Particle Dark Matter signal in DAMA/LIBRA

R. Cerulli
INFN-LNGS

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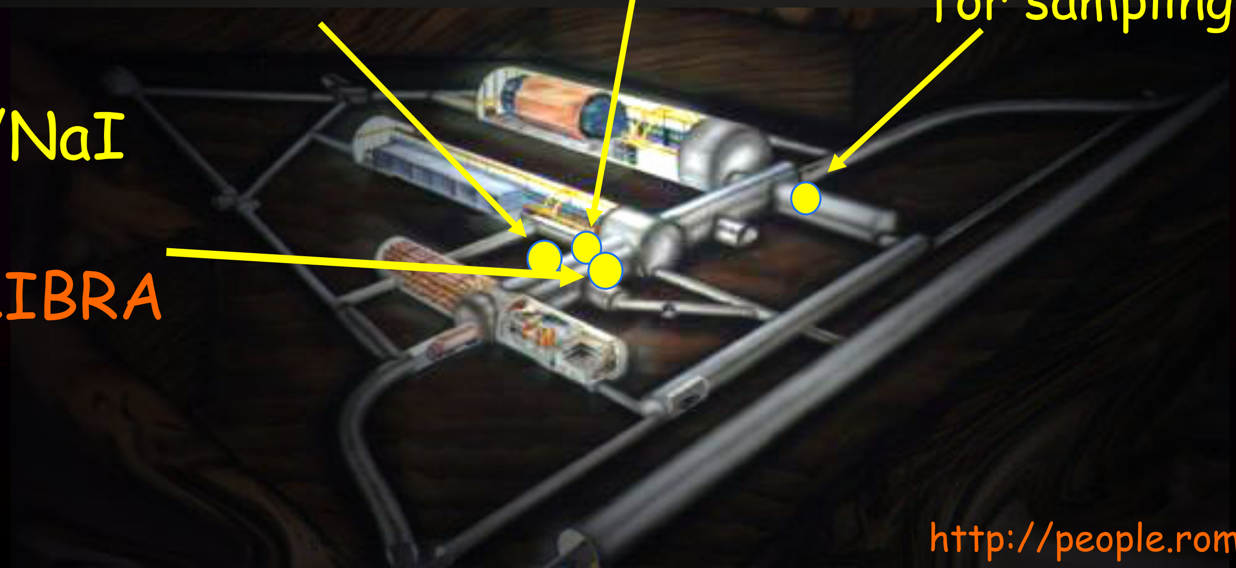
Roma2,Roma1,LNGS,IHEP/Beijing

+ 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

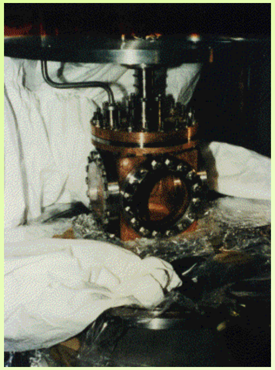


http://people.roma2.infn.it/dama

DAMA/LXe: results on rare processes

Dark Matter Investigation

- Limits on recoils investigating the DMp-^{129}Xe elastic scattering by means of PSD — NIMA482(2002)728; PLB436(1998)379
- Limits on DMp-^{129}Xe inelastic scattering — PLB387(1996)222, NJP2(2000)15.1
- Neutron calibration — PLB436(1998)379, EPJdirectC11(2001)1
- ^{129}Xe *vs* ^{136}Xe by using PSD → SD *vs* SI signals to increase the sensitivity on the SD component — foreseen/in progress



Other rare processes:

- Electron decay into invisible channels — Astrop.P.5(1996)217
- Nuclear level excitation of ^{129}Xe during CNC processes — PLB465(1999)315
- N, NN decay into invisible channels in ^{129}Xe — PLB493(2000)12
- Electron decay: $e^- \rightarrow \nu_e \gamma$ — PRD61(2000)117301
- 2β decay in ^{136}Xe — Xenon01
- 2β decay in ^{134}Xe — PLB527(2002)182
- Improved results on 2β in ^{134}Xe,^{136}Xe — PLB546(2002)23
- CNC decay ^{136}Xe → ^{136}Cs — Beyond the Desert (2003) 365
- N, NN, NNN decay into invisible channels in ^{136}Xe — 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 — Il N. Cim.A110(1997)189
- 2EC2ν ^{40}Ca decay — Astrop. Phys. 7(1997)73
- 2β decay in ^{46}Ca and in ^{40}Ca — NPB563(1999)97
- $2\beta^+$ decay in ^{106}Cd — Astrop.Phys.10(1999)115
- 2β and β decay in ^{48}Ca — NPA705(2002)29
- 2EC2ν in ^{136}Ce, in ^{138}Ce and α decay in ^{142}Ce — NIMA498(2003)352
- $2\beta^+$ 0ν, EC β^+ 0ν decay in ^{130}Ba — NIMA525(2004)535
- Cluster decay in $LaCl_3$(Ce) — NIMA555(2005)270
- CNC decay ^{139}La → ^{139}Ce — UJP51(2006)1037
- α decay of natural Eu — NPA789(2007)15
- β decay of ^{113}Cd — PRC76(2007)064603
- $\beta\beta$ decay of ^{64}Zn, ^{70}Zn, ^{180}W, ^{186}W — PLB658(2008)193, NPA826(2009)256
- $\beta\beta$ decay of ^{108}Cd and ^{114}Cd — EPJA36(2008)167
- $\beta\beta$ decay of ^{136}Ce, ^{138}Ce and ^{142}Ce with $CeCl_3$ — JPG: NPP38(2011)015103
- ^{106}Cd, and ^{116}Cd in progress

DAMA/Ge & LNGS Ge facility

- RDs on highly radiopure NaI(Tl) set-up
- several RDs on low background PMTs
- qualification of many materials
- meas. on $Li_6Eu(BO_3)_3$ (NIMA572(2007)734)
- $\beta\beta$ decay in ^{100}Mo with the 4π low-bckg HPGe facility of LNGS (NPA846(2010)143)
- search for ^{7}Li solar axions (NPA806(2008)388)
- $\beta\beta$ decay of ^{96}Ru and ^{104}Ru (EPJA42(2009)171)
- meas. with a Li_2MoO_4 (NIMA607(2009) 573)
- $\beta\beta$ decay of ^{136}Ce and ^{138}Ce (NPA824(2009)101)
- First observation of α decay of ^{190}Pt to the first excited level (137.2 keV) of ^{186}Os (PRC83(2011) 034603)
- $\beta\beta$ decay of ^{156}Dy, ^{158}Dy (NPA859(2011)126)

+Many other meas. already scheduled

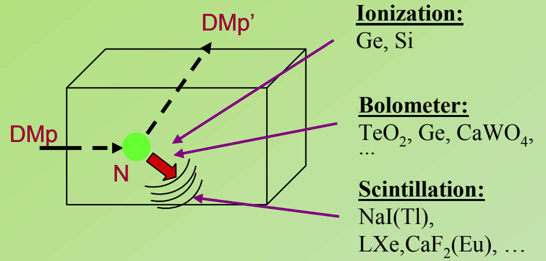
+ $CdWO_4$ and $ZnWO_4$ readiopurity studies

(NIMA626-627(2011)31, NIMA615(2010)301)

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

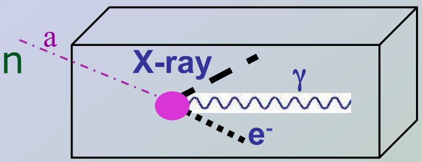
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

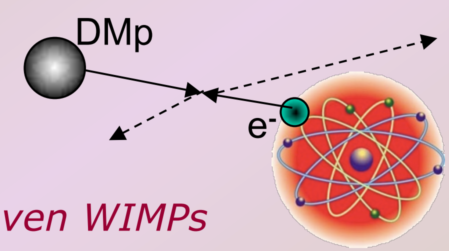
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

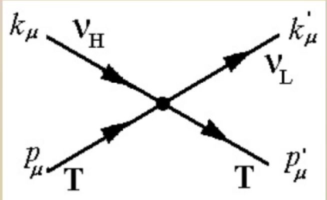
  → detection of e.m. radiation



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

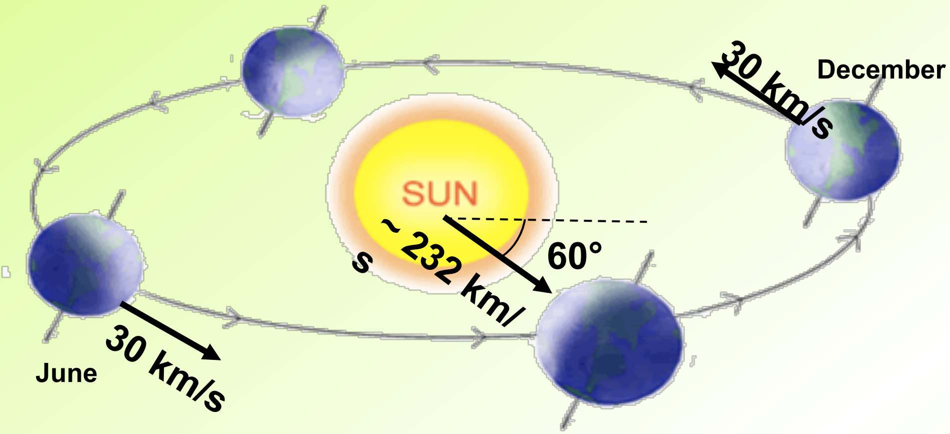
… also other ideas …

- **… and more**

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

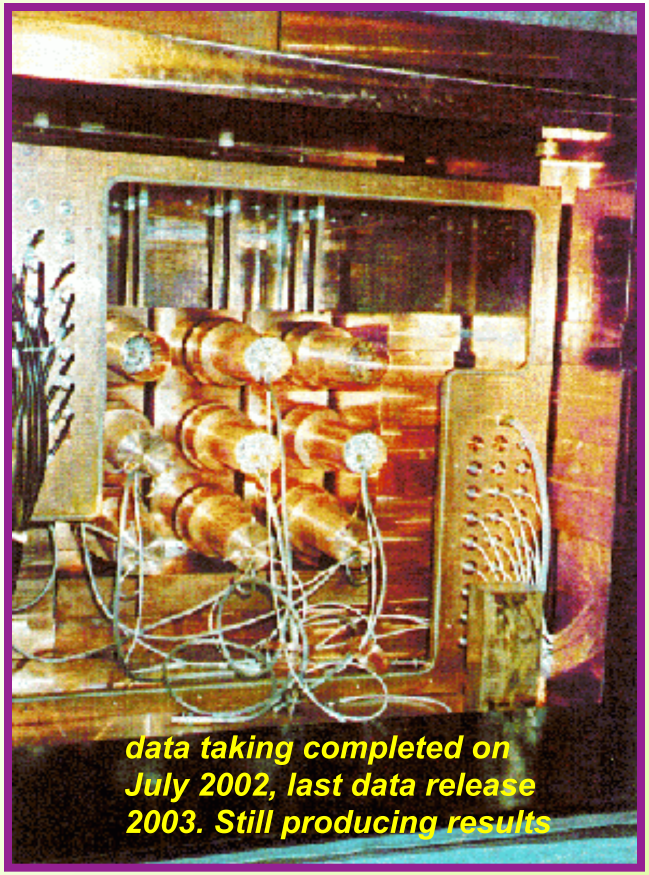
1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, 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/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

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

filling the inner Cu box with further shield

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

- ***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

...calibration procedures

The first upgrade in fall 2008

Phase 1

- Mounting of the "clean room" set-up in order to operate in HP N_2 atmosphere
- Opening of the shield of DAMA/LIBRA set-up in HP N_2 atmosphere
- Replacement of some PMTs in HP N_2 atmosphere
- Closing of the shield

Phase 2

- Dismounting of the Tektronix TDs (Digitizers + Crates)
- Mounting of the new Acqiris TD (Digitizers + Crate)
- Mounting of the new DAQ system with optical read-out
- Test of the new TDs (*hardware*) and of the new required DAQ system *(software*)

Since Oct. 2008 again in data taking

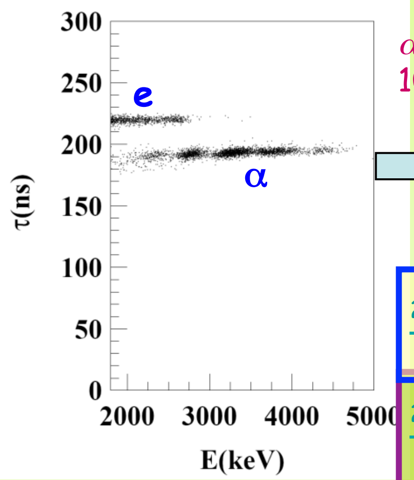
DAMA/LIBRA upgrade (2010)

- ✓ Short interruption to allow the second upgrade
- ✓ Test phase completed
- ✓ Now in data taking

- Replacement of all the PMTs with higher Q.E. ones
- Goal: lowering the energy thresholds of the experiment

- New PMTs with higher Q.E.:

Some on residual contaminants in new ULB NaI(Tl) detectors



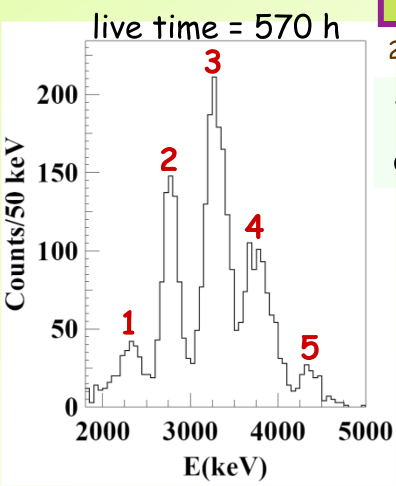
α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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

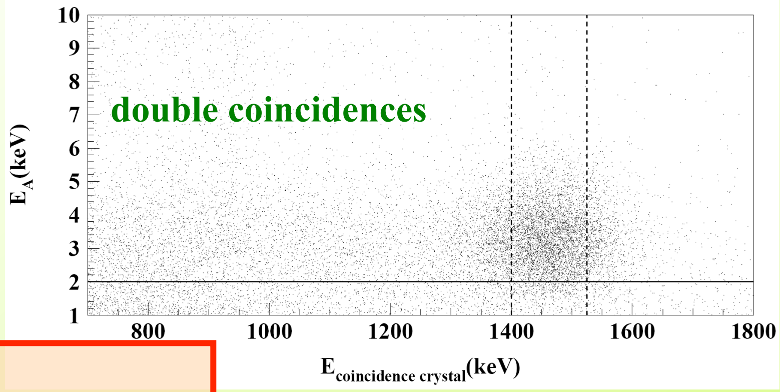


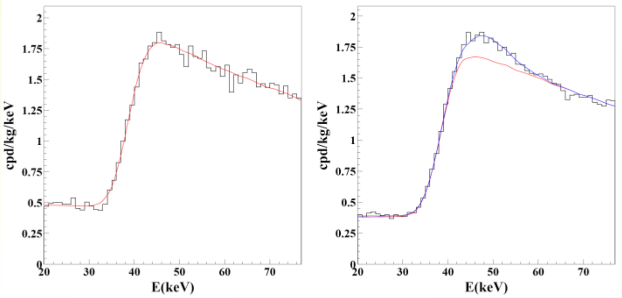
^{238}U chain splitted into 5 subchains: ^{238}U $\rightarrow$ ^{234}U $\rightarrow$ ^{230}Th $\rightarrow$ ^{226}Ra $\rightarrow$ ^{210}Pb $\rightarrow$ ^{206}Pb

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 ≈1.7×10^{-13} for all the new detectors

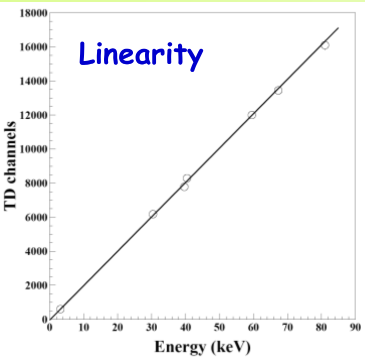
^{210}Pb in the new detectors: (5 − 30) μBq/kg.

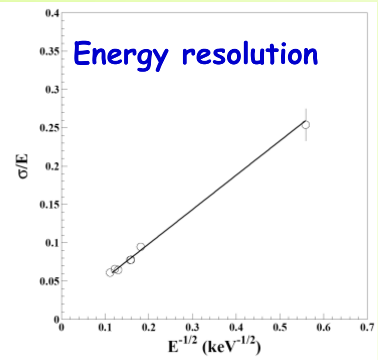
No sizable surface pollution by Radon daugthers, thanks to the new handling protocols

... more on NIMA592 (2008)297

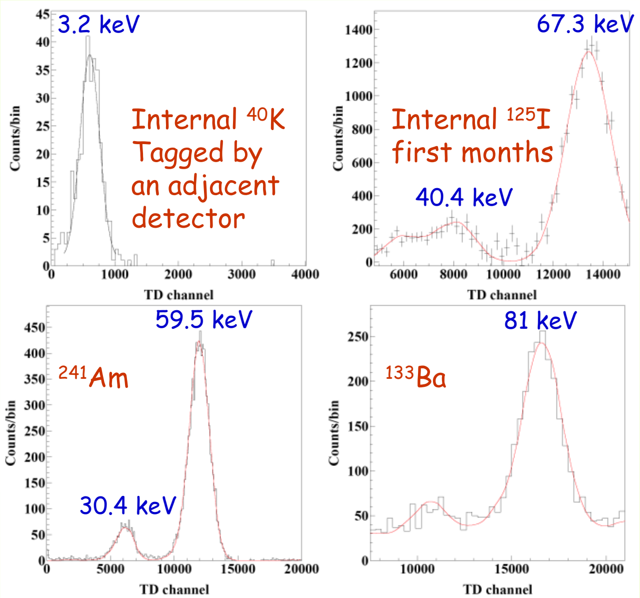
DAMA/LIBRA calibrations

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



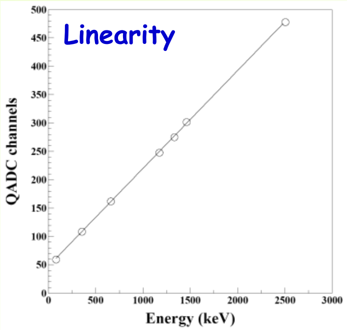


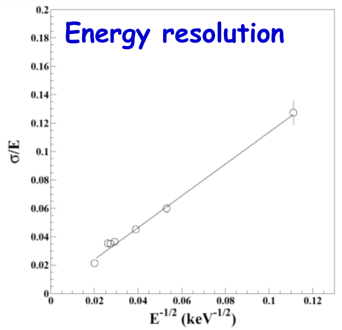
$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$



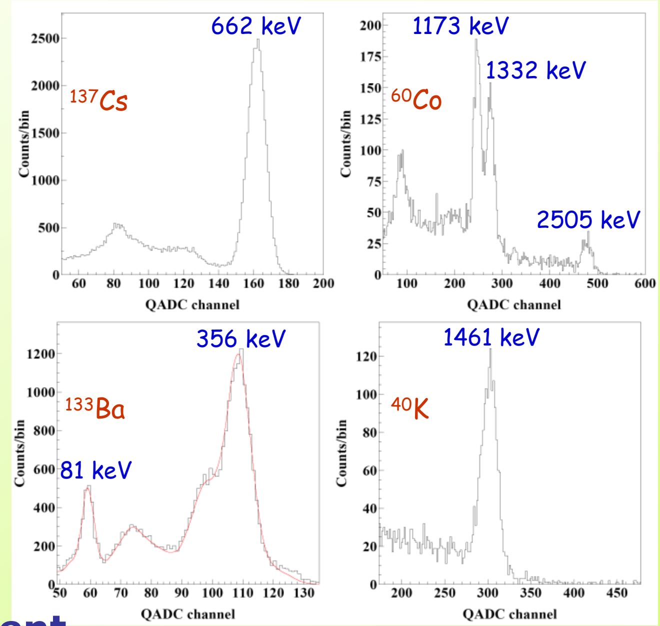
The curves superimposed to the experimental data have been obtained by simulations

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

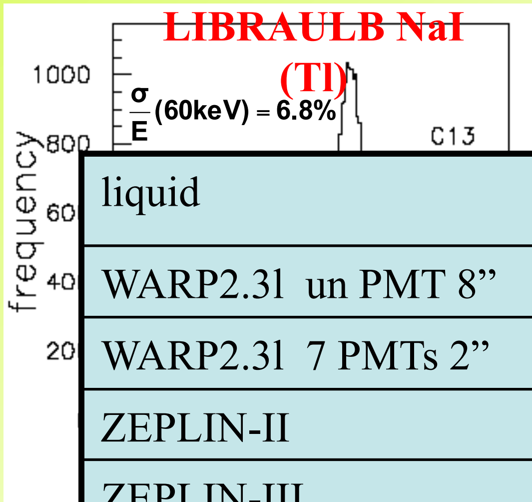


$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23) \cdot 10^{-4}$$

Thus, here and hereafter keV means keV electron equivalent

Examples of energy resolutions

DAMA/ LIBRAULB NaI (Tl)



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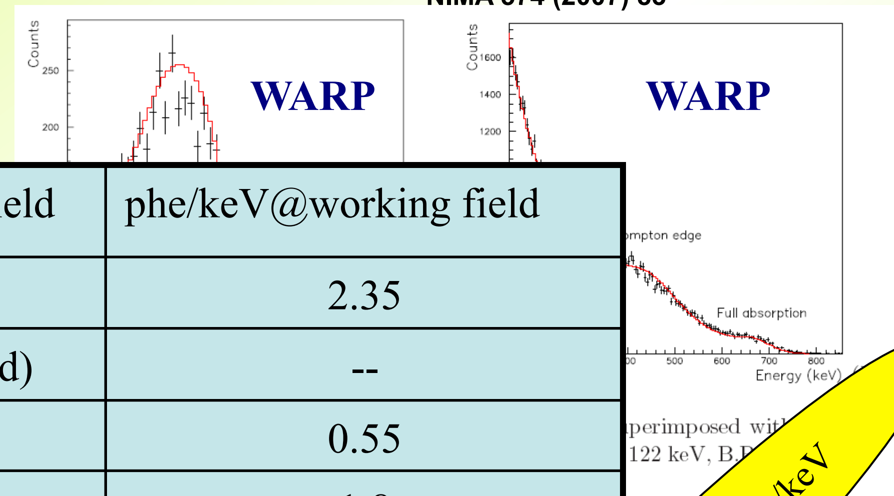

liquid	phe/keV@zero field	phe/keV@working field
WARP2.3l un PMT 8”	--	2.35
WARP2.3l 7 PMTs 2”	0.5-1 (deduced)	--
ZEPLIN-II	1.1	0.55
ZEPLIN-III		1.8
XENON10	--	2.2 (^{137}Cs), 3.1 (^{57}Co)
XENON100	2.7	1.57 (^{137}Cs), 2.2 (^{57}Co
Neon	0.93	field not forese

DAMA/LIBRA : 5.5 – 7.5 phe/keV

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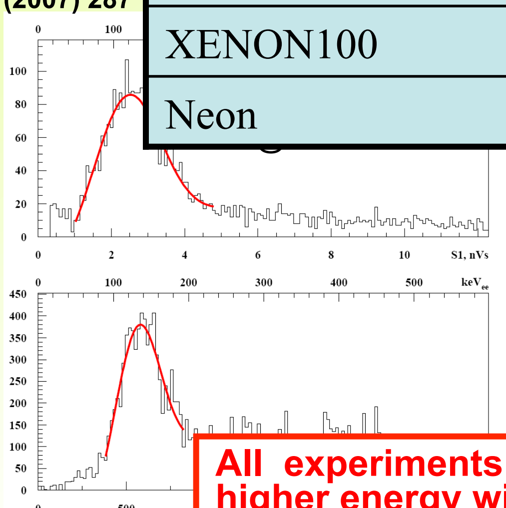
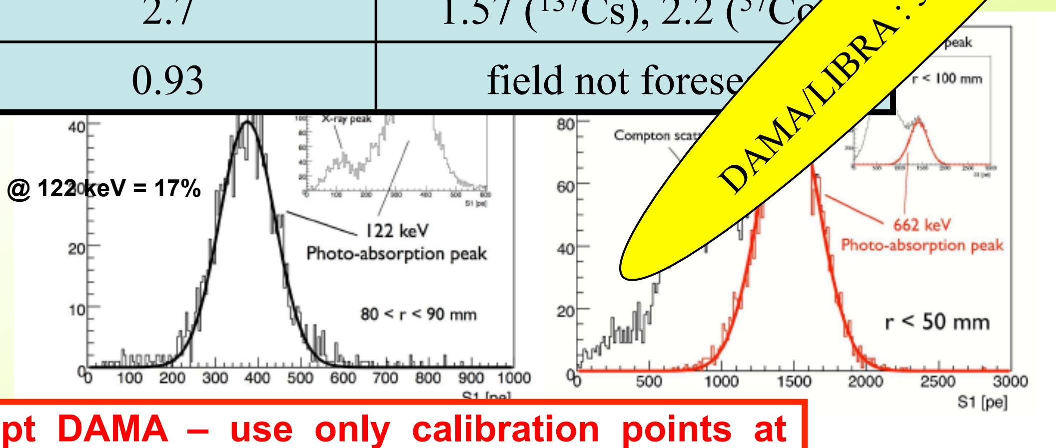


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.

σ/E @ 122 keV = 17%



All experiments – except DAMA – use only calibration points at higher energy with extrapolation to low energy

ght yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

JoP: Conf. Ser. 65 (2007) 012015

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**
- **EPJC67(2010)39**

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

... continuously running

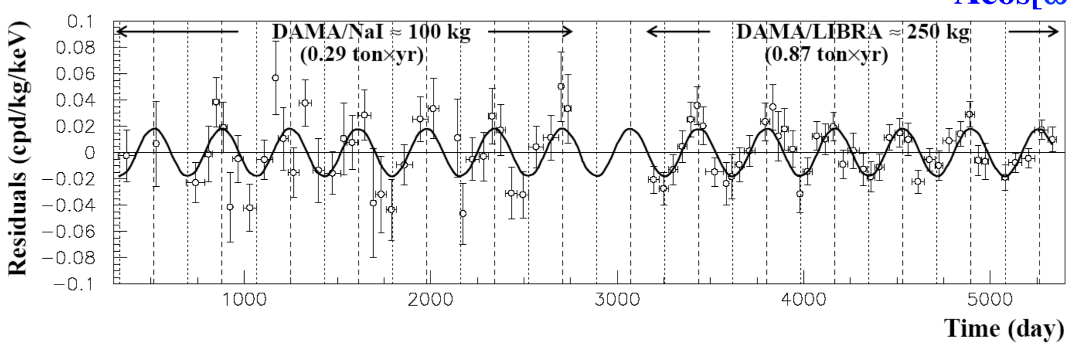
Model Independent Annual Modulation Result

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

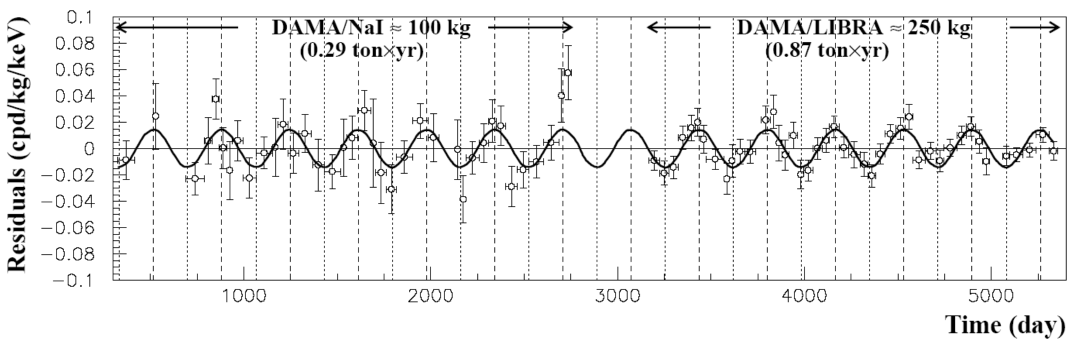
experimental single-hit residuals rate vs time and energy

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

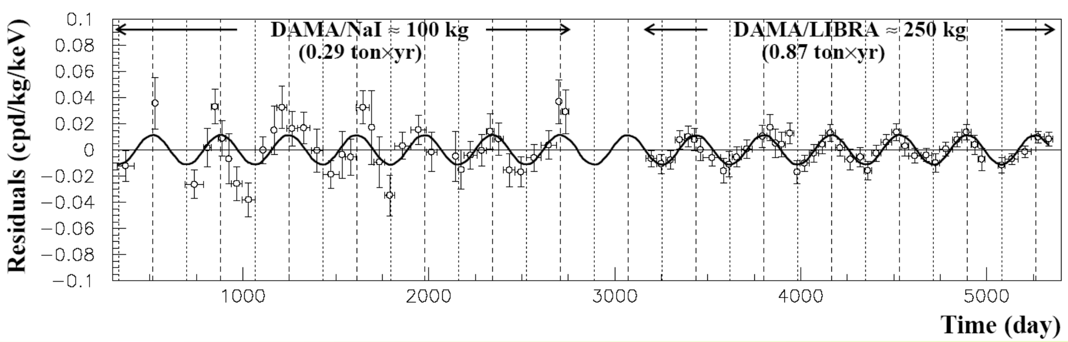
2-4 keV



2-5 keV



2-6 keV



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.

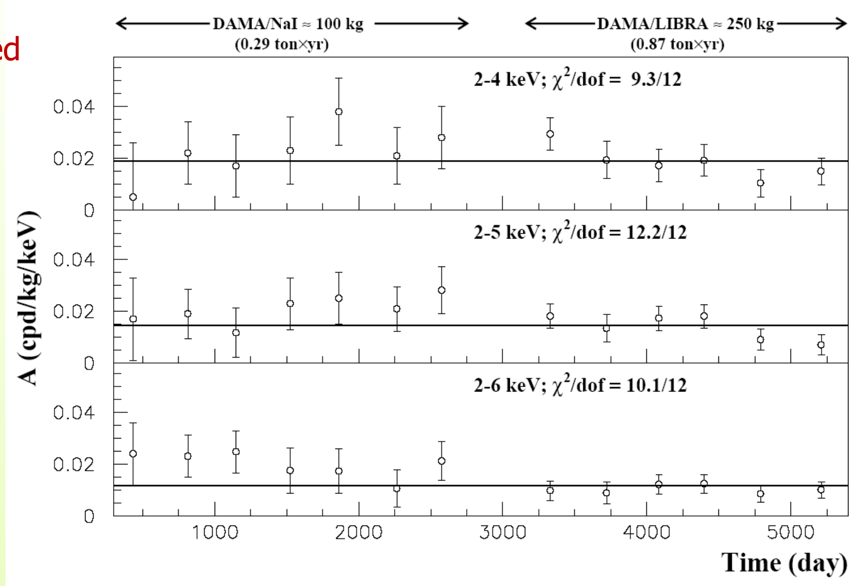
Modulation amplitudes in 13 one-year experiments (DAMA/NaI and DAMA/LIBRA)

	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

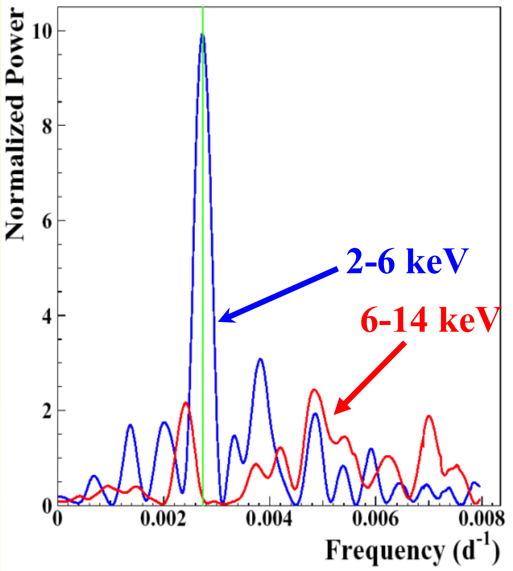
Power spectrum of single-hit residuals

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

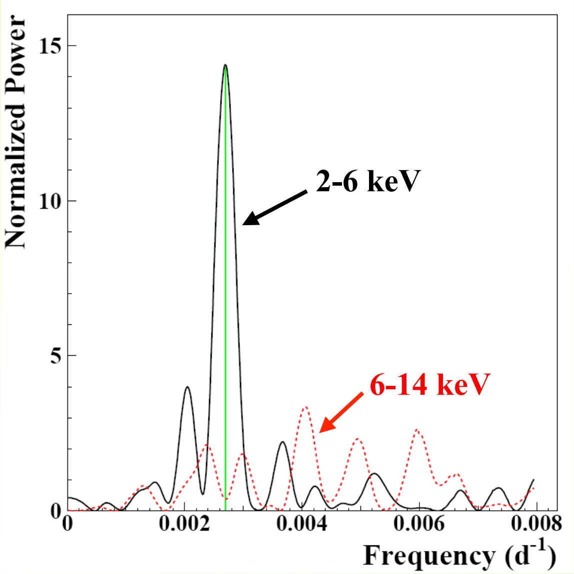
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

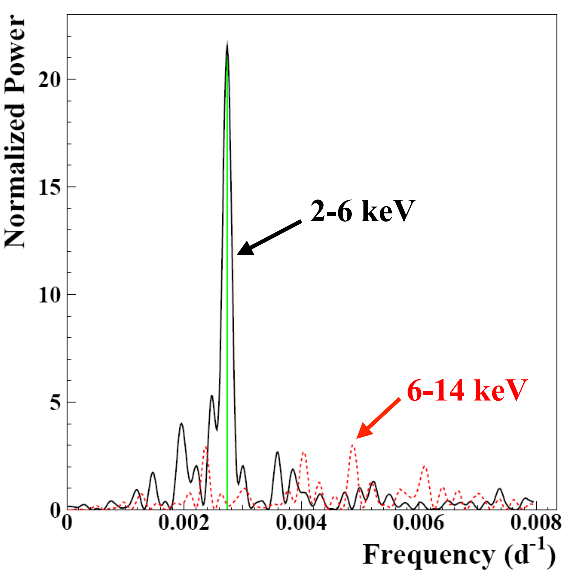
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



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
$2.737 \cdot 10^{-3}$ $d^{-1} \approx 1$ y^{-1}	2.697×10^{-3} $d^{-1} \approx 1$ yr^{-1}	2.735×10^{-3} $d^{-1} \approx 1$ yr^{-1}

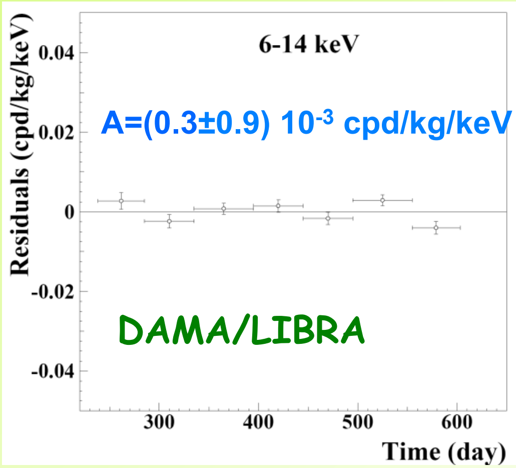
+

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

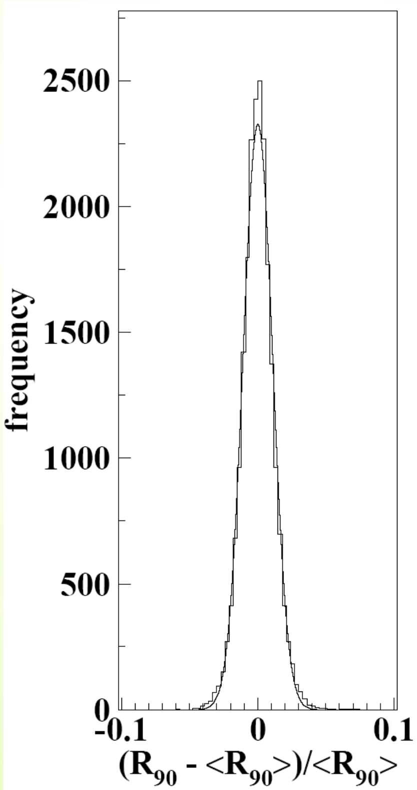
Rate behaviour above 6 keV

- **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 1-6



$\sigma \approx 1\%$, 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).

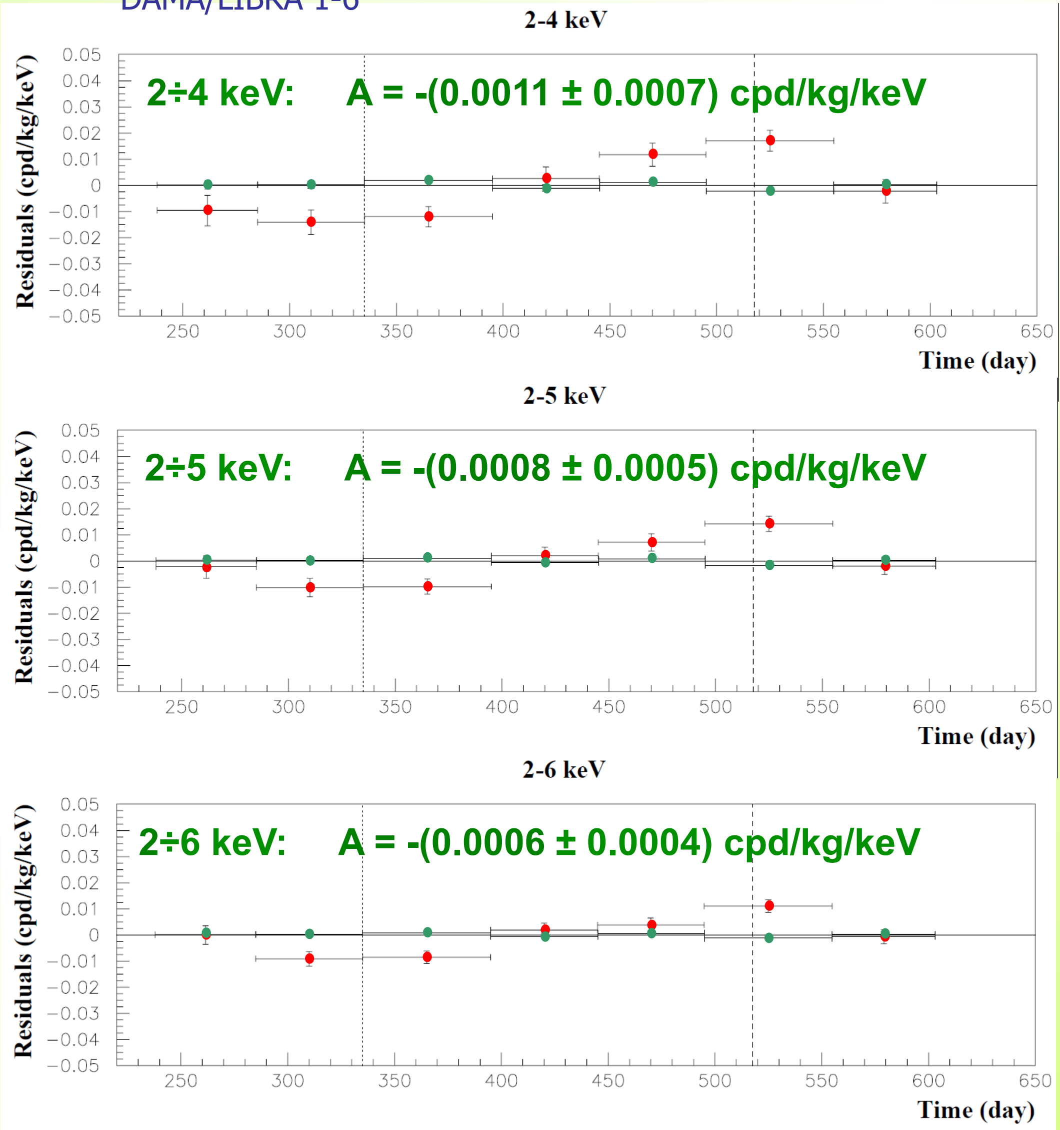
- The same hardware and software procedures as the ones followed for single-hit events

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
- present in the ***single-hit*** residuals
- absent in the ***multiple-hits*** residual

DAMA/LIBRA 1-6



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

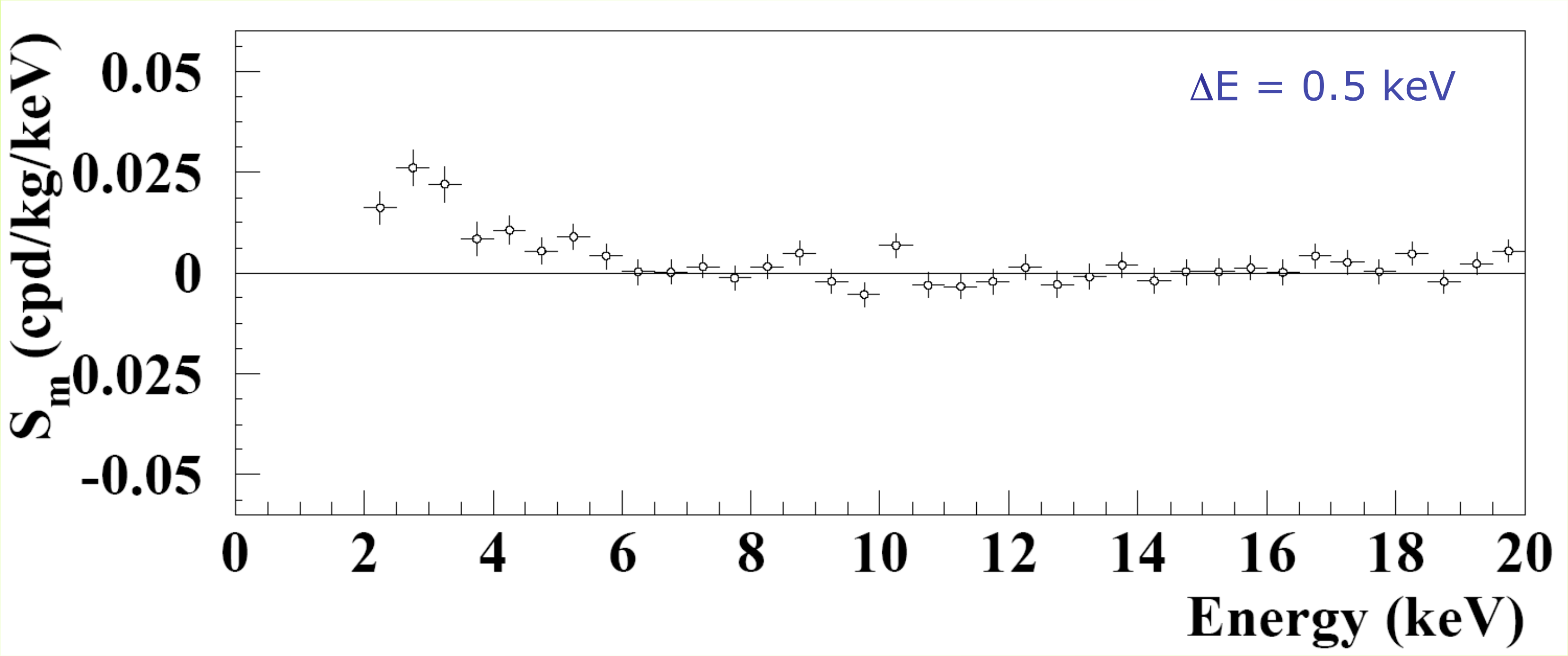
Energy distribution of the modulation amplitudes

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

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



A clear modulation is present in the (2-6) keV, while S_m values compatible with zero are present just above

The S_m values in the (6–20) keV have random fluctuations around zero with χ^2 equal to 27.5 for 28 *d.o.f.*

Statistical distributions of the modulation amplitudes (S_m)

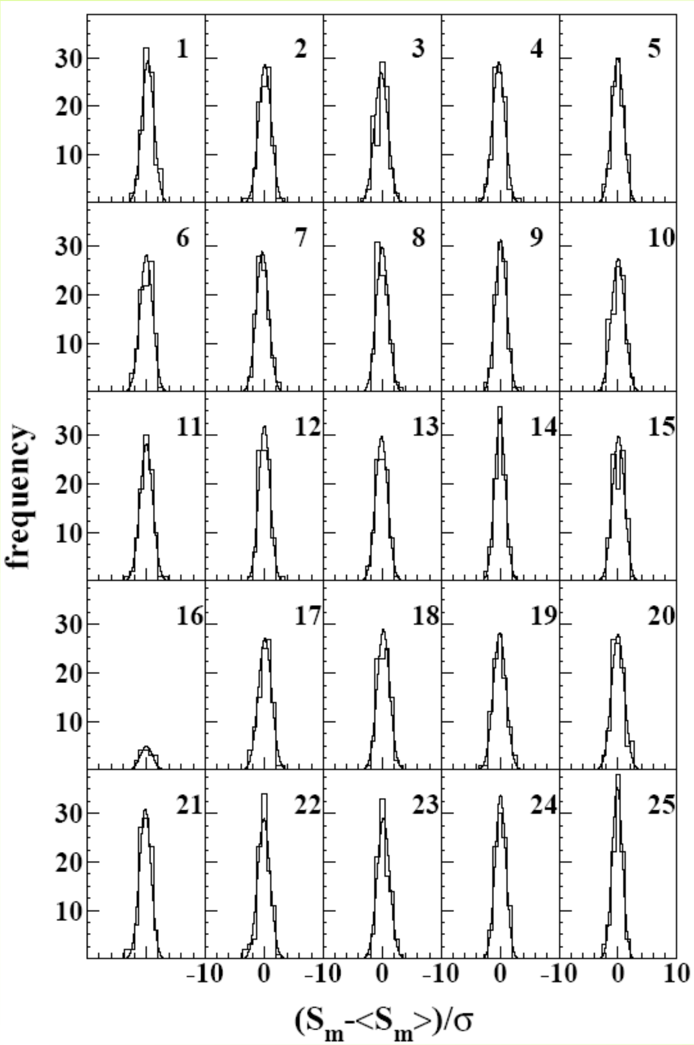
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

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)

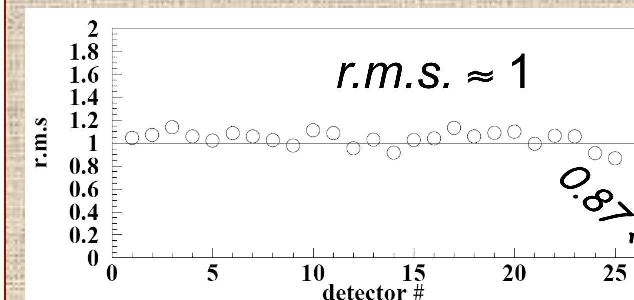


2-6 keV

Standard deviations of

(S_m-⟨S_m⟩)/σ

for each detector



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-<S_m>)/σ** is distributed as a Gaussian with a unitary standard deviation (r.m.s.)

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

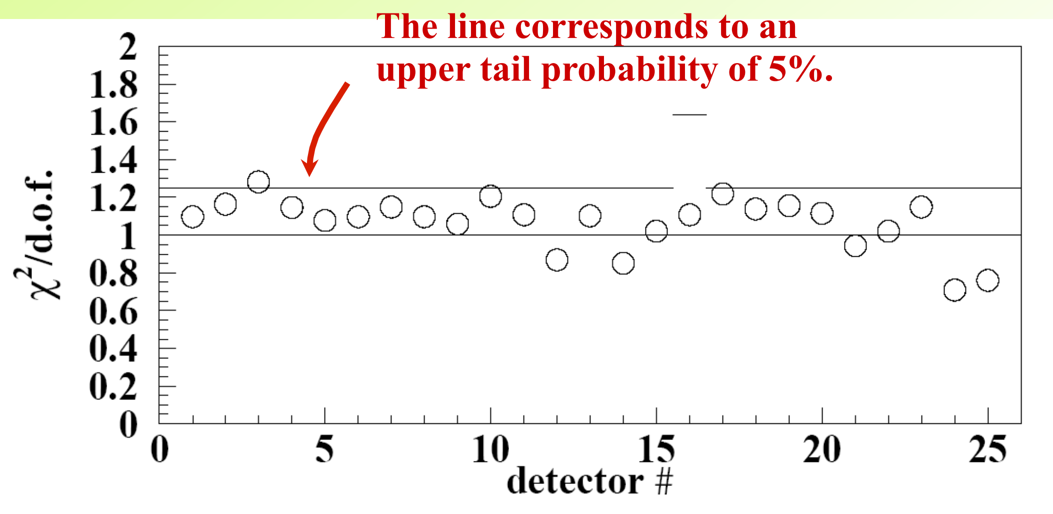
Statistical analyses about modulation amplitudes (S_m)

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

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

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

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



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 25 points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 4 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 5\times10^{-5}$ 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

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

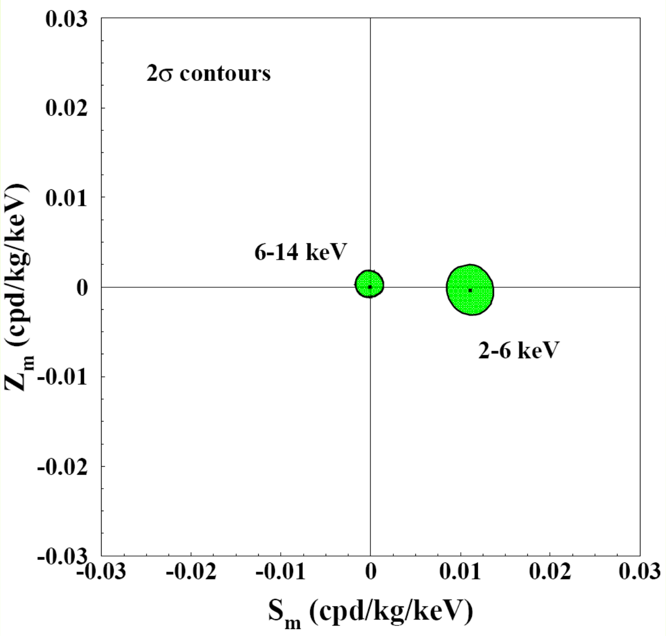
DAMA/NaI (7 years) + DAMA/LIBRA (6 years)
total exposure: 425428 kg×day = 1.17 ton×yr

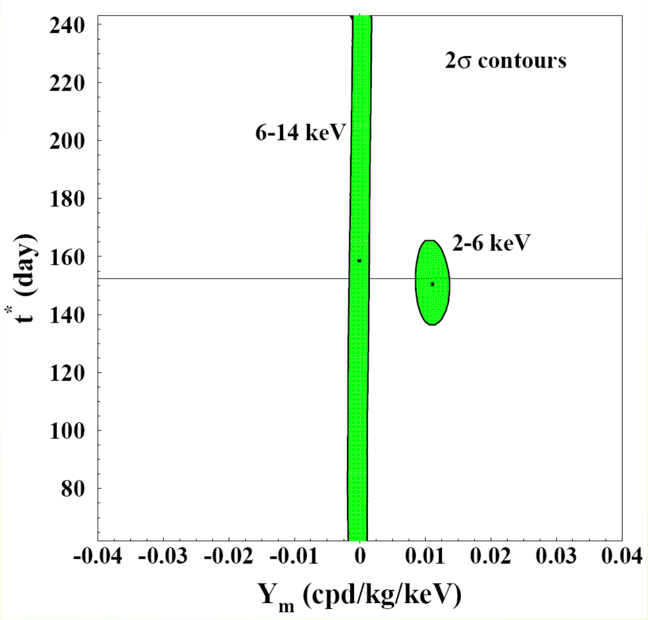
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

For Dark Matter signals:

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

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





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

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

Additional investigations on the stability parameters

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

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

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4	DAMA/LIBRA-5	DAMA/LIBRA-6
Temperature	-(0.0001 ± 0.0061) °C	(0.0026 ± 0.0086) °C	(0.001 ± 0.015) °C	(0.0004 ± 0.0047) °C	(0.0001 ± 0.0036) °C	(0.0007 ± 0.0059) °C
Flux N_2	(0.13 ± 0.22) l/h	(0.10 ± 0.25) l/h	-(0.07 ± 0.18) l/h	-(0.05 ± 0.24) l/h	-(0.01 ± 0.21) l/h	-(0.01 ± 0.15) l/h
Pressure	(0.015 ± 0.030) mbar	-(0.013 ± 0.025) mbar	(0.022 ± 0.027) mbar	(0.0018 ± 0.0074) mbar	-(0.08 ± 0.12) $\times10^{-2}$ mbar	(0.07 ± 0.13) $\times10^{-2}$ 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:

(previous exposure and details see: NIMA592(2008)297, EPJC56(2008)333, J.Phys.Conf.Ser.203(2010)012040, arXiv:1007.0595, arXiv:0912.0660)

DAMA/LIBRA 1-6

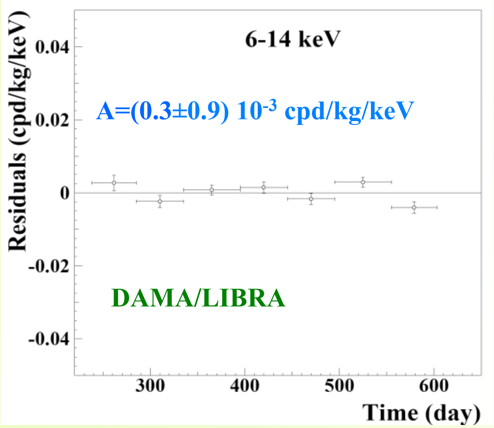
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<10^{-4} cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**<10^{-4} cpd/kg/keV**
ENERGY SCALE	Routine + instrinsic calibrations	**<1-2×10^{-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	**<3×10^{-5} cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect

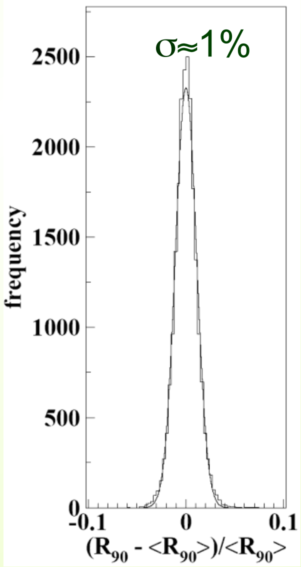
Summarizing on a hypothetical background modulation

- **No Modulation above 6 keV**

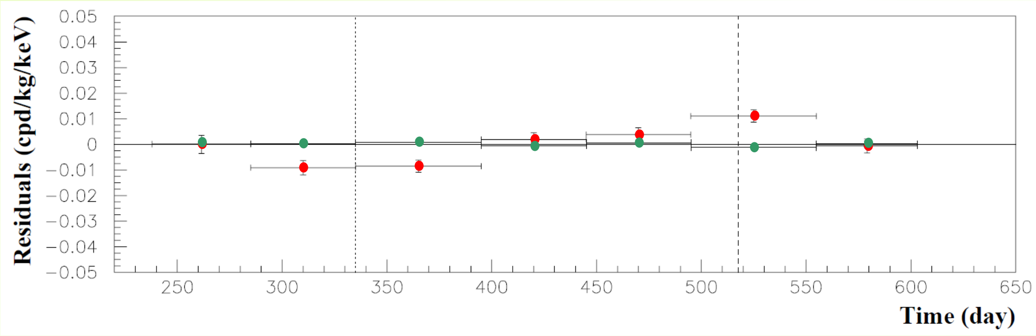


- **No modulation in the whole energy spectrum**

+ 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

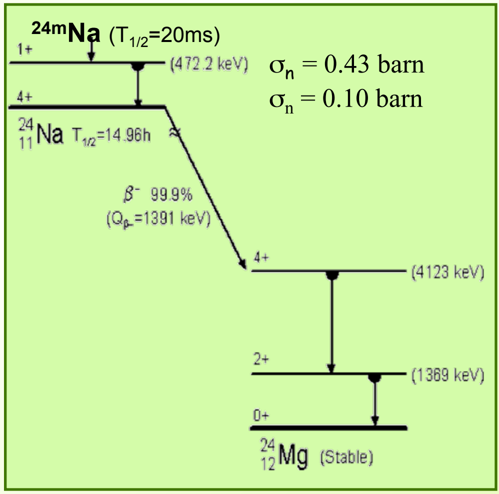
Nevertheless, additional investigations performed ...

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:

    $\Phi_n < 1.2 \times 10^{-7}$ 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:

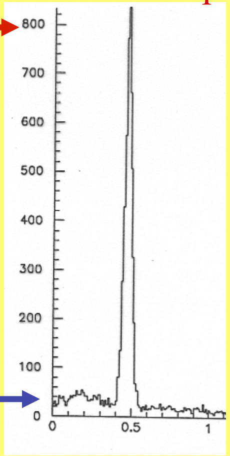
$S_m^{(thermal\ n)} < 0.8 \times 10^{-6}$ cpd/kg/keV (< 0.01% $S_m^{observed}$)

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)

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

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):

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

  - 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

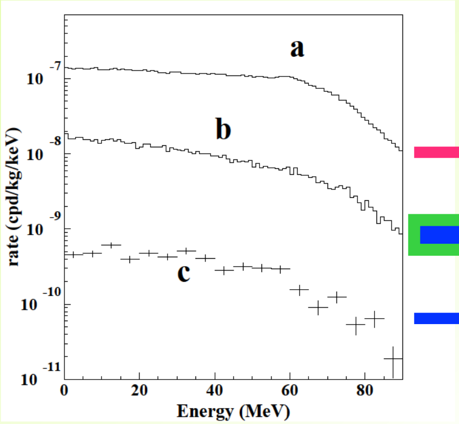
  already excluded by the multiple-hit events

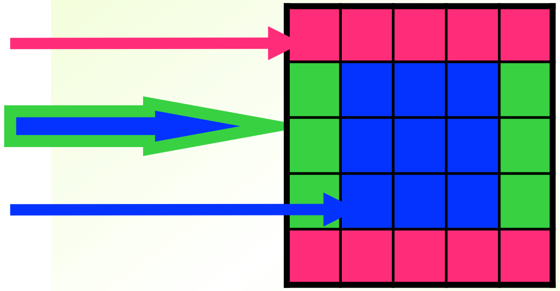
Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

The μ case

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/cm²)
R_n = (fast n by μ)/(time unit) = Φ_μ 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

$S_m^{(\mu)} < (0.4÷3) \times 10^{-5}$ 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 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
- 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

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 and BOREXINO partially overlapped with DAMA/NaI and fully with DAMA/LIBRA: 1.5% modulation and phase
LVD = July 5th ± 15 d, BOREXINO = July 6th ± 6 d

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

This phase is 7.1 σ far from July 15th and is 5.7 σ far from July 6th

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

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

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

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

Kaluza Klein particles

… and more

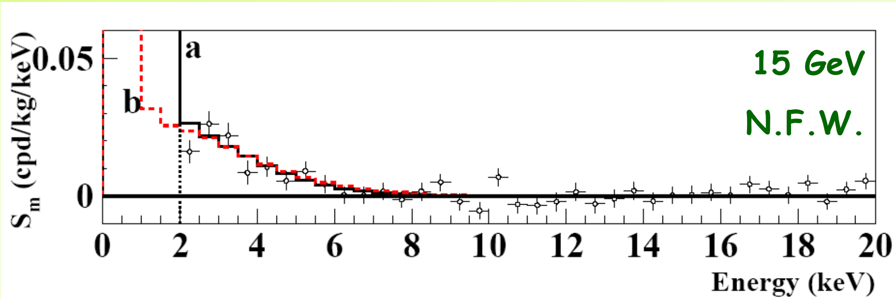
Possible model dependent positive hints from indirect searches (but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.)
not in conflict with DAMA results;
null results not in conflict as well

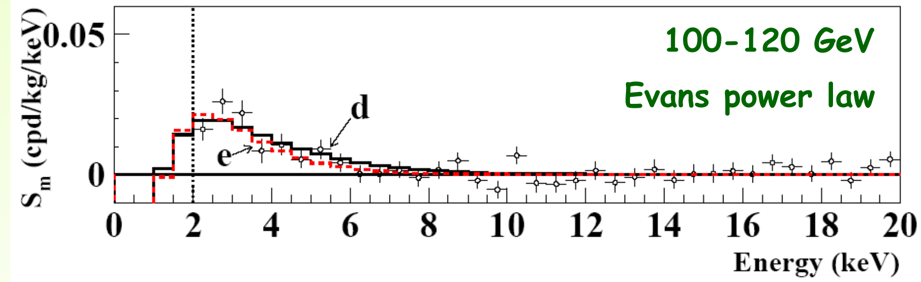
Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility of positive excess

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

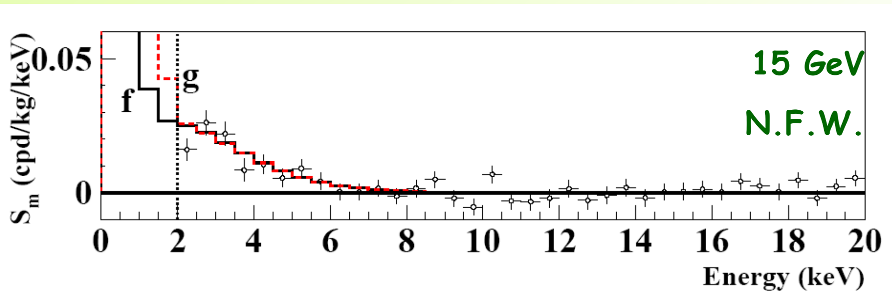
WIMP: SI

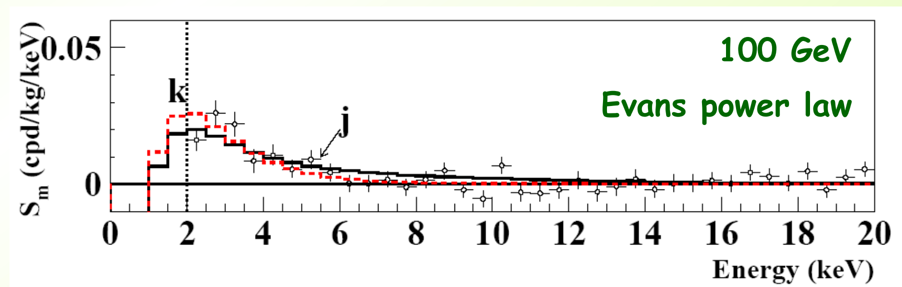
- Not best fit
- About the same C.L.



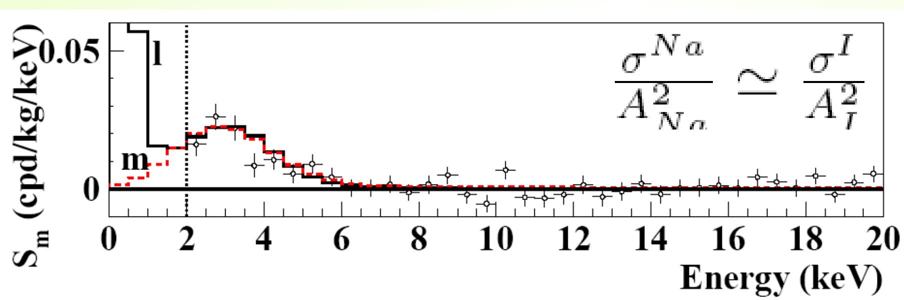


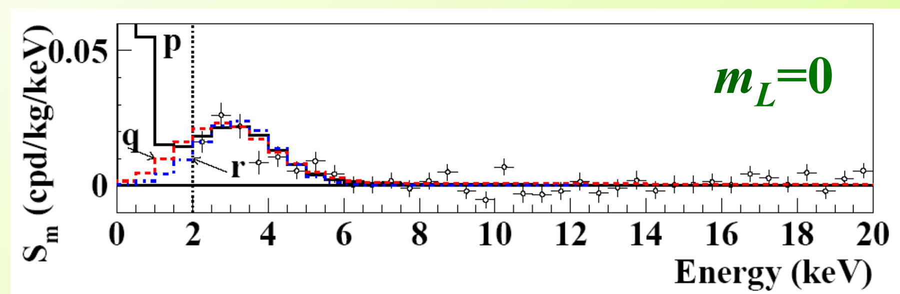
WIMP: SI & SD $\theta = 2.435$





LDM, bosonic DM





EPJC56(2008)333

Compatibility with several candidates; other ones are open

About model dependent exclusion plots

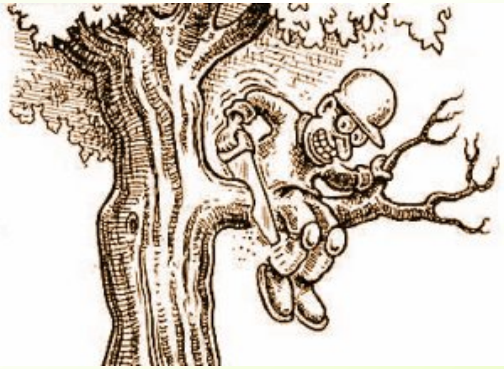
Selecting just one simplified model framework, making lots of assumptions, fixing large numbers of parameters … but…

- *which particle?*
- *which couplings? which model for the coupling?*
- *which form factors for each target material and related parameters?*
- *which nuclear model framework for each target material?*
- *Which spin factor for each case?*
- *which scaling laws?*
- *which halo profile?*
- *which halo parameters?*
- *which velocity distribution?*
- *which parameters for velocity distribution?*
- *which v_0?*
- *which v_{esc}?*
- *…etc. etc.*

and experimental aspects …

- *marginal and "selected" exposures*
- *Threshold, energy scale and energy resolution when calibration in other energy region (& few phe/keV)? Stability? Too few calibration procedures and often not in the same running conditions*
- *Selections of detectors and of data*
- *handling of (many) "subtraction" procedures and stability in time of all the cuts 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*

etc., etc.? (see e.g. arXiv:1005.3723v1, 1005.0838v3,0806.0011v2, PLB637(2006)156 …)



+ no uncertainties accounted for

no sensitivity to DM annual modulation signature

Different target materials

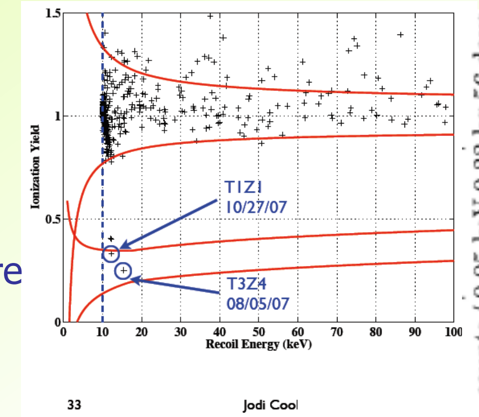
DAMA implications often presented in incorrect/ incomplete/non-updated way

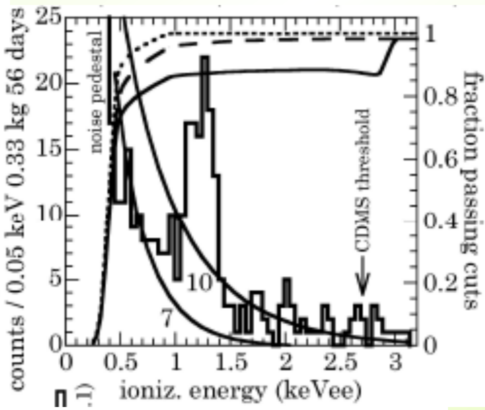
Exclusion plots have no "universal validity" and cannot disproof a model independent result in any given general model framework (they depend not only on the general assumptions largely unknown at present stage of knowledge, but on the details of their cooking) + **generally overestimated** + methodological robustness (see R. Hudson, Found. Phys. 39 (2009) 174)

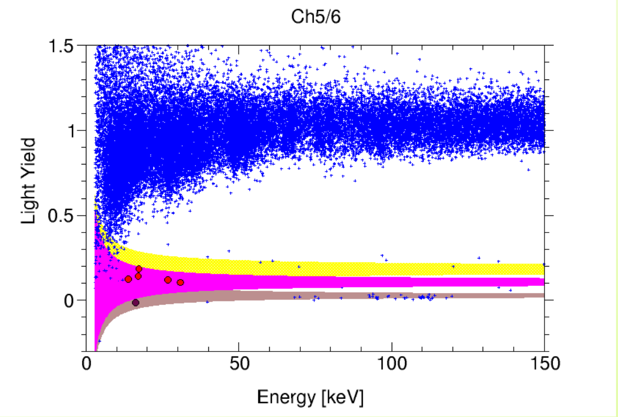
On the other hand, possible positive hints (above an estimated background) should be interpreted. Large space for compatibility.

DAMA/NaI & DAMA/LIBRA vs the recent results on 2010 (positive recoil-like excesses)

- **CoGeNT**: low-energy rise in the spectrum (irriducible by the applied background reduction procedures)
- **CDMS**: after data selection 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 data selection and cuts, 32 O candidate recoils survive in an exposure of ≈ 400 kg x day (8.7±1.2 estimated as expected from residual background)







All these recoil-like excesses, if interpreted in WIMP scenarios, are also compatible with the DAMA annual modulation result

Some recent literature discussing compatibility in various frameworks e.g.:

- Low mass neutralino (PRD81(2010)107302, PRD83 (2011)015001, arXiv:1003.0014,arXiv:1007.1005v2, arXiv: 1009.0549, arXiv:1003.0682)
- Inelastic DM (PRD79(2009)043513, arXiv:1007.2688)
- Mirror DM in various scenarios (arXiv:1001.0096, Berezhiani et al.)
- Resonant DM (arXiv:0909.2900)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Composite DM (arXiv:1003.1144)
- Light scalar WIMP through Higgs portal (arXiv:1003.2595)
- SD Inelastic DM (arXiv:0912.4264)
- Complex Scalar Dark Matter (arXiv:1005.3328)
- **... and more considering the uncertainties**

... 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: $M_1/M_2 \neq 0.5$ (<);

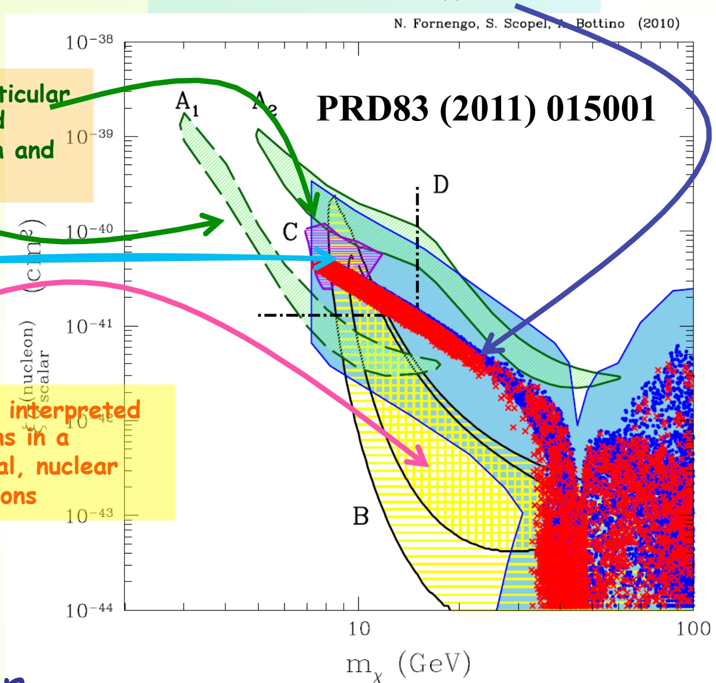
  (where M_1 and M_2 U(1) and SU(2) gaugino masses)

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 for a particular set of astrophysical, nuclear and particle Physics assumptions

If the two CDMS events are interpreted as relic neutralino interactions in a particular set of astrophysical, nuclear and particle Physics assumptions

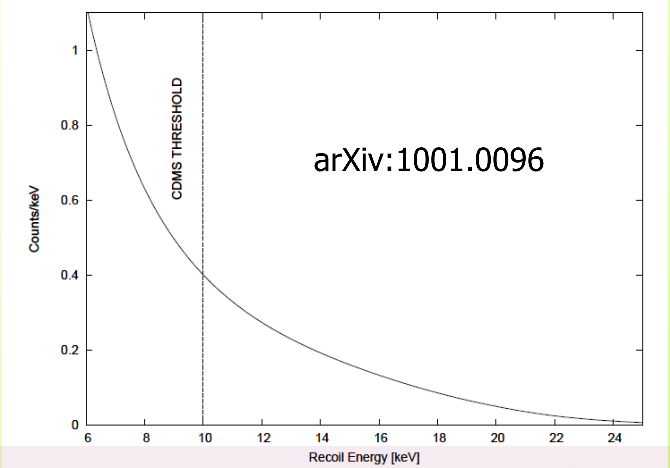


... windows for compatibility also in some recent model dependent results for COGENT (arxiv.org: 1003.0014)

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.



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:1003.0014,1007.1005), Composite DM (arXiv:1003.1144), Light scalar WIMP through Higgs portal (arXiv:1003.2595), exothermic DM (arXiv:1004.0937), iDM on Tl (arXiv:1007.2688), ...

what next

Continuously running

- Replacement of all the PMTs with higher Q.E. ones concluded

New PMTs with higher Q.E. :

- Continuing data taking in the new configuration also below the present 2 keV software energy threshold
- Reaching even higher C.L. for the model independent result and highly precisely all the modulation parameters to further investigate among the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..
- Investigation on dark matter peculiarities and second order effect
- Special data taking for other rare processes.

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 $\times$ yr – 13 annual cycles DAMA/NaI and 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
- No experiment exists whose result can be directly compared in a model independent way with those by DAMA/NaI & DAMA/LIBRA
- Recent excesses in direct searches above an evaluated background are – when interpreted as induced by some DM candidates – 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

... what next?

- Upgrade in fall 2010 concluded: replacement of all PMTs with new ones having higher Q.E. to lower the software energy threshold and improve general features.
- Collect a suitable exposure in the new running conditions to improve the knowledge about the nature of the particles and on features of related astrophysical, nuclear and particle physics aspects.
- Investigate second order effects
- R&D towards a possible 1 ton ULB NaI(Tl) set-up experiment DAMA proposed in 1996

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., and the only one which effectively exploits a model independent DM signature