Dark Matter signal in DAMA/LIBRA

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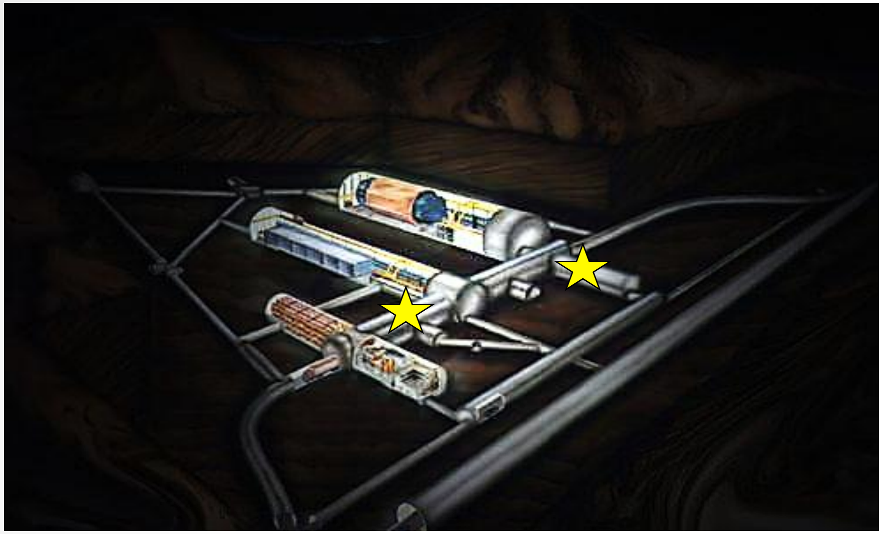
DAMA set-ups

an observatory for rare processes @ LNGS



- DAMA/LIBRA (DAMA/NaI)
- DAMA/LXe
- DAMA/R&D
- DAMA/Crys
- DAMA/Ge

Collaboration:

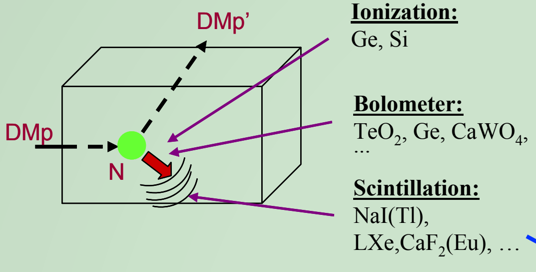
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur, India

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

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



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

  → W has 2 mass states χ+ , χ- with δ mass splitting

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

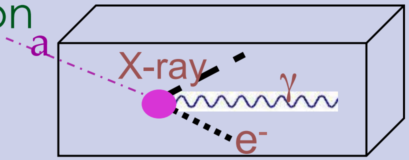
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

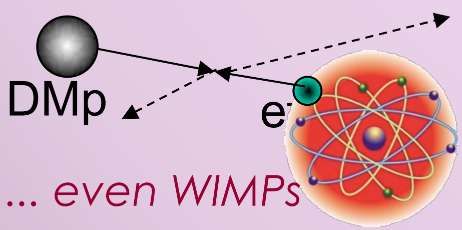
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

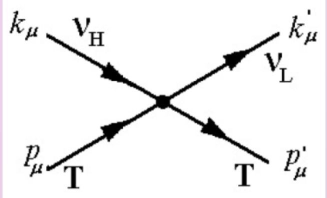


... even WIMPs

- 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 **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

... also other ideas ...

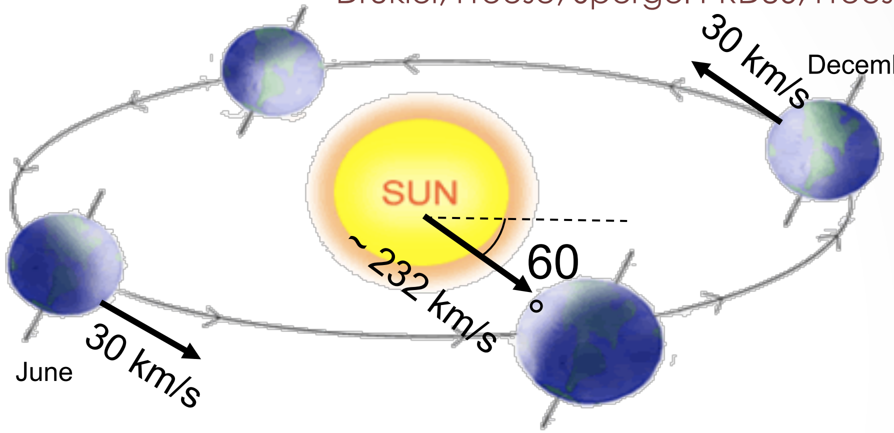
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

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

Drukier, Freese, Spergel PRD86; Freese et al. PRD88



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

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

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

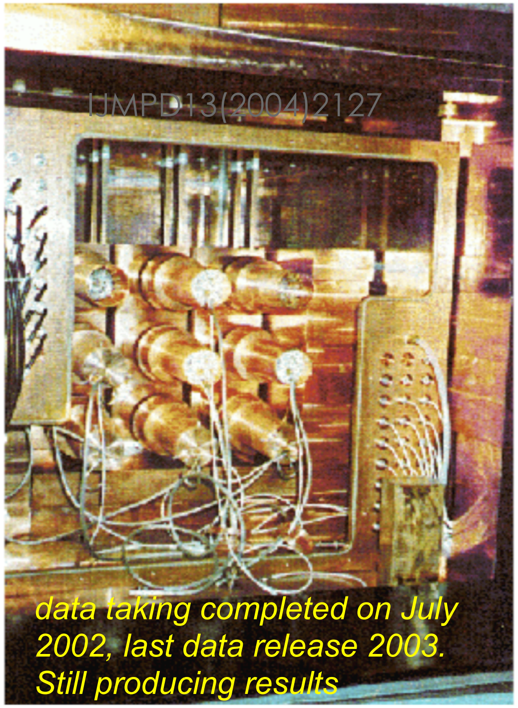
the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

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 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,



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

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- **Annual Modulation Signature** — PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

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

total exposure (7 annual cycles) 0.29 ton×yr

The DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques
(all operations involving - including photos - in HP Nitrogen atmosphere)

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

Radiopurity, performances, procedures, etc.: **NIMA592(2008)297, JINST 7 (2012) 03009**
Results on DM particles, Annual Modulation Signature: **EPJC56(2008)333, EPJC67(2010)39**
Results on rare processes: PEP violation: **EPJC62(2009)327, CNC in I: EPJC72(2012)1920**

...calibration procedures

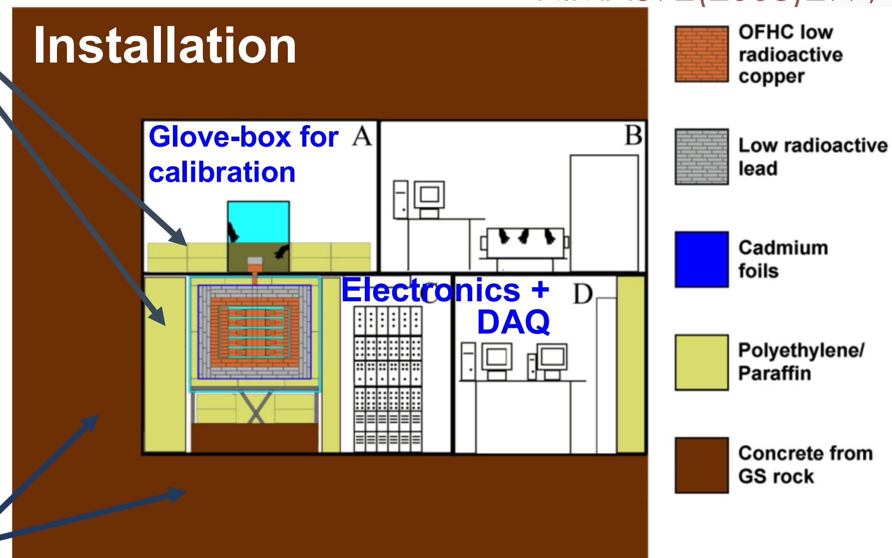
The DAMA/LIBRA set-up

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

Polyethylene/paraffin

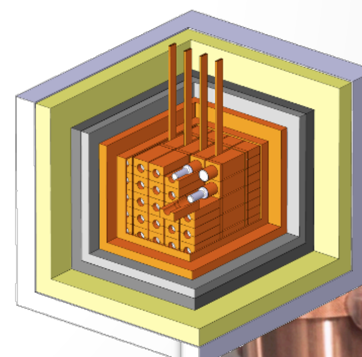
- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold

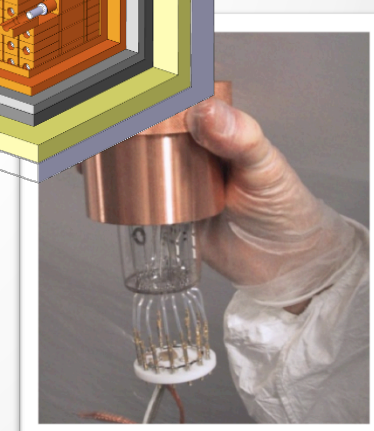
5.5-7.5 phe/keV



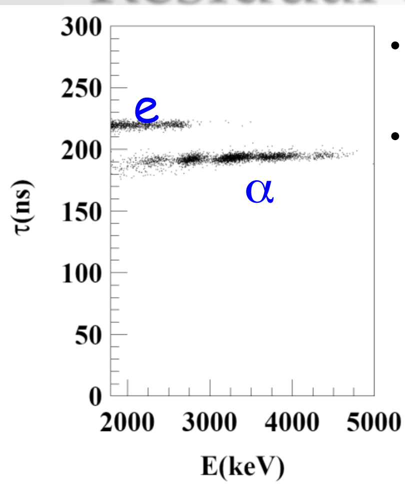
~ 1m concrete from GS rock

- 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





Residual contaminants in new ULB NaI(Tl) detectors

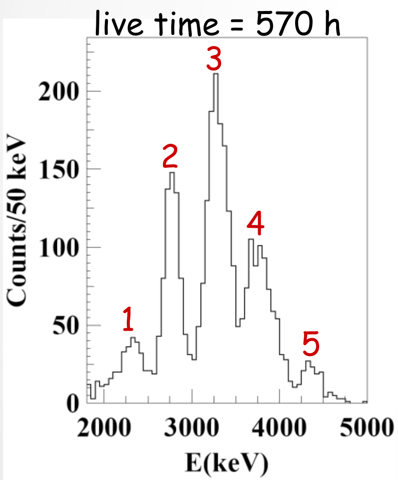


- α/e pulse shape discrimination has practically 100% effectiveness in the MeV range
- The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens a/kg/day

2nd 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: time-amplitude method. If ^{232}Th chain at equilibrium: 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 from **0.7 to 10 ppt**



^{238}U chain splitted into 5 subchains:

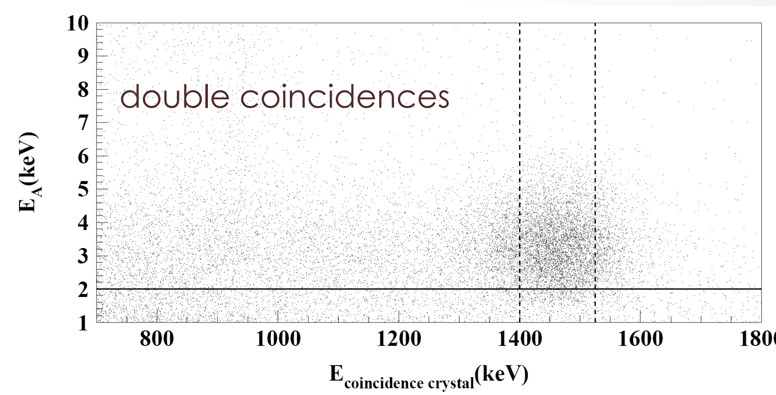
$^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

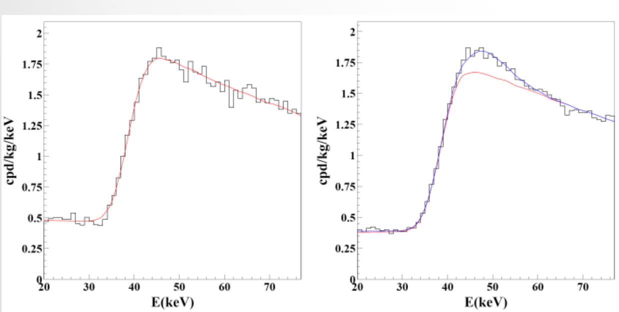
Thus, in this case: **(2.1±0.1) ppt of ^{232}Th**; **(0.35 ±0.06) ppt of ^{238}U**

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 ~20 ppb**





^{129}I and ^{210}Pb:

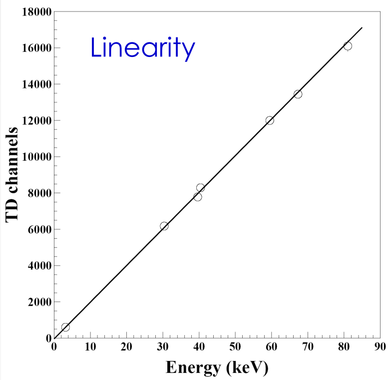
- ^{129}I/^{nat}I ≈1.7×10^{-13} for all the new detectors
- ^{210}Pb in the new detectors: (5 – 30) μBq/kg

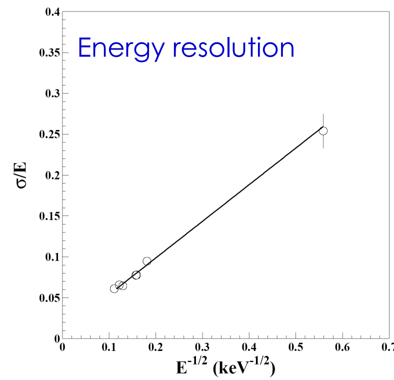
No sizable surface pollution by Radon daugthers, thanks to the new handling protocols

... more on NIMA592 (2008)297

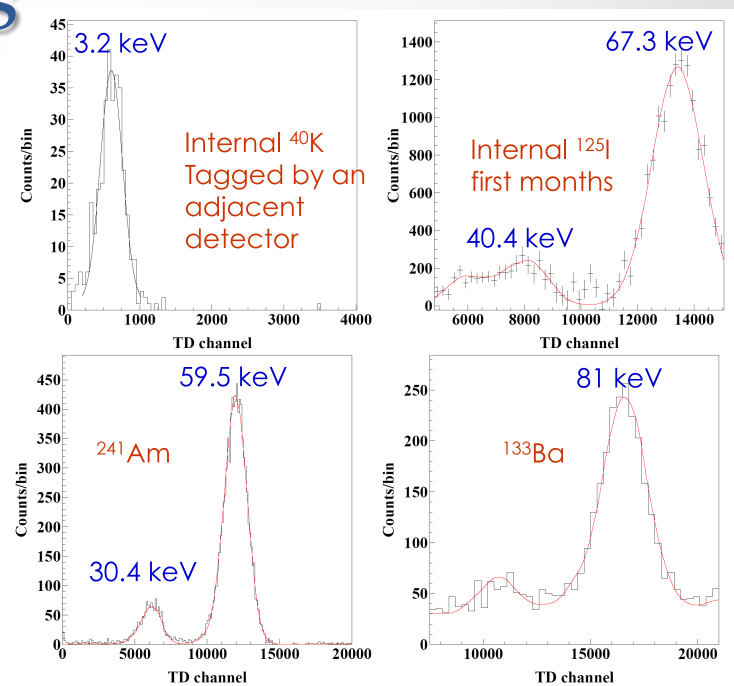
DAMA/LIBRA calibrations

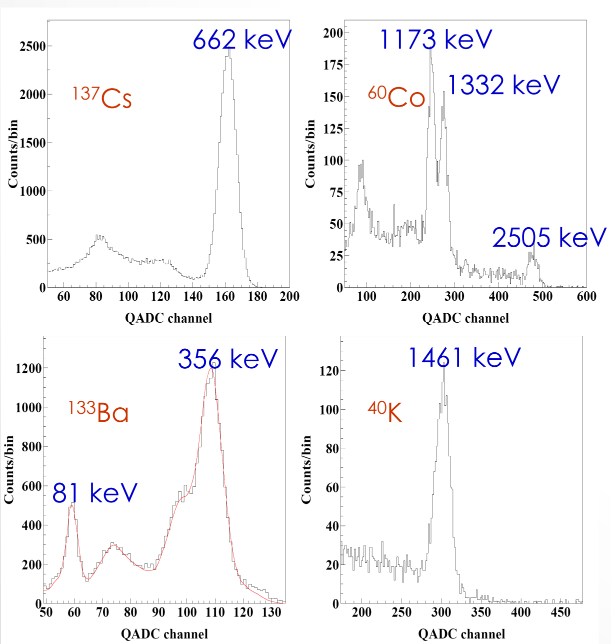
Low energy: various external gamma sources (^{241}Am, ^{133}Ba) and internal X-rays or gamma's (^{40}K, ^{125}I, ^{129}I), routine calibrations with ^{241}Am



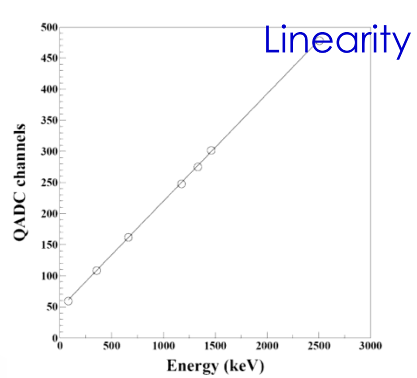


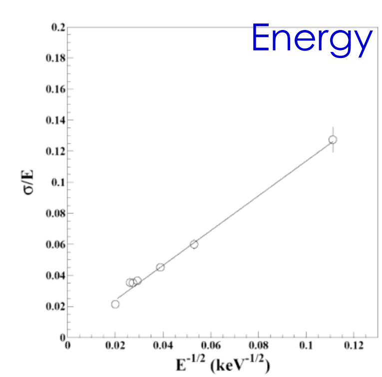
$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$





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





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

Thus, here and hereafter keV means keV electron equivalent

Infos about DAMA/LIBRA data taking

Period		Mass (kg)	Exposure (kg × day)	$\alpha-\beta^2$
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**

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

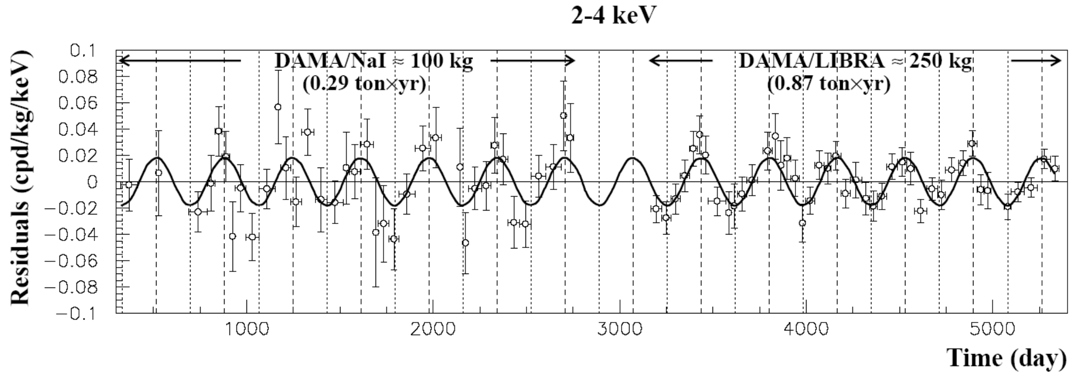
- First upgrade on Sept 2008:
  - replacement of some PMTs in HP N_2 atmosphere
  - restore 1 detector to operation
  - new Digitizers (U1063A Acqiris 1GS/s 8-bit High-Speed cPCI)
  - new DAQ system with optical read-out installed
- Second upgrade on Oct./Nov. 2010
  - replacement of all the PMTs with higher Q.E. ones

... continuously running

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



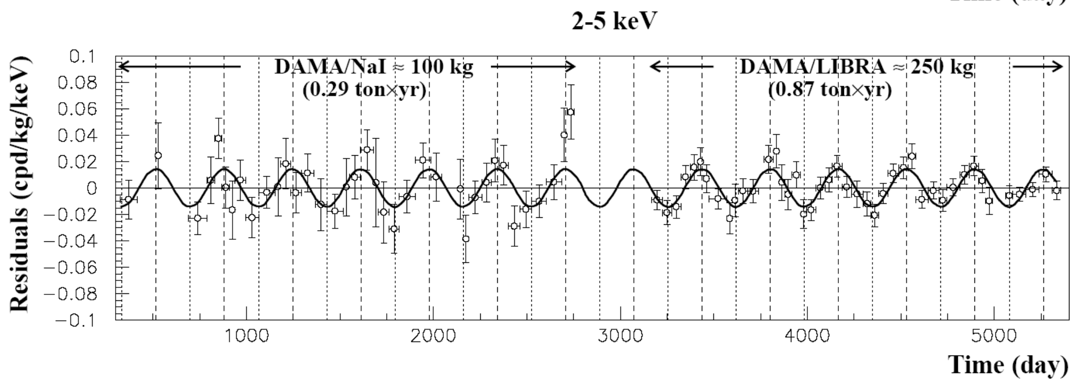
2-4 keV

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 $\Rightarrow$ P(A=0) = 7×10^{-6}



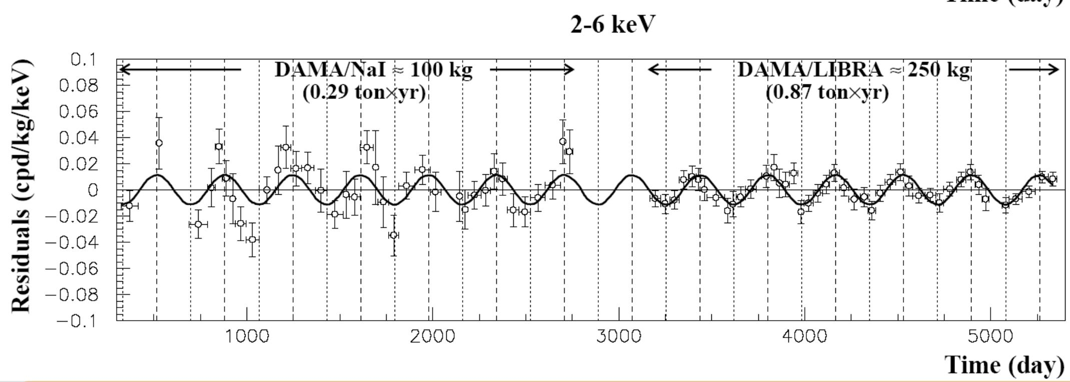
2-5 keV

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 $\Rightarrow$ 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 $\Rightarrow$ P(A=0) = 4.3×10^{-5}

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

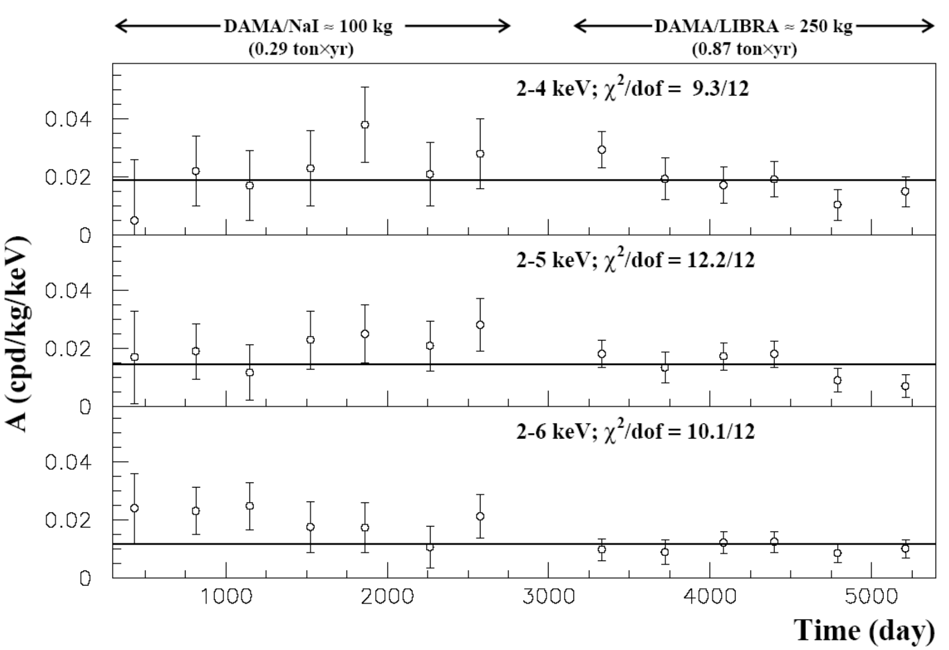
Modulation amplitudes (A), period (T) and phase (t_0) measured in DAMA/NaI and DAMA/LIBRA

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 (cpd/kg/keV)	T= 2π/ω (yr)	t_0 (day)	C.L.
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

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

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

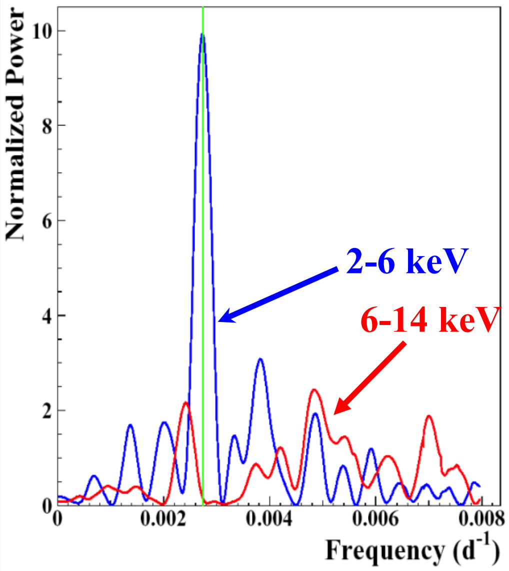
Power spectrum of single-hit residuals

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

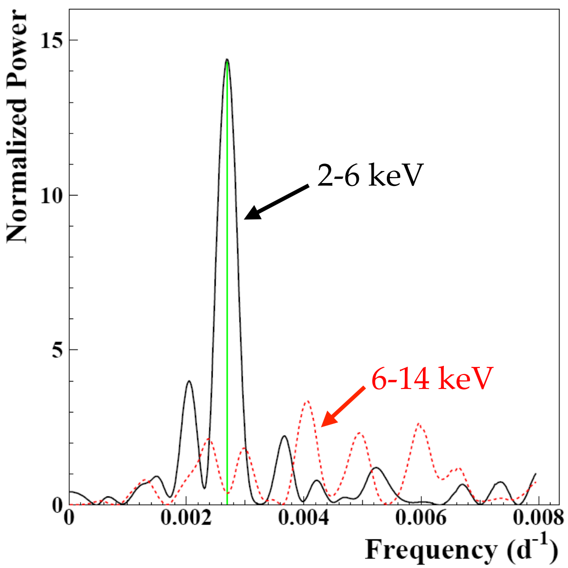
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

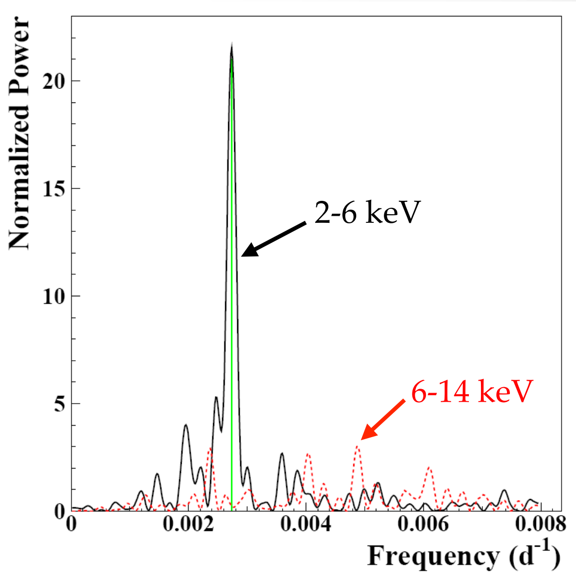
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



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}

+

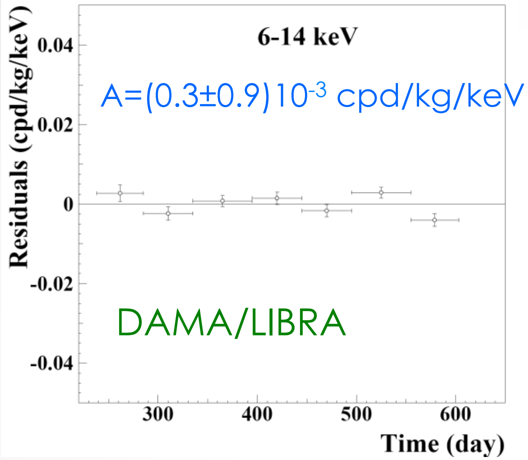
Not present in the 6-14 keV region (only aliasing peaks)

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

Rate behaviour above 6 keV

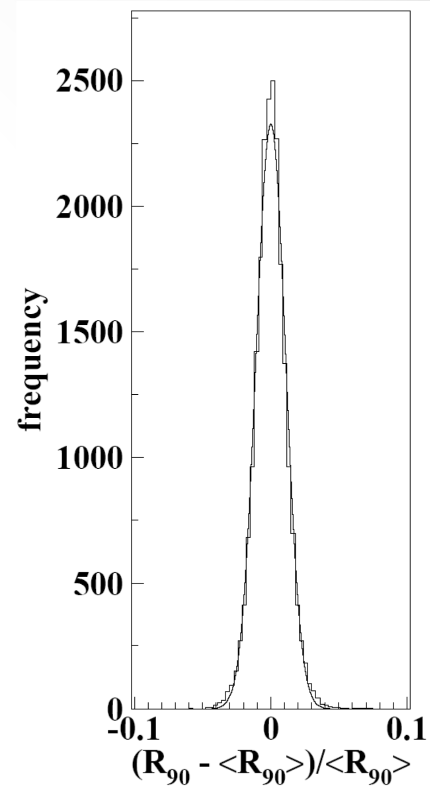
No Modulation above 6 keV

DAMALIBRA-1 to -6



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



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

No modulation in the whole energy spectrum:

Studying integral rate at higher energy, R90

- 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

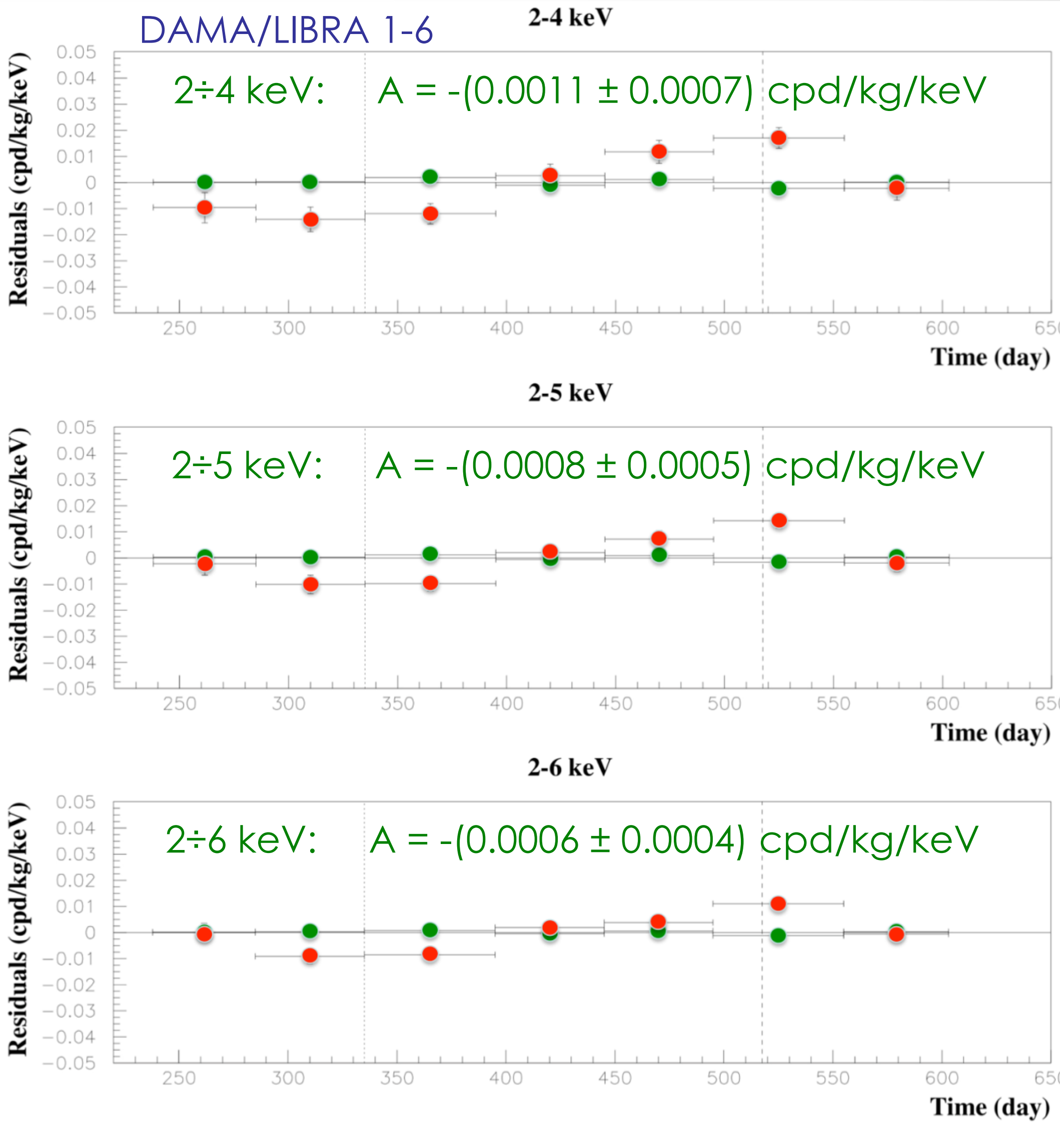
Period	Mod. Ampl.
DAMA/LIBRA-1	-(0.05±0.19) cpd/kg
DAMA/LIBRA-2	-(0.12±0.19) cpd/kg
DAMA/LIBRA-3	-(0.13±0.18) cpd/kg
DAMA/LIBRA-4	(0.15±0.17) cpd/kg
DAMA/LIBRA-5	(0.20±0.18) cpd/kg
DAMA/LIBRA-6	-(0.20±0.16) cpd/kg

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

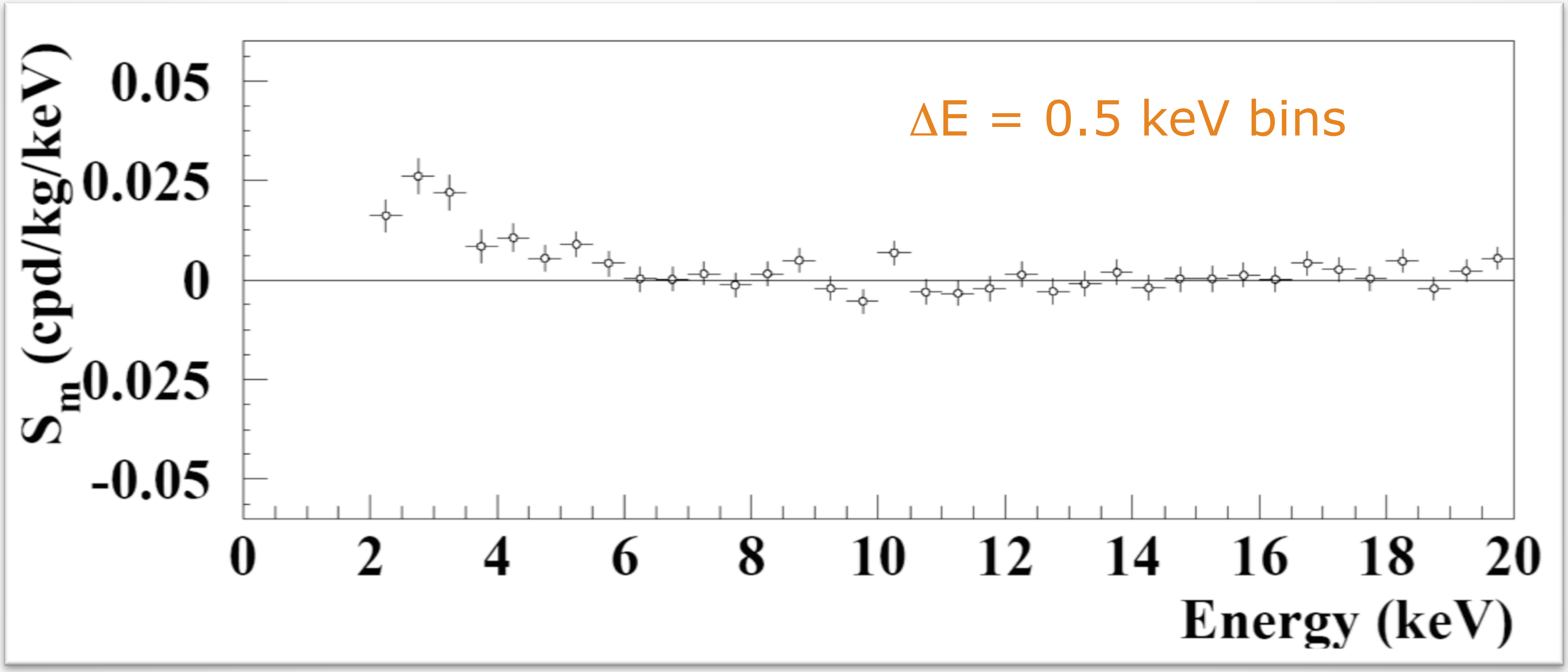
This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo, further excluding any side effect either from hardware or from software procedures or from background

Energy distribution of the modulation amplitudes

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

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

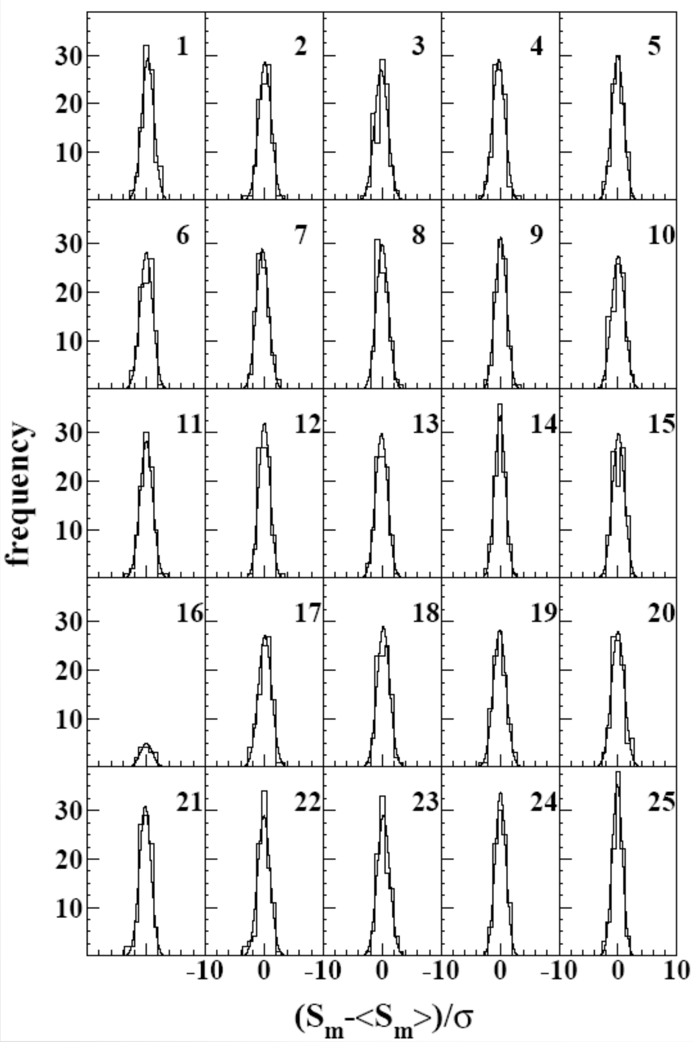
Statistical distributions of the modulation amplitudes, S_m

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

b) $\langle S_m \rangle$ = mean values over the detectors and the annual cycles for each energy bin; σ = error on S_m

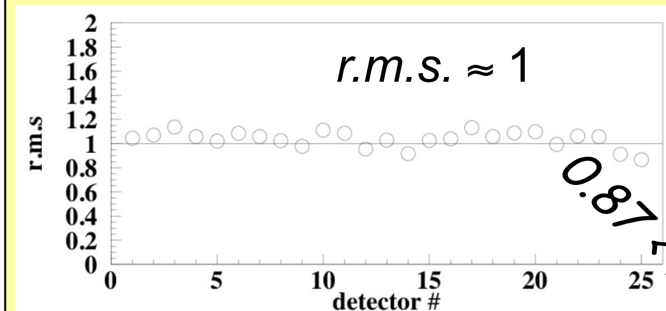
DAMA/LIBRA (6 years)
total exposure: 0.87 ton×yr

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



2-6 keV

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



0.87 < r.m.s. < 1.14

$x=(S_m - \langle S_m \rangle)/\sigma, \quad \chi^2 = \Sigma x^2$

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

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)

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

(NIMA592(2008)297, EPJC56(2008)333, arXiv:0912.0660, Can. J. Phys. 89 (2011) 11, S.I.F.Atti Conf.103 (211) (arXiv:1007.0595),to appear in Physics Procedia, EPJC72(2012)2064 and refs therein)

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 + intrinsic 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

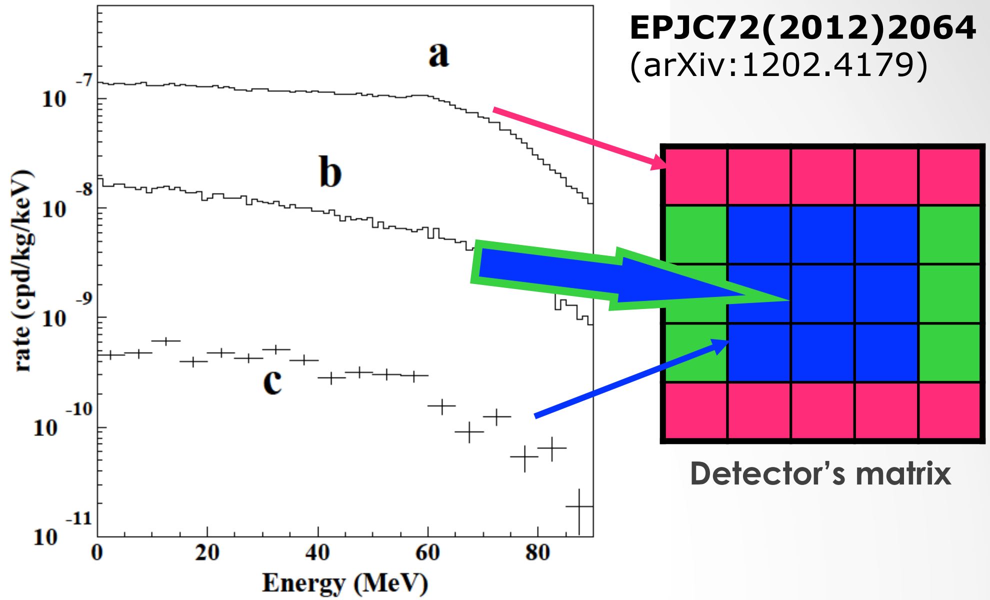
No role for μ in DAMA annual modulation result

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

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

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

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



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

$$R_n = (\text{fast n by } \mu)/(\text{time unit}) = \Phi_\mu \, Y \, M_{eff}$$

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

$$Y = 1 \div 7 \; 10^{-4} \; n/\mu/(g/cm^2)$$

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

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

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

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

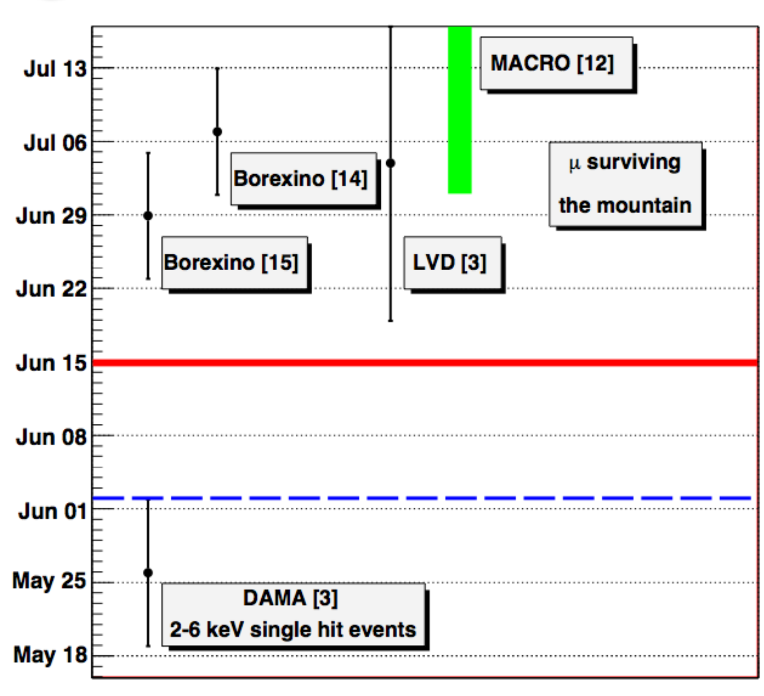
$$\boxed{S_m^{(m)} < (0.3\text{-}2.4) \times 10^{-5} \text{ cpd/kg/keV}}$$

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

Inconsistency of the phase between DAMA signal and μ modulation

For more EPJC72(2012)2064



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 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

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); other ones are open

Neutralino as LSP in various SUSY theories

a heavy n of the 4-th family

Various kinds of WIMP candidates with several different kind of interactions Pure SI, pure SD, mixed + Migdal effect +channeling,… (from low to high mass)

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

Sterile neutrino

WIMP with preferred inelastic scattering

Light Dark Matter

Self interacting Dark Matter

Mirror Dark Matter

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

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

Kaluza Klein particles

Elementary Black holes such as the Daemons

… and more

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 of possible positive hints

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

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

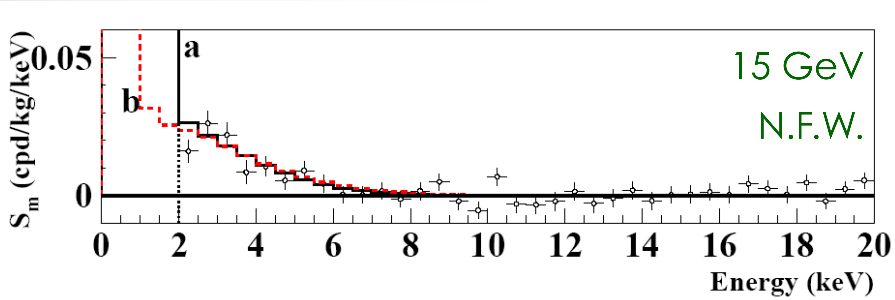
- Low mass neutralino (PRD81(2010)107302, PRD83(2011)015001, arXiv:1003.0014,arXiv:1007.1005, arXiv:1009.0549, PRD84(2011)055014, arXiv:1112.5666, PRD85(2012)095013)
- Next-to-minimal models (JCAP0908(2009)032, PRD79(2009)023510, JCAP0706(2007)008, arXiv:1009.2555,1009.0549)
- Mirror DM in various scenarios (arXiv:1001.0096, 1106.2688, PRD82(2010)095001, JCAP1107(2011)009, JCAP1009(2010)022, arXiv:1203.2387)
- Light scalar WIMP through Higgs portal (PRD82(2010)043522, JCAP0810(2010)034)
- Isospin-Violating Dark Matter (JCAP1008(2010)018, arXiv:1102.4331,1105.3734)
- Sneutrino DM (JHEP0711(2007)029, arXiv:1105.4878)
- Inelastic DM (PRD79(2009)043513, arXiv:1007.2688)
- Resonant DM (arXiv:0909.2900)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Cogent results (arXiv:1002.4703, 1106.0650)
- Composite DM (IJMPD19(2010)1385)
- iDM on Tl (arXiv:1007:2688)
- Specific two higgs doublet models (arXiv:1106.3368)
- exothermic DM (arXiv:1004.0937)
- Secluded WIMPs (PRD79(2009)115019)
- Asymmetric DM (arXiv:1105.5431)
- Leptophobic Z0 models (arXiv:1106.0885)
- SD Inelastic DM (arXiv:0912.4264)
- Complex Scalar Dark Matter (arXiv:1005.3328)
- Singlet DM (JHEP0905(2009)036, arXiv:1011.6377)
- Specific GU (arXiv:1106.3583)
- Long range forces (arXiv:1108.4661)

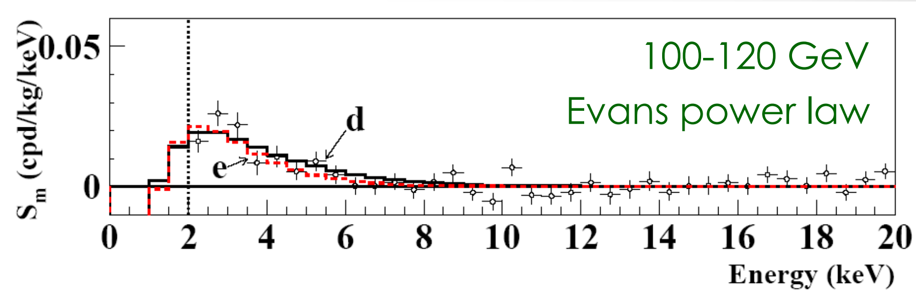
… and more (JCAP1008(2010)018, arXiv:1105.5121,1011.1499, arXiv:1108.1391, arXiv:1109.2722, arXiv:1110.5338, arXiv:1112.5457, …)

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

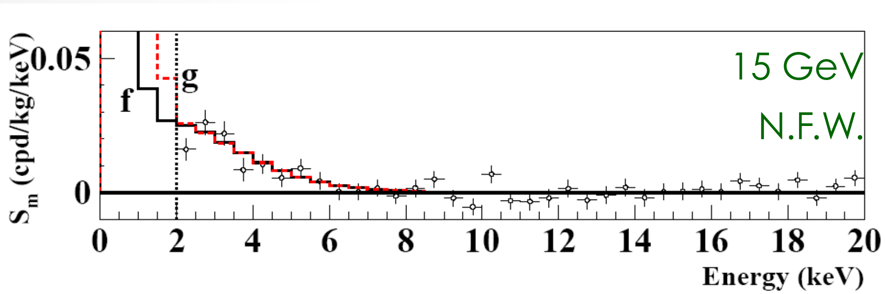
- Not best fit
- About the same C.L.

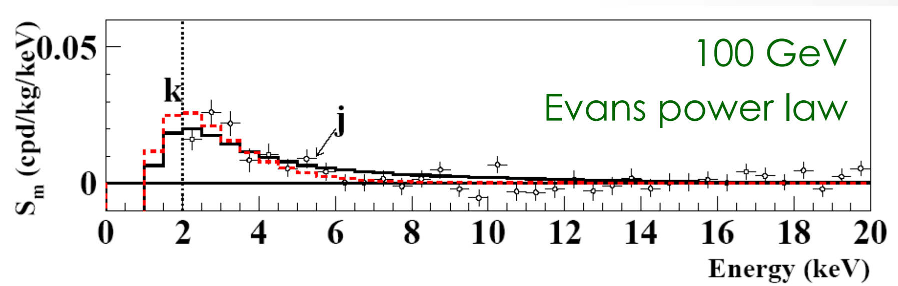
WIMP: SI



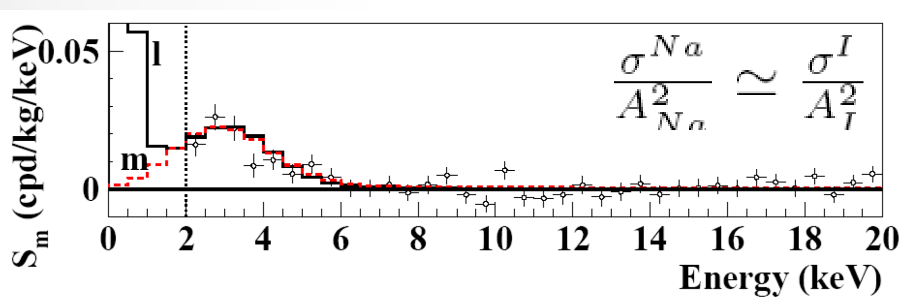


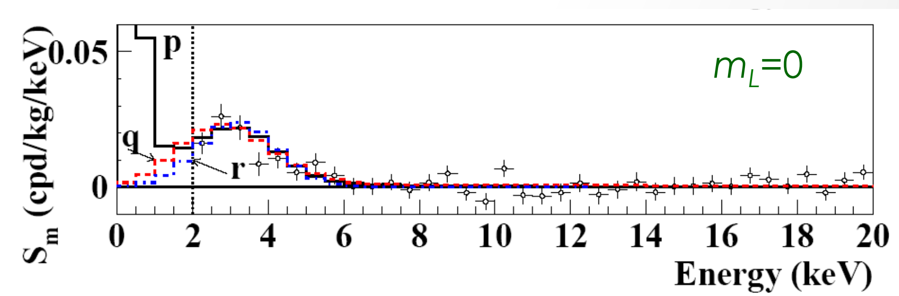
WIMP: SI & SD θ = 2.435





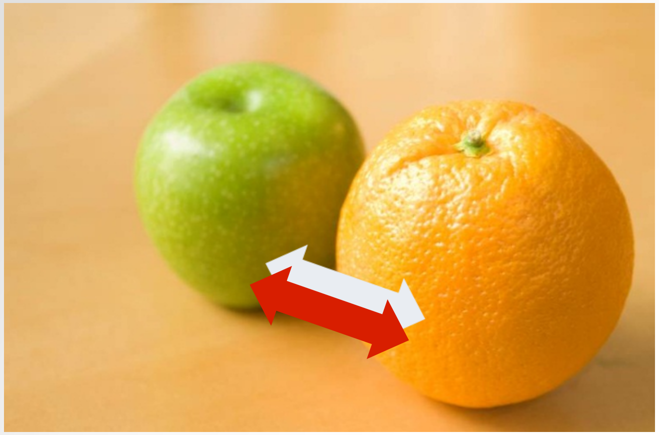
LDM, bosonic DM





Compatibility with several candidates; other ones are open

EPJC56(2008)333



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, PRD84(2011)055014

…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
- …

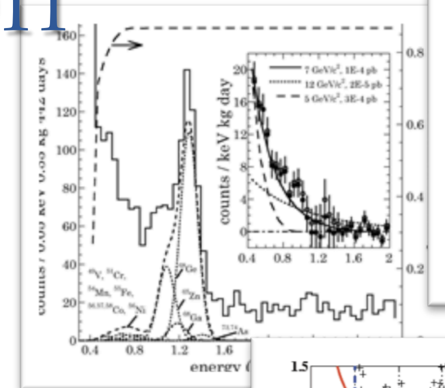
Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions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

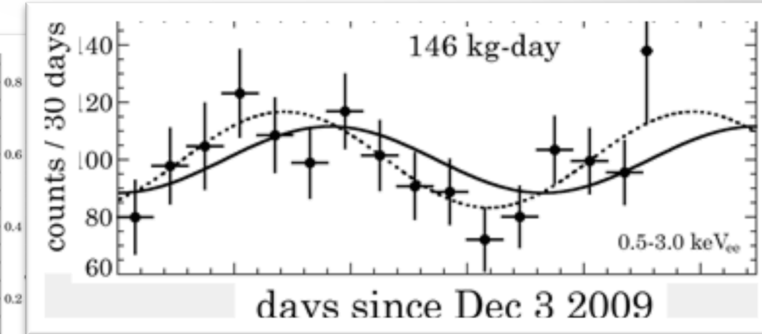
No experiment can be directly compared in model independent way with DAMA

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

CoGeNT:

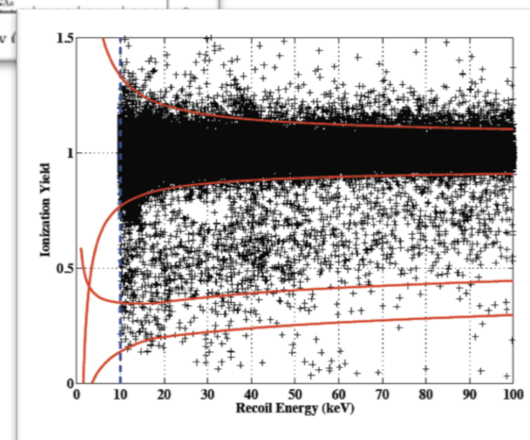
low-energy rise in the spectrum (irreducible by the applied background reduction procedures)
+ annual modulation

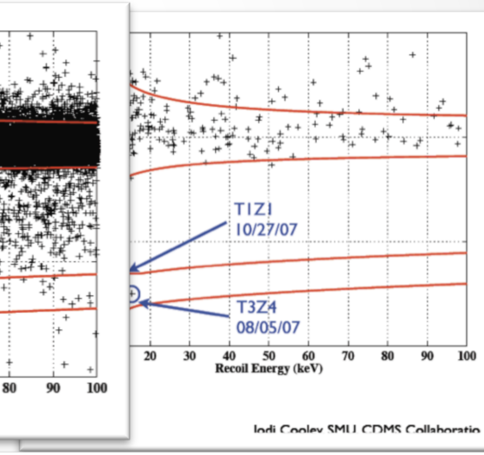




CDMS:

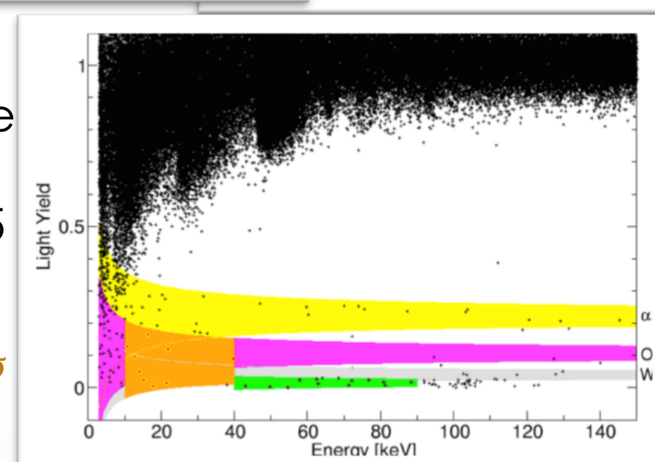
after many data selections and cuts, 2 Ge candidate recoils survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)





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 8.9σ C.L. annual modulation result in various scenarios

Interpretation of the model independent DAMA results in the case of a "WIMP" candidate with SI coupling

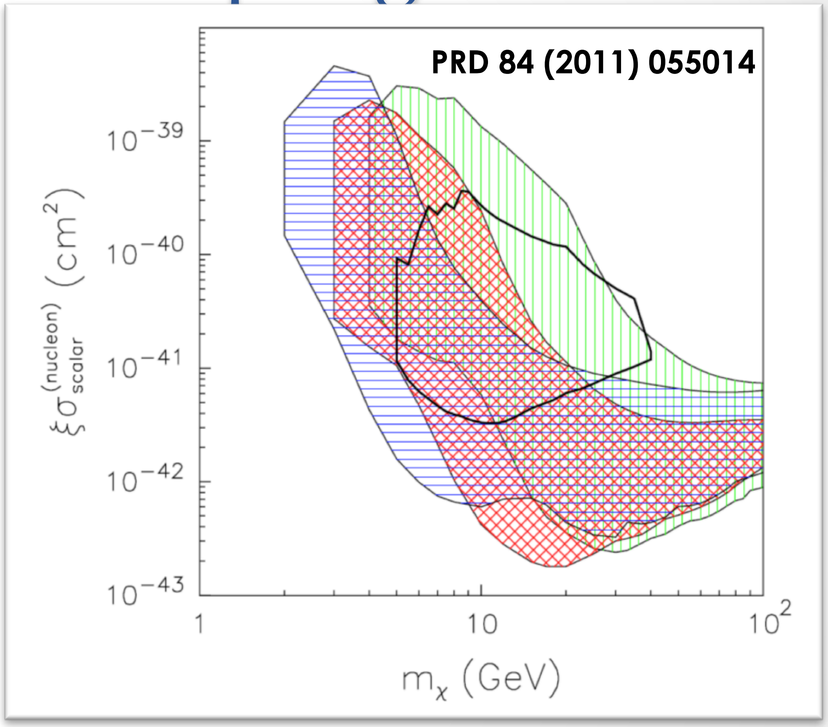
Regions allowed by DAMA experiments at 7.5σ from the null hypothesis (absence of modulation) in 3 instances for the Na and I q.f.:

1) without including the channeling effect (green vertically-hatched region)
2) by including the channeling effect (blue horizontally-hatched region)
3) without the channeling effect but using the energy-dependent Na and I q.f. as in AstrPhys33 (2010)40 (red cross-hatched region)

many of the possible astrophysical models (see PRD66 (2002)043503) + some particle and nuclear model uncertainties for a WIMP with a pure SI coupling considered

+

Allowed region obtained for the CoGeNT experiment, assuming for simplicity a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters. Region include configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation), i.e. roughly to 90% CL far from zero signal

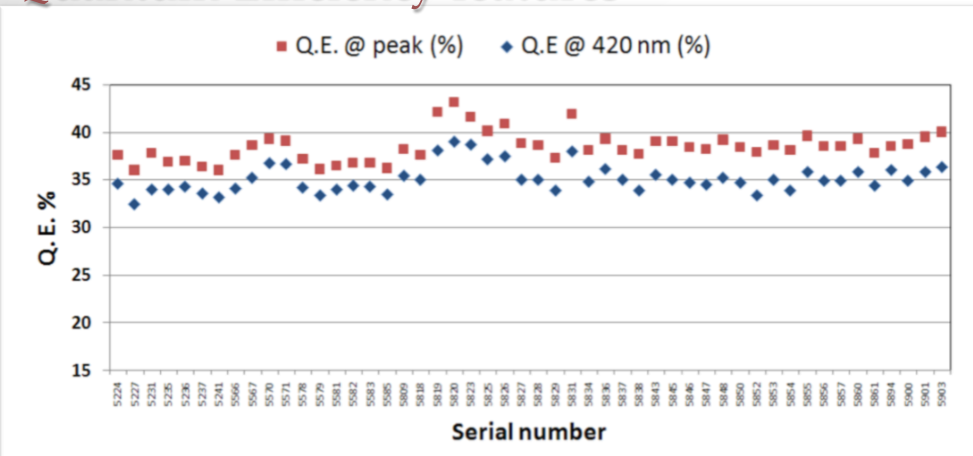


It is worth noting that, depending on other possible uncertainties not included here, the channeled (blue) horizontally-hatched region could span the domain between the present channeled region and the unchanneled one

Region allowed by CRESST (when its result is interpreted in terms of "WIMP" signal with elastic scattering on nuclei) are also compatible with the DAMA regions when uncertainties in astrophysical, particle and nuclear physics models are considered (e.g. arXiv: 1112.5666)

The new PMTs

Quantum Efficiency features

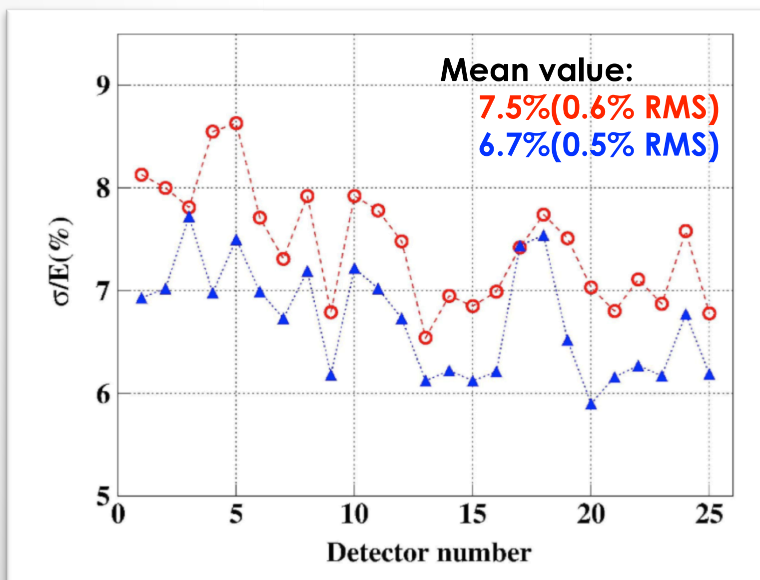


Residual Contamination

The limits are at 90% C.L.

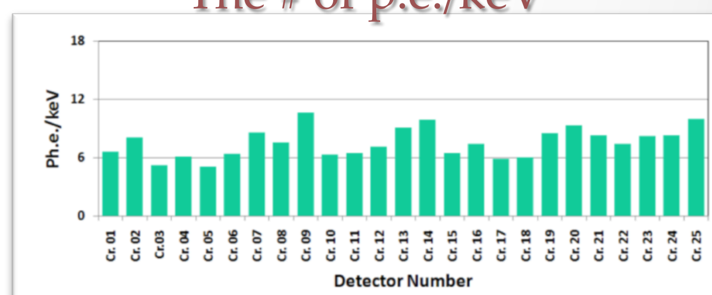
PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
Average			*0.43*	*-*	*47*	*0.12*	*83*	*0.54*	*-*	*-*
Standard deviation			*0.06*	*-*	*10*	*0,02*	*17*	*0.16*	*-*	*-*

Energy resolution



σ/E @ 59.5 keV for each detector with **new PMTs** with higher quantum efficiency (**blu points**) and with previous PMT EMI-Electron Tube (red points).

The # of p.e./keV



Previous PMTs: ph.e./keV=5.5-7.5
New PMTs: **ph.e./keV up to 10**

JINST 7(2012)03009

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo now supported at 8.9 σ C.L. (cumulative exposure 1.17 ton × yr – 13 annual cycles DAMA/NaI and DAMA/LIBRA)
- No experiment exists whose result can be directly compared in a model independent way with those by DAMA/NaI & 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. That is not restricted to DM candidate inducing only nuclear recoils

- Possible positive hints in direct searches – due to excesses above an evaluated background – are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties.
- Indirect model dependent searches not in conflict.
- Investigations other than DM

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

DAMA/LIBRA still the highest radio-pure 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., and the only one which effectively exploits a model independent DM signature