Dark Matter Annual Modulation Results by DAMA/LIBRA

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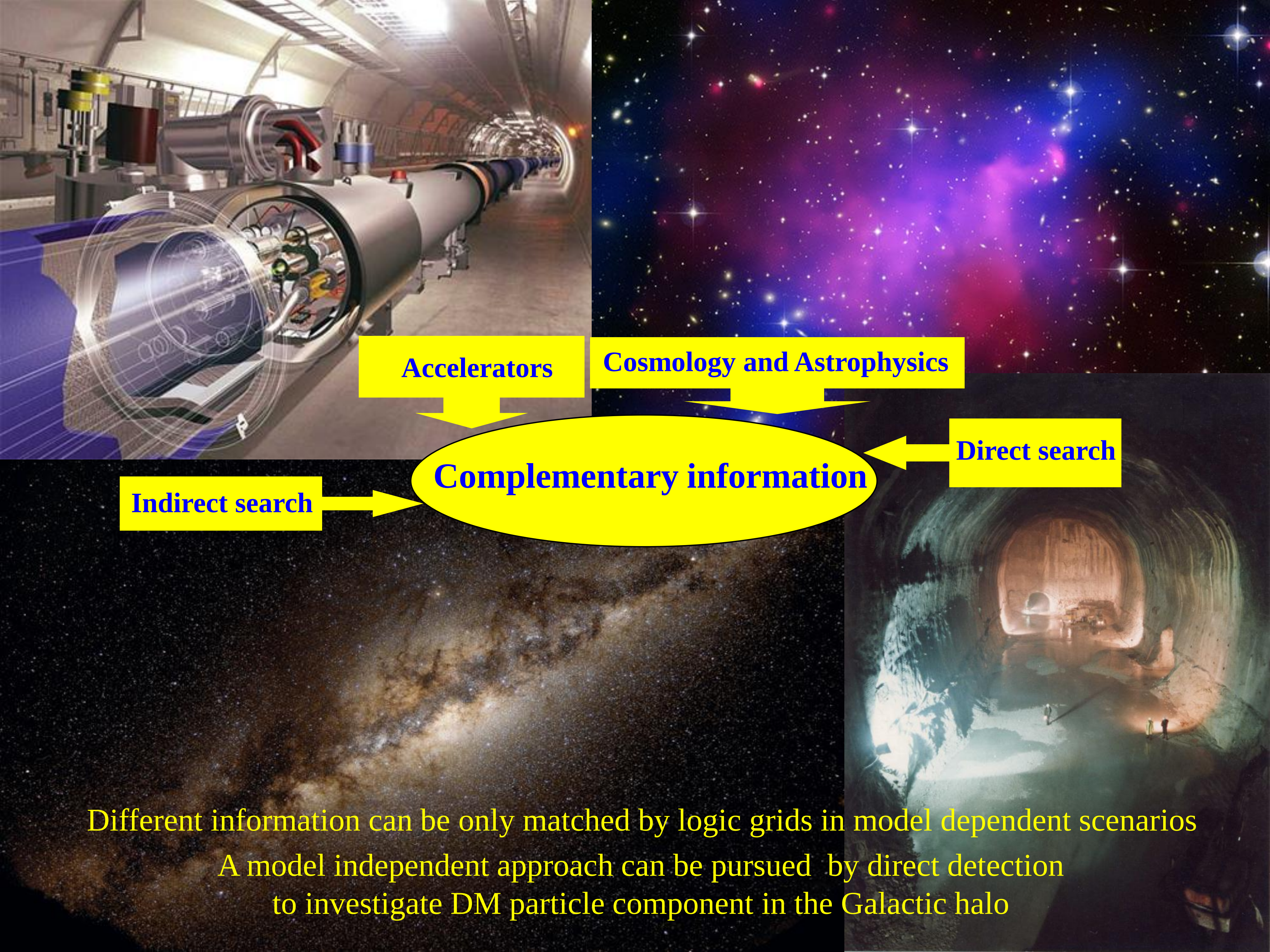
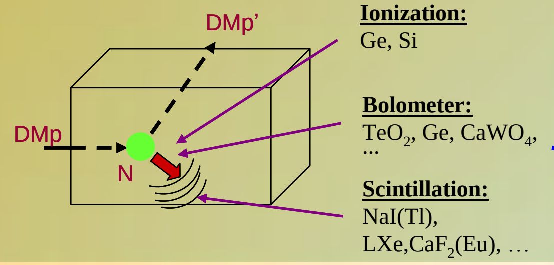
ELBA XII Workshop, 25th June 2012


Accelerators
Cosmology and Astrophysics
Direct search
Complementary information
Indirect search
Different information can be only matched by logic grids in model dependent scenarios
A model independent approach can be pursued by direct detection
to investigate DM particle component in the Galactic halo

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



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

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

  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

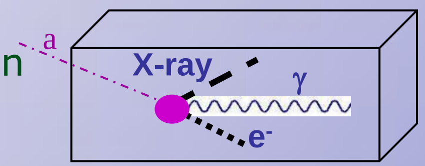
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

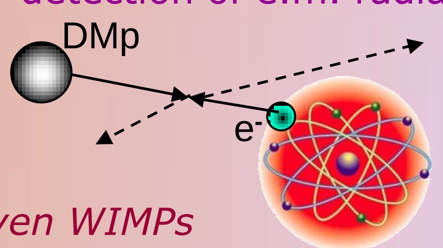
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

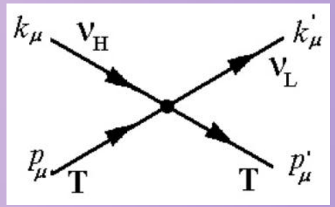


… even WIMPs

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

  → detection of electron/nucleus recoil energy

e.g. sterile ν



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

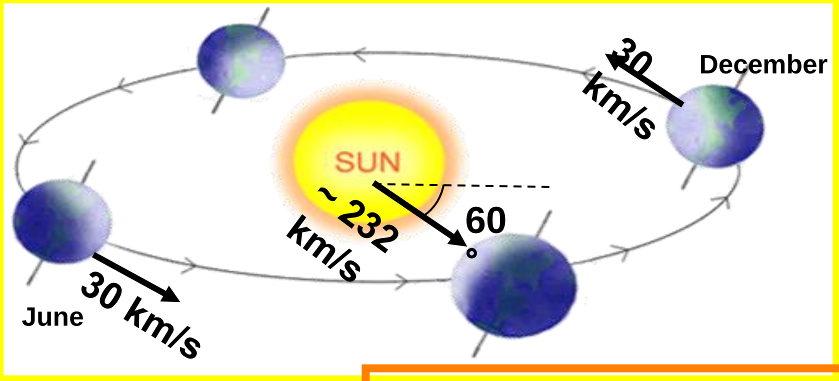
… also other ideas …

- **… and more**

A model independent signature is needed

Crystal scintillators: a reliable technology to investigate model independent signatures

- High duty cycle
- Well controlled operational conditions
- Reproducibility (no re-purification procedures or cooling down/warming up)
- Long term stability
- Effective routine calibrations down to keV in the same conditions as production runs
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios



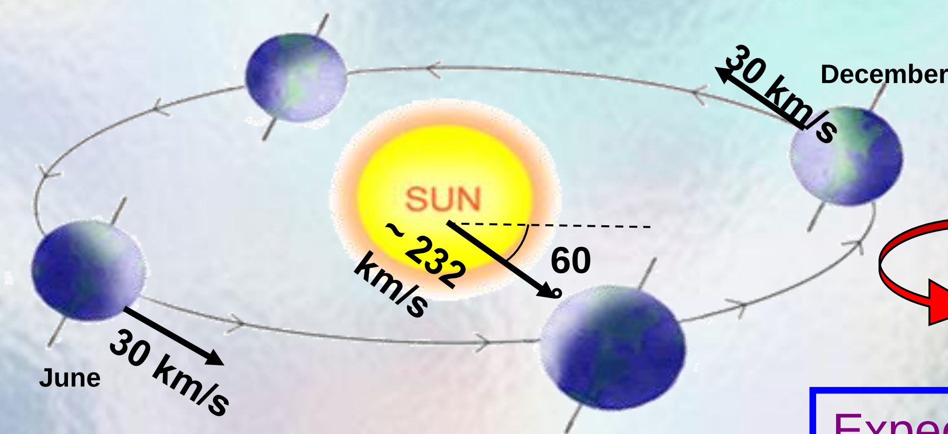
Annual modulation Annual variation of the interaction rate due to Earth motion around the Sun.

Directionality Correlation of Dark Matter impinging direction with Earth's galactic motion due to the distribution of Dark Matter particles velocities (anisotropic scintillator)

Diurnal modulation Daily variation of the interaction rate due to: i) different Earth depth crossed by the Dark Matter particles; ii) Earth rotational velocity (channeling, anisotropy, ecc.)

Investigating the presence of a DM particle component in the galactic halo by the model independent annual modulation signature

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 of the Earth's motion around the Sun moving in the Galaxy. Therefore it has different peculiarities(e.g. the phase) with respect to those effects connected with seasons

Requirements:

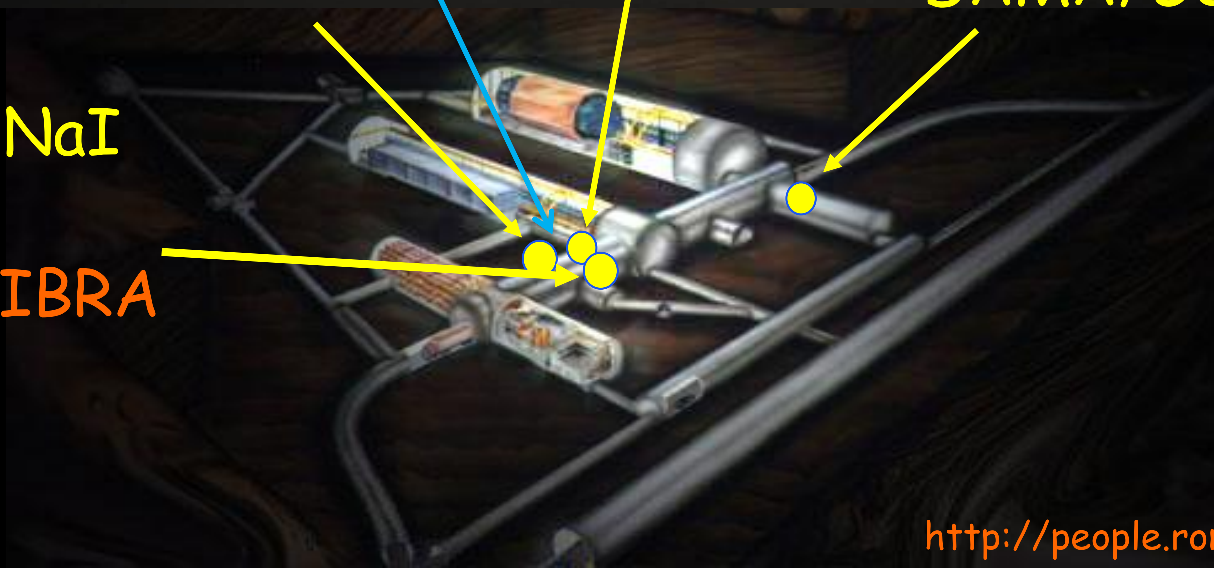
1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2nd June)
5) For single hit in a multi-detector set-up
6) With modulated amplitude in the region of maximal sensitivity < 7% (for usually adopted halo distributions, but it can be larger in case of some possible scenarios)

To mimic this signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur, India

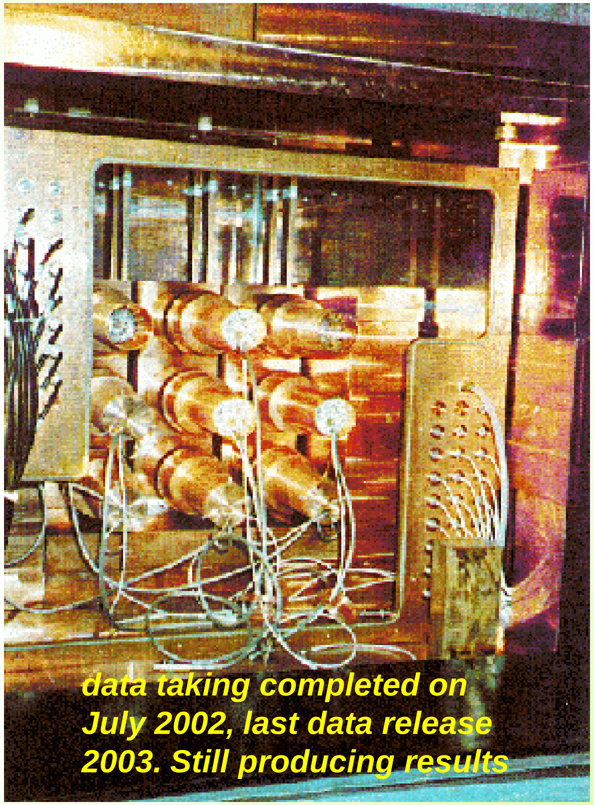
DAMA:an observatory for rare processes @LNGS



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

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 cluster decays — EPJA24(2005)51

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

Installing the DAMA/LIBRA set-up ~250 kg ULB NaI(Tl)

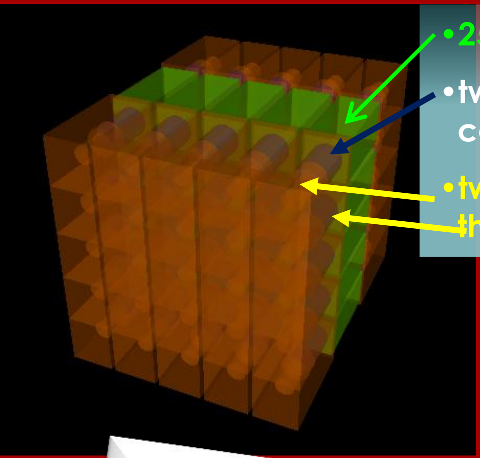
Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

- ***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

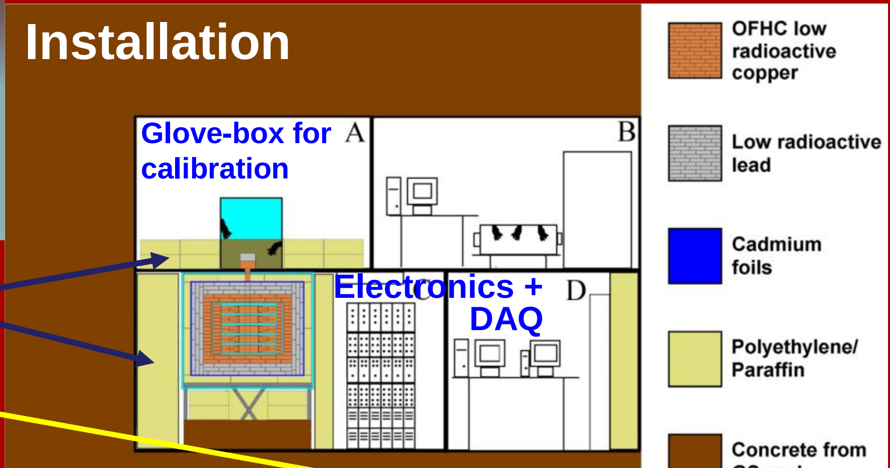
...calibration procedures

The DAMA/LIBRA set-up

For details, radiopurity, performances, etc. NIMA592(2008)297, JINST7(2012)03009

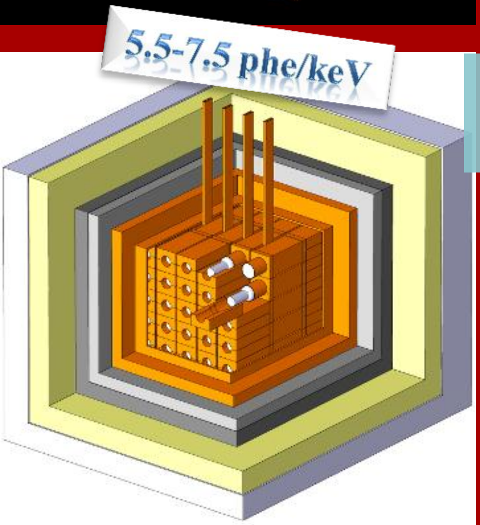


- 25x9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold



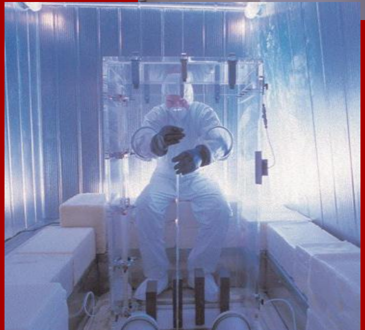
Polyethylene/paraffin

~1m concrete from GS rock



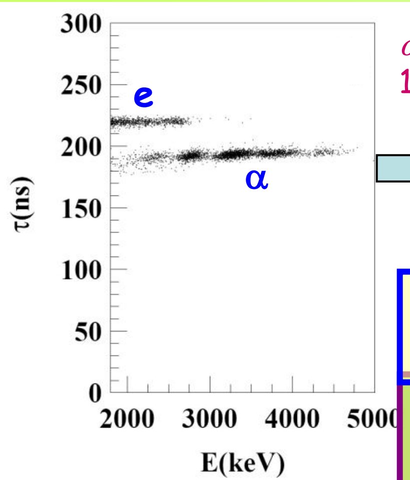
Multicomponent passive shield:
>10 cm of Cu, 15 cm of Pb, Cd foils, 10/40 cm Polyethylene/paraffin +

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Three-level system to exclude Radon from the detectors
- Installation in air conditioning + huge heat capacity of shield
- *Calibrations in the same running conditions as production runs*



- 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



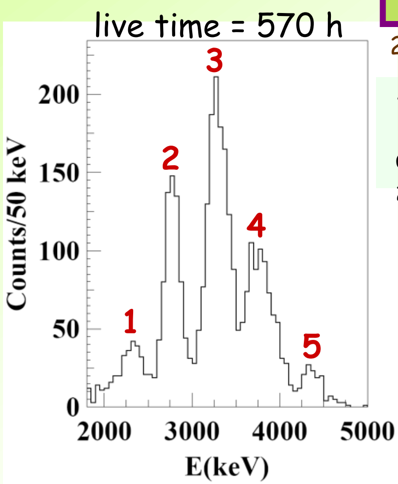
α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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

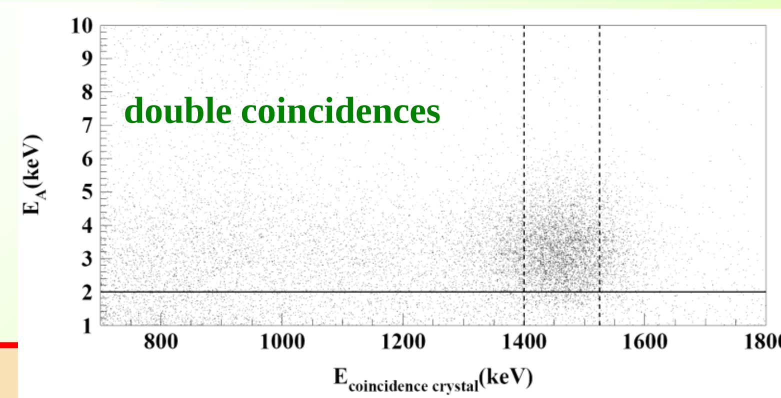
^{238}U residual contamination — First estimate: considering the measured α and ^{232}Th activity, if ^{238}U chain at equilibrium $\Rightarrow$ ^{238}U contents in new detectors typically range from 0.7 to 10 ppt

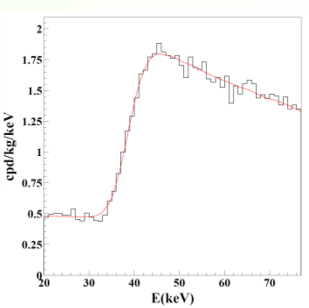


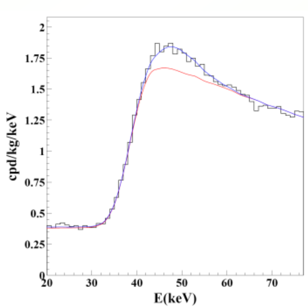
^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

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.

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







^{129}I and ^{210}Pb

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

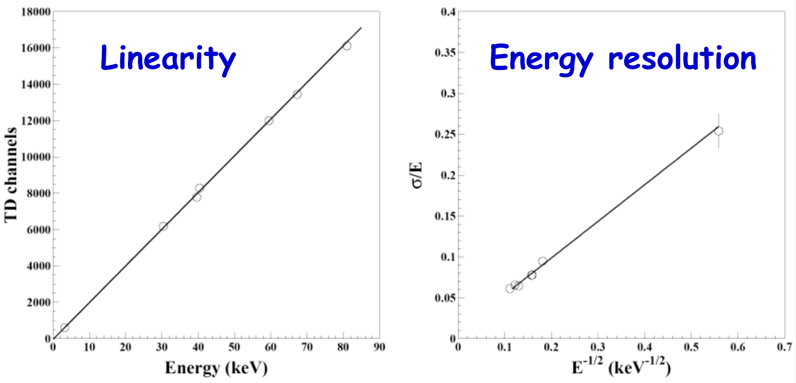
^{210}Pb in the new detectors: (5 – 30) μBq/kg.

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

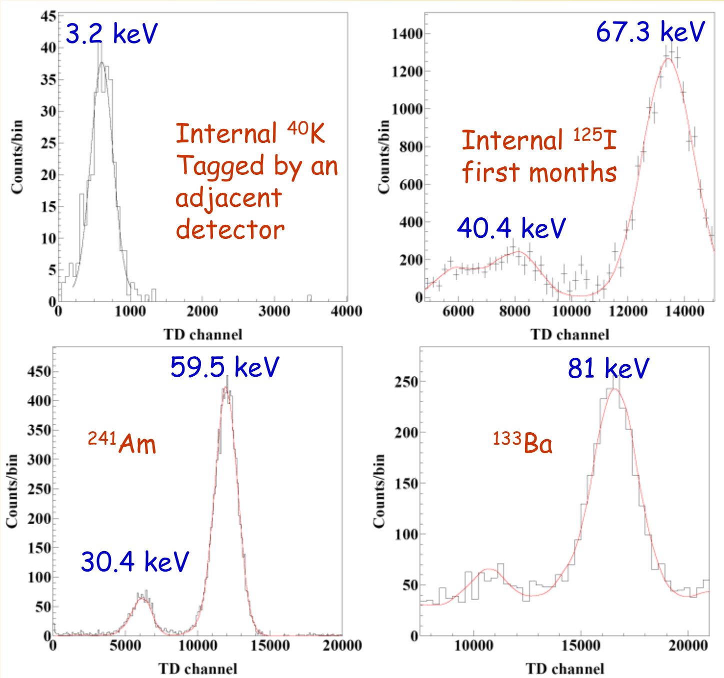
... more on NIMA592(2008)297

DAMA/LIBRA calibrations

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

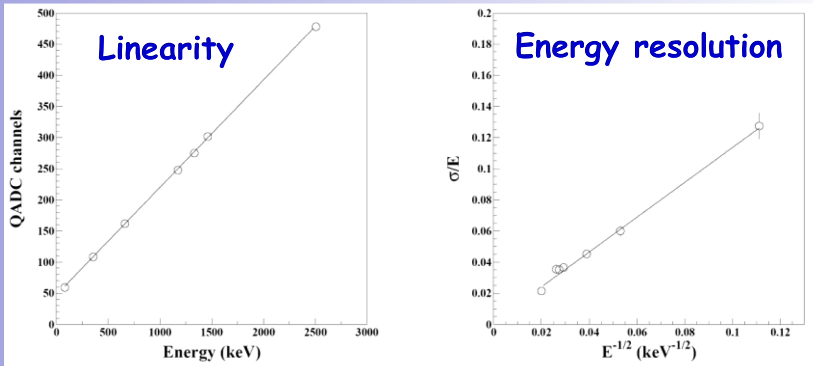


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1)\cdot 10^{-3}$$

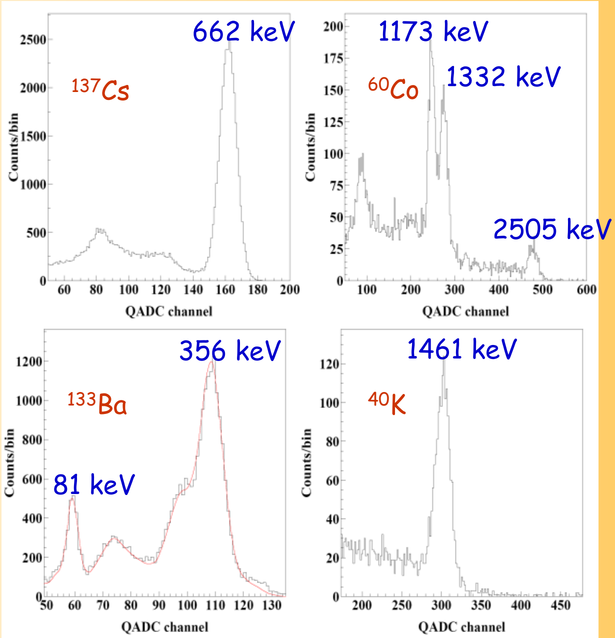


The curves superimposed to the experimental data have been obtained by simulations

High energy: external sources of gamma rays (e.g. ^{137}Cs, ^{60}Co and ^{133}Ba) and gamma rays of 1461 keV due to ^{40}K decays in an adjacent detector, tagged by the 3.2 keV X-rays



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

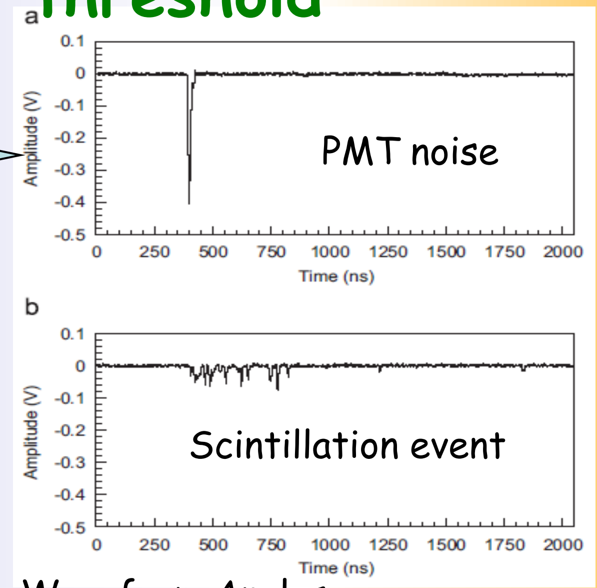


$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23)\cdot 10^{-4}$$

Thus, here and hereafter keV means keV electron equivalent

Noise rejection near the energy threshold

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

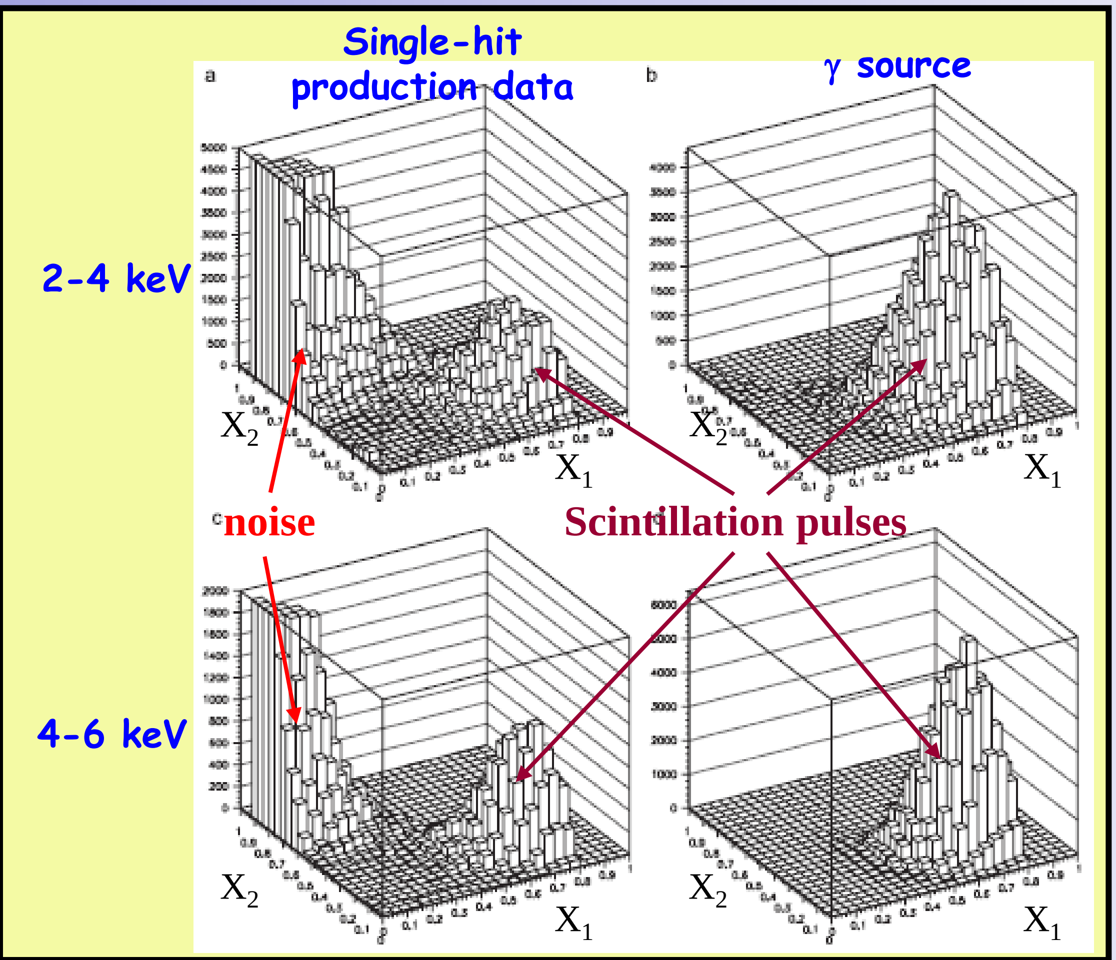


The different time characteristics of PMT noise (decay time of order of tens of ns) and of scintillation event (decay time about 240 ns) can be investigated building several variables

From the Waveform Analyser 2048 ns time window:

$$X_1 = \frac{\text{Area (from 100 ns to 600 ns)}}{\text{Area (from 0 ns to 600 ns)}};$$

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



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

This is the only procedure applied to the analysed data

Infos about 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

- **calibrations: ≈72 M events from sources**
- **acceptance window eff: 82 M events (≈3M events/keV)**

- **EPJC56(2008)333**
- **EPJC67(2010)39**

•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

Second upgrade on Nov/Dec 2010

all PMTs replaced with new ones of higher Q.E.

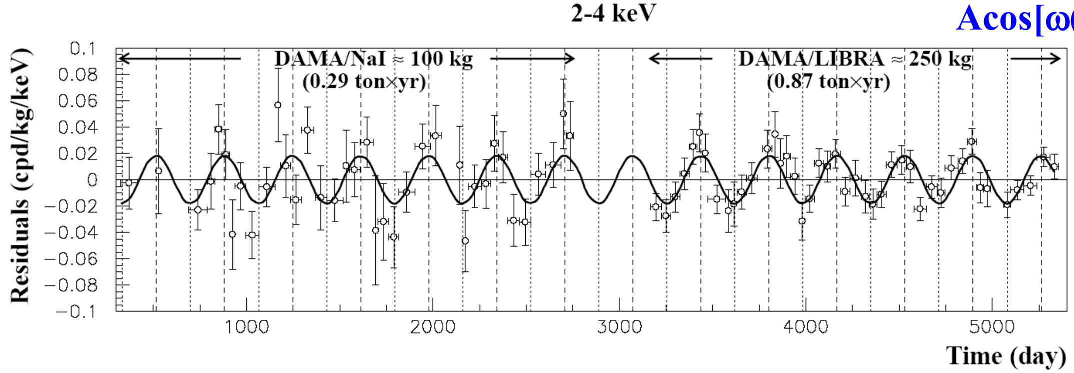
Since Dec 2010 data taking and optimizations in this new configuration started

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



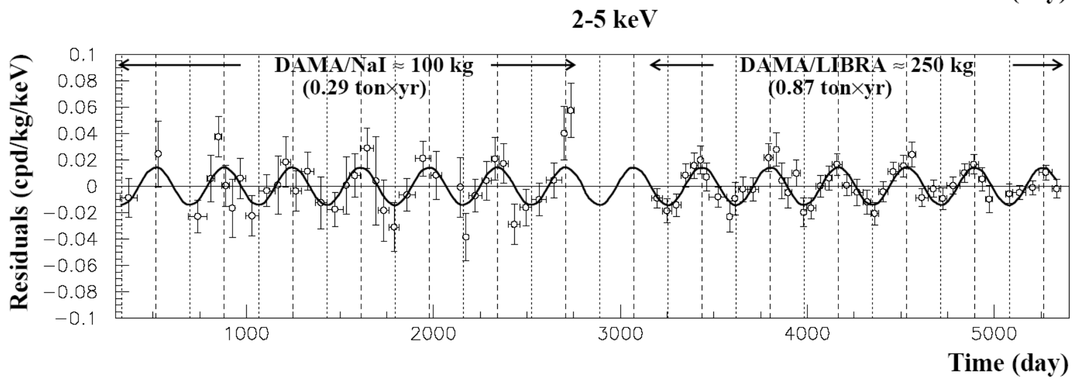
2-4 keV

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}



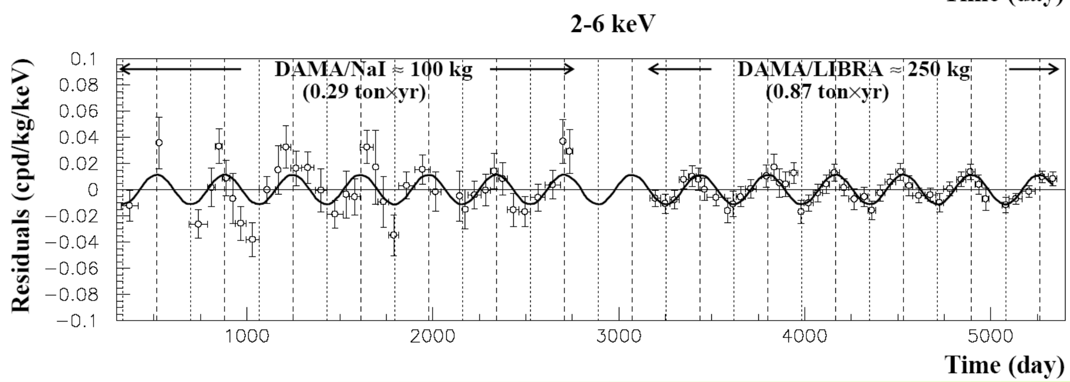
2-5 keV

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.

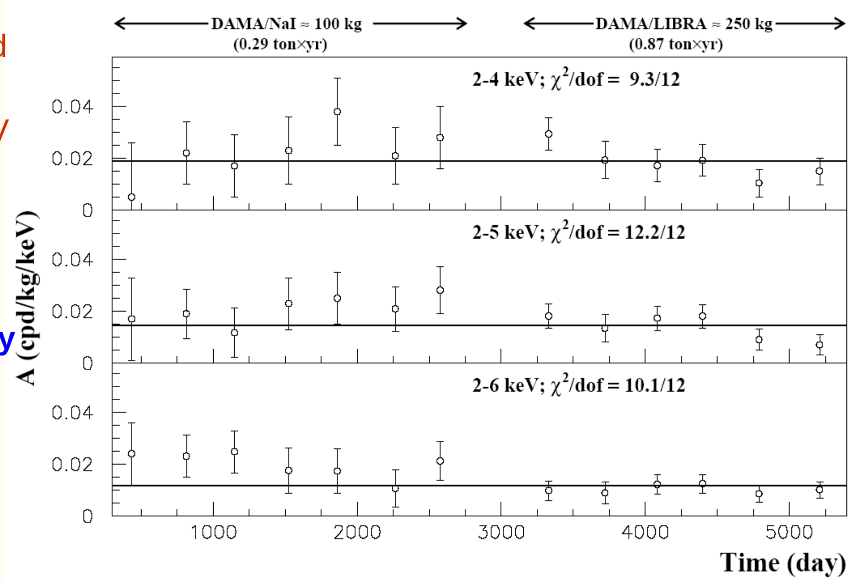
Modulation amplitudes (A), period (T) and phase (t_0) measured in DAMA/NaI and DAMA/LIBRA

	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 **$A\cos[\omega(t-t_0)]$**

- 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

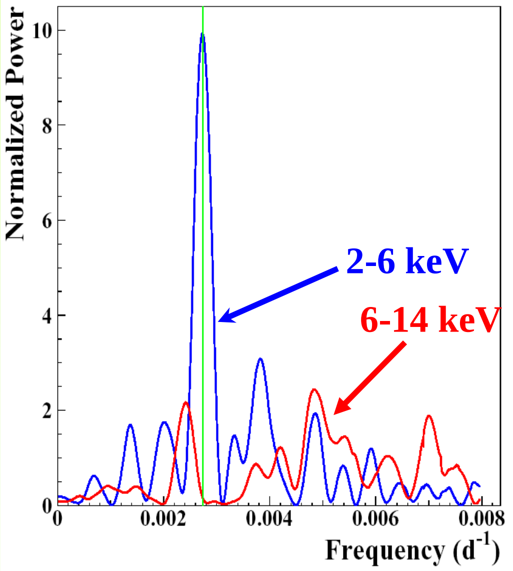
Power spectrum of single-hit residuals

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

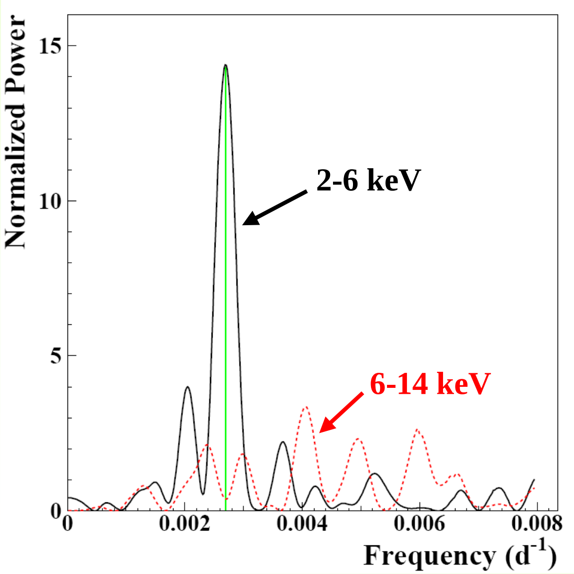
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

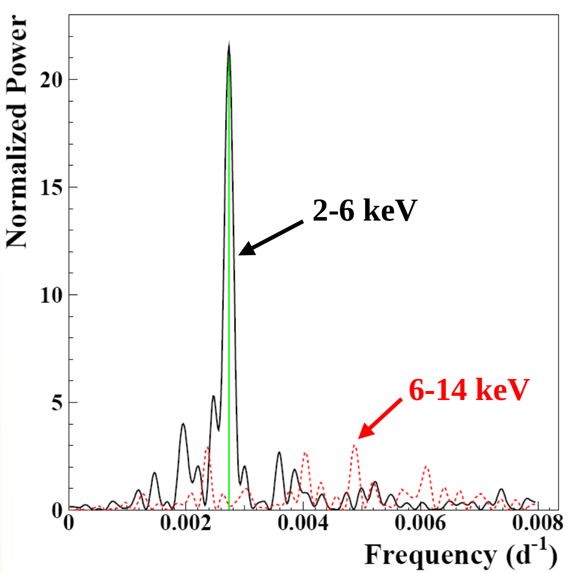
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



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
2.737×10^{-3} d^{-1} ≈ 1 y^{-1}	2.697×10^{-3} d^{-1} ≈ 1 yr^{-1}	2.735×10^{-3} d^{-1} ≈ 1 yr^{-1}

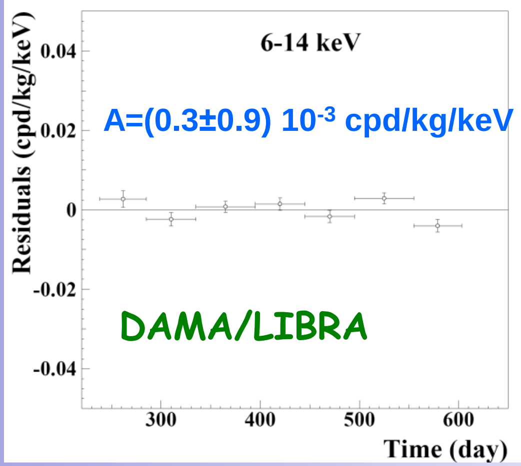
+

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

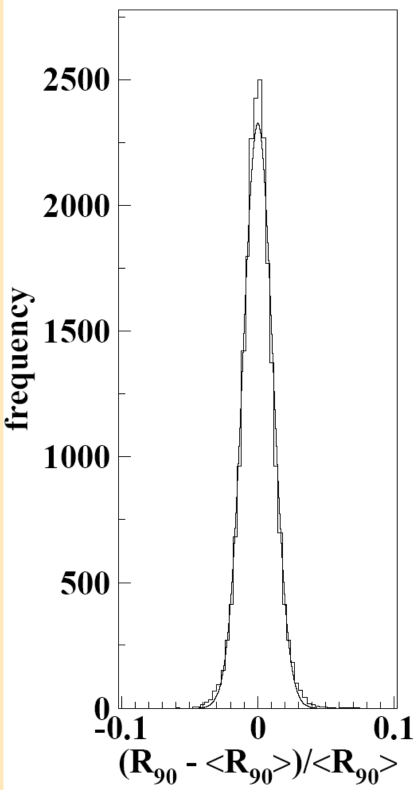
Rate behaviour above 6 keV

- **No Modulation above 6 keV**



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
→ statistically consistent with zero

DAMALIBRA-1 to -6



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

- **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

+ 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 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

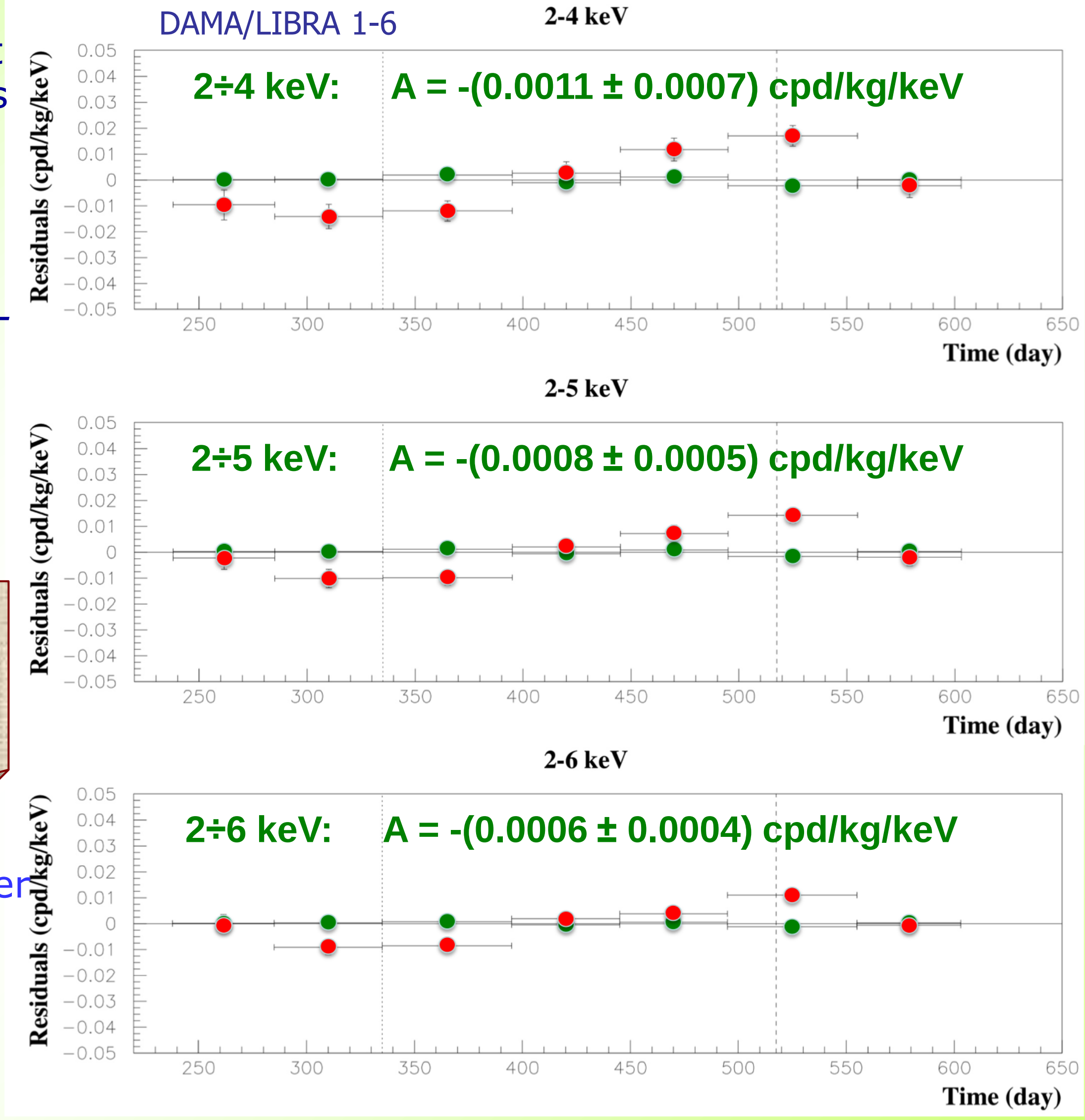
- Each detector has its own TDs read-out → pulse profiles of *multiple-hits* events (multiplicity > 1) acquired (exposure: 0.87 ton×yr).

- The same hardware and software procedures as those 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:
- present in the ***single-hit*** residuals
- absent in the ***multiple-hits*** residual



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

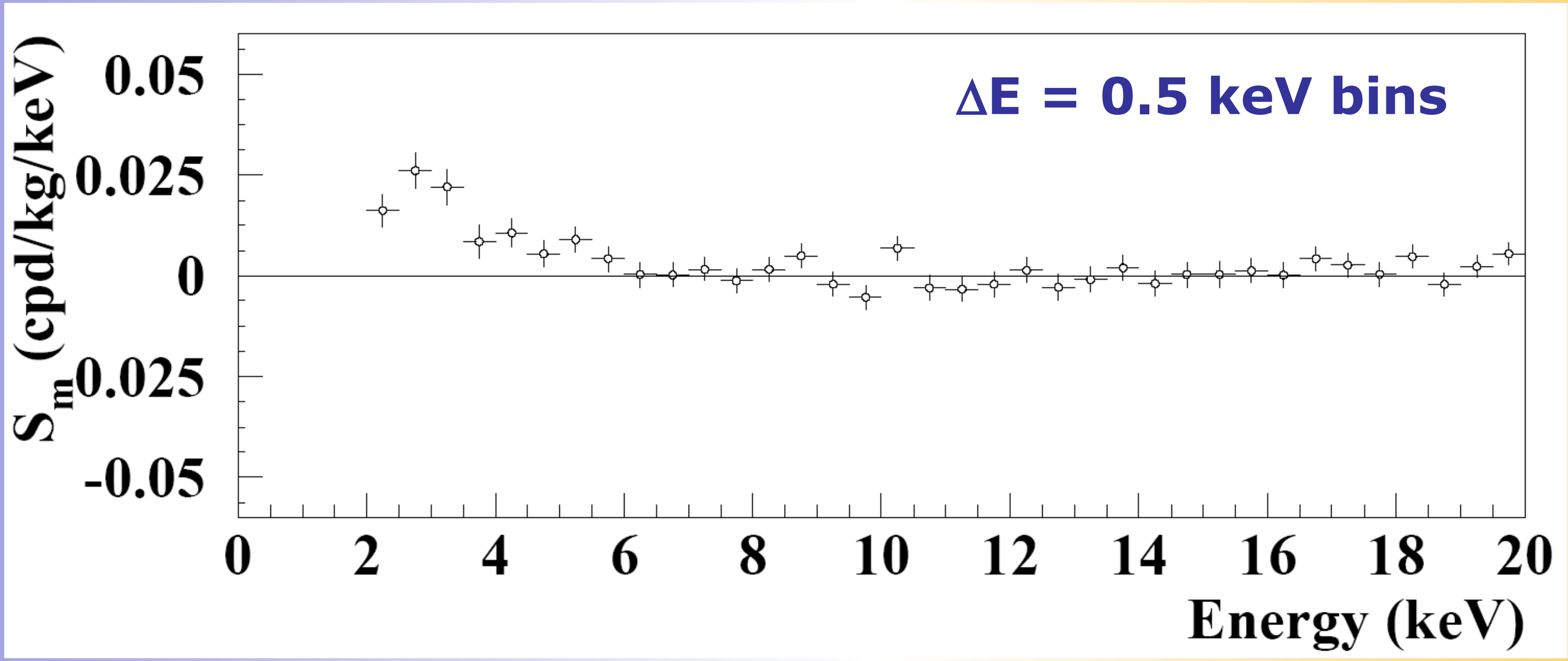
Energy distribution of the modulation amplitudes

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

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



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)

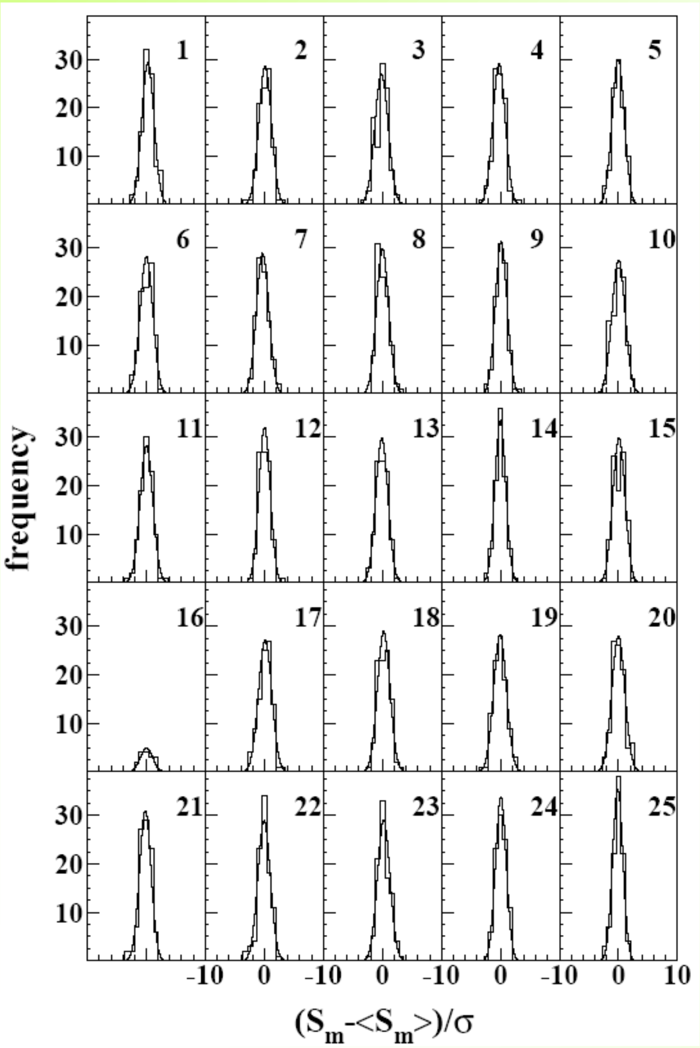
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

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)

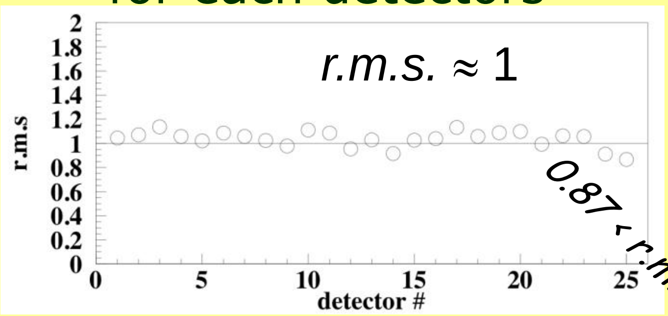


2-6 keV

Standard deviations of

$\mathbf{(S_m-\langle S_m\rangle)/\sigma}$

for each detectors



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 $\mathbf{(S_m-<S_m>)/\sigma}$ 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

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

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

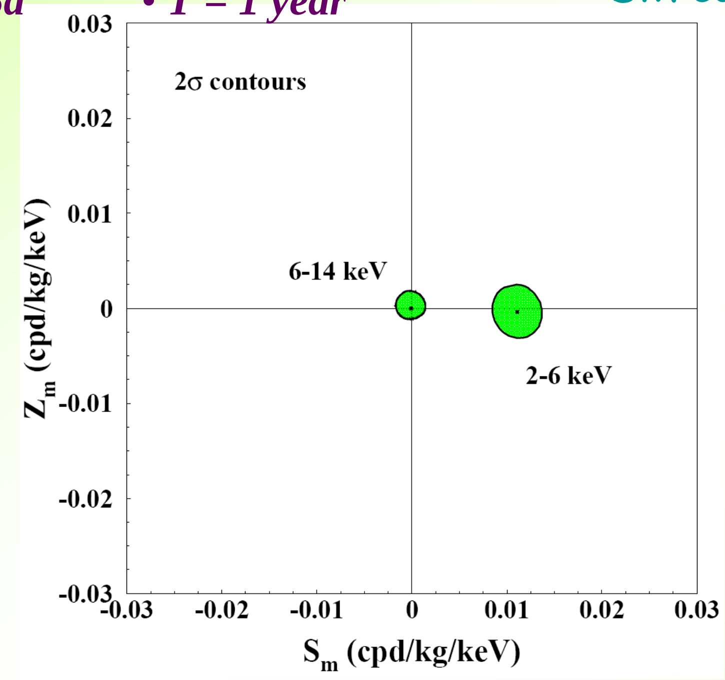
total exposure: 425428 kg×day = 1.17 ton×yr

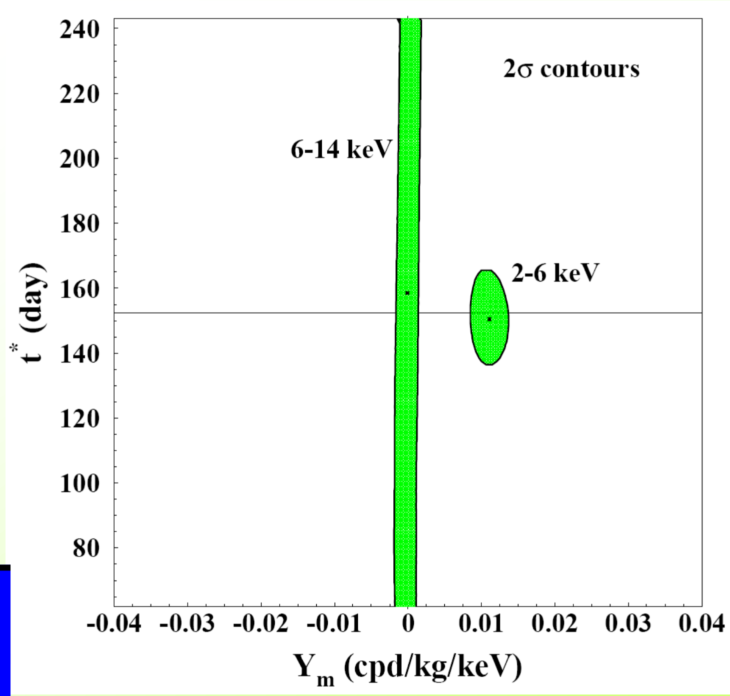
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

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	--

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

(previous exposure and details see: NIMA592(2008)297, EPJC56(2008)333, arXiv:0912.4200, arXiv:1007.0595)

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.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ 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	**$<1\text{-}2\times10^{-4}$ 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	**$<3\times10^{-5}$ cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

→

Thus, they cannot mimic the observed annual modulation effect

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

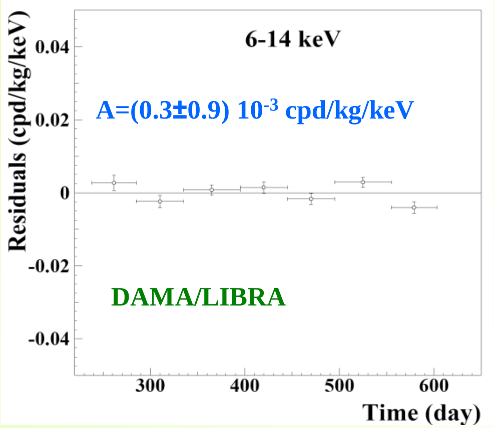
Running conditions stable at a level better than 1% also in the two new running periods

	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) $\times 10^{-2}$ mbar	(0.07 ± 0.13) $\times 10^{-2}$ 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) $\times 10^{-2}$ Hz	(0.09 ± 0.17) $\times 10^{-2}$ Hz	-(0.03 ± 0.20) $\times 10^{-2}$ Hz	(0.15 ± 0.15) $\times 10^{-2}$ Hz	(0.03 ± 0.14) $\times 10^{-2}$ Hz	(0.08 ± 0.11) $\times 10^{-2}$ 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)

Summarizing on a hypothetical background modulation

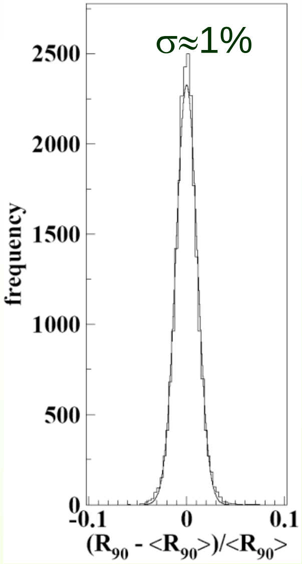
- **No Modulation above 6 keV**



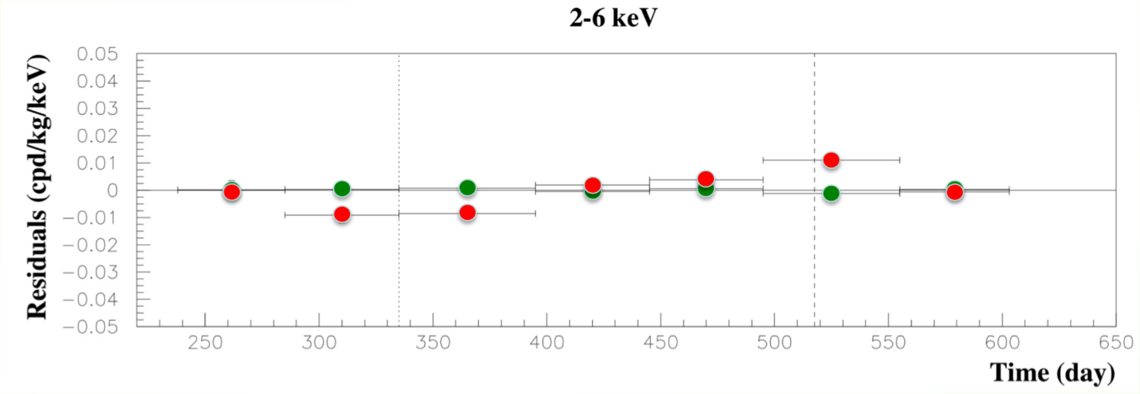
- **No modulation in the whole energy spectrum**

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

→ ~ 100σ far away



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



multiple-hits residual rate (green points) vs single-hit residual rate (red points)

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

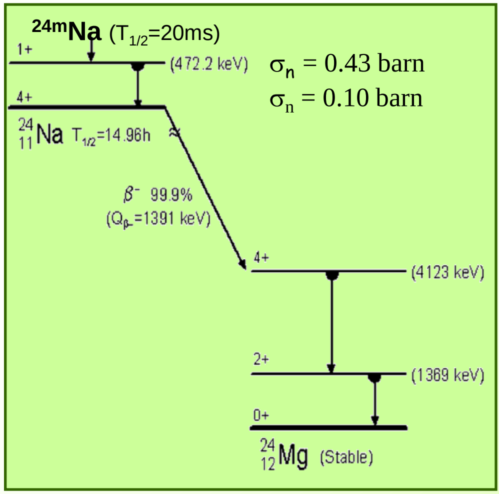
Nevertheless, additional investigations performed ...

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

NO

- **Thermal neutrons flux measured at LNGS :**

Φ_n = 1.08 10^{-6} n cm^{-2} s^{-1} (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:

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

- 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:

⇨ $S_m^{(\text{thermal n})} < 0.8 \times 10^{-6}$ 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

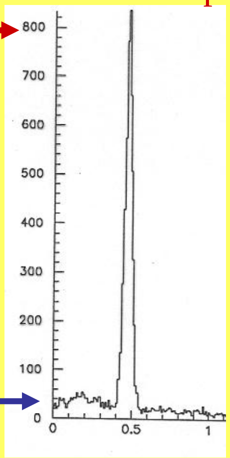
Already excluded also by R_{90} analysis

MC simulation of the process

When Φ_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):

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

  - 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 accompained by thermalized component)

  already excluded also by R_{90}

- a modulation amplitude for multiple-hit events different from zero

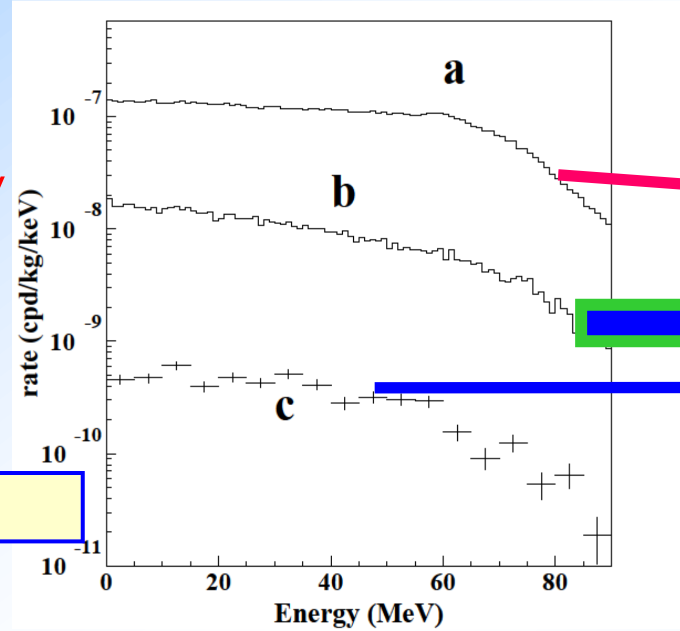
  already excluded by the multiple-hit events

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

The μ case

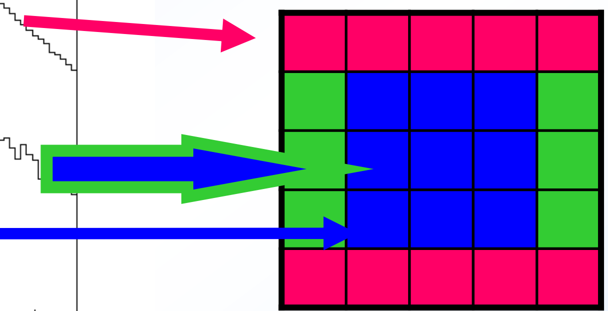
DAMA/LIBRA surface ≈0.13 m^2
μ flux @ DAMA/LIBRA ≈2.5 μ/day

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



Single-hit events

For more arXiv:1202.4179
In press on EPJC



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

Case of fast neutrons produced by μ

Measured neutron Yield @ LNGS:
$Y = 1 \div 7 \; 10^{-4} \; n/\mu/(g/cm^2)$
R_n = (fast n by μ)/(time unit) = $\Phi_\mu \, Y \, M_{eff}$

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.)

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

→ $S_m^{(\mu)} < (0.3\text{-}2.4) \times 10^{-5}$ **cpd/kg/keV**

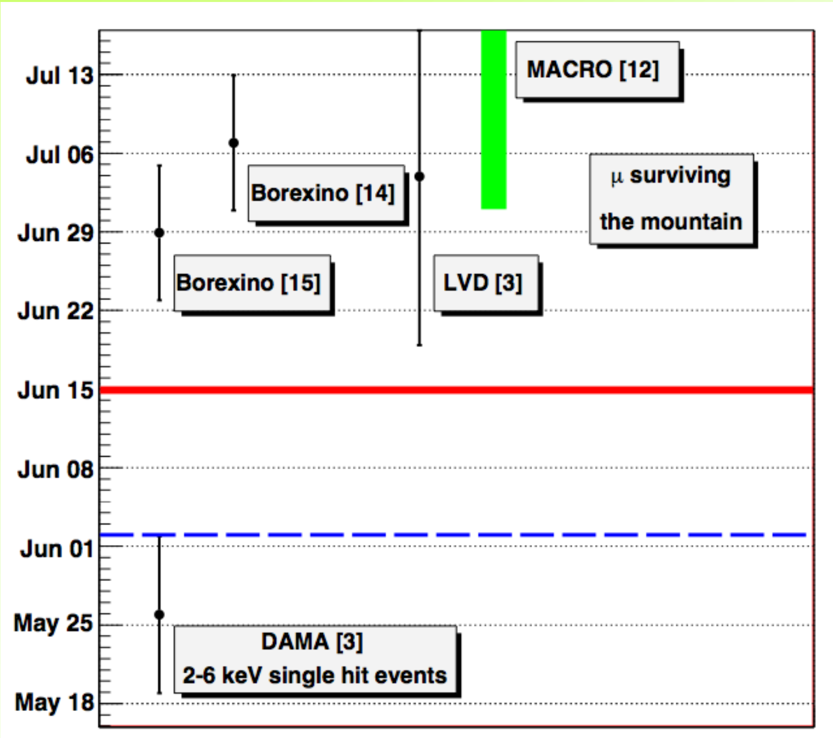
Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events

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

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

about the phase of muons ...

For more arXiv:1202.4179
In press on EPJC



μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈$3 \cdot 10^{-4}$ $m^{-2}s^{-1}$; 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 phase 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)

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

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

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

It cannot mimic the signature: different phase

Inconsistency of the phase between DAMA signal and μ modulation

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, 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

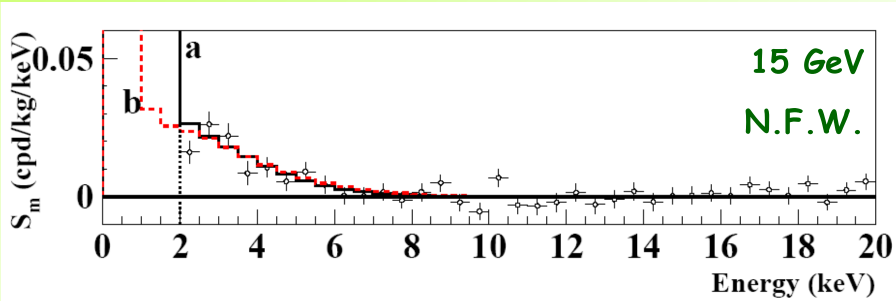
6. The measured modulation amplitude in NaI(Tl) of the *single-hit* events in (2-6) keV is: (0.0116 ± 0.0013) cpd/kg/keV (8.9σ C.L.).

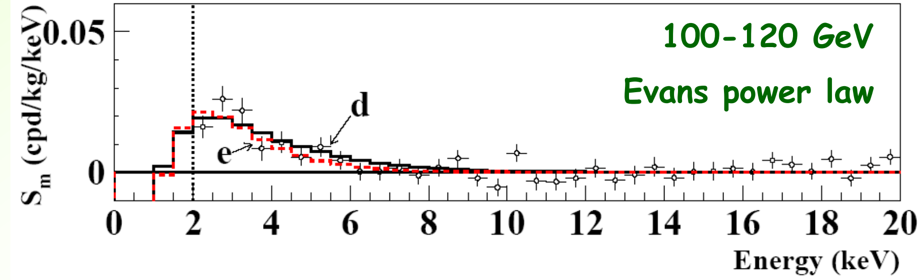
No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

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

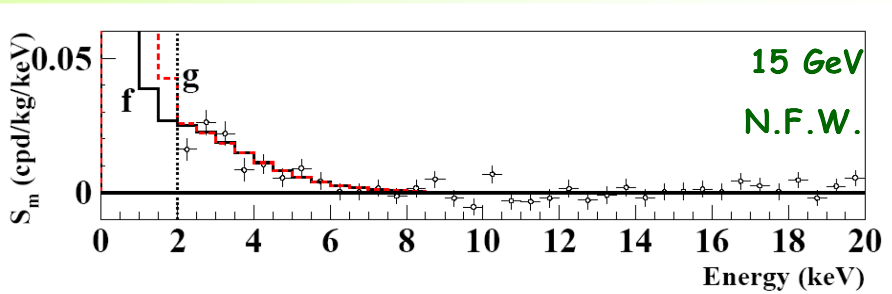
- Not best fit
- About the same C.L.

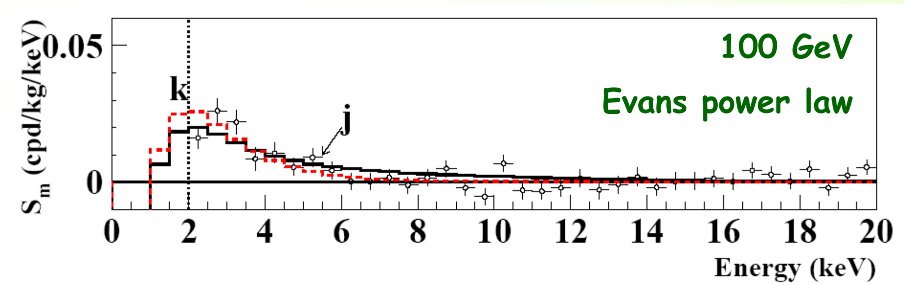
WIMP: SI



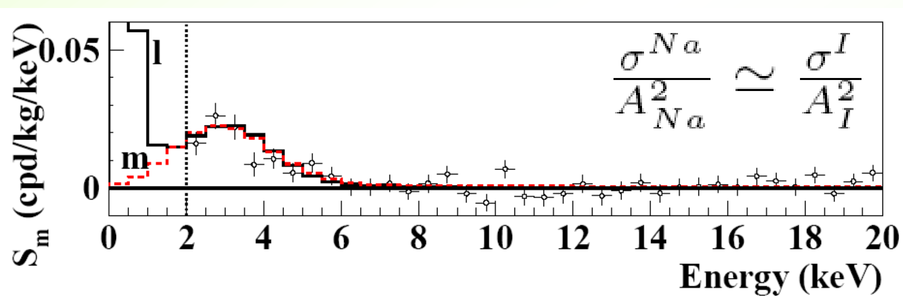


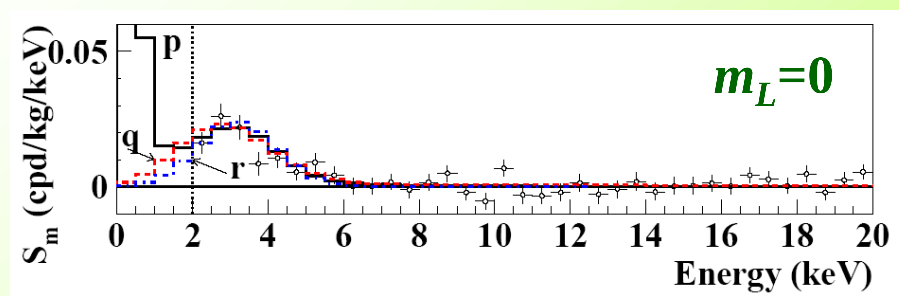
WIMP: SI & SD $\theta = 2.435$





LDM, bosonic DM





EPJC56(2008)333

Compatibility with several candidates; other ones are open

About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD85(2012)095013

…models…

- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

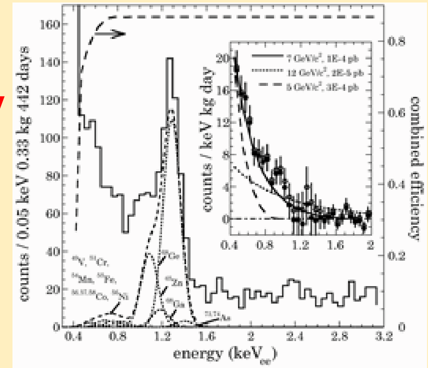
…and experimental aspects…

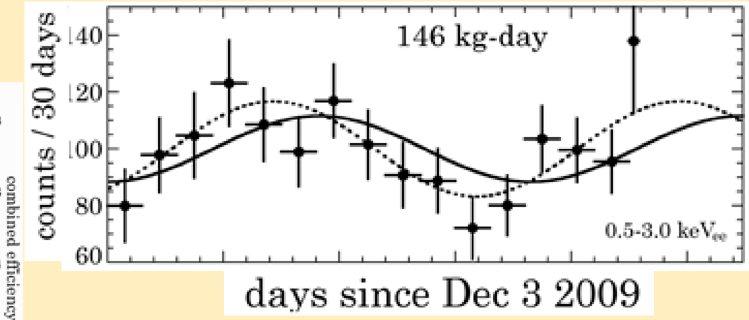
- Exposures
- Energy threshold
- Detector response(phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling
- …

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

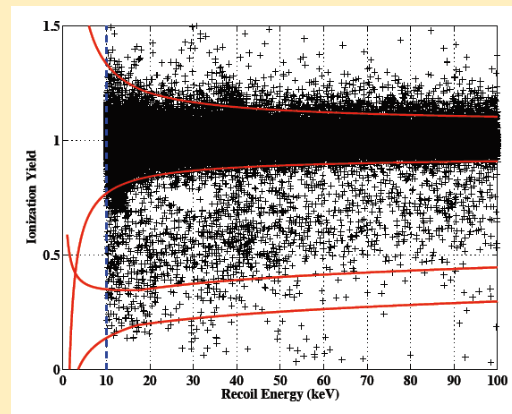
DAMA/NaI & DAMA/LIBRA vs recent possible positive hints 2010/2011

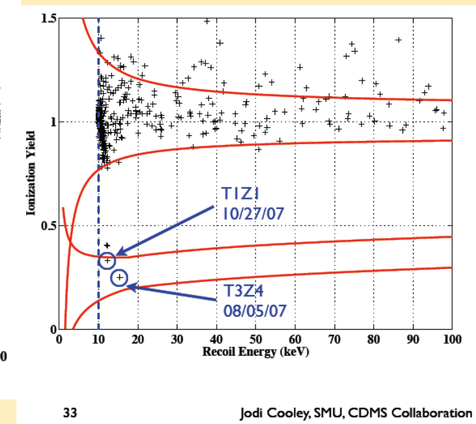
- **CoGeNT:** low-energy rise in the spectrum (irreducible by the applied background reduction procedures) + annual modulation



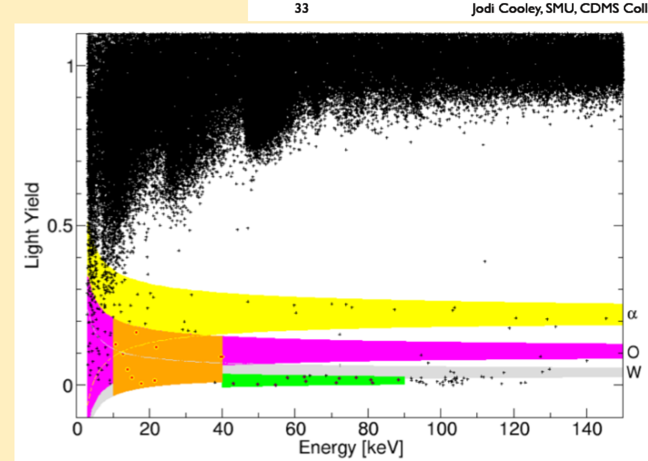


- **CDMS:** after many data selections and cuts, 2 Ge candidate recoils survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)





- **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)



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

... an example in literature...

Supersymmetric expectations in MSSM

- assuming for the neutralino a dominant purely SI coupling
- when releasing the gaugino mass unification at GUT scale: $M_1/M_2 \neq 0.5$ (<);

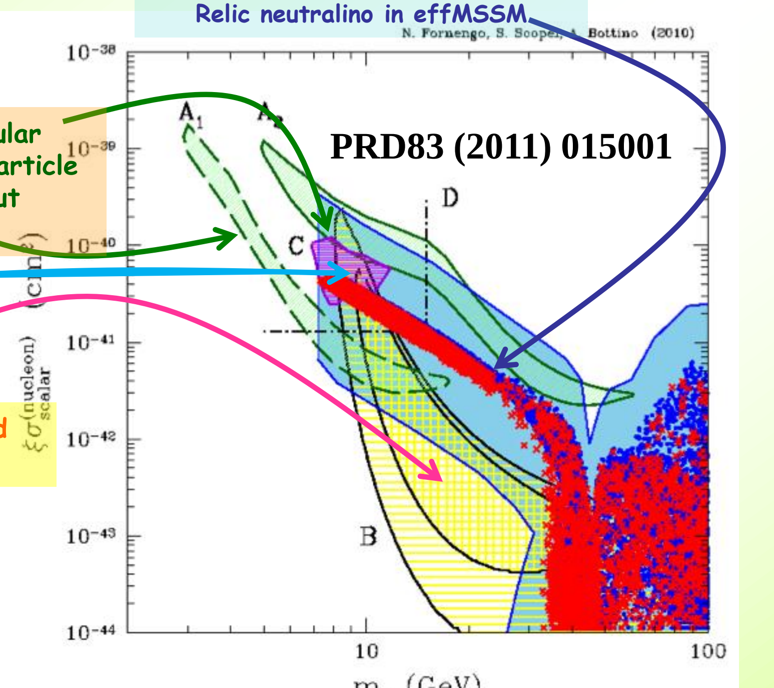
(where M_1 and M_2 U(1) and SU(2) gaugino masses)

Relic neutralino in effMSSM

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

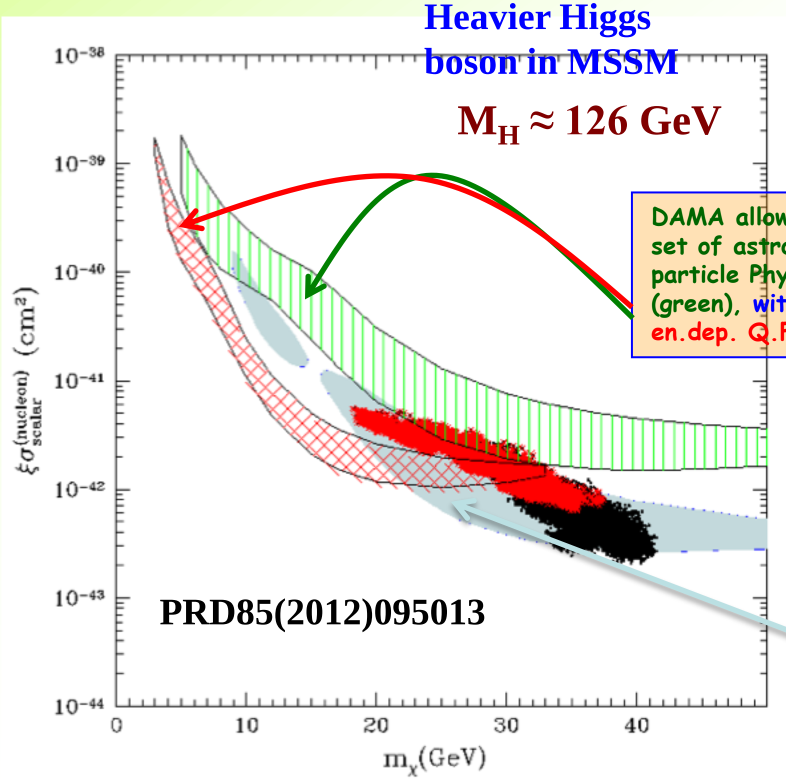
CoGeNT and CRESST

If the two CDMS events are interpreted as relic neutralino interactions



Heavier Higgs boson in MSSM

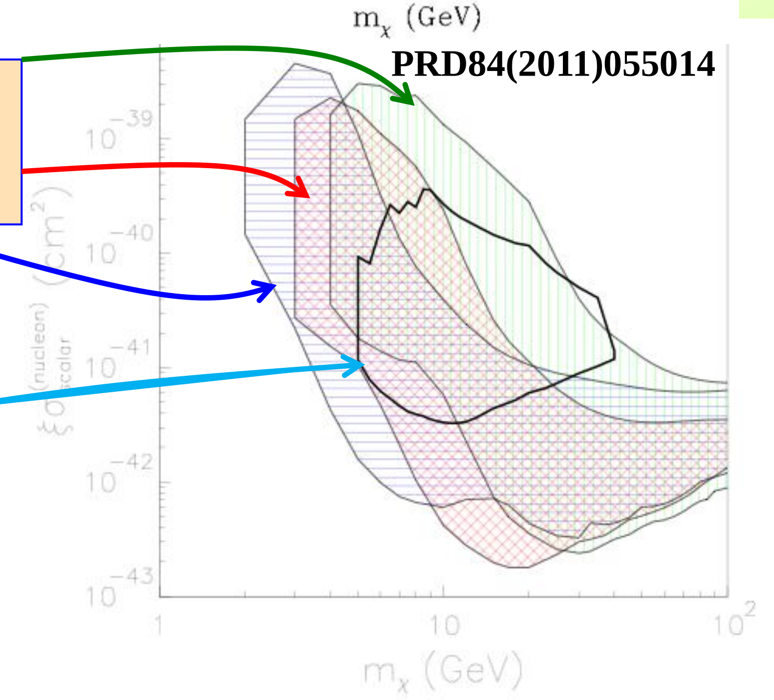
$M_H \approx 126$ GeV



DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with en.dep. Q.F.(red)

CoGeNT

CRESST



... 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.

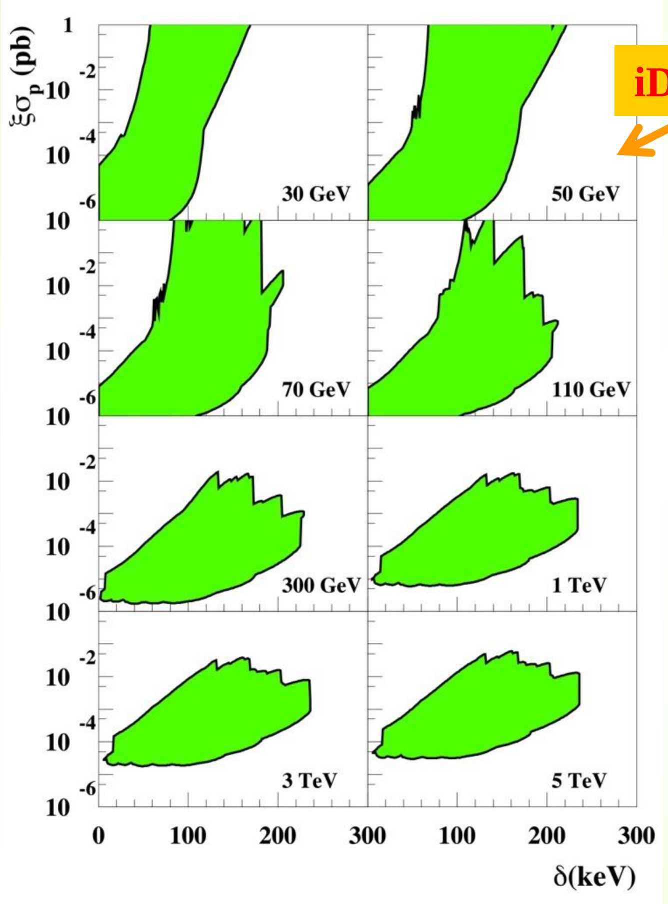
$$\chi^- + N \rightarrow \chi^+ + N$$

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

→ Kinematical constraint for iDM

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

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



iDM interaction on Iodine nuclei

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iDM interaction on Tl nuclei of the NaI(Tl) dopant?

- For **large splittings**, the dominant scattering in NaI(Tl) can occur 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

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

well compatible with several candidates

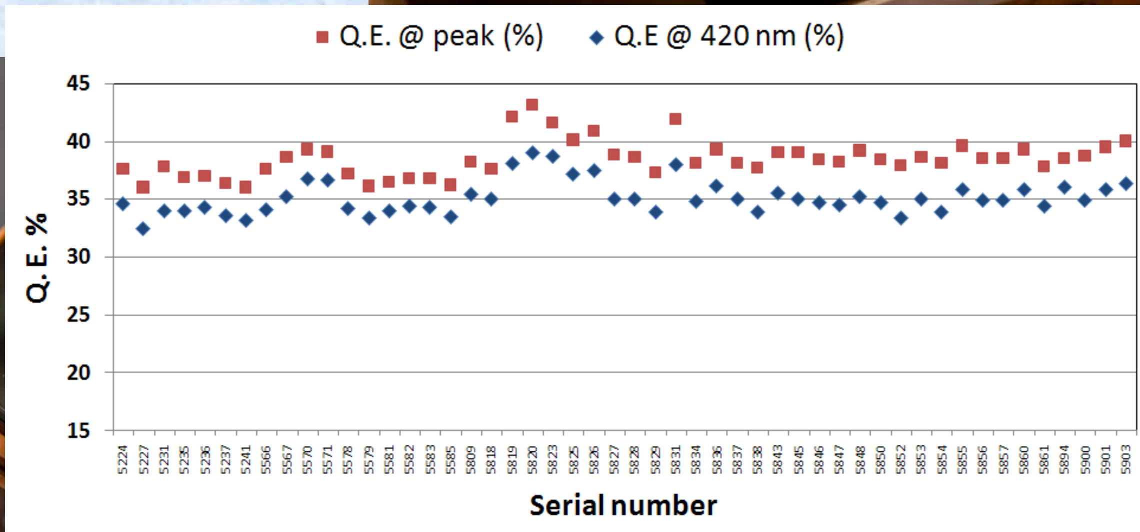
(in many possible astrophysical, nuclear and particle physics scenarios)

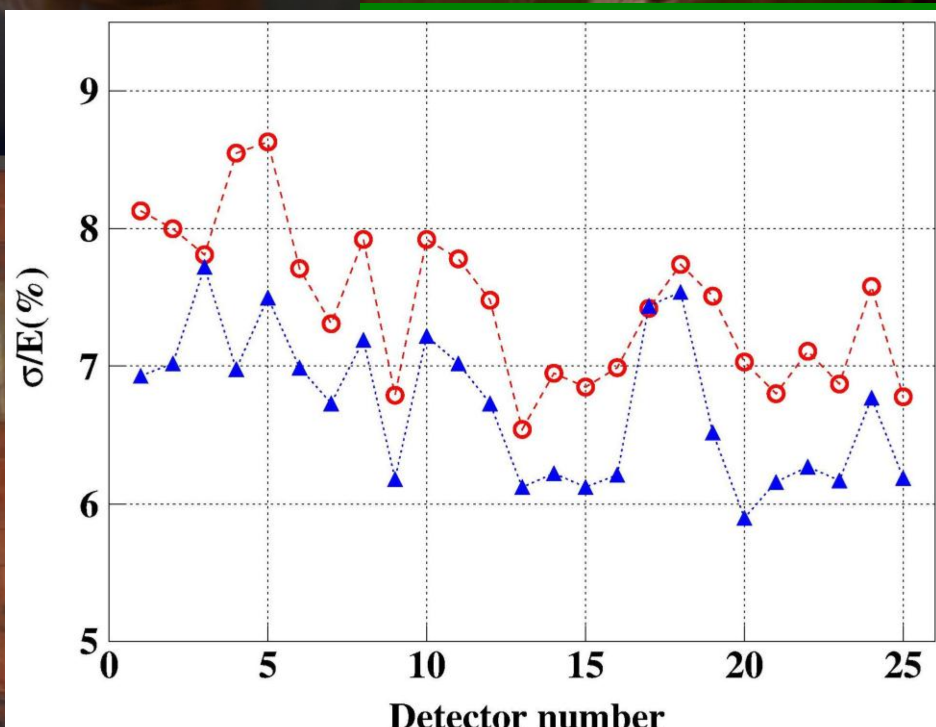
Lowmassneutralino(PRD8(2010)107302,PRD83(2011)015001,PRD84(2011)055014,arXiv:1003.0014,1007.1005,1106.1066,1112.5666),PRD85(2012)095013, Nex-to-minimal models (JCAP0908(2009)032, PRD79(2009)023510, JCAP0706(2007)008, arXiv:1009.2555,1009.0549), Inelastic DM (PRD79(2009)043513), Sneutrino DM (JHEP0711(2007)029,arXiv:1105.4878), Resonant DM (arXiv:0909.2900), Cogent results (arXiv:1002.4703,1106.0650), DM from exotic 4th generation quarks (arXiv:1002.3366), Composite DM (IJMPD19(2010)1385), Light scalar WIMP through Higgs portal (PRD82(2010)043522, JCAP0810(2010)034), Specific two higgs doublet models (arXiv:1106.3368), exothermic DM (arXiv:1004.0937), Secluded WIMPs (PRD79(2009)115019), iDM on Tl(arXiv:1007.2688),MirrorDM (arXiv:1001.0096,1106.2688,PRD82(2010)095001,JCAP1107(2011)009,JCAP1009(2010)022), Asymmetric DM (arXiv:1105.5431), Isospin-violating models (JCAP1008(2010)018, arXiv:1102.4331,1105.3734), Singlet DM (JHEP0905 (2009) 036, arXiv:1011.6377), Specific GU (arXiv:1106.3583), Long range forces (arXiv:1108.4661), Light DM in leptophobic-Z'-models (arXiv:1106.0885), Complex DM (arXiv:1005.3328), and more (arXiv:1105.5121, 1105.3734,1011.1499, JCAP1008(2010)018, PRD82(2010)115019, JCAP1002(2010)14, arXiv:1112.5457...

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, null results not in conflict as well

Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with positive excesses

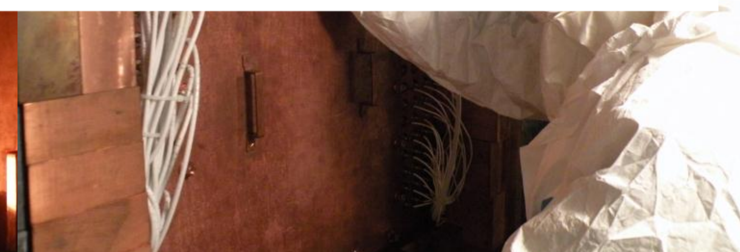
Second upgrade on Nov/Dec 2010





new ones

	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
	47	*0.12*	*83*	*0.54*	-	-
	10	*0,02*	*17*	*0.16*	-	-



Since Dec 2010 data taking and optimizations in this new configuration started

WHAT NEXT?

- **Upgrade in fall 2010 concluded: all PMTs replaced with new ones of higher Q.E. to lower the software energy threshold and improve general features.**
- **New preamplifiers and trigger modules realised to further implement low energy studies.**
- **Suitable exposure planned in the new running conditions to deeper study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects.**
- **A possible 1 ton ULB NaI(Tl) set-up experiment proposed by DAMA in 1996**

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo now supported at 8.9σ C.L. (cumulative exposure 1.17 ton$\times$yr – 13 annual cycles DAMA/NaI and DAMA/LIBRA)
- Updating of corollary analyses in some of the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc. is in progress.
- Upgrade in fall 2010 concluded and further improvements foreseen.
- Analyses/data taking to investigate other rare processes in progress

DAMA/LIBRA still the highest radiopure set-up in the field with the largest sensitive mass, full control of running conditions, the largest duty-cycle, exposure orders of magnitude larger than any other activity in the field, etc.