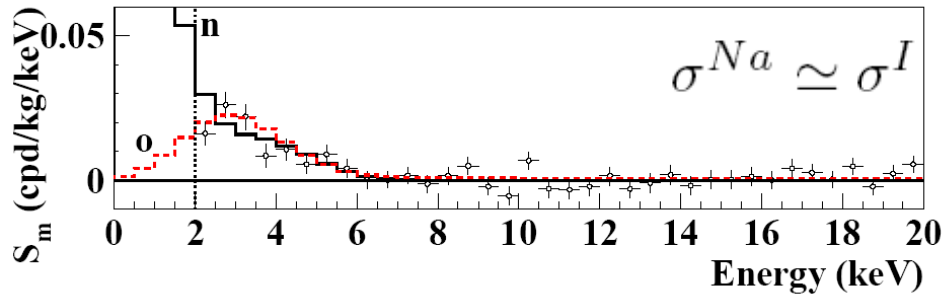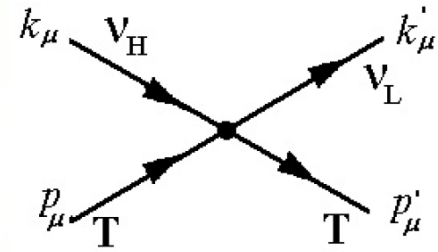
Light bosonic candidate
(as in IJMPA21(2006)1445): axion-like particles totally absorbed by target material
- Not best fit
- About the same C.L.
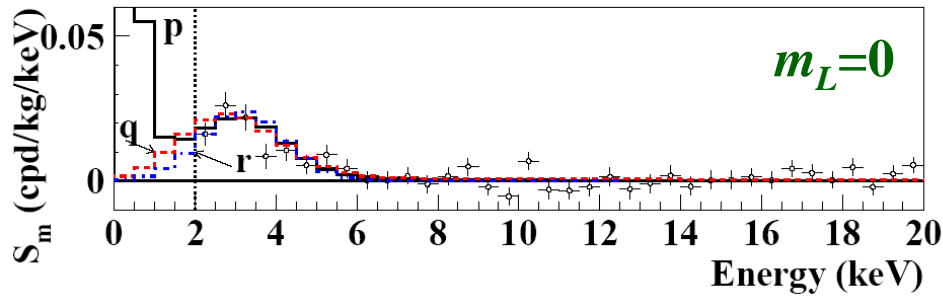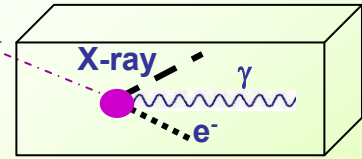
curve *r*: also pseudoscalar axion-like candidates (e.g. majoron)
m_a=3.2 keV g_{aee}= 3.9 10^{-11}

(NFW) halo model as in [4, 34], local density = 0.17 GeV/cm³, local velocity = 170 km/s

Curve label	DM particle	Interaction	Set as in [4]	m_H	Δ	Cross section (pb)
l	LDM	coherent on nuclei	A	30 MeV	18 MeV	$\xi\sigma^{coh}_m = 1.8 \times 10^{-6}$
m	LDM	coherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma^{coh}_m = 2.8 \times 10^{-6}$
n	LDM	incoherent on nuclei	A	30 MeV	3 MeV	$\xi\sigma^{inc}_m = 2.2 \times 10^{-2}$
o	LDM	incoherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma^{inc}_m = 4.6 \times 10^{-2}$
p	LDM	coherent on nuclei	A	28 MeV	28 MeV	$\xi\sigma^{coh}_m = 1.6 \times 10^{-6}$
q	LDM	incoherent on nuclei	A	88 MeV	88 MeV	$\xi\sigma^{inc}_m = 4.1 \times 10^{-2}$
r	LDM	on electrons	–	60 keV	60 keV	$\xi\sigma^e_m = 0.3 \times 10^{-6}$

About interpretation

- ✓ Not a unique reference model for Dark Matter particles
- ✓ Not a single set of assumptions for parameters in the astrophysical, nuclear and particle physics related arguments
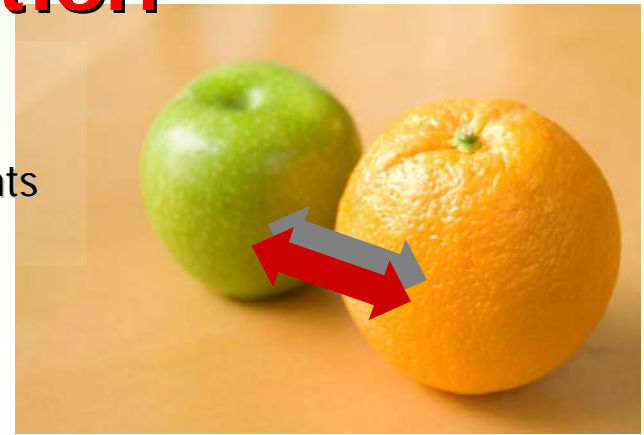- ✓ Often comparisons are made in inconsistent way

model-dependent analysis: selecting just one model framework by fixing many parameters and by adopting several (astrophysical, nuclear and particle physics) assumptions

- which particle?
- which interaction couplings?
- which Form Factors for each target-material?
- which Spin Factors?
- which nuclear model framework?
- which scaling laws?
- which halo model, profile and parameters?
- is there a presence of non-thermalized components in the halo parameters?
- which velocity distribution?
- which parameters for velocity distribution?
- which instrumental quantities?
- ...

Exclusion plots have no "universal validity" (they depend on the recipe)

… and experimental aspects …

- Marginal and "selected" exposures. Threshold, small detector response (few phe/keV), energy scale and energy resolution; calibrations in other energy region. Stability of all the operating conditions. Selections of detectors and of data. Handling of (many) "subtraction" procedures and stability in time of all the selection windows and related quantities, etc. Efficiencies. Fiducial volume vs disuniformity of detector, response in liquids? Used values in the calculation (q.f., etc.). Used approximations. ...

For example, which L_{eff} in liquid Xenon experiments?
arXiv:0909.1063, arXiv:1005.0838

No experiment can be directly compared in model independent way with DAMA
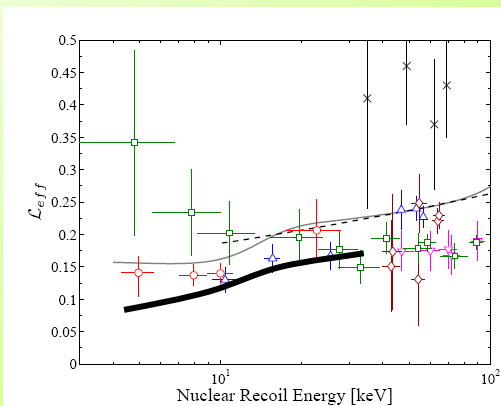
# ... some examples appeared in literature...

Supersymmetric expectations in MSSM

- Assuming for the neutralino a dominant purely SI coupling

- when releasing the gaugino mass unification at GUT scale: $M_1/M_2 \neq 0.5$ (<);

  (where M_1 and M_2 U(1) and SU(2) gaugino masses)

… windows for compatibility also in some recent model dependent results for COGENT (arxiv.org:1003.0014)

Relic neutralino in effMSSM

DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions with and without channeling

**If the two CDMS events are interpreted as relic neutralino interactions**

CoGeNT 2008
CoGeNT 2010
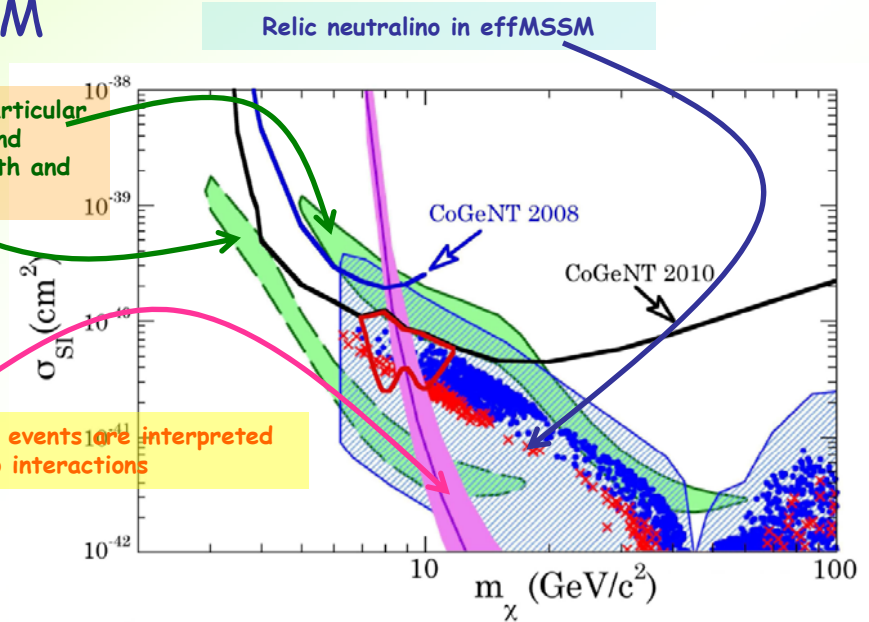
Mirror Dark Matter

➤ DAMA compatible with O′ interactions

➤ Recoil energy spectrum predicted for the CDMS II

➤ The two CDMS events are compatible with Fe′ interactions

DAMA/Libra which probe the lighter O' component. Note that our estimate of $\epsilon\sqrt{\xi_{Fe'}}$ from the CDMSII events can be combined with the $\epsilon\sqrt{\xi_{O'}}$ value inferred from the DAMA/Libra experiment to yield $\xi_{Fe'}/\xi_{O'} \approx 10^{-2}$. It is interesting that this is the same order of magnitude as the corresponding quantity for ordinary matter in our galaxy and demonstrates that our combined interpretation of the DAMA/Libra experiment and the two CDMSII events is plausible.

arXiv:1001.0096
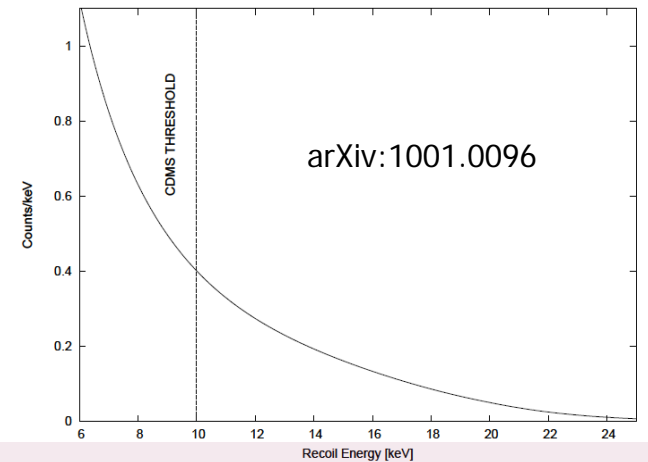
Some other papers on compatibility among results: **Inelastic DM (PRD79(2009)043513), Resonant DM (arXiv:0909.2900), Cogent results (arXiv:1002.4703), DM from exotic 4th generation quarks (arXiv:1002.3366), Light WIMP DM (arXiv:1003.0014), Composite DM (arXiv:1003.1144), Light scalar WIMP through Higgs portal (arXiv:1003.2595), ...**

DM particle with preferred inelastic interaction
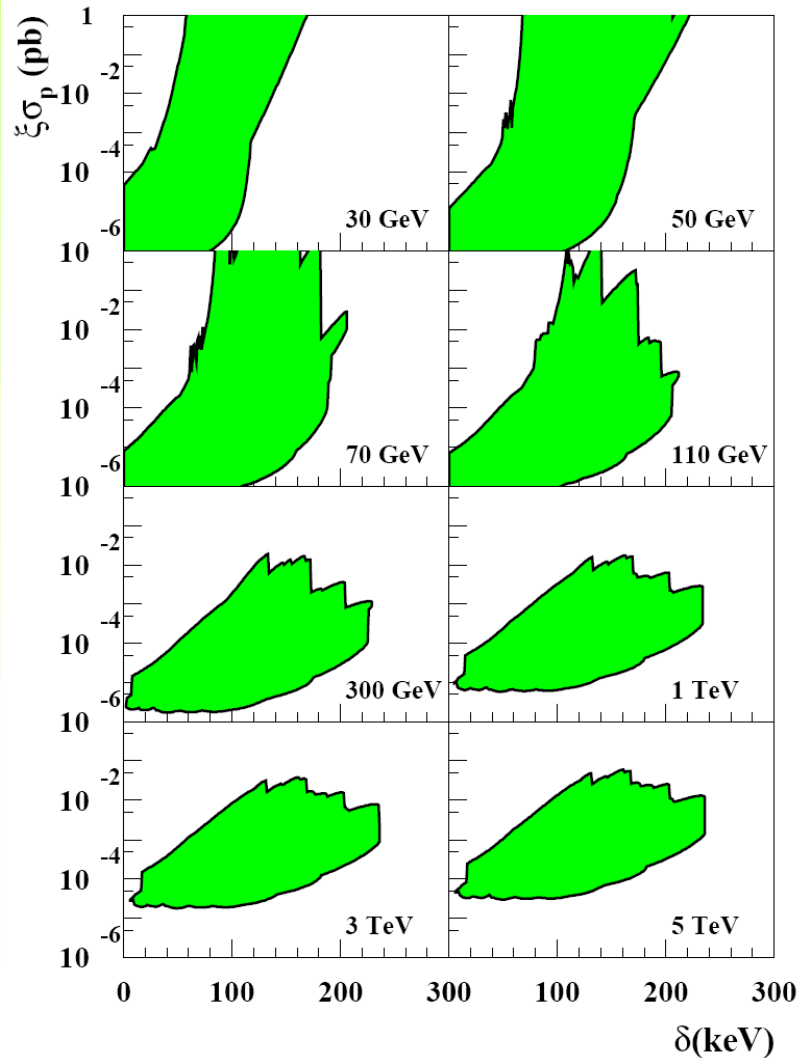
- Inelastic Dark Matter:

W + N → W* + N

→ W has Two mass states $\chi+$, $\chi-$ with δ mass splitting

→ Kinematical constraint for the inelastic scattering of $\chi-$ on a nucleus

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

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo now supported at 8.9 σ C.L. by the cumulative 1.17 ton × yr exposure over 13 annual cycles by the former DAMA/NaI and the present DAMA/LIBRA

- 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

- Updated/new model dependent corollary investigations on the nature of the DM particle in progress also in the light of some recent strongly model dependent claims

- Investigations other than DM

... and for the future and perspectives see next talk by R. Cerulli

... and ...