

*The Dark Matter **annual modulation** signature as a probe of the dark side of the Universe*

Speakable in quantum mechanics: atomic,
nuclear and subnuclear physics tests
Trento, August 29, Sept 2, 2011



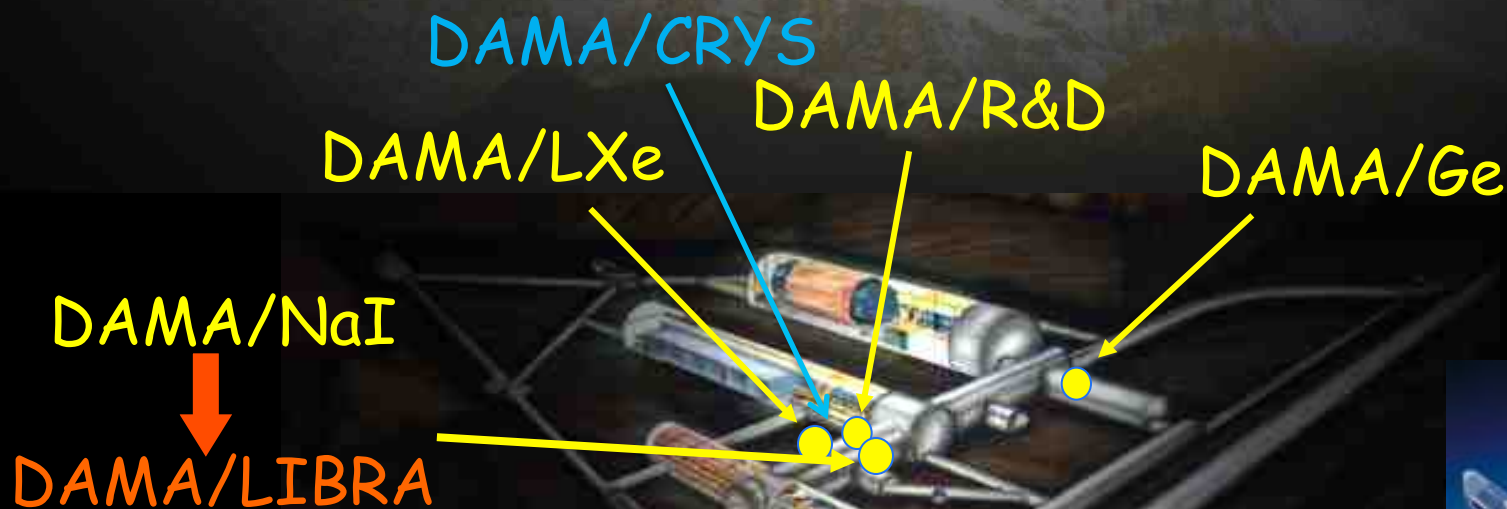
P. Belli
INFN-Roma Tor Vergata

Roma2, Roma1, LNGS, IHEP/Beijing

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



DAMA: an observatory for rare processes @LNGS



DAMA/LXe: results on rare processes

Dark Matter Investigation

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



Other rare processes:

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

NIMA482(2002)728

PLB436(1998)379

PLB387(1996)222, NJP2(2000)15.1

PLB436(1998)379, EPJdirectC11(2001)1

foreseen/in progress

Astrop.P.5(1996)217

PLB465(1999)315

PLB493(2000)12

PRD61(2000)117301

Xenon01

PLB527(2002)182

PLB546(2002)23

Beyond the Desert (2003) 365

EPJA27 s01 (2006) 35



DAMA/Ge & LNGS Ge facility

- RDs on highly radiopure NaI(Tl) set-up
- several RDs on low background PMTs
- qualification of many materials
- meas. on $\text{Li}_6\text{Eu}(\text{BO}_3)_3$ (NIMA572(2007)734)
- $\beta\beta$ decay in ^{100}Mo with the 4π low-bckg HPGe facility of LNGS (NPA846(2010)143)
- search for ^7Li 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)
- First search for $\beta\beta$ decay in ^{190}Pt and ^{198}Pt (EPJA47(2011)91)
- $\beta\beta$ decay of ^{156}Dy , ^{158}Dy (NPA859(2011)126)
- + Many other meas. already scheduled
- + CdWO_4 and ZnWO_4 radiopurity studies (NIMA626-627(2011)31, NIMA615(2010)301)

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

• Particle Dark Matter search with $\text{CaF}_2(\text{Eu})$



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

NPB563(1999)97,

Astrop.Phys.7(1997)73

Il N. Cim.A110(1997)189

Astrop. Phys. 7(1997)73

NPB563(1999)97

Astrop.Phys.10(1999)115

NPA705(2002)29

NIMA498(2003)352

NIMA525(2004)535

NIMA555(2005)270

UJP51(2006)1037

NPA789(2007)15

PRC76(2007)064603

PLB658(2008)193, NPA826(2009)256

EPJA36(2008)167

JPG: NPP38(2011)015103

JINST6(2011)P08011

• α decay of natural Eu

• β decay of ^{113}Cd

• $\beta\beta$ decay of ^{64}Zn , ^{70}Zn , ^{180}W , ^{186}W

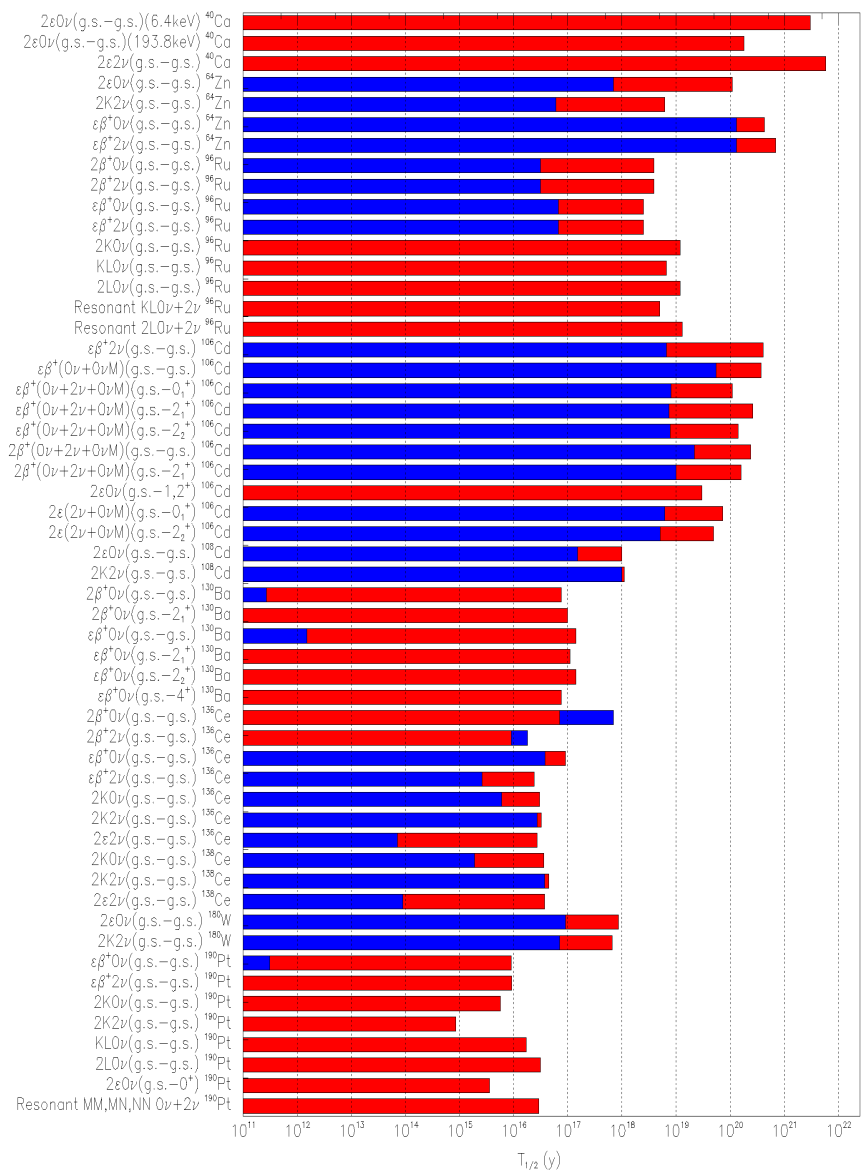
• $\beta\beta$ decay of ^{108}Cd and ^{114}Cd

• $\beta\beta$ decay of ^{136}Ce , ^{138}Ce and ^{142}Ce

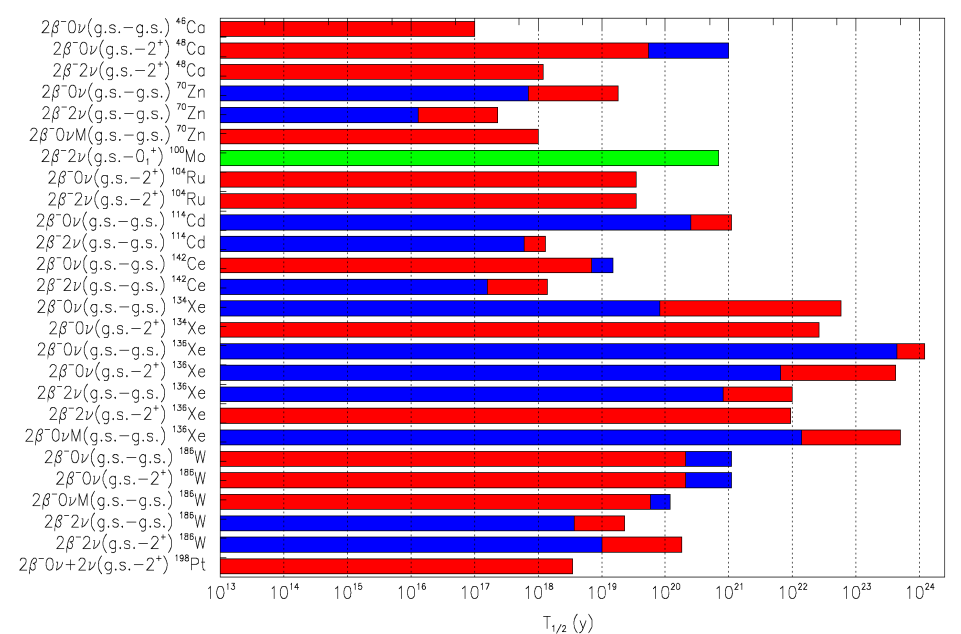
with CeCl_3

• ^{106}Cd , and ^{116}Cd in progress

Summary of searches for $\beta\beta$ decay modes in various isotopes (partial list)



$T_{1/2}$ experimental limits by DAMA (in red) and previous ones (in blue). All the limits are at 90% C.L. except for $0\nu2\beta^+$ in ^{136}Ce and $2\beta^+0\nu$ in ^{142}Ce at 68% C.L.. In green observed!

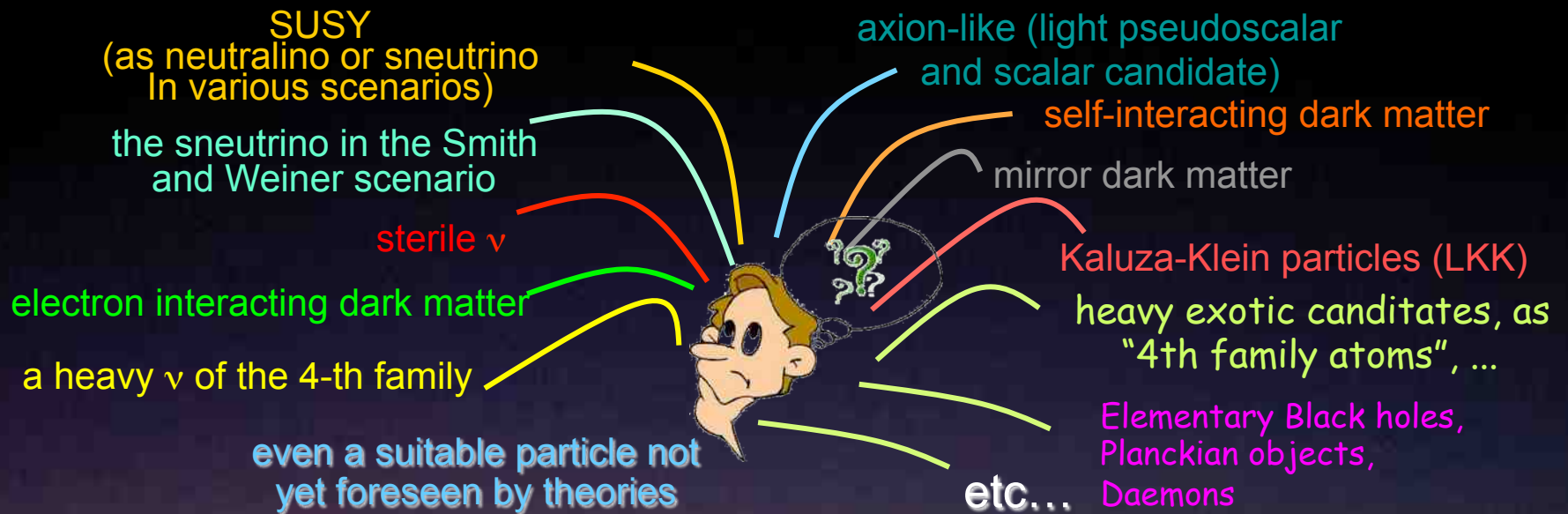


ARMONIA: New observation (green) of $2\nu2\beta^-$ $^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$ (g.s. $\rightarrow 0_1^+$) decay

- Many competitive limits obtained on lifetime of $2\beta^+$, $\epsilon\beta^+$ and 2ϵ processes (^{40}Ca , ^{64}Zn , ^{96}Ru , ^{106}Cd , ^{108}Cd , ^{130}Ba , ^{136}Ce , ^{138}Ce , ^{180}W , ^{190}Pt).
 - The limits on $2\beta^-$ modes in ^{136}Xe are the presently best ones for this isotope
 - First searches for resonant $\beta\beta$ decays in some isotopes
- Many publications on detectors developments and results
Many future measurements in preparation



Relic DM particles from primordial Universe



&

(& invisible axions, ν 's)

Right halo model and parameters?





What accelerators can do:

to demonstrate the existence of some of the possible DM candidates

What accelerators cannot do:

to credit that a certain particle is the Dark Matter solution or the “single” Dark Matter particle solution...

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



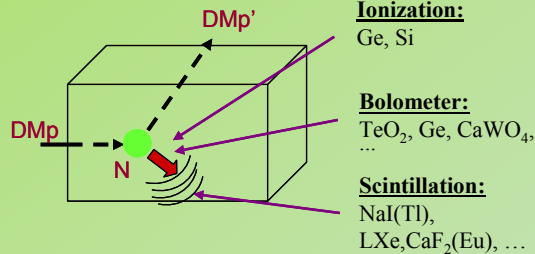
DM direct detection method using a model independent approach and a low-background widely-sensitive target material



Some direct detection processes:

- Scatterings on nuclei

→ detection of nuclear recoil energy



- Inelastic Dark Matter: $\mathbf{W} + \mathbf{N} \rightarrow \mathbf{W}^* + \mathbf{N}$

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

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

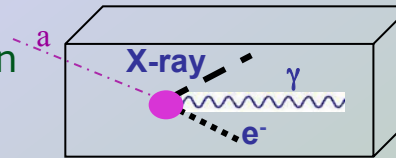
$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

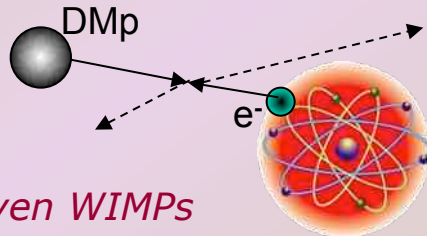
- Conversion of particle into e.m. radiation

→ detection of γ , X-rays, e^-



- Interaction only on atomic electrons

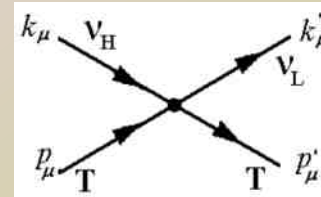
→ detection of e.m. radiation



... 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

... also other ideas ...

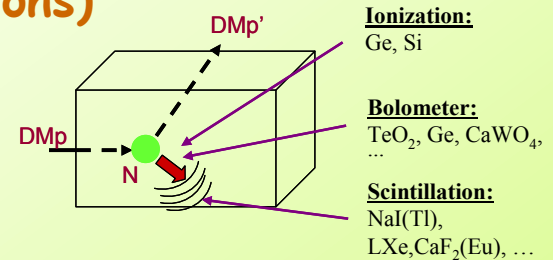
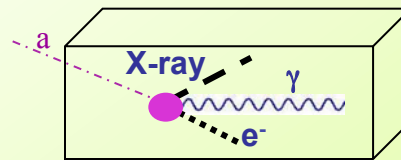
e.g. signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

- ... and more

The direct detection experiments can be classified in two classes, depending on what they are based:

1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a “model-independent” signature

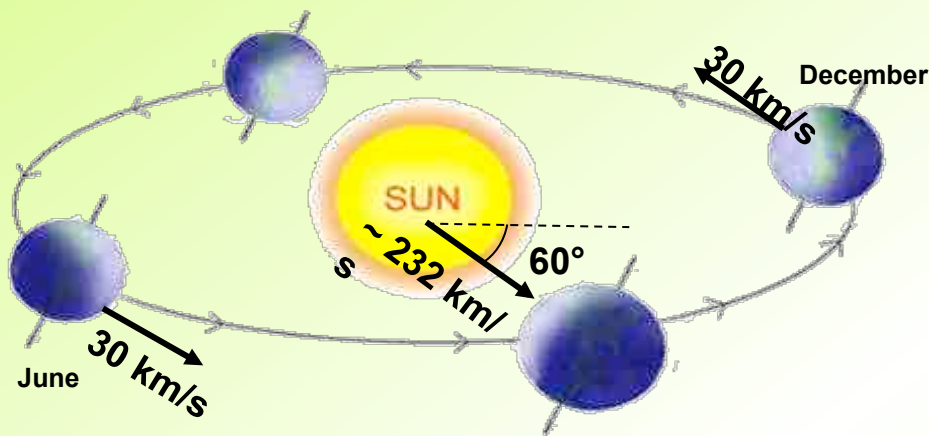
2. on the use of uncertain techniques of rejection of electromagnetic background (adding systematical effects and lost of candidates with pure electromagnetic productions)



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



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

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

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

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

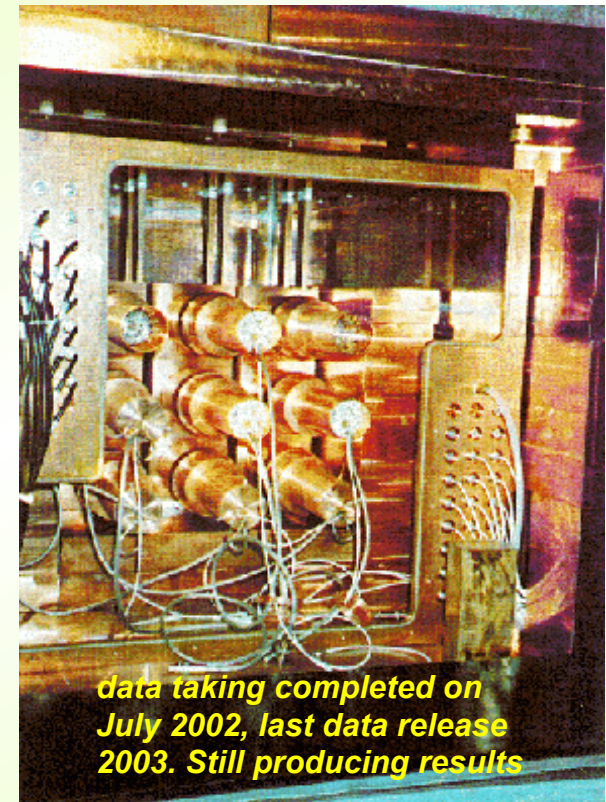
Results on rare processes:

- 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 \times 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

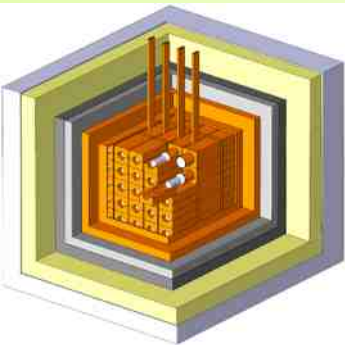


The DAMA/LIBRA set-up

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

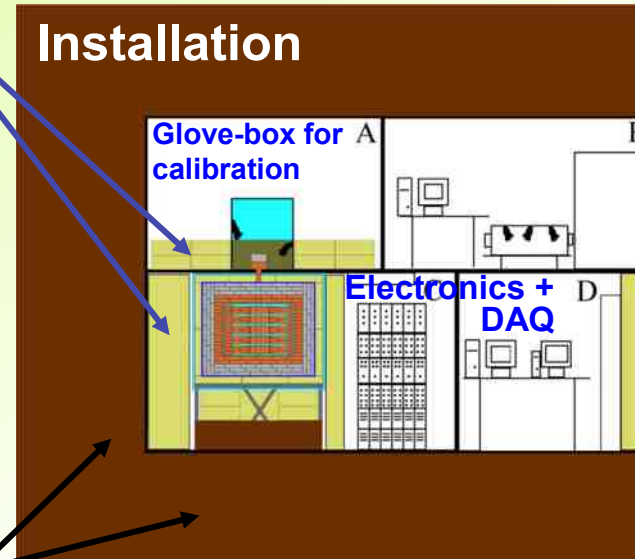
Polyethylene/paraffin

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



5.5-7.5 phe/keV

Installation



- OFHC low radioactive copper
- Low radioactive lead
- Cadmium foils
- Polyethylene/Paraffin
- Concrete from GS rock

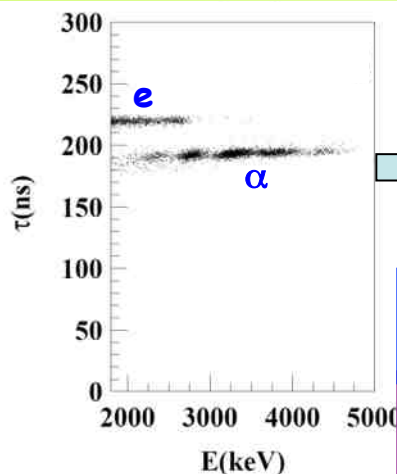


~ 1m concrete from GS rock

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waweform Analyzer Acqiris DC270 (2chs per detector), 1 Gsample/s, 8 bit, bandwidth 250 MHz
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy



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



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

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

Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling

^{232}Th residual contamination

From time-amplitude method. If ^{232}Th chain at equilibrium: it ranges from 0.5 ppt to 7.5 ppt

^{238}U residual contamination

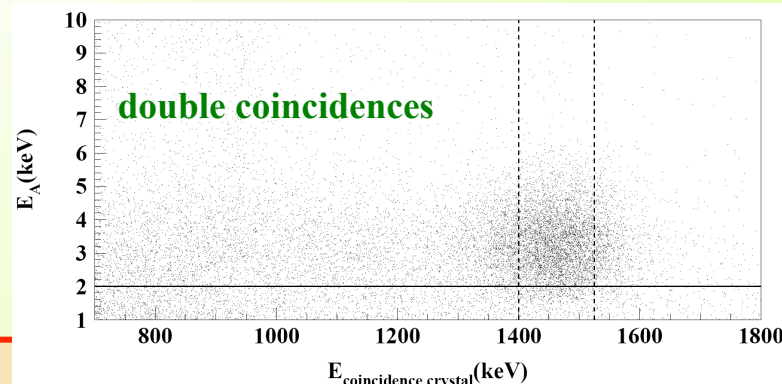
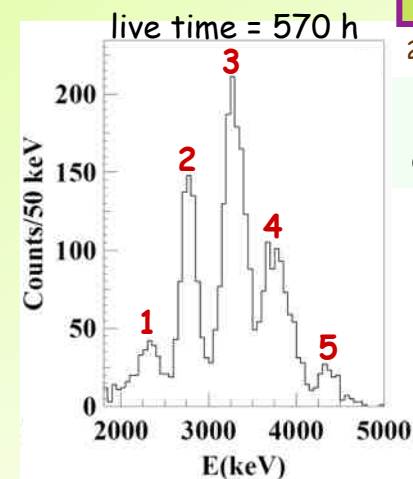
First estimate: considering the measured α and ^{232}Th activity, if ^{238}U chain at equilibrium \Rightarrow ^{238}U contents in new detectors typically range from 0.7 to 10 ppt

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

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) $\mu\text{Bq/kg}$ for $^{234}\text{U} + ^{230}\text{Th}$; (21.7 ± 1.1) $\mu\text{Bq/kg}$ for ^{226}Ra ; (24.2 ± 1.6) $\mu\text{Bq/kg}$ for ^{210}Pb .

$^{\text{nat}}\text{K}$ residual contamination

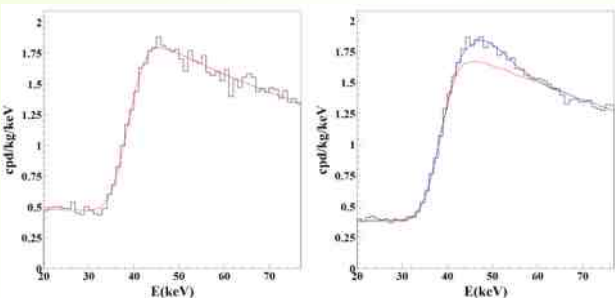
The analysis has given for the $^{\text{nat}}\text{K}$ content in the crystals values not exceeding about 20 ppb



^{129}I and ^{210}Pb

$^{129}\text{I}/^{\text{nat}}\text{I} \approx 1.7 \times 10^{-13}$ for all the new detectors

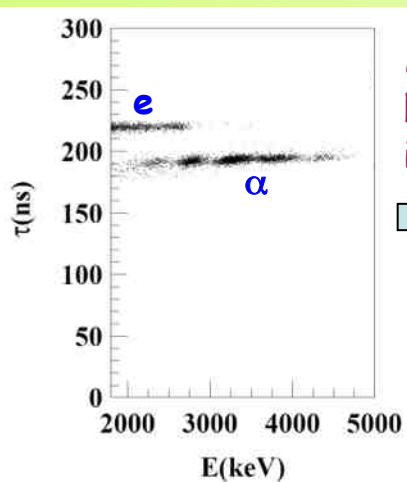
^{210}Pb in the new detectors: $(5 - 30)$ $\mu\text{Bq/kg}$.



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

... more on NIMA592 (2008)297

Some on residual contaminants in NaI(Tl) detectors



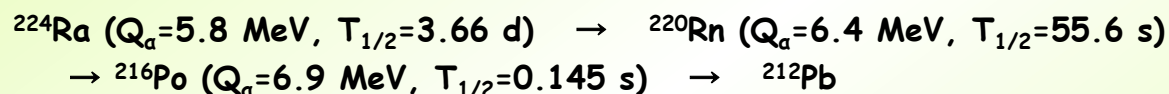
α /e pulse shape discrimination has practically 100% effectiveness in the MeV range

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

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^{232}Th residual contamination

Time-amplitude method: arrival time and energy of each event used for selection of fast decay chains in ^{232}Th family



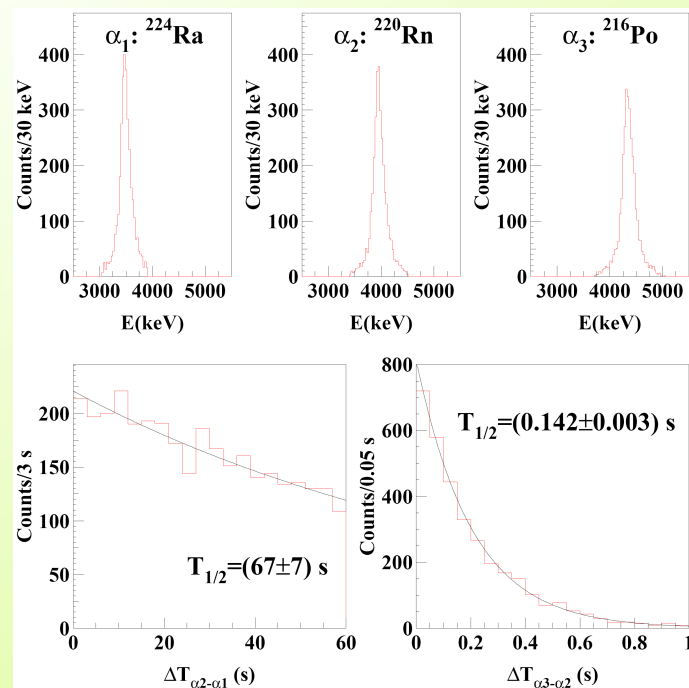
α peaks as well as the distributions of the time intervals between the events are in a good agreement with those expected

$$\alpha/\beta = 0.467(6) + 0.0257(10) \times E_\alpha [\text{MeV}]$$

\Rightarrow ^{228}Th activity ranging from 2 to about 30 $\mu\text{Bq/kg}$ in the DAMA/LIBRA detectors (in agreement with Bi-Po analysis)

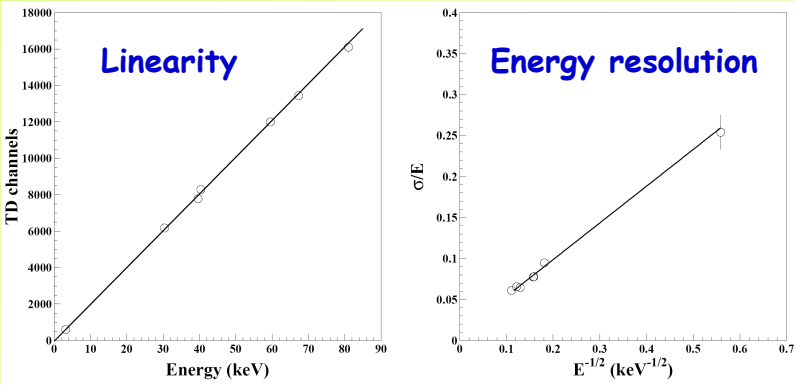
If ^{232}Th chain at equilibrium: ^{232}Th contents in new detectors typically range from 0.5 ppt to 7.5 ppt

Example: 3310 triple delayed coincidences in 8100 kg \times day $\rightarrow (9.0 \pm 0.4) \mu\text{Bq/kg}$



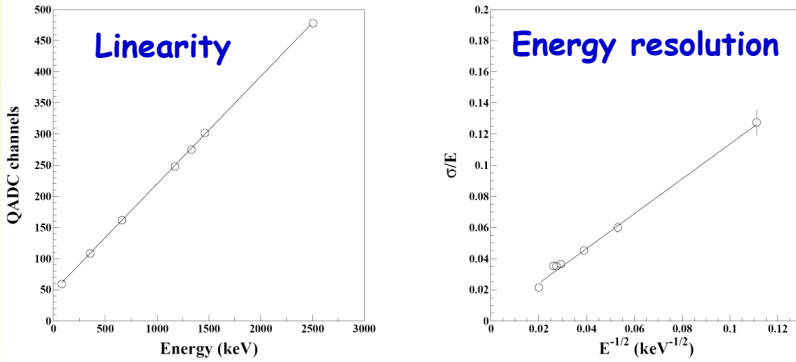
DAMA/LIBRA calibrations

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



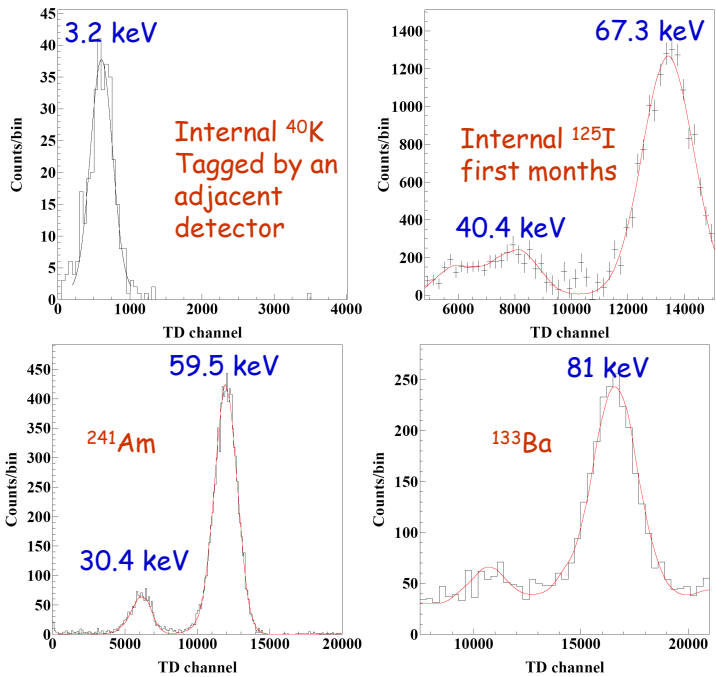
$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(\text{keV})}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

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

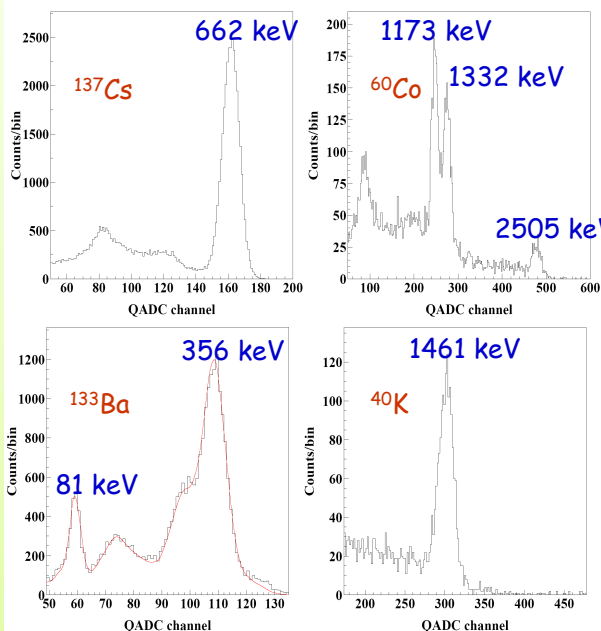


$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(\text{keV})}} + (17 \pm 23) \cdot 10^{-4}$$

Thus, here and hereafter keV means keV electron equivalent



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



Examples of energy resolutions

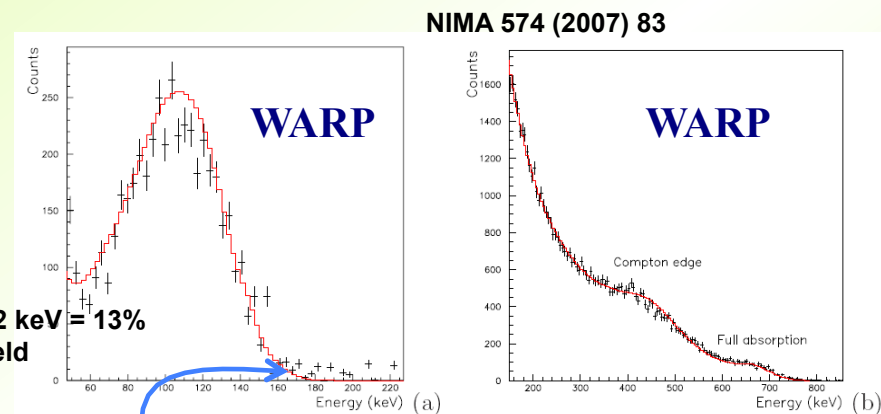
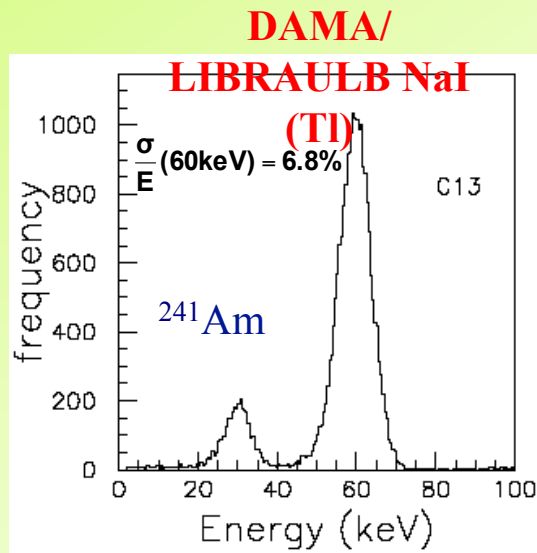


Fig. 2. Energy spectra taken with external γ -ray sources, superimposed with the corresponding Monte Carlo simulations. (a) ^{57}Co source ($E = 122$ keV, B.R. 85.6%, and 136 keV, B.R. 10.7%), (b) ^{137}Cs source ($E = 662$ keV).

subtraction of the spectrum ?

ZEPLIN-II

AP 28 (2007) 287

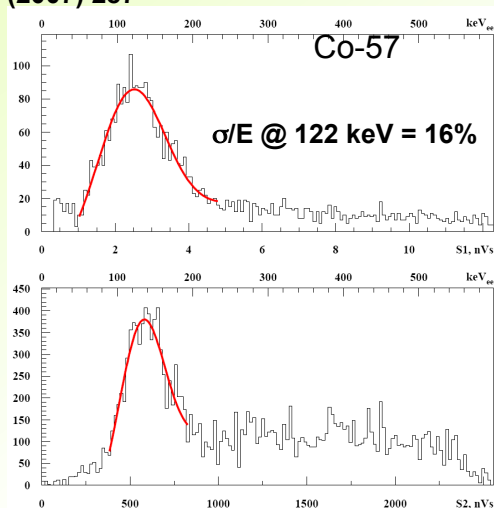
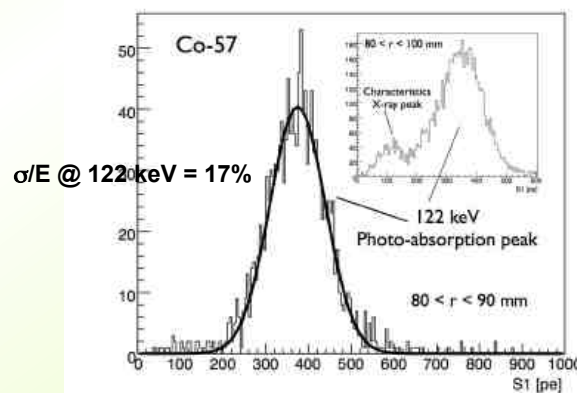


Fig. 5. Typical energy spectra for ^{57}Co γ -ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ -ray spectrum. The energy resolution of the detector is derived from the width of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

XENON10



XENON10

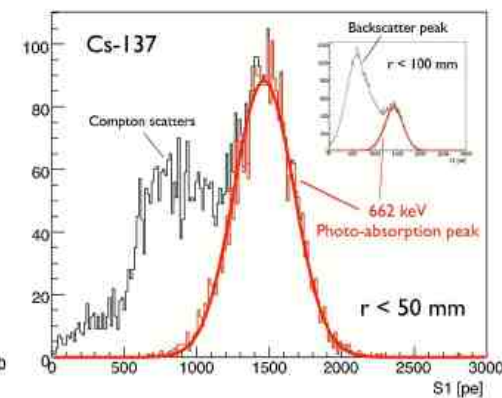
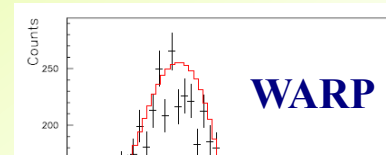
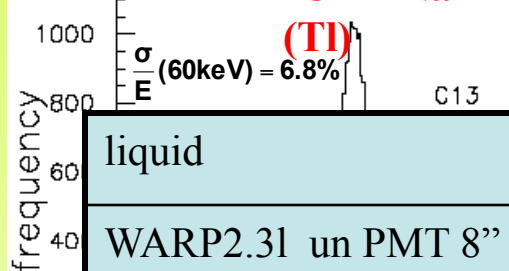


Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

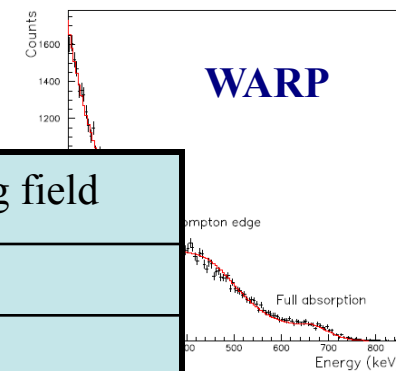
Examples of energy resolutions

DAMA/

LIBRAULB NaI



NIMA 574 (2007) 83



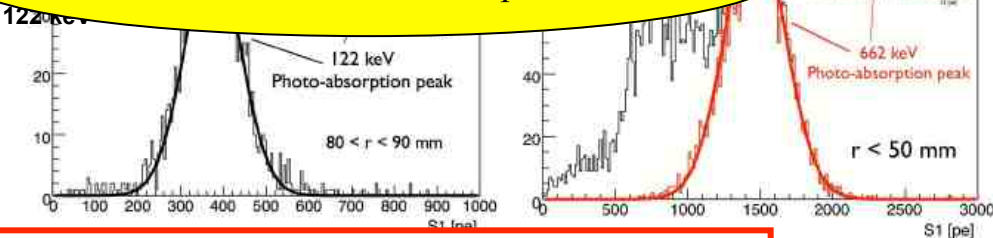
liquid	phe/keV@zero field	phe/keV@working field
WARP2.31 un PMT 8''	--	2.35
WARP2.31 7 PMTs 2''	0.5-1 (deduced)	--
ZEPLIN-II	1.1	0.55
ZEPLIN-III		1.8
XENON10	--	2.2 (^{137}Cs), 3.1 (^{57}Co)
XENON100	2.7	1.57 (^{137}Cs), 2.2 (^{57}Co)
Neon	0.93	field not foreseen

DAMA/LIBRA : 5.5 – 7.5 phe/keV

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

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 @ 122keV



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

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 (≈ 3 M events/keV)**

- EPJC56(2008)333

- EPJC67(2010)39

DAMA/Nal (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 N₂ 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





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



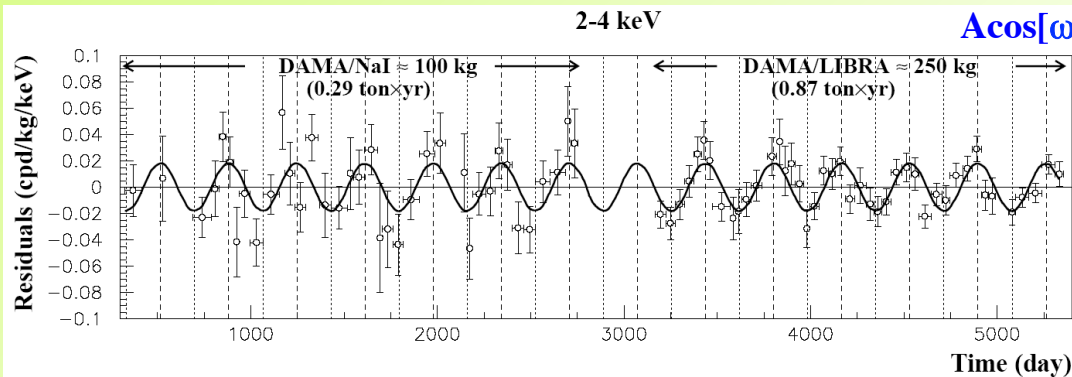
- New PMTs with higher Q.E.:



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



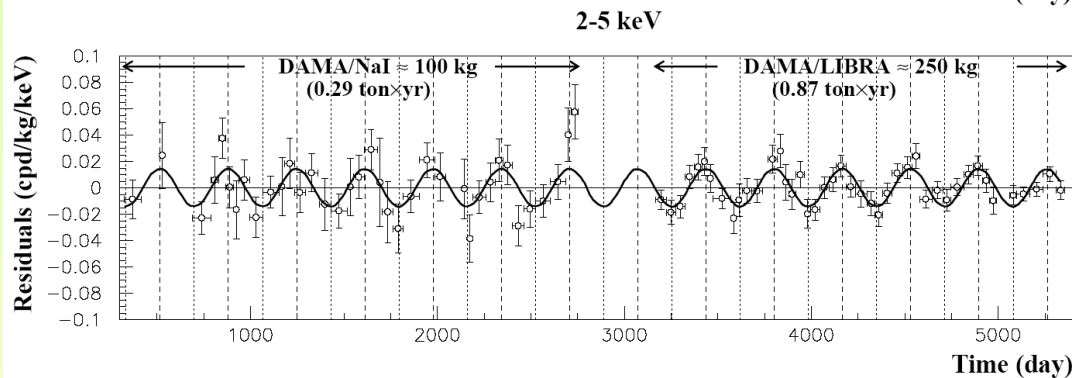
2-4 keV

$$A = (0.0183 \pm 0.0022) \text{ cpd/kg/keV}$$

$$\chi^2/\text{dof} = 75.7/79 \quad \mathbf{8.3 \sigma \text{ C.L.}}$$

Absence of modulation? No

$$\chi^2/\text{dof} = 147/80 \Rightarrow P(A=0) = 7 \times 10^{-6}$$



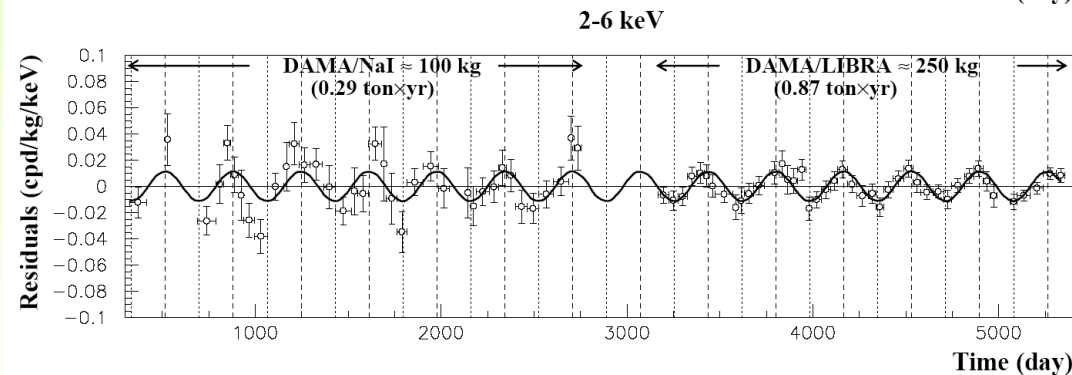
2-5 keV

$$A = (0.0144 \pm 0.0016) \text{ cpd/kg/keV}$$

$$\chi^2/\text{dof} = 56.6/79 \quad \mathbf{9.0 \sigma \text{ C.L.}}$$

Absence of modulation? No

$$\chi^2/\text{dof} = 135/80 \Rightarrow P(A=0) = 1.1 \times 10^{-4}$$



2-6 keV

$$A = (0.0114 \pm 0.0013) \text{ cpd/kg/keV}$$

$$\chi^2/\text{dof} = 64.7/79 \quad \mathbf{8.8 \sigma \text{ C.L.}}$$

Absence of modulation? No

$$\chi^2/\text{dof} = 140/80 \Rightarrow P(A=0) = 4.3 \times 10^{-5}$$

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

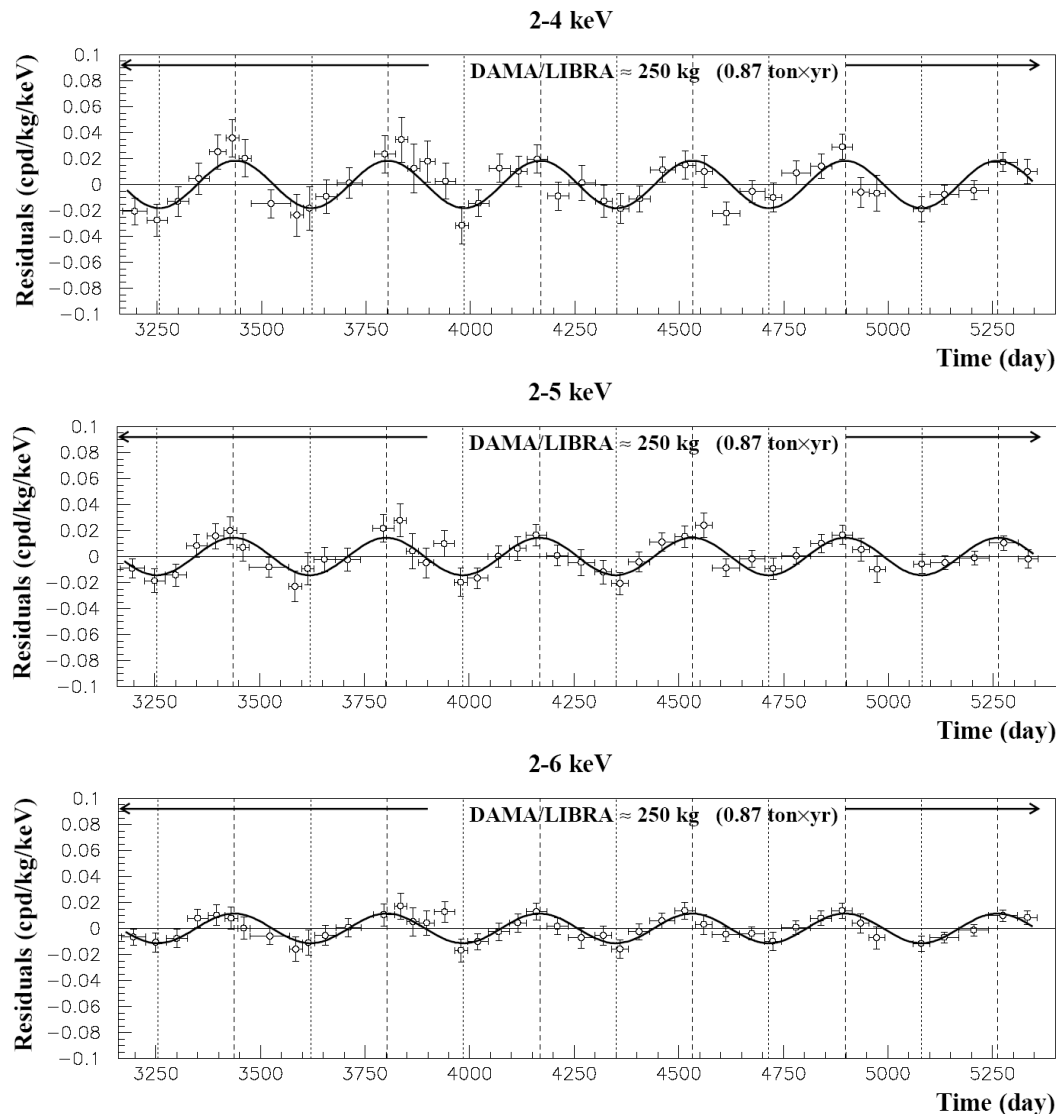
Model Independent Annual Modulation Result

experimental single-hit residuals rate vs time and energy

$\text{Acos}[\omega(t-t_0)]$; continuous lines: $t_0 = 152.5$ d, $T = 1.00$ y

DAMA/LIBRA 1-6 (0.87 ton×yr)

The fit has been done on the DAMA/NaI & DAMA/LIBRA data (1.17 ton × yr)



2-4 keV

$A = (0.0183 \pm 0.0022)$ cpd/kg/keV

$\chi^2/\text{dof} = 75.7/79$ **8.3 σ C.L.**

Absence of modulation? No

$\chi^2/\text{dof} = 147/80 \Rightarrow P(A=0) = 7 \times 10^{-6}$

2-5 keV

$A = (0.0144 \pm 0.0016)$ cpd/kg/keV

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2-6 keV

$A = (0.0114 \pm 0.0013)$ cpd/kg/keV

$\chi^2/\text{dof} = 64.7/79$ **8.8 σ C.L.**

Absence of modulation? No

$\chi^2/\text{dof} = 140/80 \Rightarrow P(A=0) = 4.3 \times 10^{-5}$

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

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

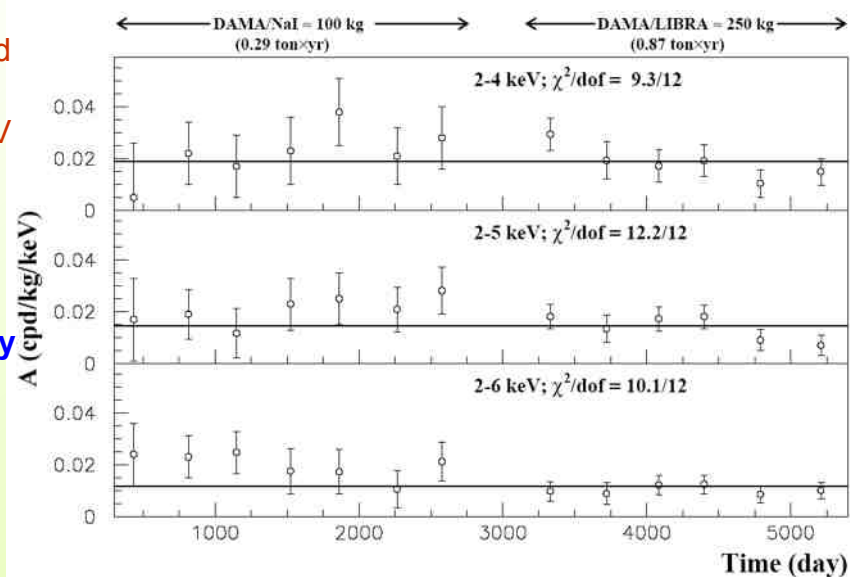
	A (cpd/kg/keV)	T= $2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI (7 years)				
(2÷4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2÷5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2÷6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA (6 years)				
(2÷4) keV	0.0180 ± 0.0025	0.996 ± 0.002	135 ± 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 $\sim 2\sigma$ which corresponds to a modest, but non negligible probability.

The χ^2 test ($\chi^2 = 9.3, 12.2$ 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

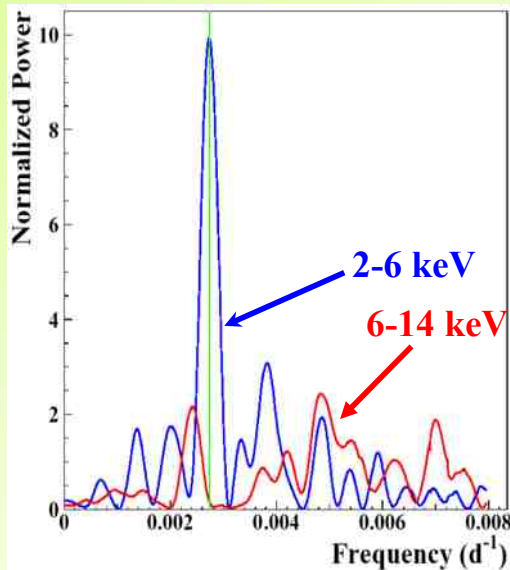
Power spectrum of single-hit residuals

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

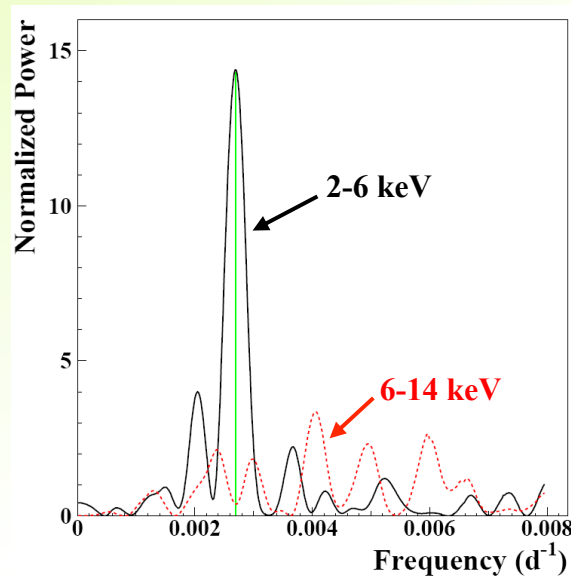
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

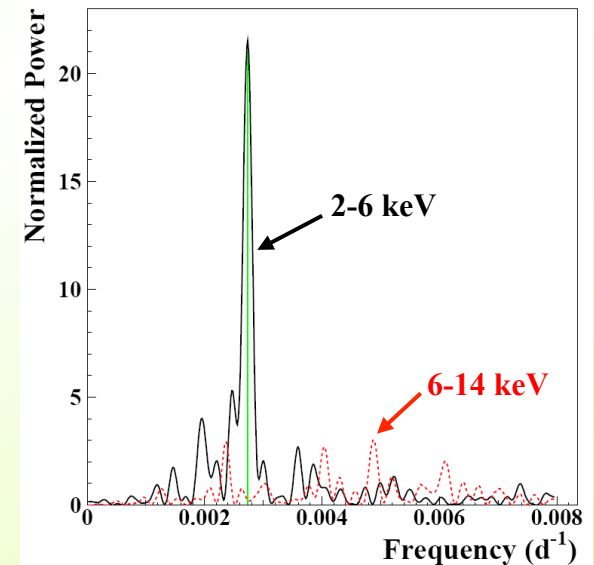
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



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
 $2.737 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}$

DAMA/LIBRA
 $2.697 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$

DAMA/NaI+LIBRA
 $2.735 \times 10^{-3} \text{ d}^{-1} \approx 1 \text{ yr}^{-1}$

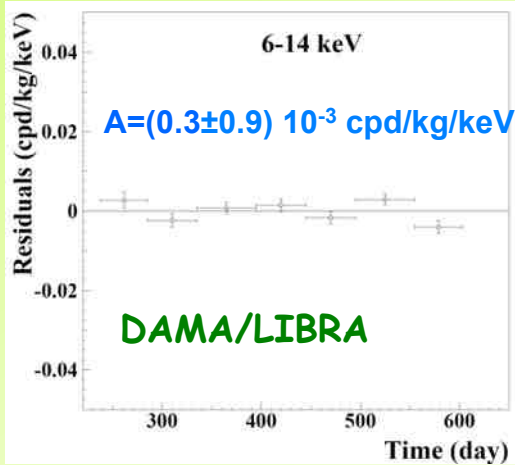
+

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

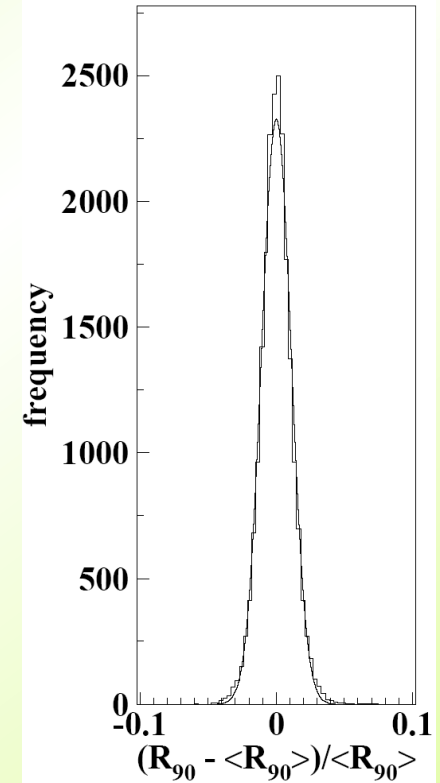


Mod. Ampl. (6-10 keV): cpd/kg/keV

- (0.0016 ± 0.0031) DAMA/LIBRA-1
- $-(0.0010 \pm 0.0034)$ DAMA/LIBRA-2
- $-(0.0001 \pm 0.0031)$ DAMA/LIBRA-3
- $-(0.0006 \pm 0.0029)$ DAMA/LIBRA-4
- $-(0.0021 \pm 0.0026)$ 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	$-(0.05 \pm 0.19) \text{ cpd/kg}$
DAMA/LIBRA-2	$-(0.12 \pm 0.19) \text{ cpd/kg}$
DAMA/LIBRA-3	$-(0.13 \pm 0.18) \text{ cpd/kg}$
DAMA/LIBRA-4	$(0.15 \pm 0.17) \text{ cpd/kg}$
DAMA/LIBRA-5	$(0.20 \pm 0.18) \text{ cpd/kg}$
DAMA/LIBRA-6	$-(0.20 \pm 0.16) \text{ cpd/kg}$

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

No modulation above 6 keV

This accounts for all sources of bckg and is consistent with studies on the various components

Multiple-hits events in the region of the signal

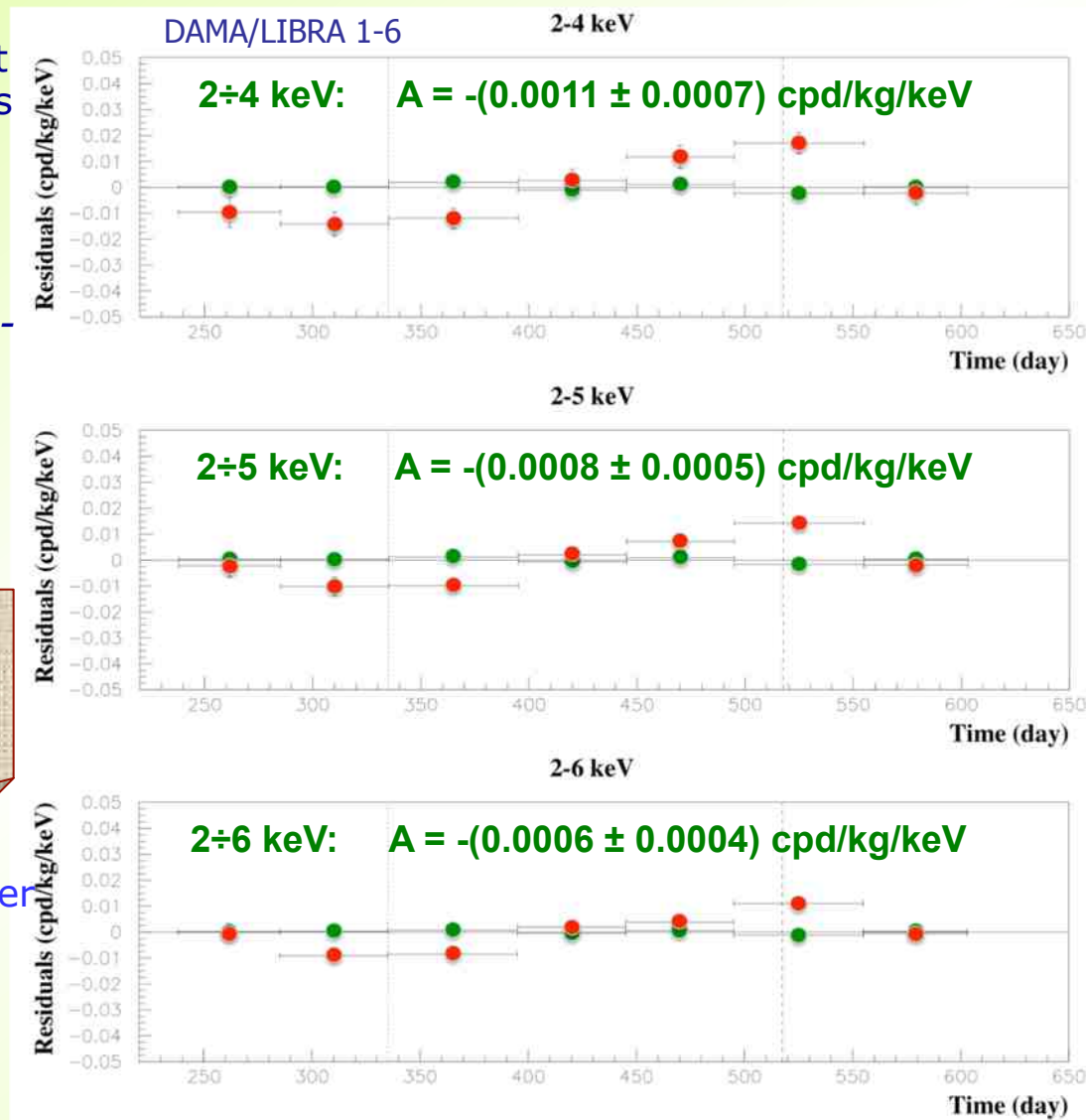
- Each detector has its own TDs read-out
→ pulse profiles of *multiple-hits* events
(multiplicity > 1) acquired (exposure: 0.87 ton×yr).
- The same hardware and software procedures as those followed for *single-hit* events

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

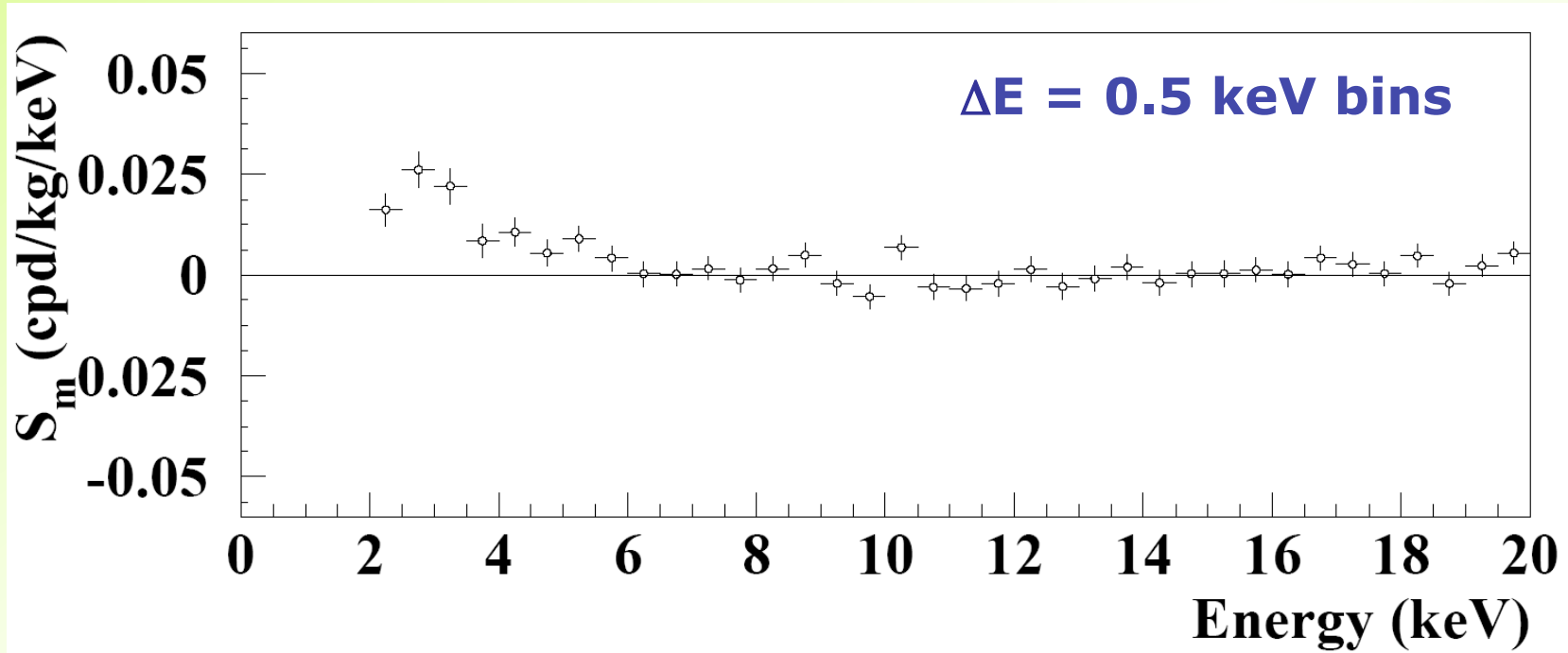
Energy distribution of the modulation amplitudes

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

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 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)

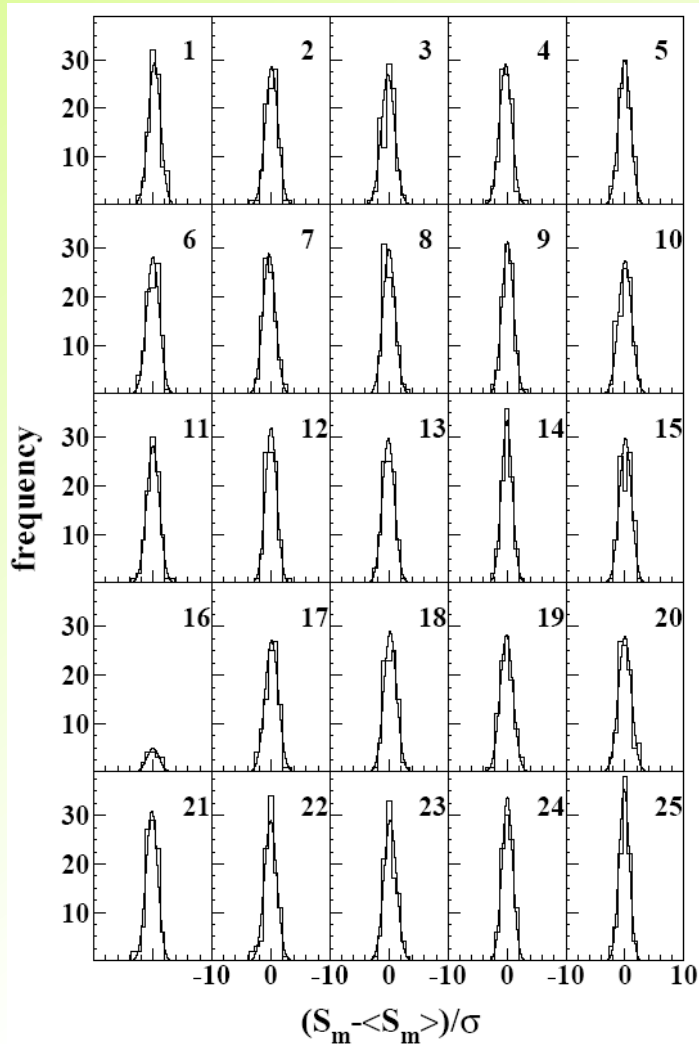
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

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)

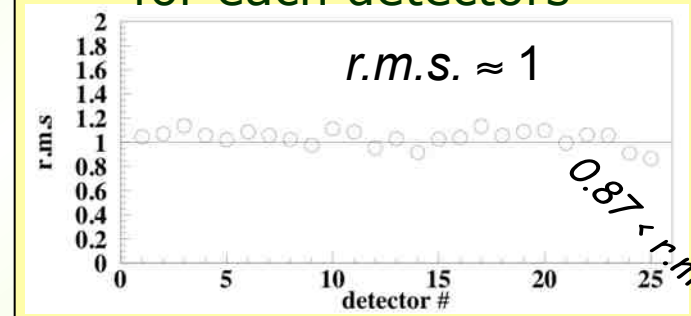
total exposure: 0.87 ton×yr

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



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

$$\chi^2 = \sum x^2$$

Individual S_m values follow a normal distribution since $(S_m - \langle S_m \rangle) / \sigma$ is distributed as a Gaussian with a unitary standard deviation (r.m.s.)



S_m statistically well distributed in all the detectors and annual cycles

Statistical analyses about modulation amplitudes (S_m)

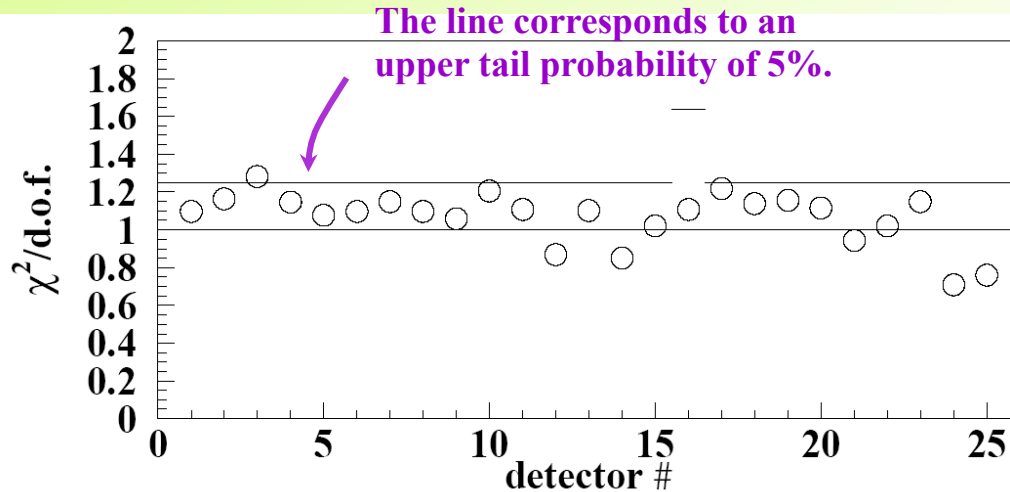
$$x = (S_m - \langle S_m \rangle) / \sigma,$$

$$\chi^2 = \sum x^2$$

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

DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr



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

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

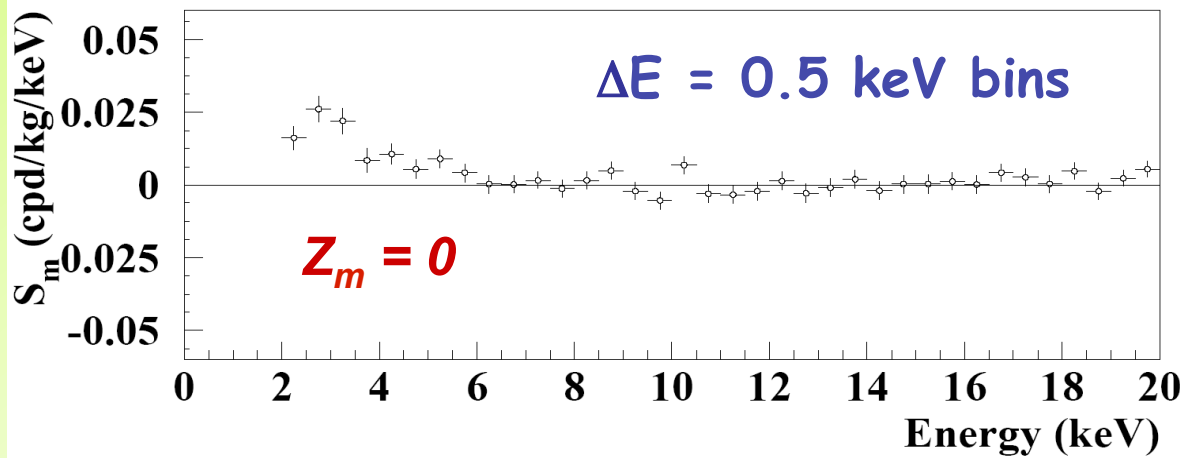
- The mean value of the twenty-five points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 4 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 5 \times 10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error ($\leq 4\%$ or $\leq 0.5\%$, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

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

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

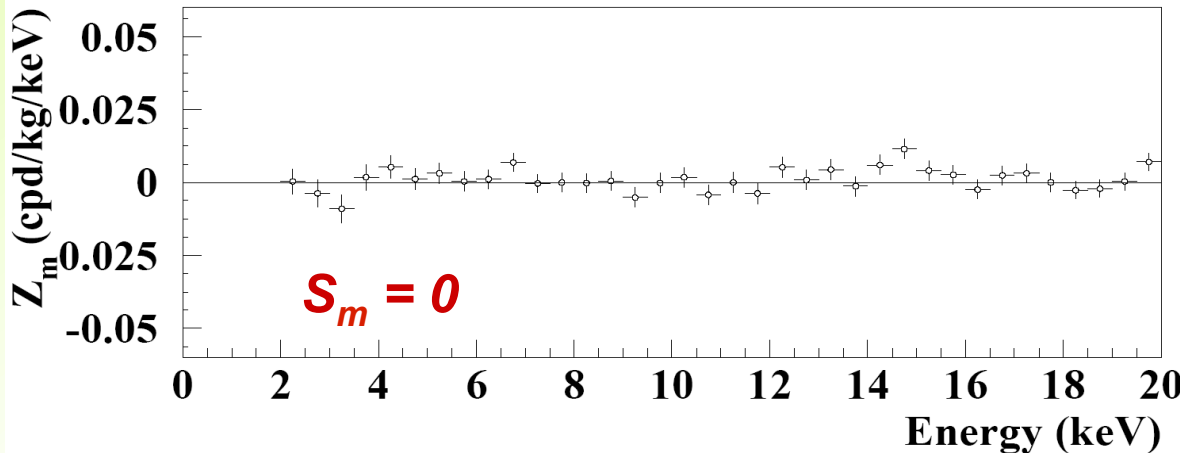
DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

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



$t_0 = 152.5$ day (2° June)

*maximum at 2° June
as for DM particles*



*maximum at 1° September
T/4 days after 2° June*

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

Is there a sinusoidal contribution in the signal? Phase $\neq 152.5$ day?

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

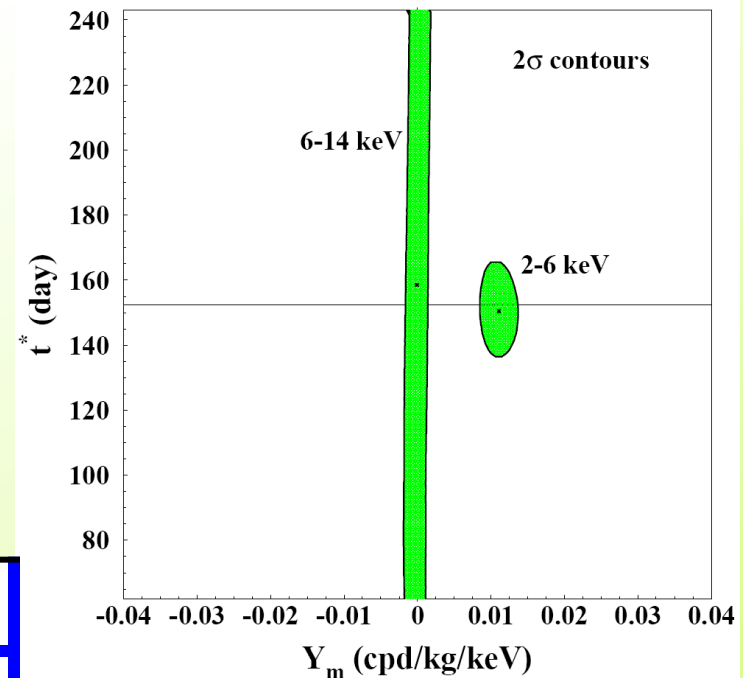
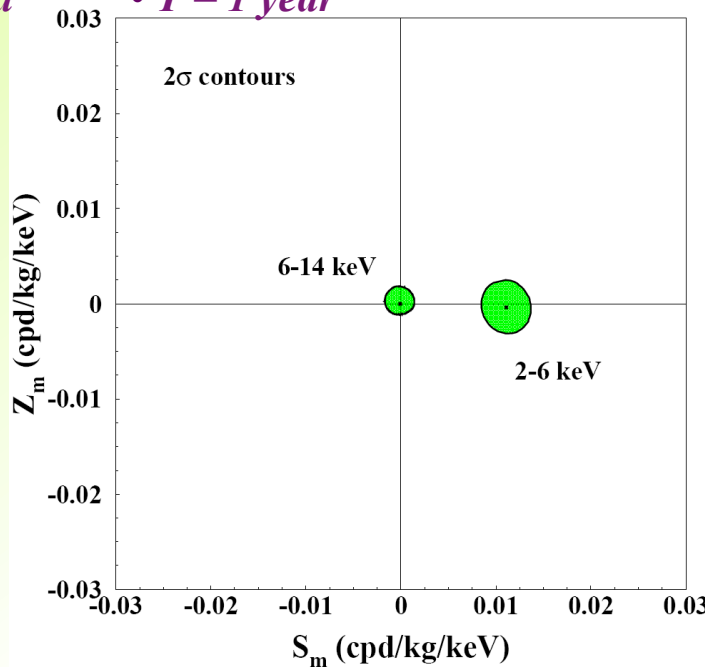
total exposure: 425428 kg×day = 1.17 ton×yr

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

For Dark Matter signals:

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

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

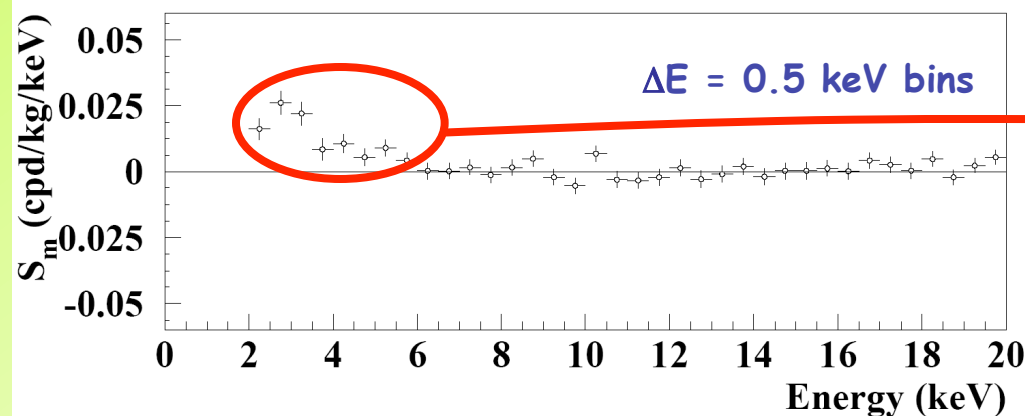
All the measured amplitudes well compatible with zero

+ none can account for the observed effect

(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

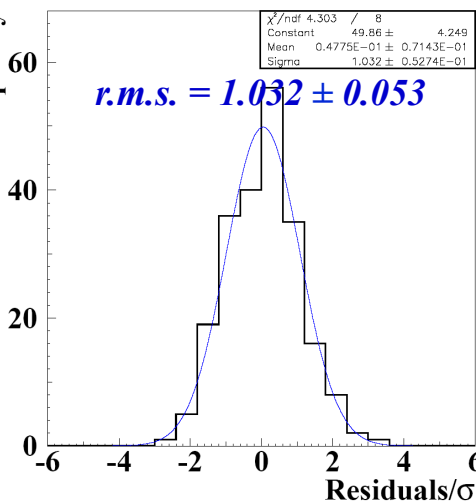
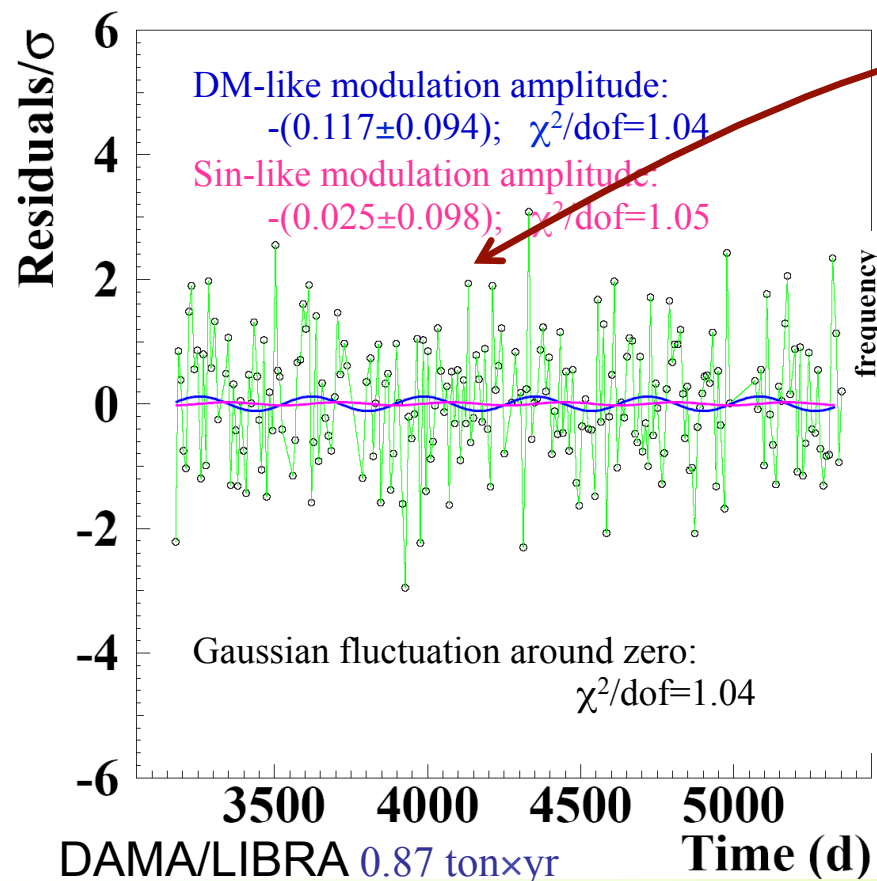
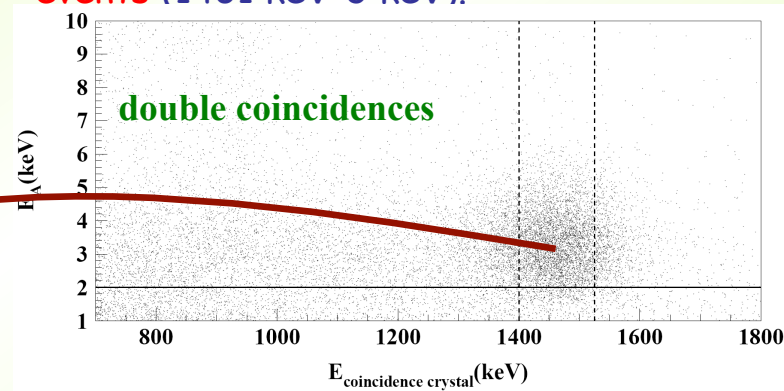
No role for ^{40}K in the experimental S_m

also see arXiv:0912.0660



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

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



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

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

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

NO

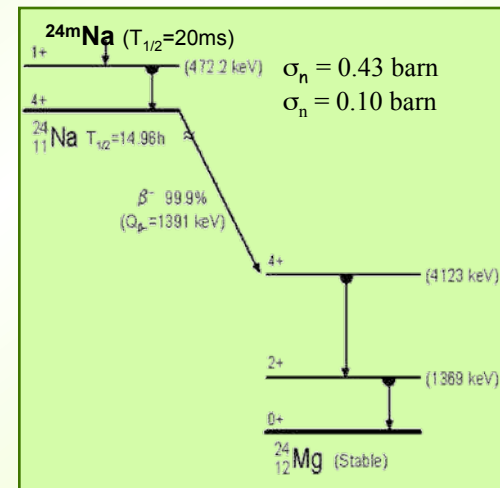
- Thermal neutrons flux measured at LNGS :

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

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

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

- 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 = $\Phi_n \sigma_n N_T < 0.022 \text{ captures/day/kg}$

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

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

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

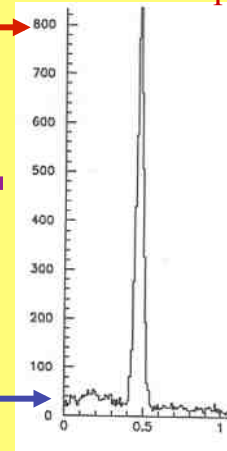
Already excluded also by R_{90} analysis

MC simulation of the process

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

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

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



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:

$$\Phi_n = 0.9 \cdot 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \text{ (Astropart.Phys.4 (1995)23)}$$

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

HYPOTHESIS: assuming - very cautiously - a 10% neutron modulation: $\Rightarrow S_m^{(\text{fast n})} < 10^{-4} \text{ cpd/kg/keV} (< 0.5\% S_m^{\text{observed}})$

- Experimental upper limit on the fast neutrons flux “surviving” the neutron shield in DAMA/LIBRA:
 - through the study of the inelastic reaction $^{23}\text{Na}(n,n')^{23}\text{Na}^*(2076 \text{ keV})$ 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 accompanied by thermalized component)
already excluded also by R_{90}
- ▶ a modulation amplitude for multiple-hit events different from zero
already excluded by the multiple-hit events

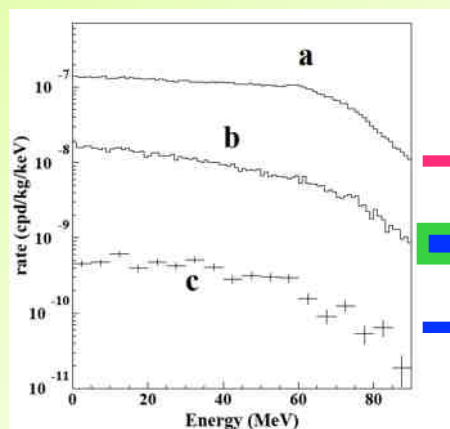
Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

The μ case

MonteCarlo simulation

- muon intensity distribution
 - Gran Sasso rock overburden map
- events where just one detector fires

DAMA/LIBRA surface $\approx 0.15 \text{ m}^2$
 μ flux @ DAMA/LIBRA $\approx 2.5 \mu/\text{day}$



1.

Case of fast neutrons produced by μ

Φ_μ @ LNGS $\approx 20 \mu \text{ m}^{-2} \text{ d}^{-1}$ ($\pm 2\%$ modulated)
 Measured neutron Yield @ LNGS: $Y = 1.7 \cdot 10^{-4} \text{ n}/\mu/(\text{g}/\text{cm}^2)$
 $R_n = (\text{fast n by } \mu)/(\text{time unit}) = \Phi_\mu Y M_{\text{eff}}$

Annual modulation amplitude at low energy due to μ modulation:

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

$\left\{ \begin{array}{l} g = \text{geometrical factor}; \quad \varepsilon = \text{detection eff. by elastic scattering} \\ f_{\Delta E} = \text{energy window (E>2keV) eff.}; \quad f_{\text{single}} = \text{single hit eff.} \end{array} \right\}$

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

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

Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events
It cannot mimic the signature: already excluded also by R_{90} , by *multi-hits* analysis + different phase, etc.

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

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

?

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

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

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 $\pm 15 \text{ d}$, BOREXINO = July 6th $\pm 6 \text{ d}$

DAMA/NaI + DAMA/LIBRA
 measured a stable phase: May, 26th $\pm 7 \text{ days}$

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

R_{90} , multi-hits, phase, and other analyses

NO

more about the phase of muons ...

2.

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)

μ flux @ LNGS (MACRO, LVD, BOREXINO)
 $\approx 3 \cdot 10^{-4} \text{ m}^{-2}\text{s}^{-1}$; modulation amplitude 1.5%; phase:

July 6 ± 6 days (BOREXINO, CSN2 sept. 2010)

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

DAMA Phase

No Compatibility

Borexino Phase

DAMA phase + 3σ

MAY

JUNE

JULY

The DAMA phase is 5.7σ far from the LVD/BOREXINO phases of muons (7.3σ far from MACRO measured phase)

- 1) if we assume for a while that the real value of the DAMA phase is June 16th (that is 3σ fluctuation from the measured value), it is well far from all the measured phases of muons by LVD, MACRO and BOREXINO, in all the years
- 2) Moreover, considering the seasonal weather condition in Gran Sasso, it is quite impossible that the maximum temperature of the outer atmosphere (on which μ flux modulation is dependent) is observed in the middle of June


Inconsistency of the phase between DAMA signal and μ modulation

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

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



+ they cannot
satisfy all the requirements of
annual modulation signature



Thus, they cannot mimic
the observed annual
modulation effect

Summarizing

- 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 \times 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 many possible astrophysical, nuclear and particle physics scenarios)

Neutralino as LSP in various SUSY theories

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

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

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

Sterile neutrino

Self interacting Dark Matter

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

Elementary Black holes such as the Daemons

Kaluza Klein particles

... and more

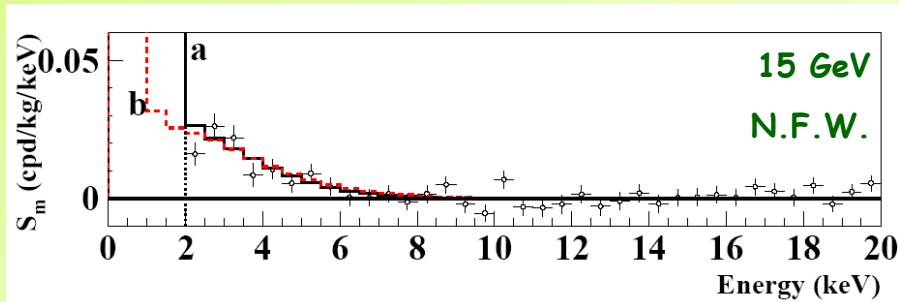


Possible model dependent positive hints from indirect searches (but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.)
not in conflict with DAMA results;

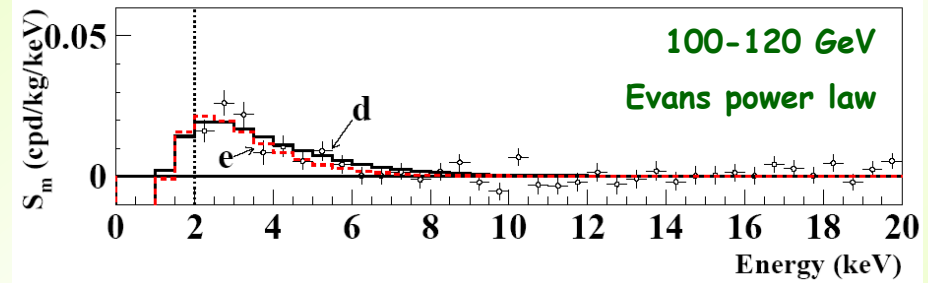
Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with positive excesses

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

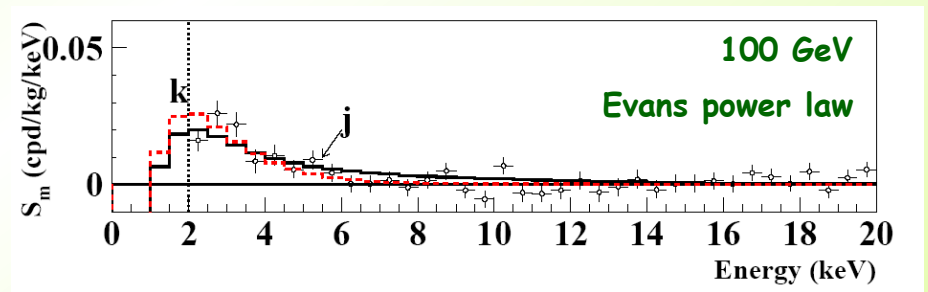
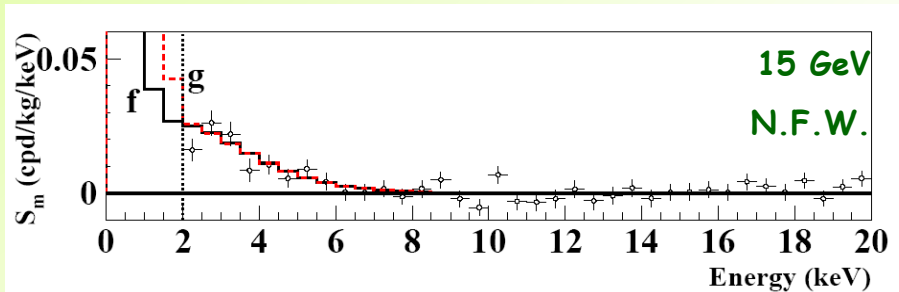
WIMP: SI



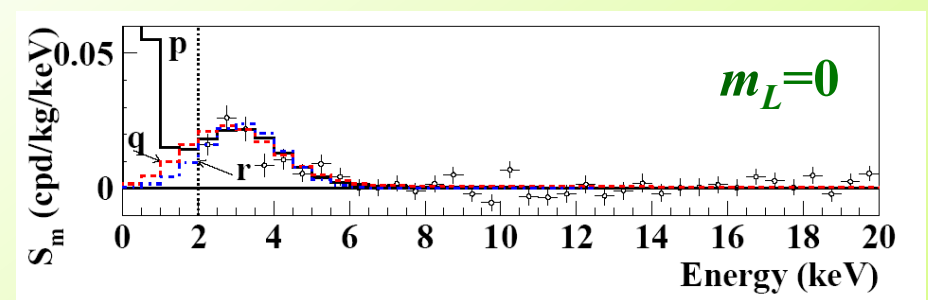
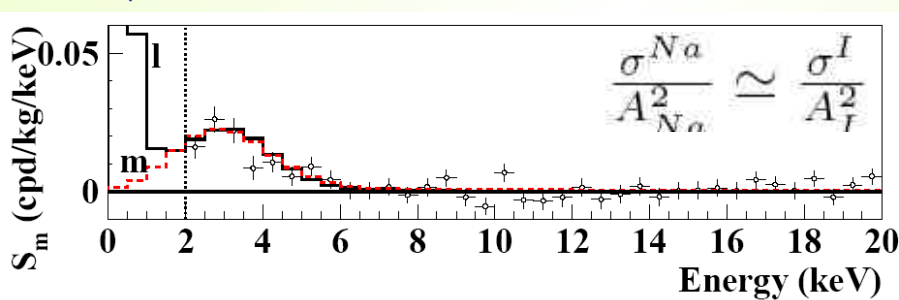
- Not best fit
- About the same C.L.



WIMP: SI & SD $\theta = 2.435$



LDM, bosonic DM



EPJC56(2008)333

Compatibility with several candidates; other ones are open

About interpretation

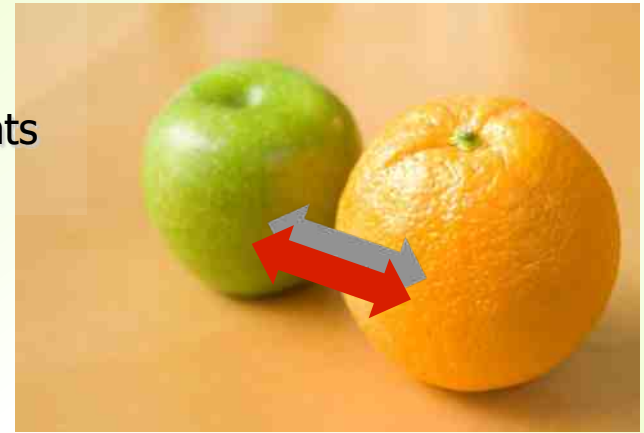
- ✓ Not a unique reference model for Dark Matter particles
- ✓ Not a single set of assumptions for parameters in the astrophysical, nuclear and particle physics related arguments
- ✓ Often comparisons are made in inconsistent way

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

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

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

For example, which L_{eff} in liquid Xenon experiments?
arXiv:0909.1063, 1005.0838, 1005.3723, 1106.0653,



... and experimental aspects ...

- **Marginal and “selected” exposures.** Threshold, small detector response (few phe/keV), energy scale and energy resolution; calibrations in other energy region. Stability of all the operating conditions. Selections of detectors and of data. Handling of (many) “subtraction” procedures and stability in time of all the selection windows and related quantities, etc. Efficiencies. Fiducial volume vs disuniformity of detector, response in liquids? Used values in the calculation (q.f., etc.). Used approximations. ... arXiv:0806.0011, PLB637 156

1106.0653: “A lingering critical question is to what extent a determination of L_{eff} performed using highly-optimized compact calibration detectors like those in ... can be applied with confidence to a much larger device like the XENON100 detector, featuring a small S1 light-detection efficiency (just ~6%), different hardware trigger configuration, data processing, etc.”

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

Examples of uncertainties in models and scenarios

see for some details e.g.:

Riv.N.Cim.26 n.1 (2003) 1, IJMPD13(2004)2127,
EPJC47 (2006)263, IJMPA21 (2006)1445

Nature of the candidate and couplings

- WIMP class particles (neutrino, sneutrino, etc.): SI, SD, mixed SI&SD, preferred inelastic + e.m. contribution in the detection
- Light bosonic particles
- Kaluza-Klein particles
- Mirror dark matter
- Heavy Exotic candidate
- ...etc. etc.

Scaling laws of cross sections for the case of recoiling nuclei

- Different scaling laws for different DM particle:

$$\sigma_A \propto \mu^2 A^2 (1 + \epsilon_A)$$

$\epsilon_A = 0$ generally assumed

$\epsilon_A \approx \pm 1$ in some nuclei? even for neutralino candidate in MSSM (see Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301)

Halo models & Astrophysical scenario

- Isothermal sphere \Rightarrow very simple but unphysical halo model
- Many consistent halo models with different density and velocity distribution profiles can be considered with their own specific parameters (see e.g. PRD61(2000)023512)
- Caustic halo model
- Presence of non-thermalized DM particle components
- Streams due e.g. to satellite galaxies of the Milky Way (such as the Sagittarius Dwarf)
- Multi-component DM halo
- Clumpiness at small or large scale
- Solar Wakes
- ...etc. ...

Form Factors for the case of recoiling nuclei

- Many different profiles available in literature for each isotope
- Parameters to fix for the considered profiles
- Dependence on particle-nucleus interaction
- In SD form factors: no decoupling between nuclear and Dark Matter particles degrees of freedom + dependence on nuclear potential

Spin Factors for the case of recoiling nuclei

- Calculations in different models give very different values also for the same isotope
- Depend on the nuclear potential models
- Large differences in the measured counting rate can be expected using:
 - either SD not-sensitive isotopes
 - or SD sensitive isotopes depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the ^{23}Na and ^{127}I cases).

Instrumental quantities

- Energy resolution
- Efficiencies
- Quenching factors
- Channeling effects
- Their dependence on energy
- ...

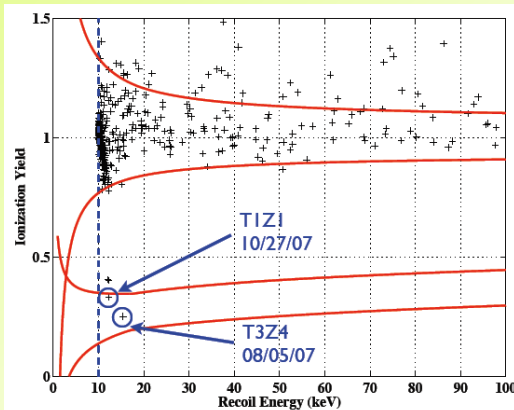
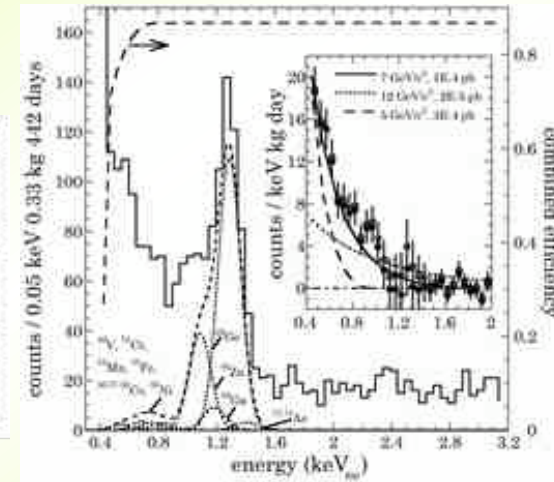
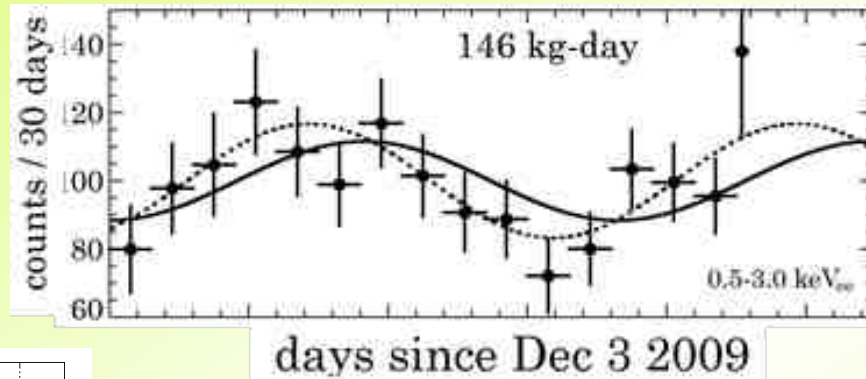
Quenching Factor

- differences are present in different experimental determinations of q for the same nuclei in the same kind of detector depending on its specific features (e.g. q depends on dopant and on the impurities; in liquid noble gas e.g. on trace impurities, on presence of degassing/releasing materials, on thermodynamical conditions, on possibly applied electric field, etc); assumed 1 in bolometers
- channeling effects possible increase at low energy in scintillators (dL/dx)
- possible larger values of q (AstropPhys33 (2010) 40)
 - \rightarrow energy dependence

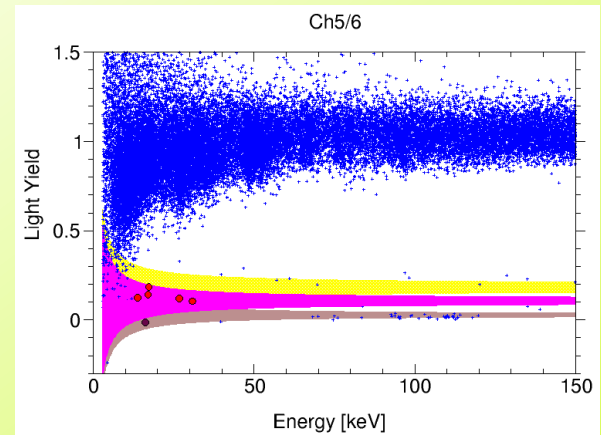
... and more ...

DAMA/NaI & DAMA/LIBRA vs the recent results on 2010/11 (positive excesses)

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



- **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 excesses, if interpreted in WIMP scenarios, are also compatible with the DAMA annual modulation result in various scenarios

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, arXiv:1106.4667 in press on PRD)
- 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)
- 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)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Composite DM (IJMPD19(2010)1385)
- iDM on TI (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)
- Light scalar WIMP through Higgs portal (arXiv:1003.2595)
- 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 (arXiv:1105.5121, 1105.3734, 1011.1499, JCAP1008(2010)018, PRD82(2010)115019, ...)

... 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:
 $M_1/M_2 \approx 0.5 (<)$;
 (where M_1 and M_2 U(1) and SU(2) gaugino masses)

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

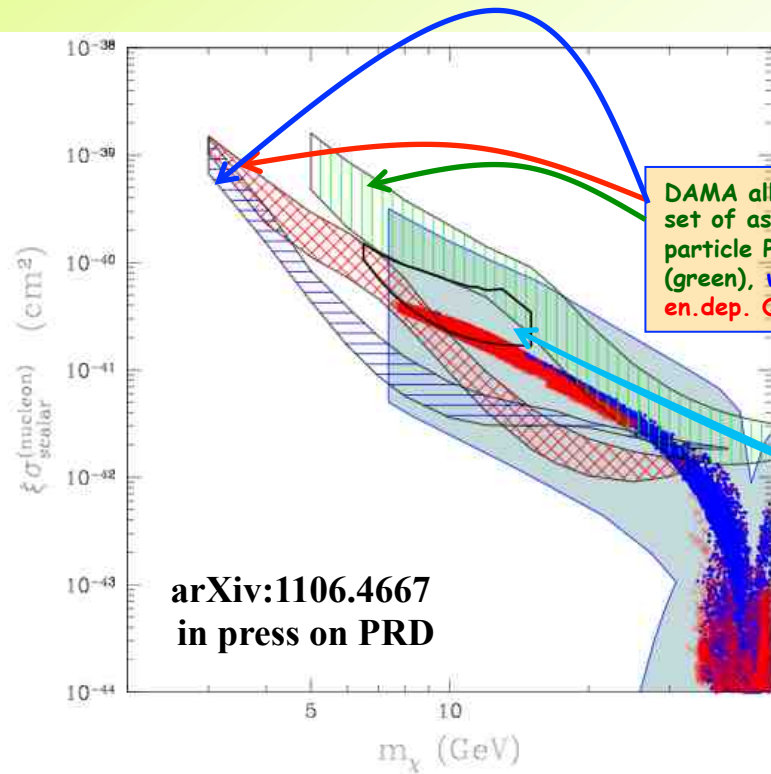
CoGeNT and CRESST

If the two CDMS events are interpreted as relic neutralino interactions

Relic neutralino in effMSSM

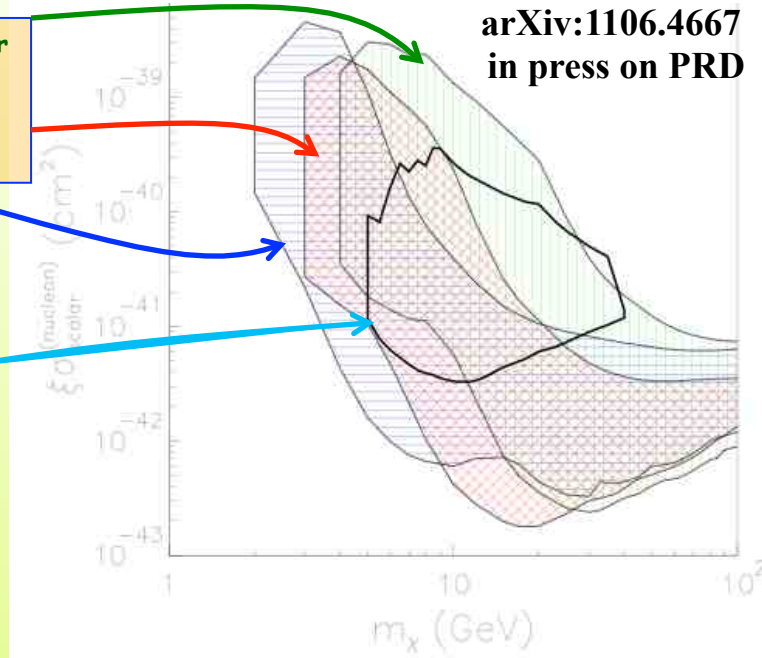
N. Fornengo, S. Scopel, F. Bottino (2010)

PRD83 (2011) 015001



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



... 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

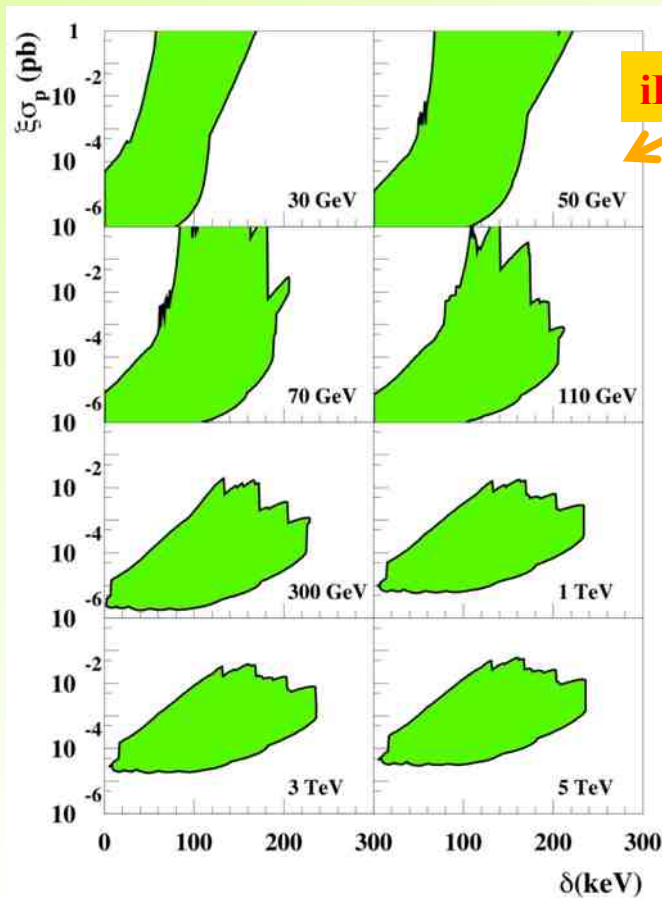
$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

DAMA/NaI+DAMA/LIBRA

Slices from the 3-dimensional allowed volume

iDM interaction on Iodine nuclei

Fund. Phys. 40(2010)900



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

- For **large splittings**, the dominant scattering in NaI(Tl) can occur off of **Thallium nuclei**, with $A \sim 205$, 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



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 8.9σ C.L. (cumulative exposure $1.17 \text{ ton} \times \text{yr}$ – 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



- 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

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