Signals from the Dark Universe: the annual modulation results by DAMA/LIBRA

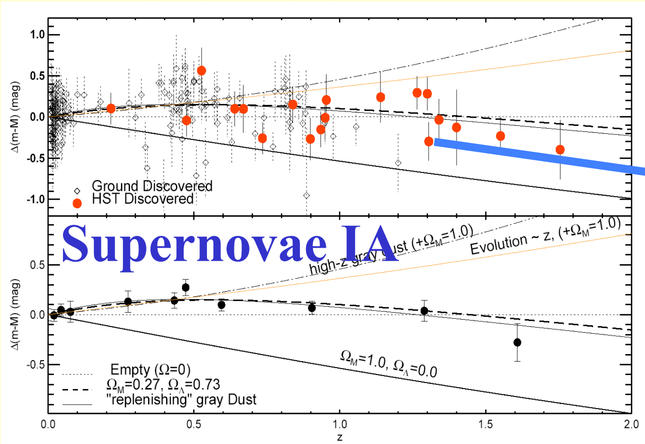
SISSA

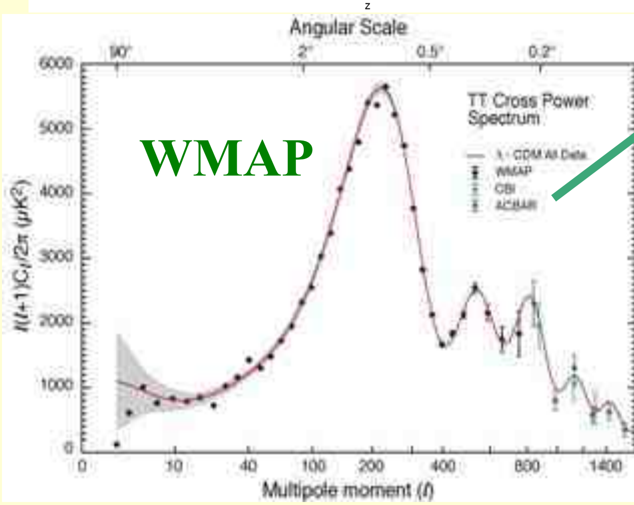
Trieste, January 10, 2011

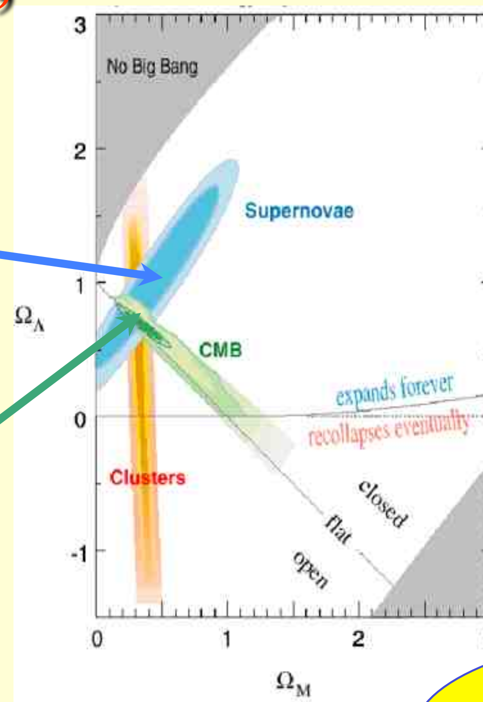
P. Belli

INFN-Roma Tor Vergata

"Concordance model"







$\Omega = \Omega_\Lambda + \Omega_M =$ **close to 1**

Ω = density/critical density

6 atoms of H/m^3

$$\Omega_\Lambda \approx 0.74$$
$$\Omega_M \approx 0.26$$

The Universe is flat

Primordial Nucleosynthesis

Observations on:
- light nuclei abundance
- microlensings
- visible light.

Structure formation in the Universe

The baryons give "too small" contribution

$\Omega_b \sim 4\%$

Non baryonic **Cold Dark Matter** is dominant

$\Omega_{CDM} \sim 22\%,$
$\Omega_{HDM,\nu} < 1\ \%$

~ 90% of the matter in the Universe is non baryonic

A large part of the Universe is in form of non baryonic Cold Dark Matter particles

Relic DM particles from primordial Universe

SUSY
(as neutralino or sneutrino
In various scenarios)

the sneutrino in the Smith
and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not
yet foreseen by theories

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects,
Daemons

etc…

(& invisible axions, ν's)

&

Right halo model and parameters?

- Composition?
  DM multicomponent also
  in the particle part?
- Right related nuclear and
  particle physics?

Non thermalized components?

Caustics?

clumpiness?

etc… etc…

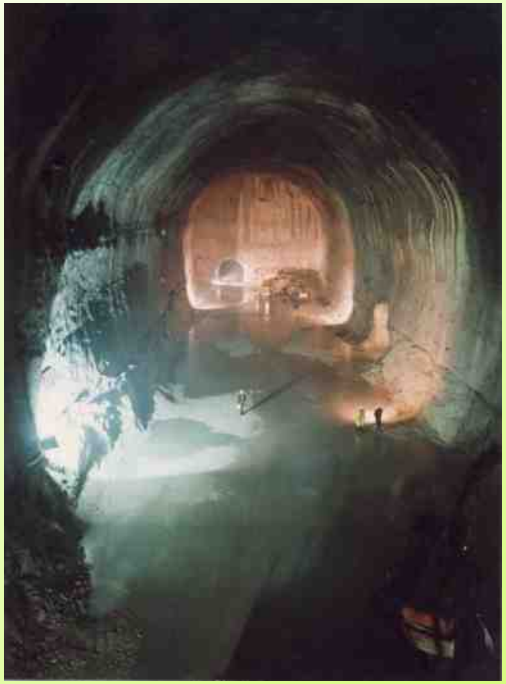
What accelerators can do:

to demostrate the existence of some of the possible DM candidates

What accelerators cannot do:

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

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

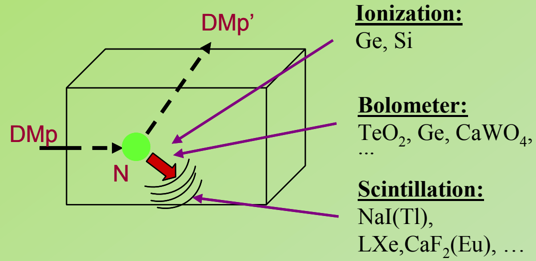


DM direct detection method using a model independent approach and a low-background widely-sensitive target material

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



- 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

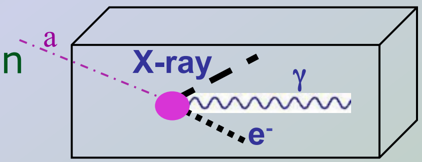
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

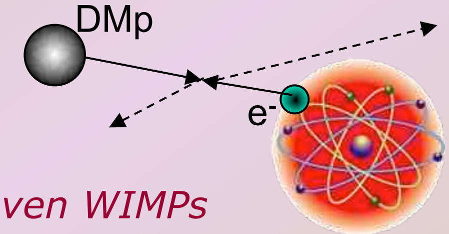
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

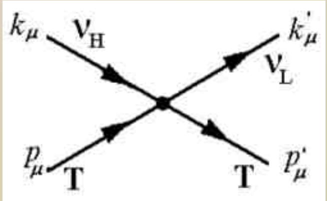
  → detection of e.m. radiation



… even WIMPs

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

  → detection of electron/nucleus recoil energy



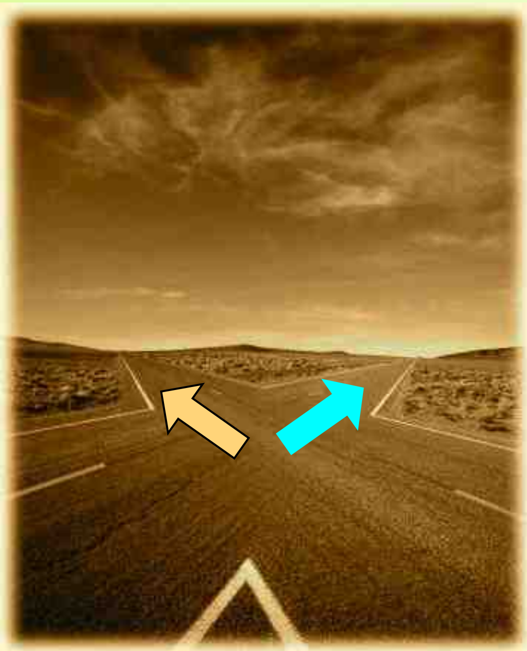
e.g. sterile ν

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 …

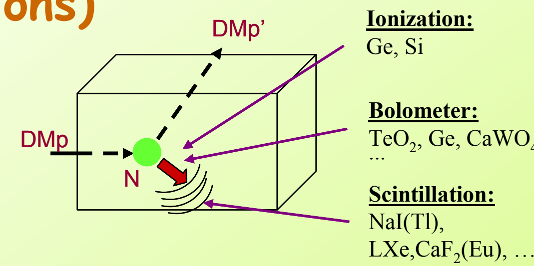
- **… and more**

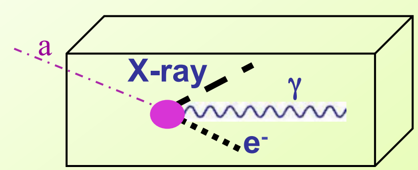
The direct detection experiments can be classified in two classes, depending on what they are based:



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)

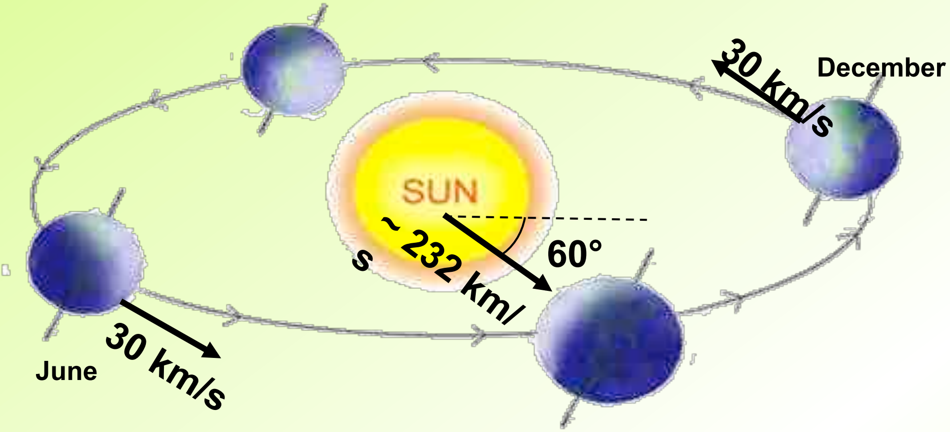




The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

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_{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
- $t_0 = 2^{nd}$ 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

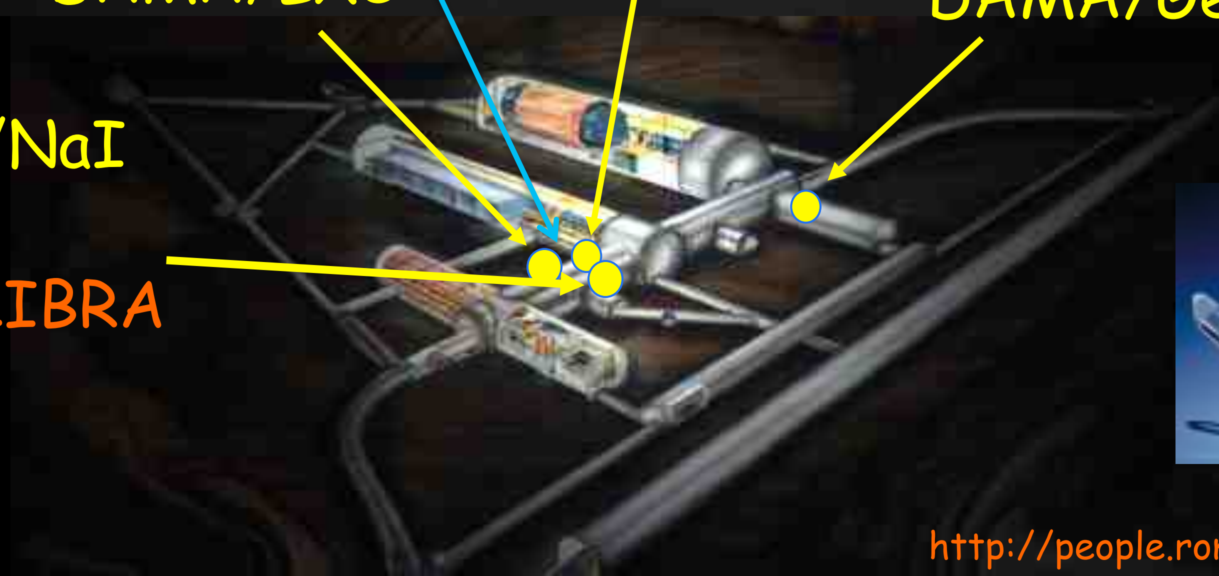
To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

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

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 membership

Overall membership in the DAMA activities

Spokesperson: R. Bernabei

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

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

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

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

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

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

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

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

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

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

+ in neutron measurements:

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

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

DAMA/LXe: results on rare processes

Dark Matter Investigation

NIMA482(2002)728

- Limits on recoils investigating the DMp-^{129}Xe elastic scattering by means of PSD — 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 $^{136}Xe \rightarrow {}^{136}Cs$ — 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 $^{139}La \rightarrow {}^{139}Ce$ — UJP51(2006)1037
- α decay of natural Eu — NPA789(2007)15
- β decay of ^{113}Cd — PRC76(2007)064603
- ββ decay of ^{64}Zn, ^{70}Zn, ^{180}W, ^{186}W — PLB658(2008)193, NPA826(2009)256, JPG:NPP38(2011)115107
- ββ decay of ^{108}Cd and ^{114}Cd — EPJA36(2008)167
- ββ decay of ^{136}Ce, ^{138}Ce and ^{142}Ce with $CeCl_3$ — JPG: NPP38(2011)015103
- ^{106}Cd, and ^{116}Cd in progress — JINST6(2011)P08011

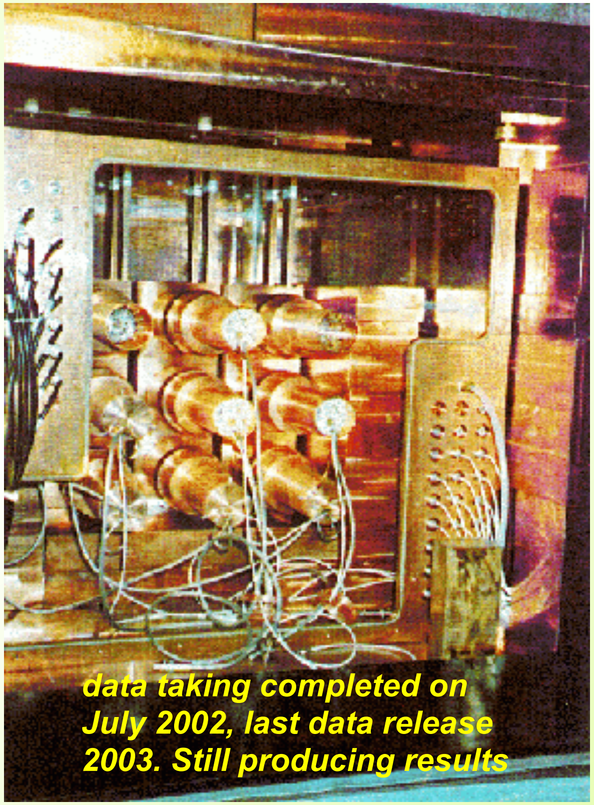
DAMA/Ge & LNGS Ge facility

- 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)
- ββ 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)
- ββ decay of ^{96}Ru and ^{104}Ru (EPJA42(2009)171)
- meas. with a Li_2MoO_4 (NIMA607(2009) 573)
- ββ 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)
- ββ decay in ^{190}Pt and ^{198}Pt (EPJA47(2011)91)
- ββ decay of ^{156}Dy, ^{158}Dy (NPA859(2011)126)
- Contaminations of $SrI_2(Eu)$ (NIMA670(2012)10)

+Many other meas. already scheduled

+ $CdWO_4$ and $ZnWO_4$ readiopurity studies (NIMA626-627(2011)31, NIMA615(2010)301)

The pioneer DAMA/NaI: ≈100 kg highly radiopure NaI(Tl)



Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

Results on rare processes:

- Possible Pauli exclusion principle violation — PLB408(1997)439
- CNC processes — PRC60(1999)065501
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) — PLB460(1999)235
- Search for solar axions — PLB515(2001)6
- Exotic Matter search — EPJdirect C14(2002)1
- Search for superdense nuclear matter — EPJA23(2005)7
- Search for heavy clusters decays — EPJA24(2005)51

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- Annual Modulation Signature

PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004) 2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008) 023506, MPLA23(2008)2125.

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

total exposure (7 annual cycles) 0.29 ton×yr

The 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)

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

- ***Radiopurity,performances, procedures, etc.:*** NIMA592(2008)297
- ***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

DAMA @ LNGS

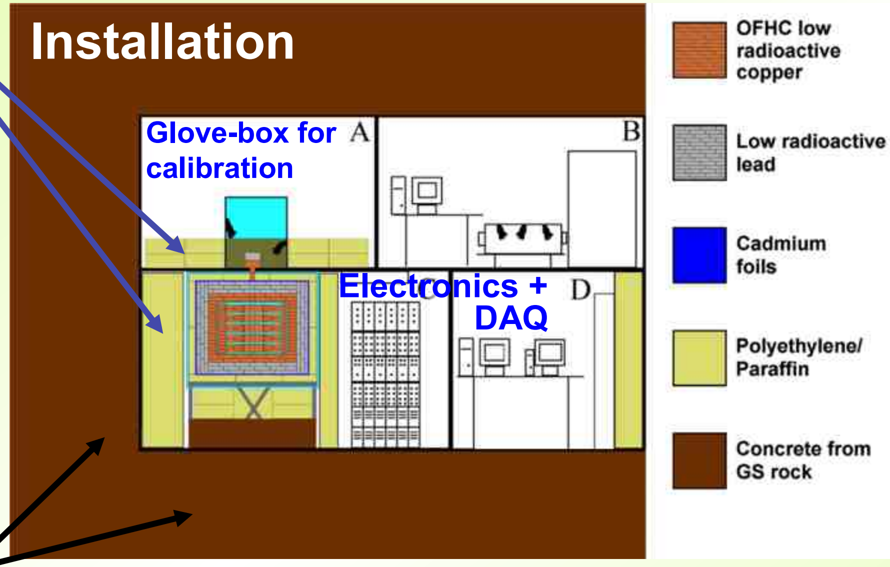
...calibration procedures

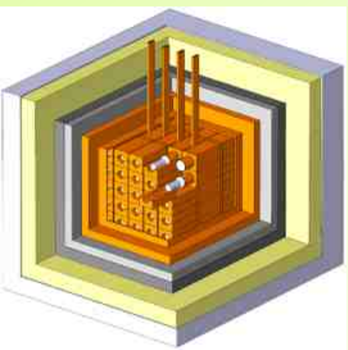
The DAMA/LIBRA set-up

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



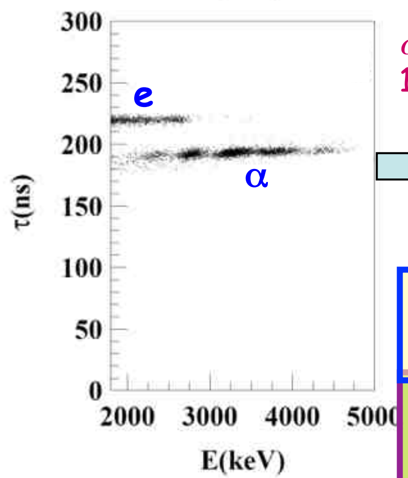


5.5-7.5 phe/keV

~ 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

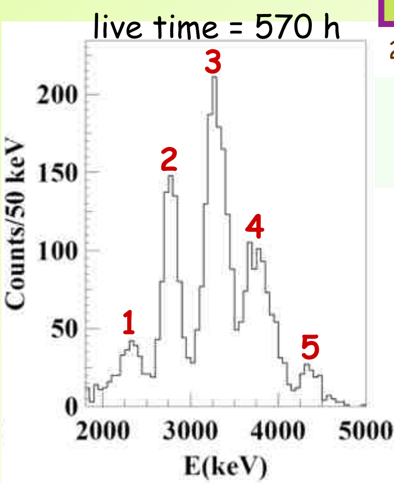
Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling

<u>^{232}Th residual contamination</u>

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

<u>^{238}U residual contamination</u>

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



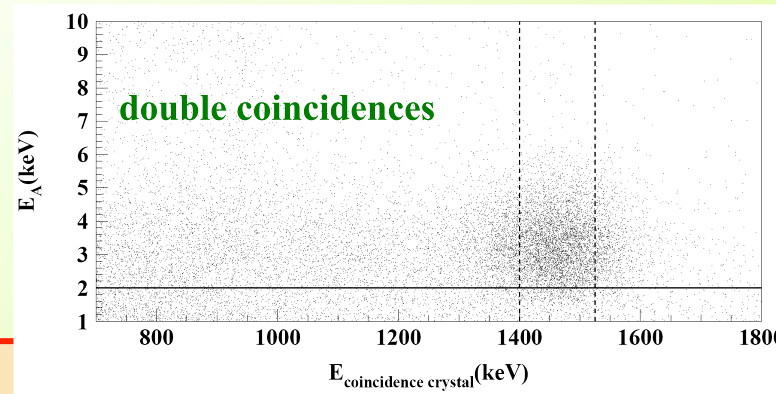
^{238}U chain splitted into 5 subchains: ^{238}U $\rightarrow$ ^{234}U $\rightarrow$ ^{230}Th $\rightarrow$ ^{226}Ra $\rightarrow$ ^{210}Pb $\rightarrow$ ^{206}Pb

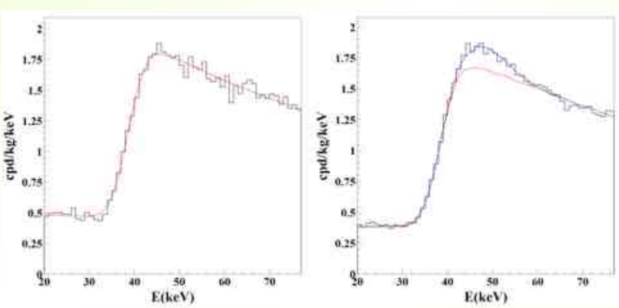
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

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.

<u>^{nat}K residual contamination</u>

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





<u>^{129}I and ^{210}Pb</u>

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

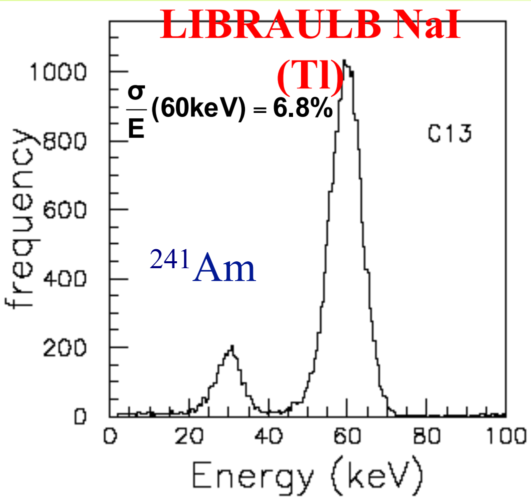
^{210}Pb in the new detectors: (5 − 30) μBq/kg.

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

... more on NIMA592 (2008)297

Examples of energy resolutions

DAMA/ LIBRAULB NaI (Tl)



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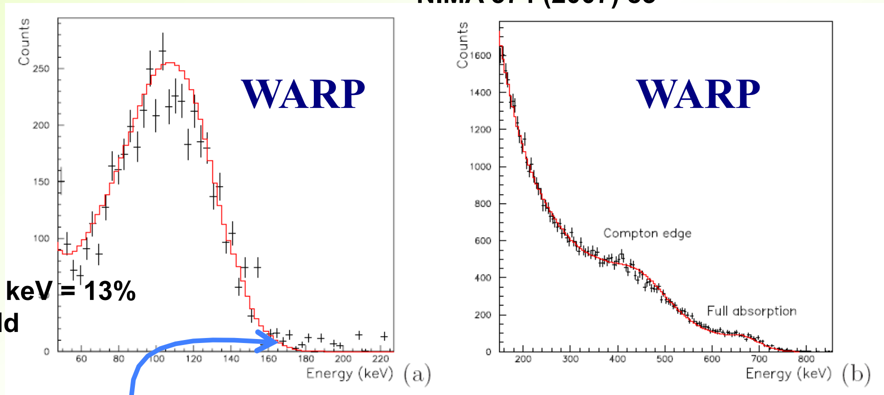

σ/E @ 122 keV = 13%
at zero field

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

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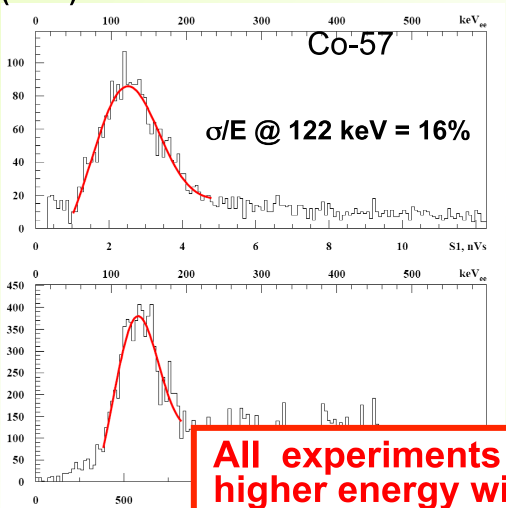
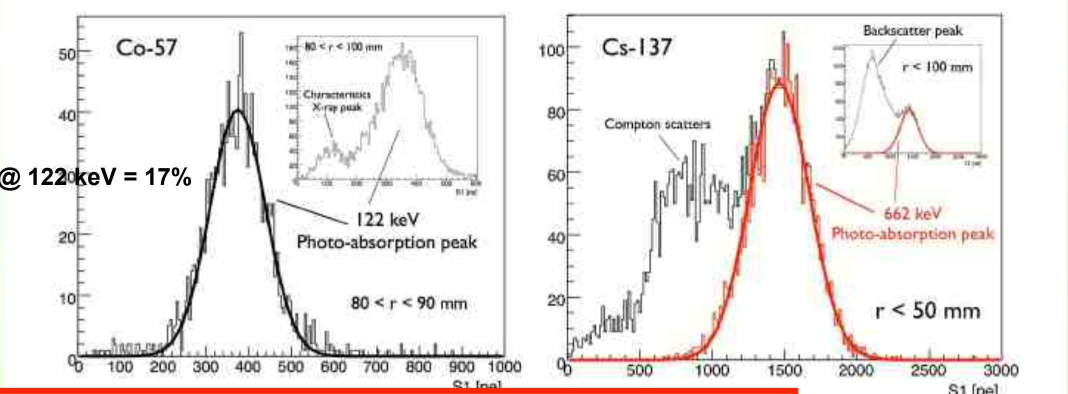


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of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

XENON10 XENON10

σ/E @ 122 keV = 17%



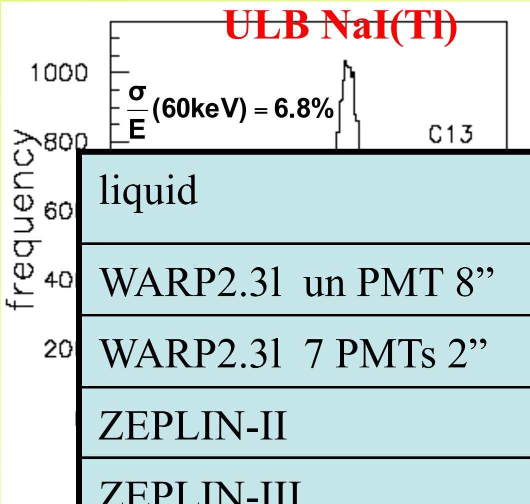
All experiments – except DAMA – use only calibration points at higher energy with extrapolation to low energy

...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

Examples of energy resolutions

DAMA/LIBRA
ULB NaI(Tl)



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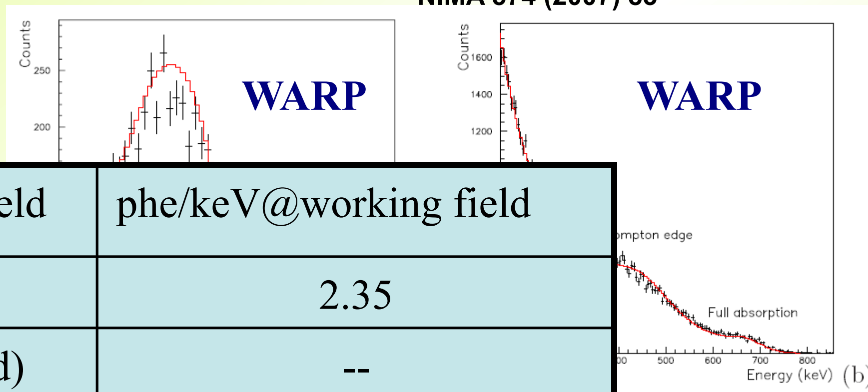

...perimposed with the ...122 keV, B.R. 85.6%,

...rum ?

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

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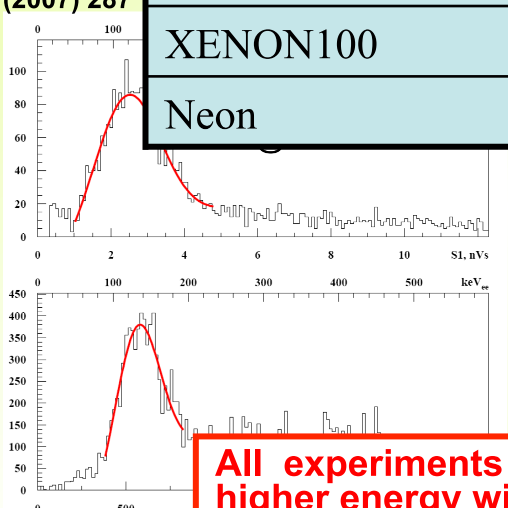
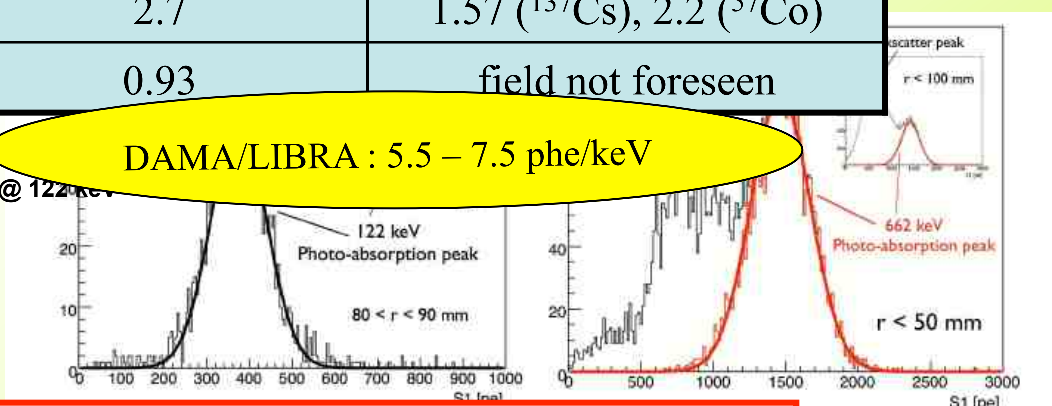


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of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

σ/E @ 122 keV



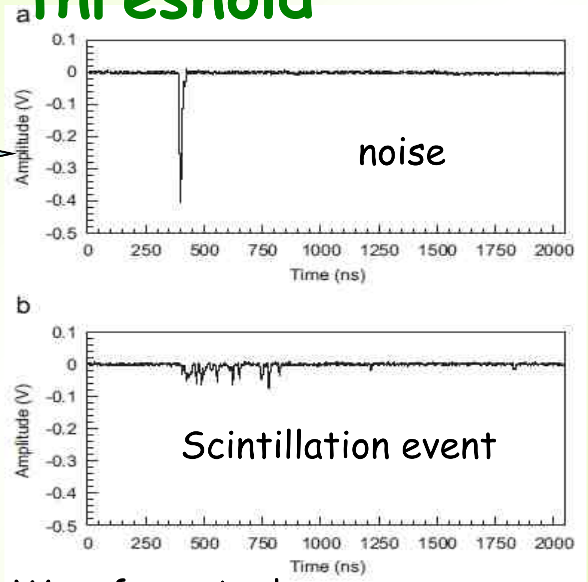
All experiments – except DAMA – use only calibration points at higher energy with extrapolation to low energy

...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.

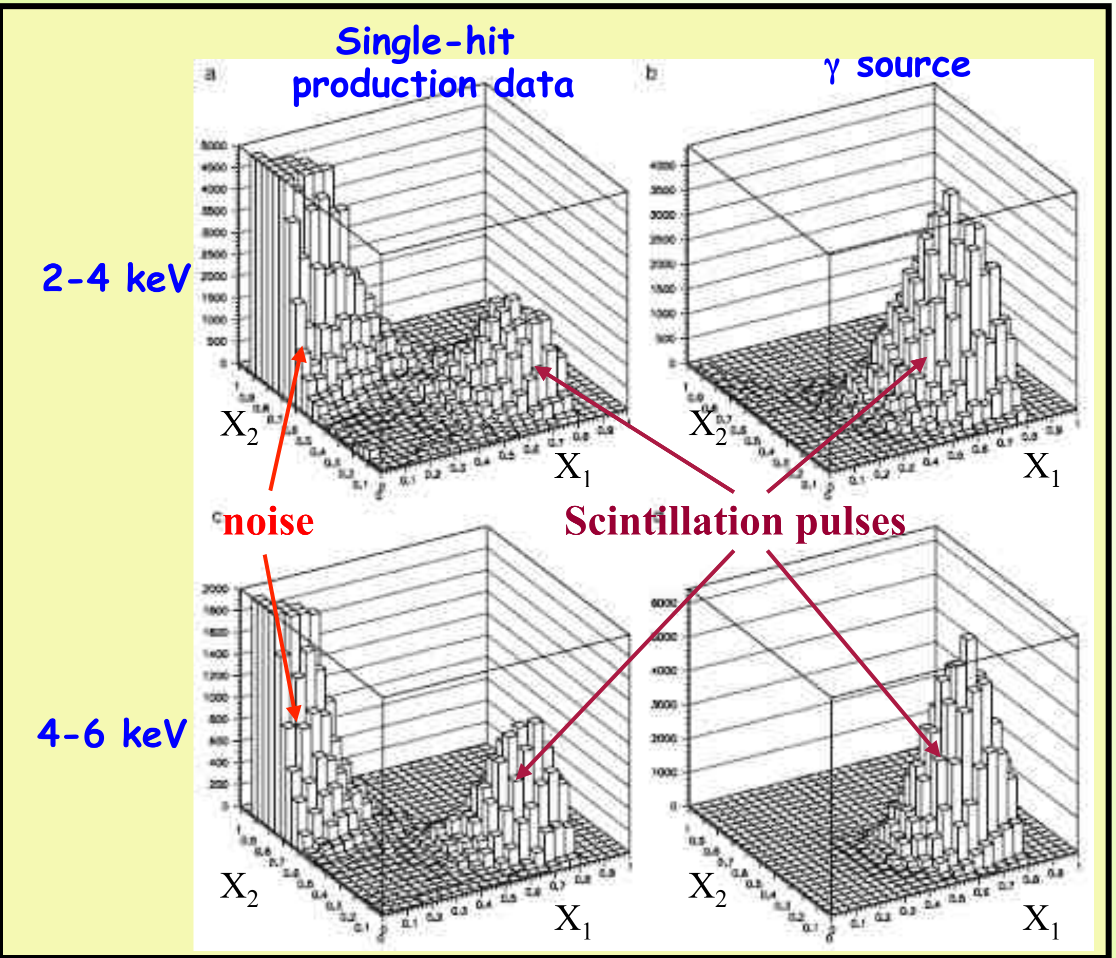
JoP: Conf. Ser. 65 (2007) 012015

Noise rejection near the energy threshold

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



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



From the Waveform Analyser 2048 ns time window:

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

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

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

This is the only procedure applied to the analysed data

Infos about DAMA/LIBRA data taking

Period		Mass (kg)	Exposure (kg × day)	α-β²
DAMA/LIBRA-1	Sep. 9, 2003 – July 21, 2004	232.8	51405	0.562
DAMA/LIBRA-2	July 21, 2004 – Oct. 28, 2005	232.8	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 – July 18, 2006	232.8	39445	0.591
DAMA/LIBRA-4	July 19, 2006 – July 17, 2007	232.8	49377	0.541
DAMA/LIBRA-5	July 17, 2007 – Aug. 29, 2008	232.8	66105	0.468
DAMA/LIBRA-6	Nov. 12, 2008 – Sep. 1, 2009	242.5	58768	0.519
DAMA/LIBRA-1 to -6	**Sep. 9, 2003 – Sep. 1, 2009**		**317697 = 0.87 ton×yr**	**0.519**

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

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

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

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

•First upgrade on Sept 2008:

- replacement of some PMTs in HP N_2 atmosphere
- restore 1 detector to operation
- new Digitizers installed (U1063A Acqiris 1GS/s 8-bit High-Speed cPCI)
- new DAQ system with optical read-out installed

Second upgrade on Nov/Dec 2010

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

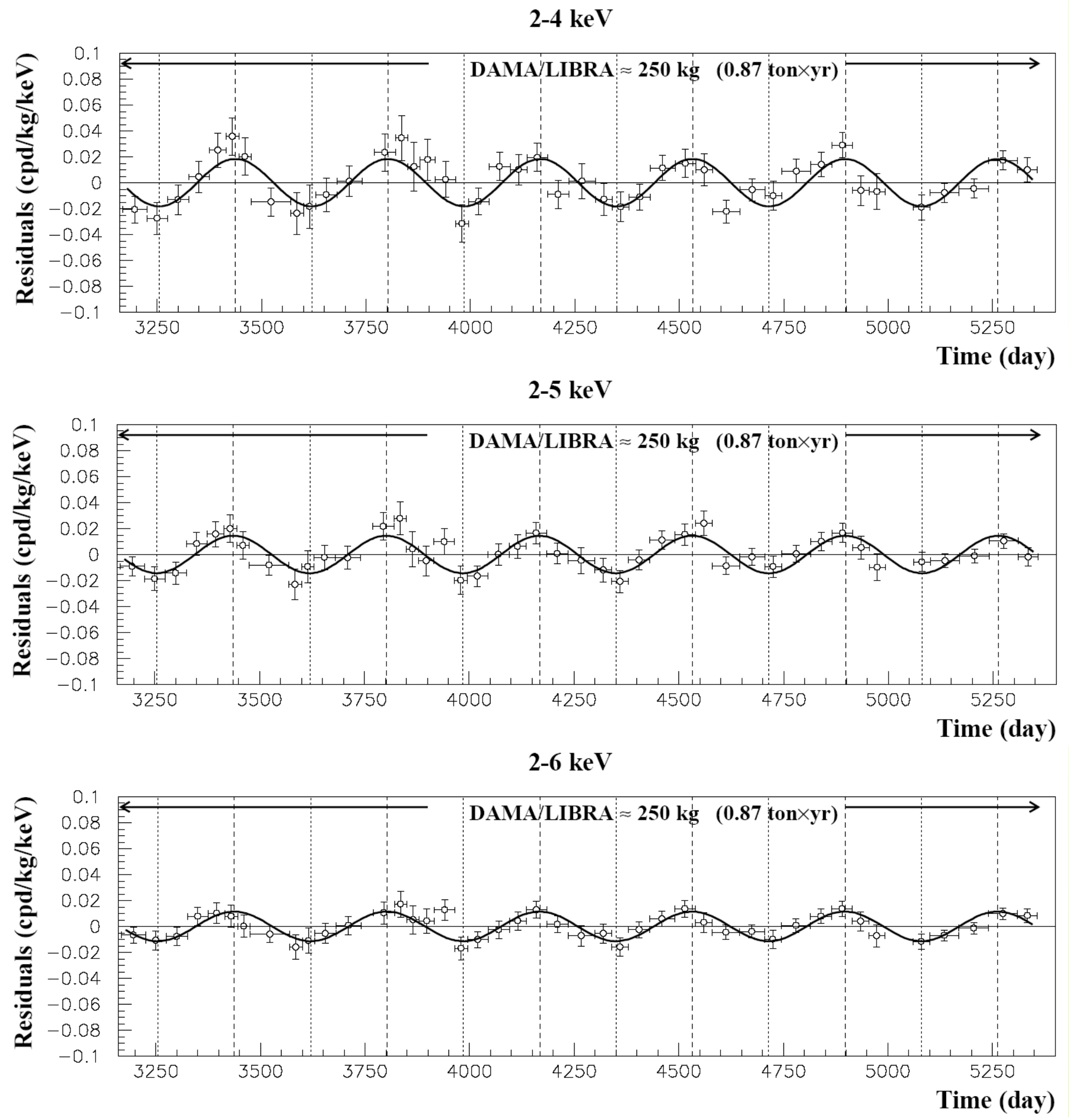
Since Dec 2010 data taking and optimizations in this new configuration started

Model Independent Annual Modulation Result

experimental single-hit residuals rate vs time and energy

DAMA/LIBRA 1-6 (0.87 ton×yr)

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



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

2-4 keV

A=(0.0183±0.0022) cpd/kg/keV

χ^2/dof = 75.7/79 **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=147/80 ⇒ P(A=0) = 7×10^{-6}

2-5 keV

A=(0.0144±0.0016) cpd/kg/keV

χ^2/dof = 56.6/79 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=135/80 ⇒ P(A=0) = 1.1×10^{-4}

2-6 keV

A=(0.0114±0.0013) cpd/kg/keV

χ^2/dof = 64.7/79 **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=140/80 ⇒ P(A=0) = 4.3×10^{-5}

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

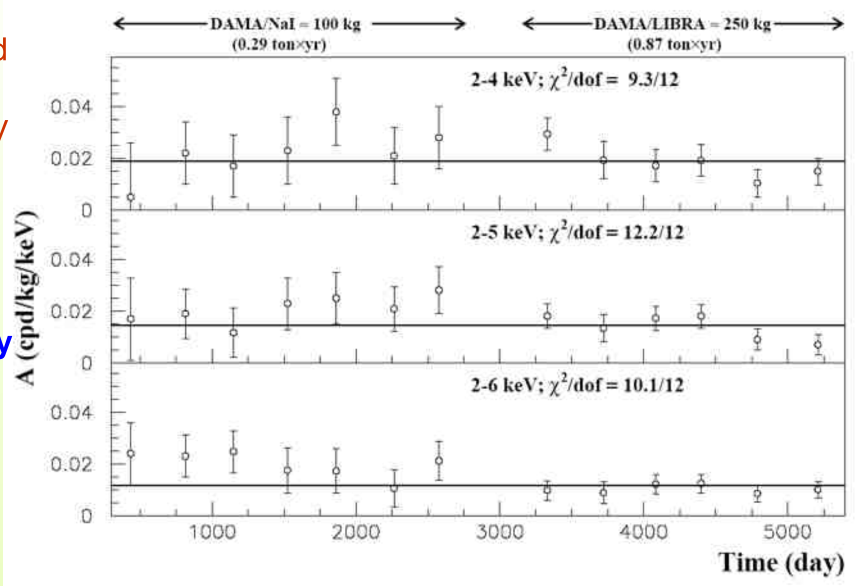
Modulation amplitudes (A), period (T) and phase (t_0) measured in DAMA/NaI and DAMA/LIBRA

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

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

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

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



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

Compatibility among the annual cycles

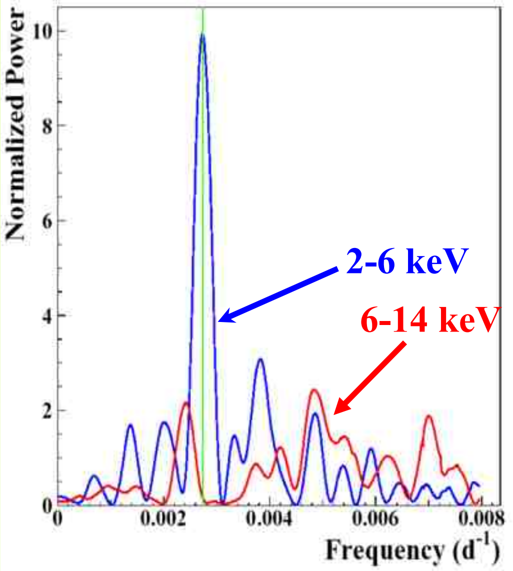
Power spectrum of single-hit residuals

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

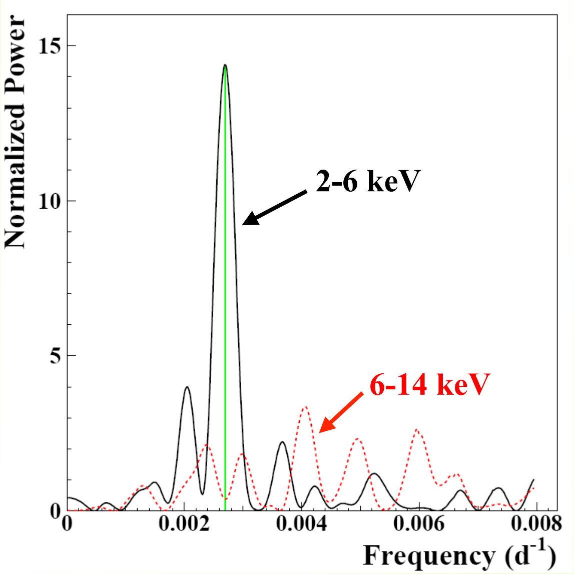
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

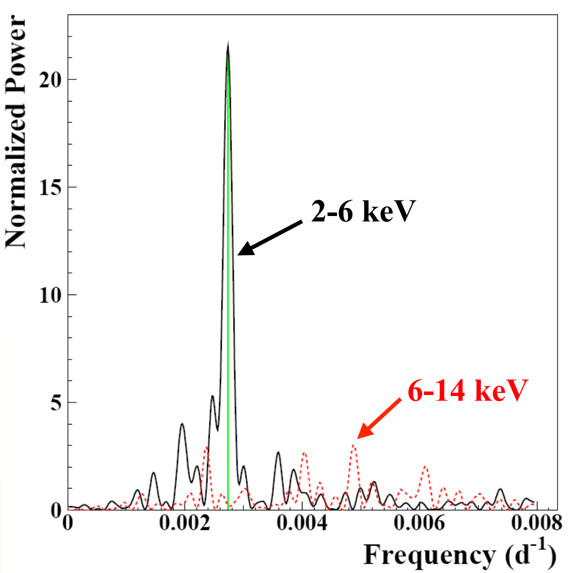
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



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



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



Principal mode in the 2-6 keV region:

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

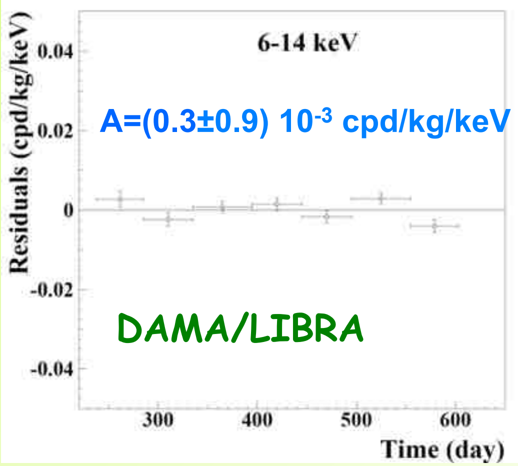
+

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

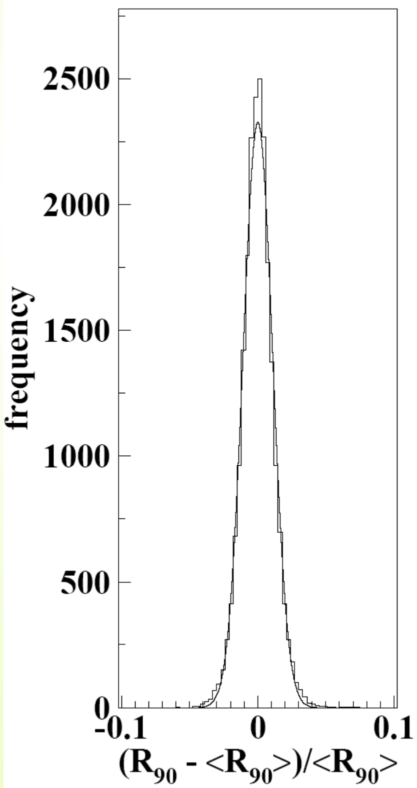
- **No Modulation above 6 keV**



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 to -6



σ ≈ 1%, fully accounted by statistical considerations

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

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

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

consistent with zero

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

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

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

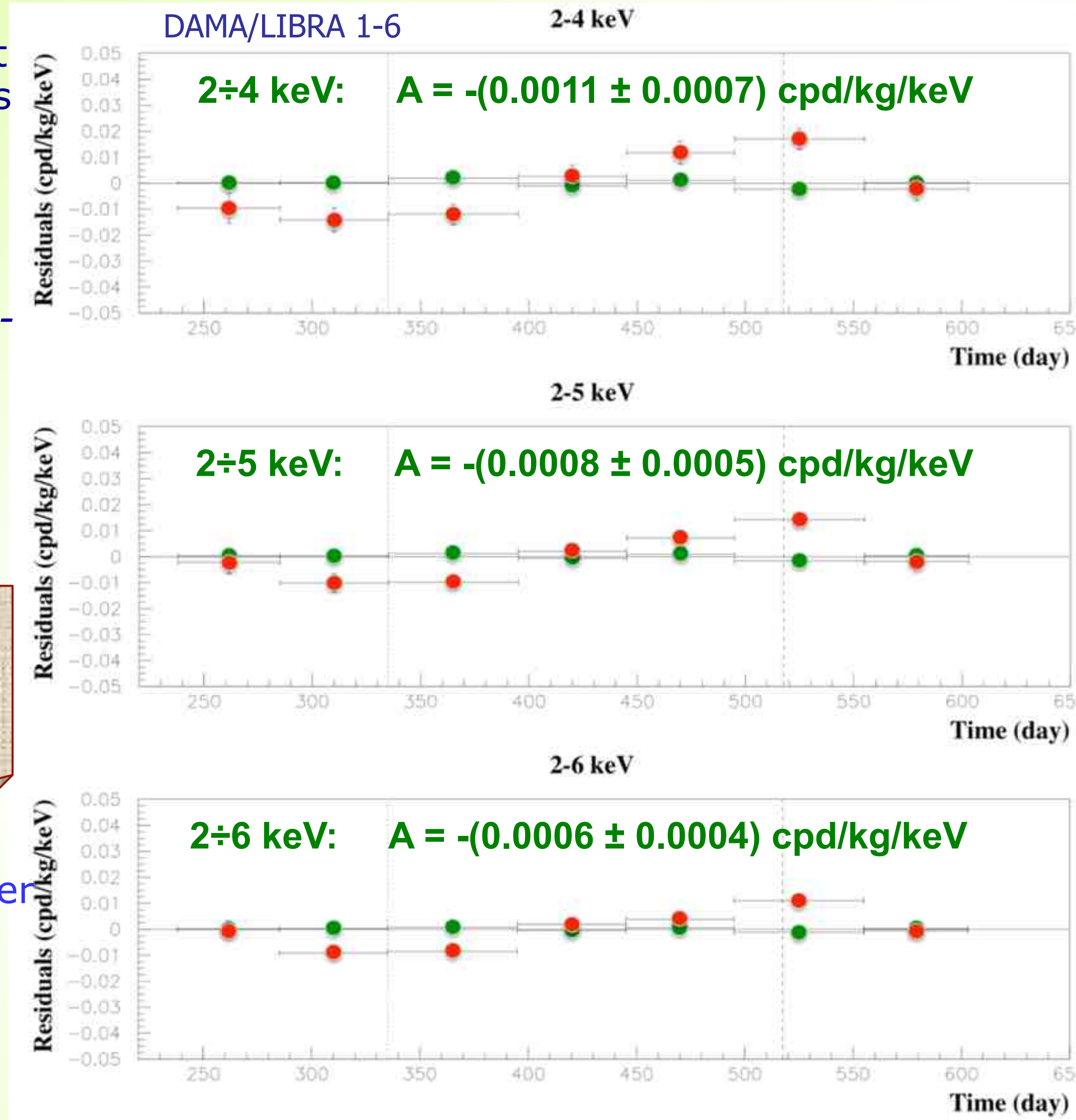
Multiple-hits events in the region of the signal

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

- The same hardware and software procedures as those followed for *single-hit* events

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

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



Evidence of annual modulation with proper features as required by the DM annual modulation signature:
- present in the ***single-hit*** residuals
- absent in the ***multiple-hits*** residual

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

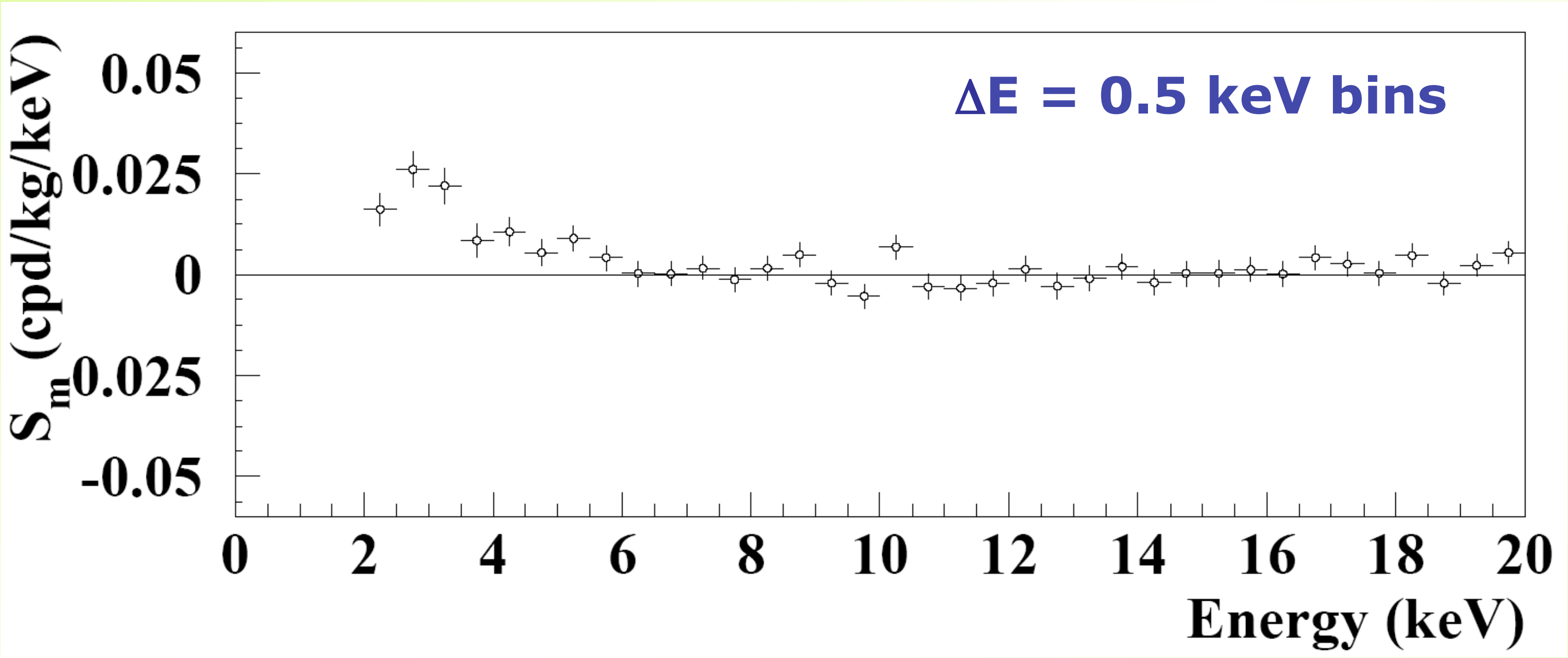
Energy distribution of the modulation amplitudes

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

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)

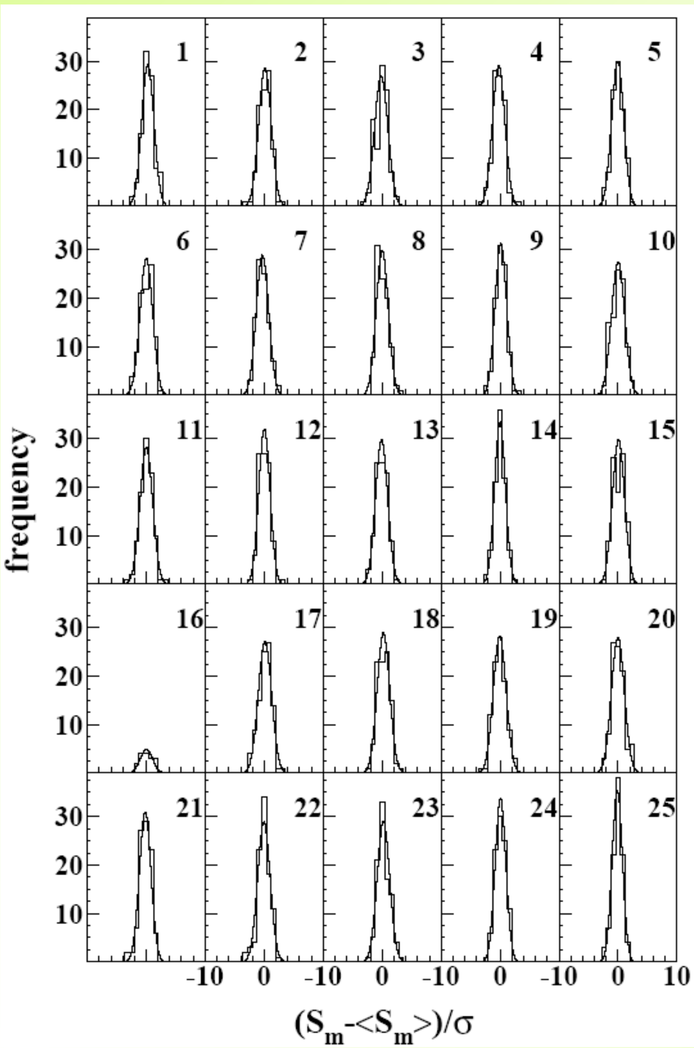
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

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)

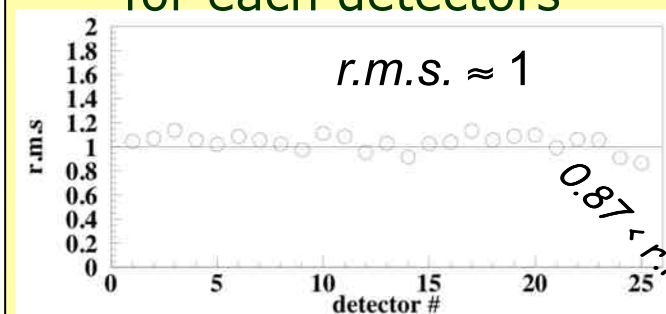


2-6 keV

Standard deviations of

$(S_m - \langle S_m \rangle)/\sigma$

for each detectors



0.87 < r.m.s. < 1.14

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

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

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

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

Statistical analyses about modulation amplitudes (S_m)

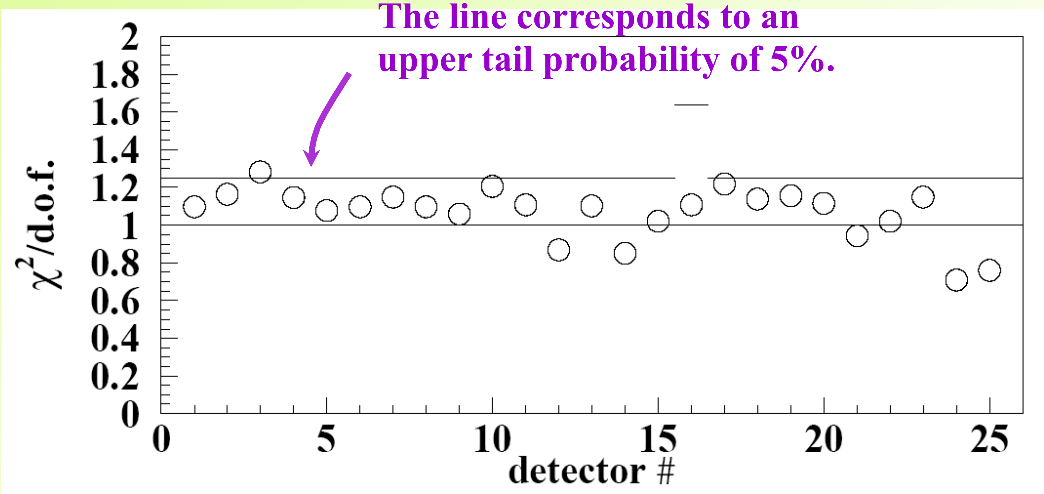
$x=(S_m-\langle S_m\rangle)/\sigma$,

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

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

DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr



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

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

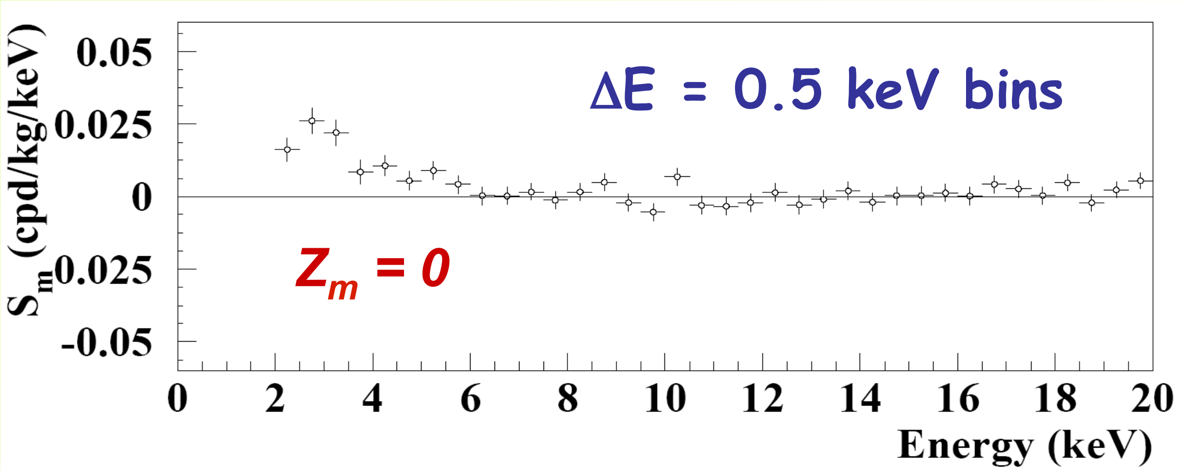
- The mean value of the twenty-five points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 4\times10^{-4}$ cpd/kg/keV, if quadratically combined,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

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)

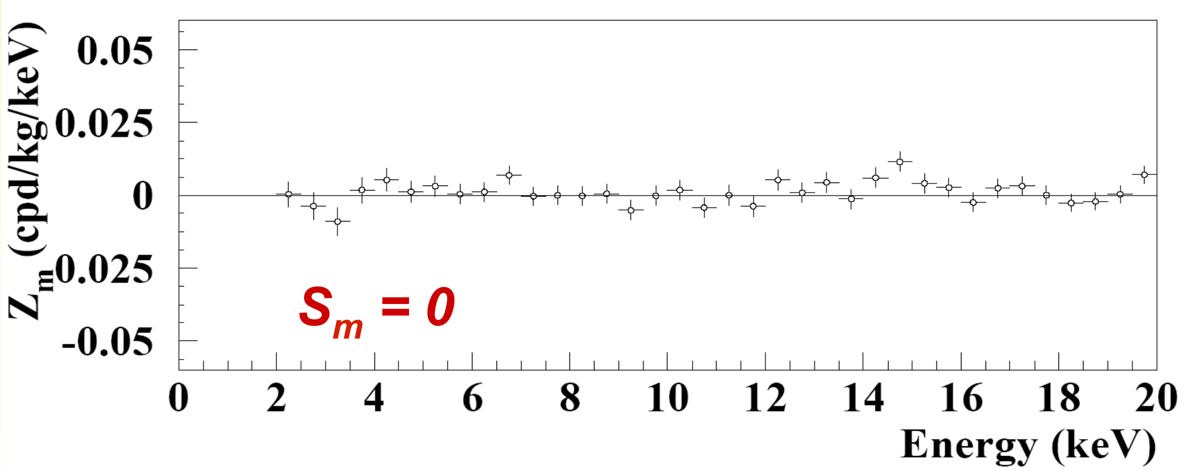
total exposure: 425428 kg×day = 1.17 ton×yr



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

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

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

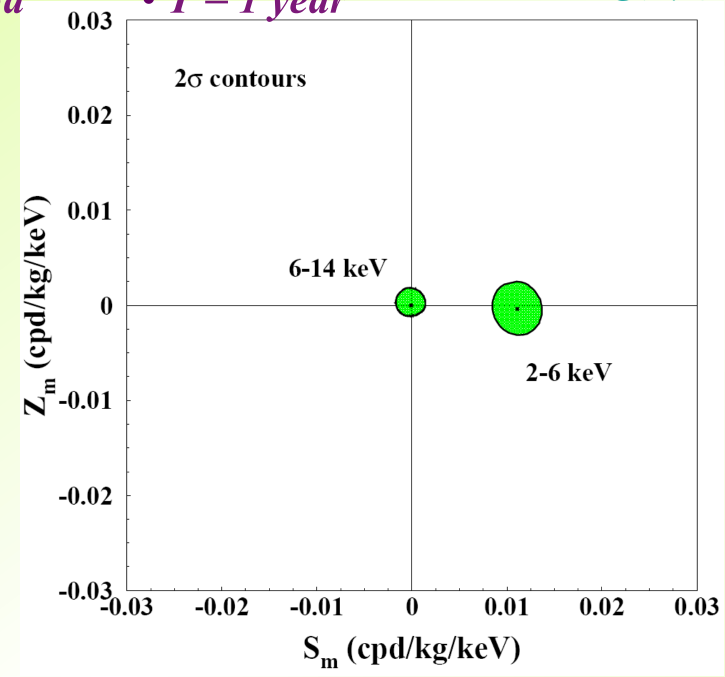
total exposure: 425428 kg×day = 1.17 ton×yr

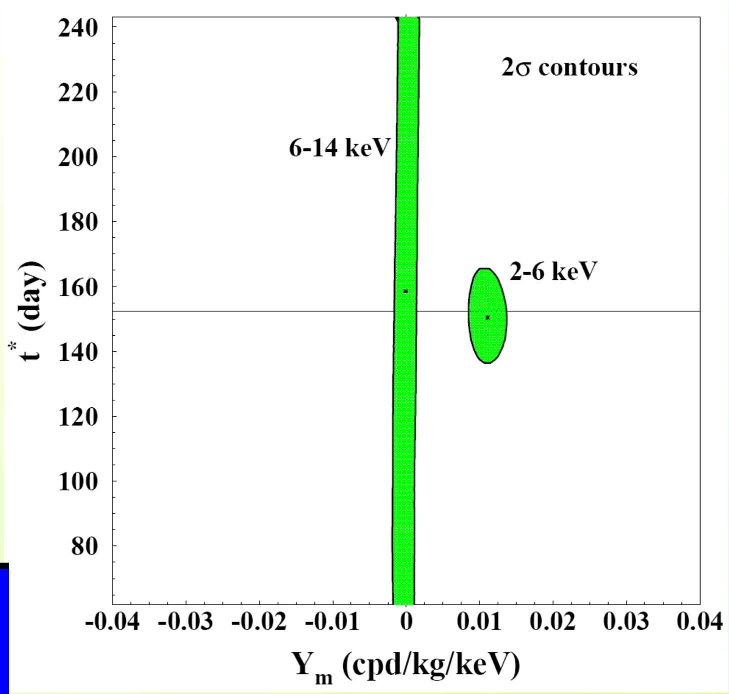
$$R(t) = S_0 + S_m \cos[\omega(t-t_0)] + Z_m \sin[\omega(t-t_0)] = S_0 + Y_m \cos[\omega(t-t^*)]$$

For Dark Matter signals:

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

Phase as function of energy

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

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

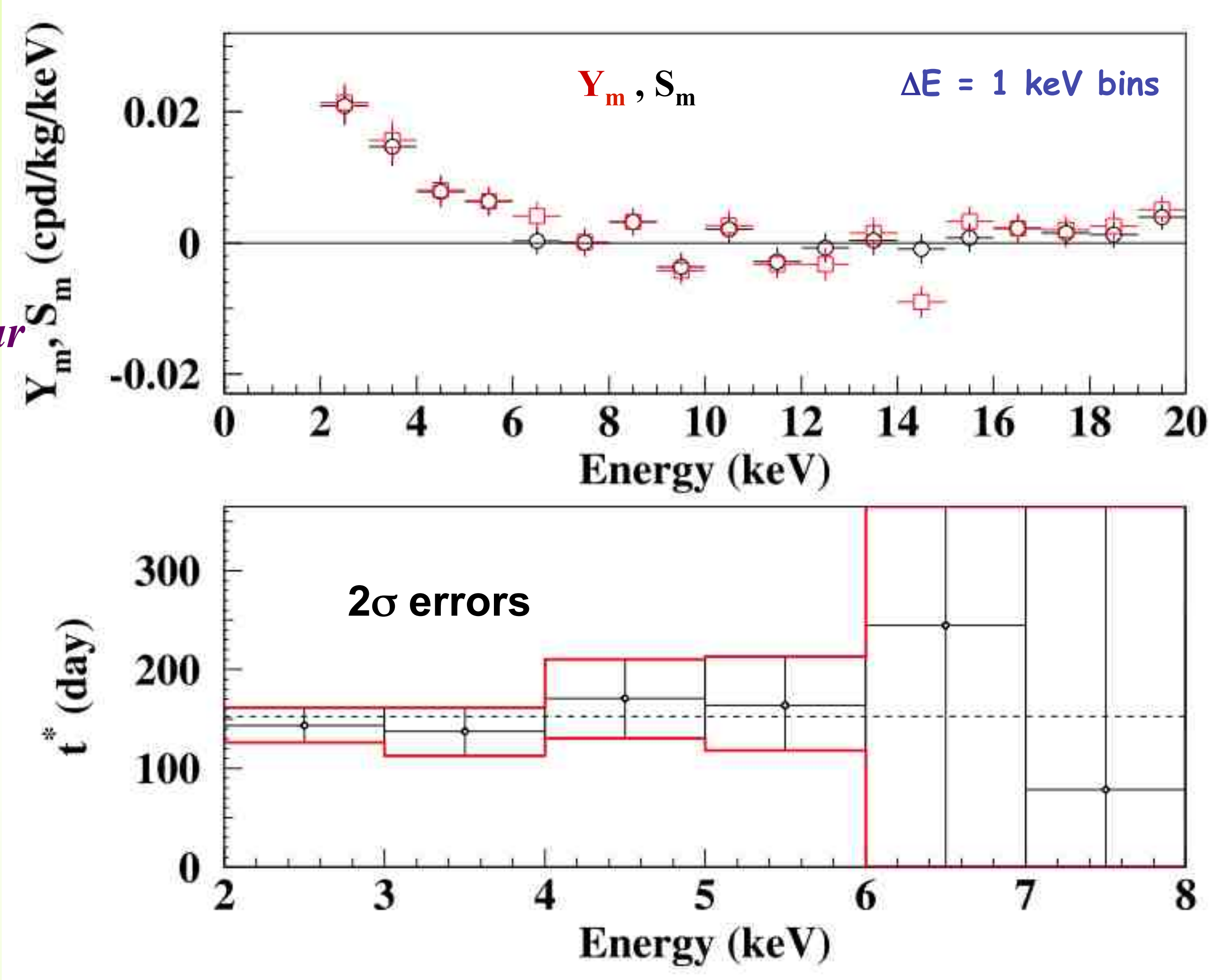
total exposure: 425428 kg×day = 1.17 ton×yr

For DM signals:

$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

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



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

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

Additional investigations on the stability parameters

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

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

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4	DAMA/LIBRA-5	DAMA/LIBRA-6
Temperature	-(0.0001 ± 0.0061) °C	(0.0026 ± 0.0086) °C	(0.001 ± 0.015) °C	(0.0004 ± 0.0047) °C	(0.0001 ± 0.0036) °C	(0.0007 ± 0.0059) °C
Flux N_2	(0.13 ± 0.22) l/h	(0.10 ± 0.25) l/h	-(0.07 ± 0.18) l/h	-(0.05 ± 0.24) l/h	-(0.01 ± 0.21) l/h	-(0.01 ± 0.15) l/h
Pressure	(0.015 ± 0.030) mbar	-(0.013 ± 0.025) mbar	(0.022 ± 0.027) mbar	(0.0018 ± 0.0074) mbar	-(0.08 ± 0.12) $\times 10^{-2}$ mbar	(0.07 ± 0.13) $\times 10^{-2}$ mbar
Radon	-(0.029 ± 0.029) Bq/m^3	-(0.030 ± 0.027) Bq/m^3	(0.015 ± 0.029) Bq/m^3	-(0.052 ± 0.039) Bq/m^3	(0.021 ± 0.037) Bq/m^3	-(0.028 ± 0.036) Bq/m^3
Hardware rate above single photoelectron	-(0.20 ± 0.18) $\times 10^{-2}$ Hz	(0.09 ± 0.17) $\times 10^{-2}$ Hz	-(0.03 ± 0.20) $\times 10^{-2}$ Hz	(0.15 ± 0.15) $\times 10^{-2}$ Hz	(0.03 ± 0.14) $\times 10^{-2}$ Hz	(0.08 ± 0.11) $\times 10^{-2}$ Hz

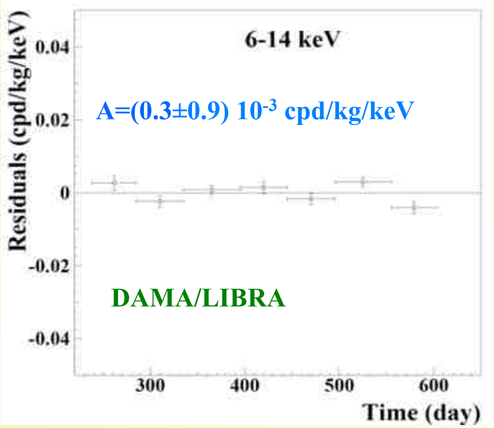
All the measured amplitudes well compatible with zero

\+ none can account for the observed effect

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

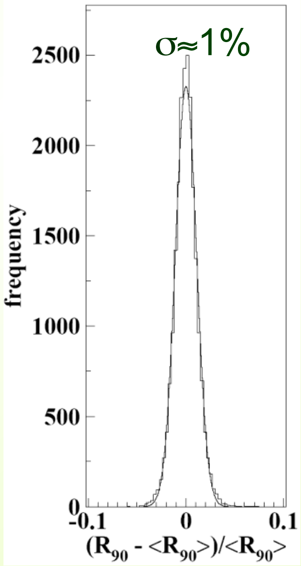
Summarizing on a hypothetical background modulation

- **No Modulation above 6 keV**

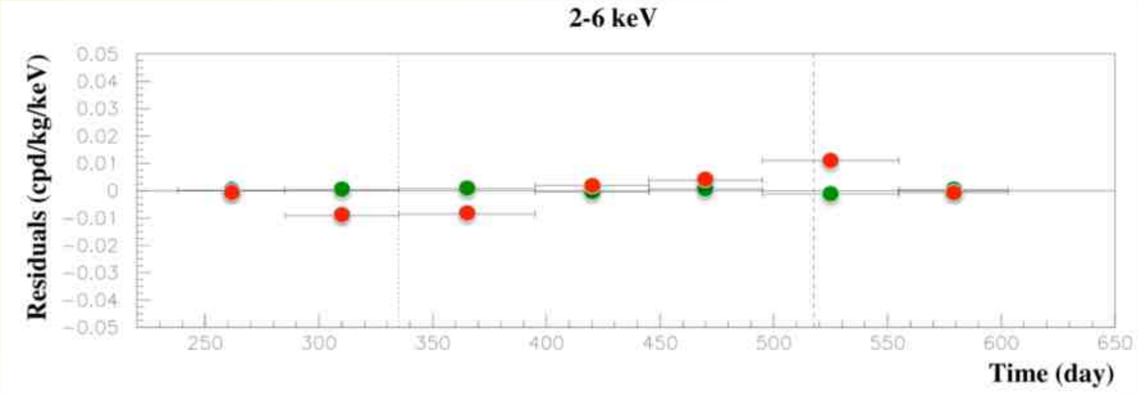


- **No modulation in the whole energy spectrum**

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



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



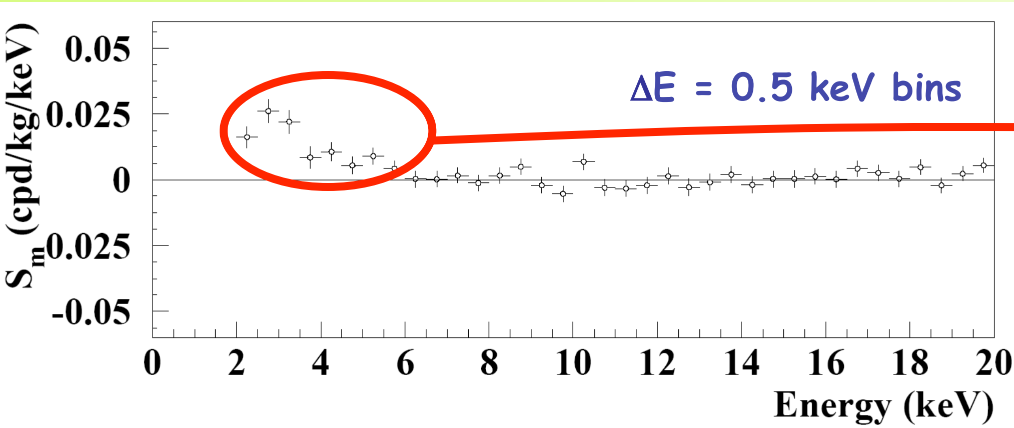
multiple-hits residual rate (green points) vs single-hit residual rate (red points)

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

Nevertheless, additional investigations performed ...

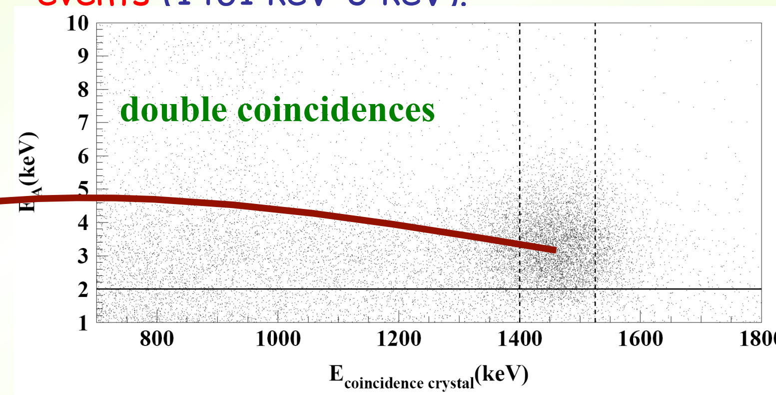
No role for ^{40}K in the experimental S_m

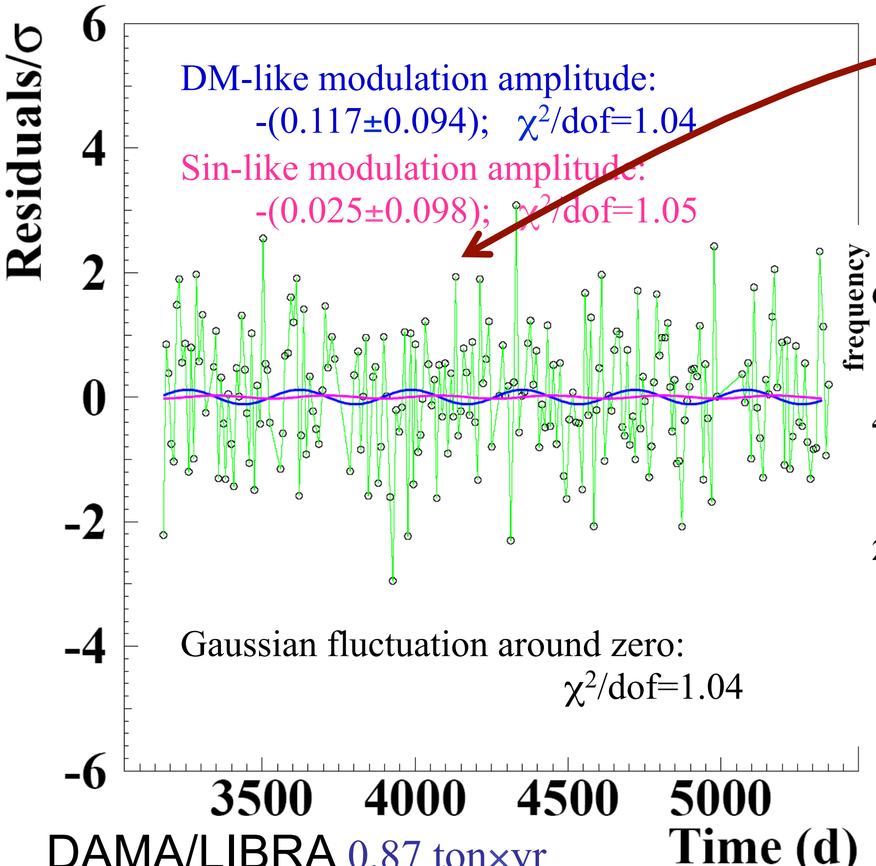
also see arXiv:0912.0660

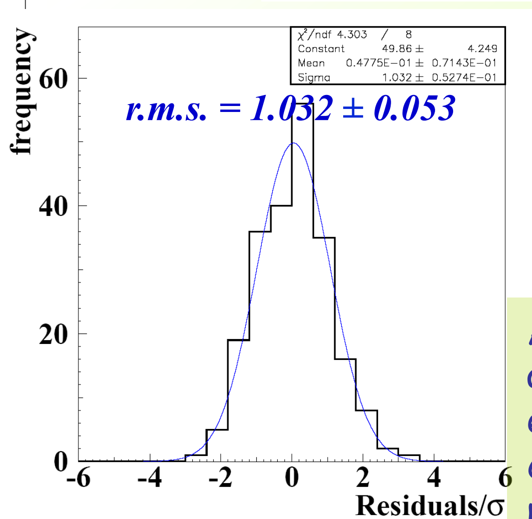


The experimental S_m cannot be due to ^{40}K for many reasons.

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







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

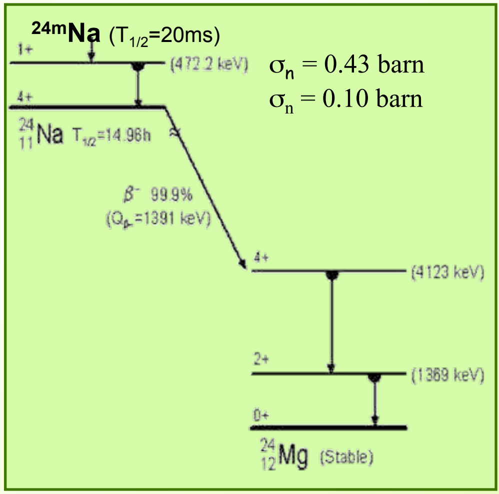
Any modulation contribution around 3 keV in the single-hit events from the hypothetical cases of: i) ^{40}K "exotic" modulated decay; ii) spill-out effects from double to single events and viceversa, is ruled out at more than 10 σ

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:

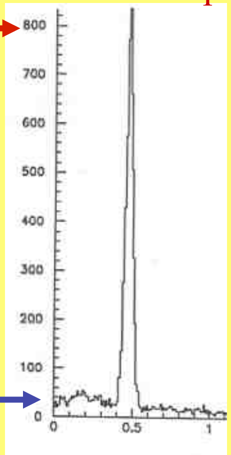
⇒ $S_m^{(thermal\ n)} < 0.8 \times 10^{-6}$ cpd/kg/keV (< 0.01% $S_m^{observed}$)

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)

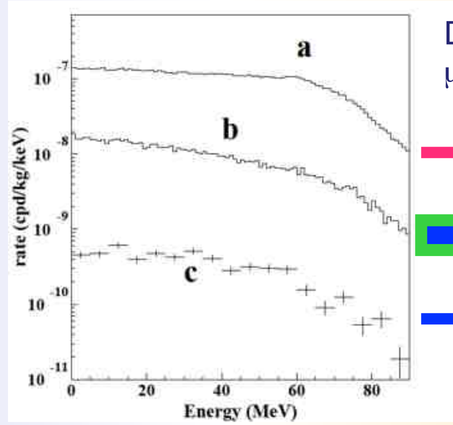
In all the cases of neutron captures (^{24}Na, ^{128}I, ...) a possible thermal n modulation induces a variation in all the energy spectrum

Already excluded also by R_{90} analysis

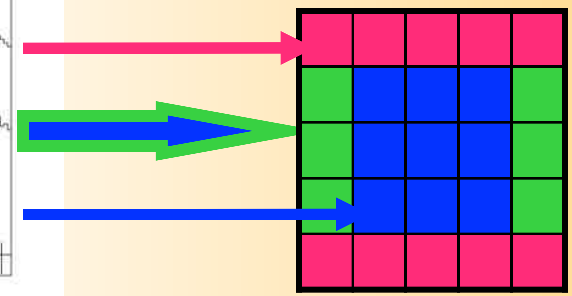
The μ case

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

events where just one detector fires



DAMA/LIBRA surface ≈ 0.15 m^2
μ flux @ DAMA/LIBRA ≈ 2.5 μ/day



Case of fast neutrons produced by μ

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

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

→ $S_m^{(\mu)} < (0.4\div3) \times 10^{-5}$ **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 5^{th} ± 15 d, BOREXINO = July 7^{th} ± 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**

more about the phase of muons …

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) $\approx 3 \cdot 10^{-4}$ $m^{-2}s^{-1}$; modulation amplitude 1.5%; phase:

July 7 ± 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

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

Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + instrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

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 many possible astrophysical, nuclear and particle physics scenarios)

Neutralino as LSP in various SUSY theories

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

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

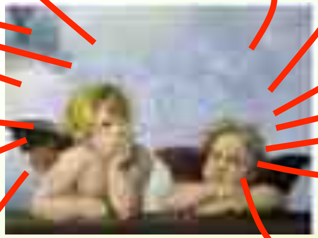
Mirror Dark Matter

Light Dark Matter

Self interacting Dark Matter

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

Sterile neutrino



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

Elementary Black holes such as the Daemons

Kaluza Klein particles

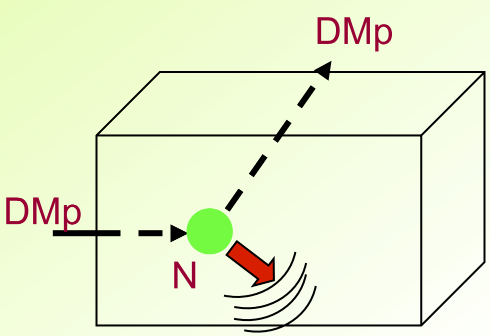
… and more

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

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

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

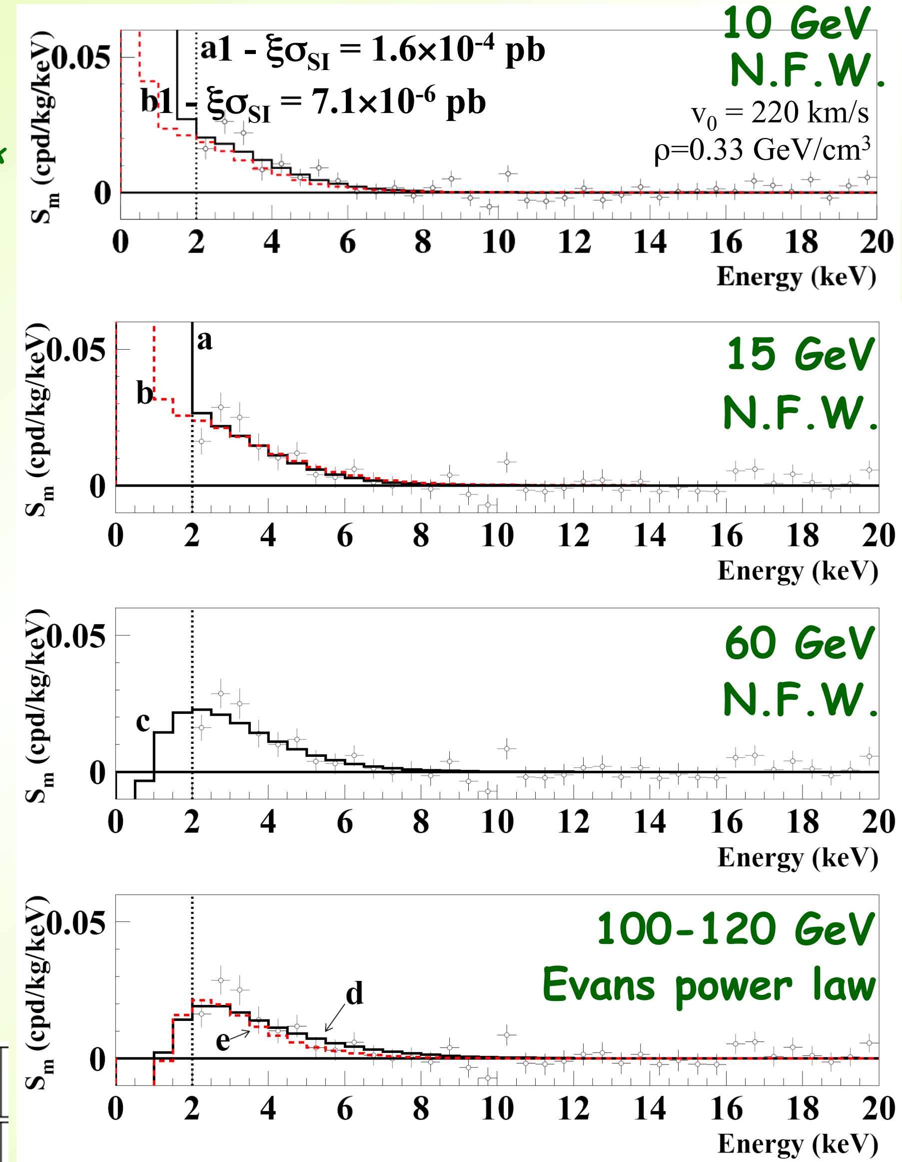


About the same C.L.

...scaling from NaI

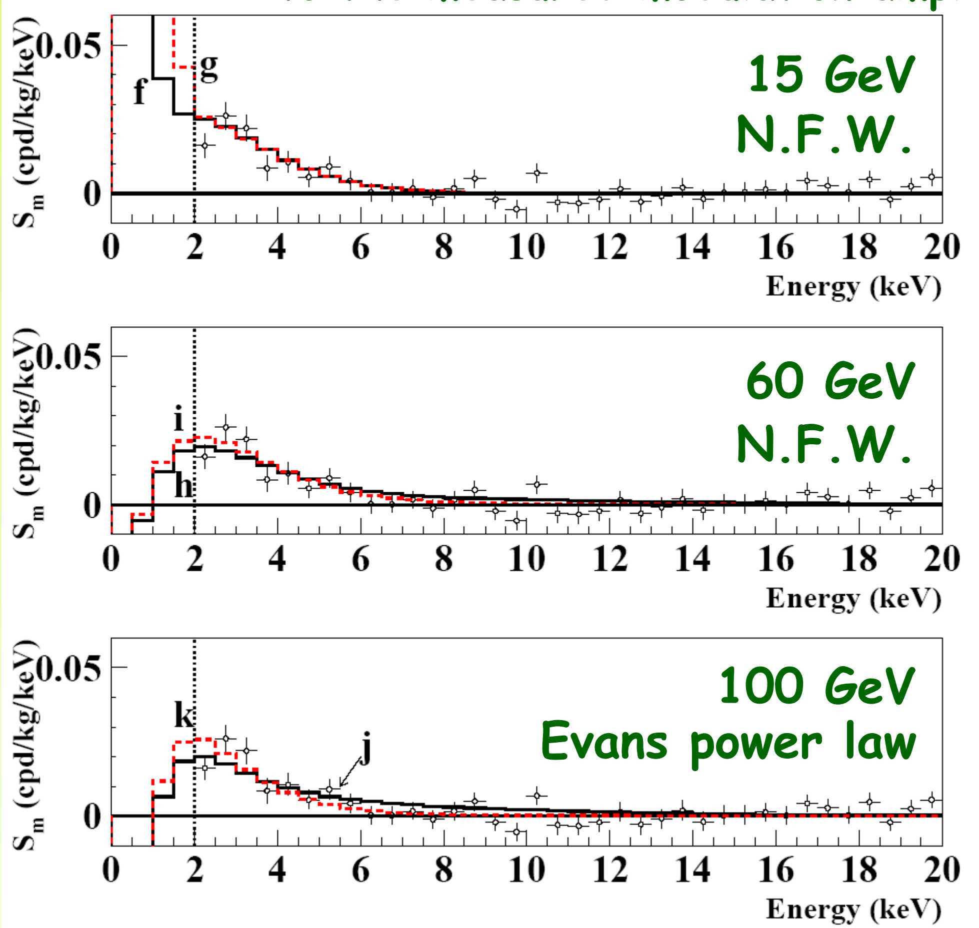
Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)
a	A5 (NFW)	0.2	A	15 GeV	3.1×10^{-4}
b	A5 (NFW)	0.2	A	15 GeV	1.3×10^{-5}
c	A5 (NFW)	0.2	B	60 GeV	5.5×10^{-6}
d	B3 (Evans power law)	0.17	B	100 GeV	6.5×10^{-6}
e	B3 (Evans power law)	0.17	A	120 GeV	1.3×10^{-5}

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



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

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

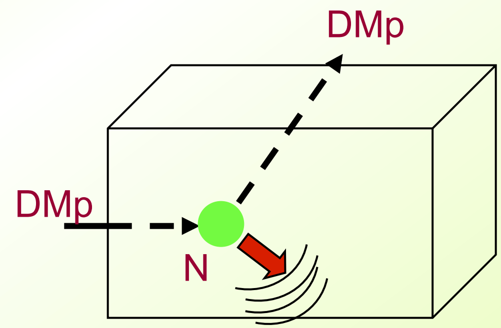


WIMP DM candidate as in [4]

Elastic scattering on nuclei

SI & SD mixed coupling

$v_0 = 170$ km/s



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

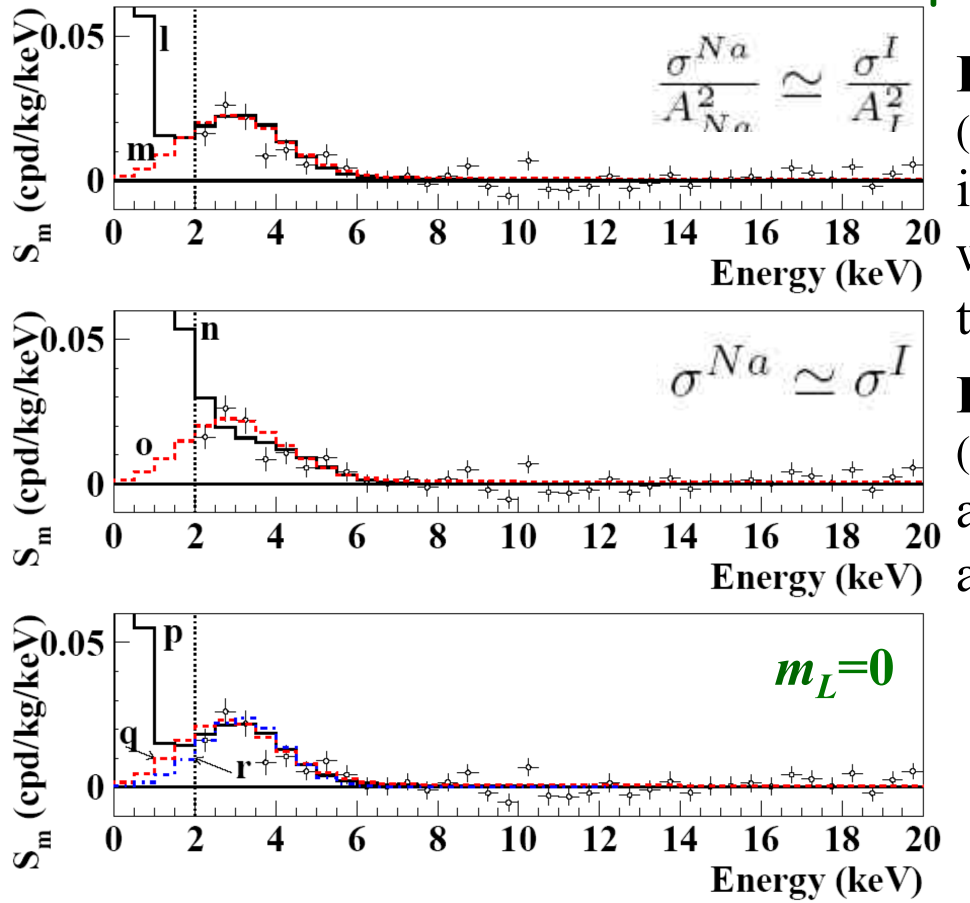
...scaling from NaI

$$\theta = 2.435$$

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

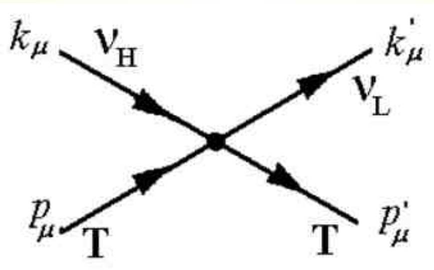
[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

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



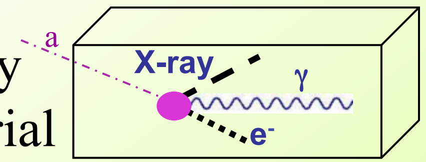
LDM candidate

(as in MPLA23(2008)2125):
inelastic interaction with electron or nucleus targets



Light bosonic candidate

(as in IJMPA21(2006)1445):
axion-like particles totally absorbed by target material



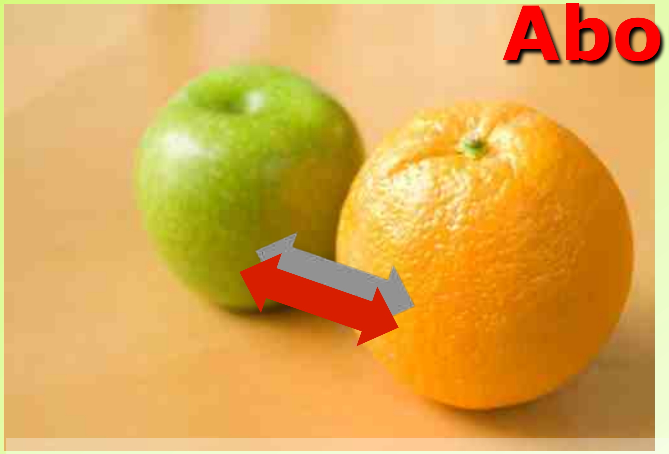
- Not best fit
- About the same C.L.

curve *r*: also pseudoscalar axion-like candidates (e.g. majoron)
m_a=3.2 keV g_{aee}= 3.9 10^{-11}

(NFW) halo model as in [4, 34], local density = 0.17 GeV/cm^3, local velocity = 170 km/s

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

About interpretation



See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014

…models…

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

…and experimental aspects…

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

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

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

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:

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

$\varepsilon_A = 0$ *generally assumed*

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

Halo models & Astrophysical scenario

- Isothermal sphere ⇒ 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

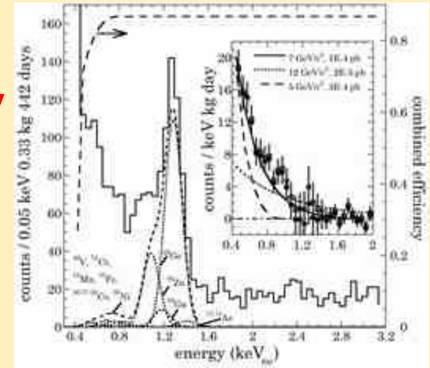
- differences are present in different experimental determinations of q for the same nuclei in the same kind of detector depending on its specific features (e.g. q depends on dopant and on the impurities; in liquid noble gas e.g.on trace impurities, on presence of degassing/ releasing materials, on thermodynamical 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)

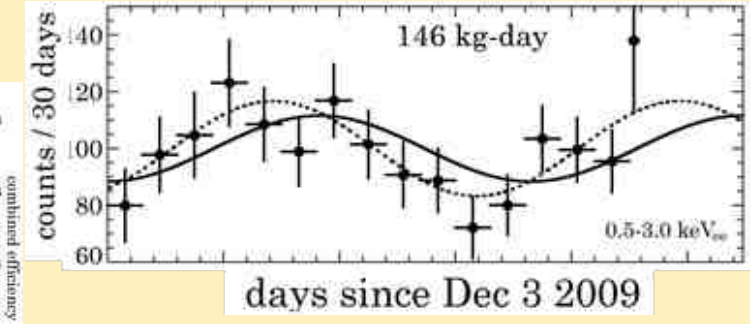
  → energy dependence

… and more …

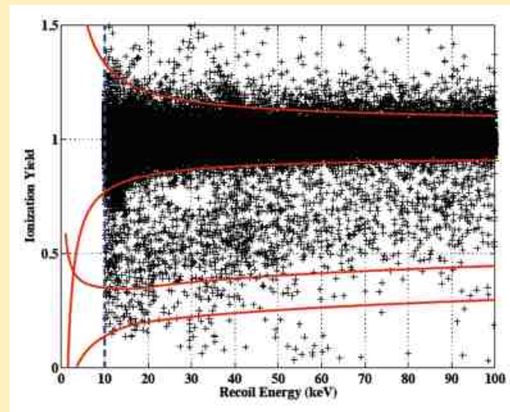
DAMA/NaI & DAMA/LIBRA vs recent possible positive hints 2010/2011

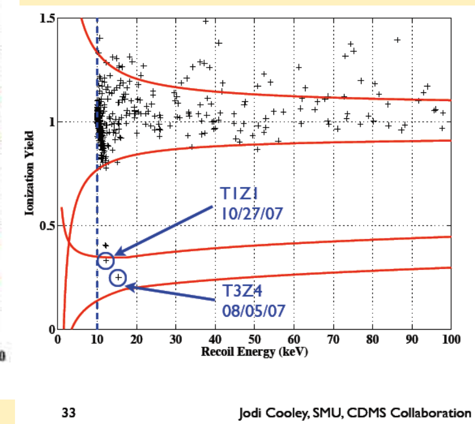
- **CoGeNT:** low-energy rise in the spectrum (irreducible by the applied background reduction procedures) + annual modulation



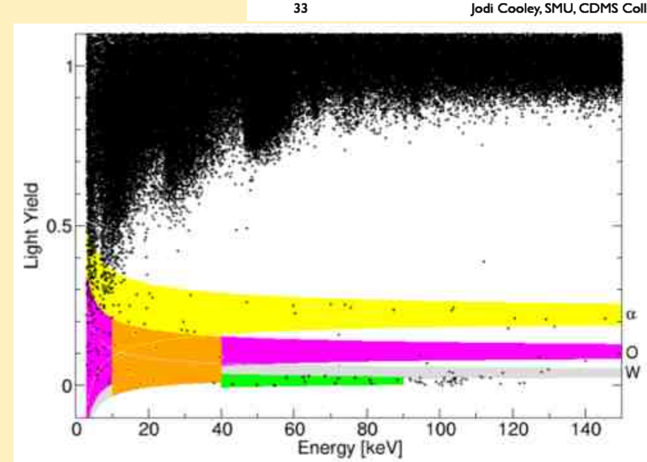


- **CDMS:** after many data selections and cuts, 2 Ge candidate recoils survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)





- **CRESST:** after many data selections and cuts, 67 candidate recoils in the O/Ca bands survive in an exposure of 730 kg x day (expected residual background: 40-45 events, depending on minimization)



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

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

well compatible with several candidates

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

- Low mass neutralino (PRD81(2010)107302, PRD83(2011)015001, arXiv:1003.0014,arXiv:1007.1005, arXiv:1009.0549, PRD84(2011)055014, arXiv:1112.5666)
- 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 Tl (arXiv:1007:2688)

- Specific two higgs doublet models (arXiv:1106.3368)
- exothermic DM (arXiv:1004.0937)
- Secluded WIMPs (PRD79(2009)115019)
- Asymmetric DM (arXiv:1105.5431)
- 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, …)

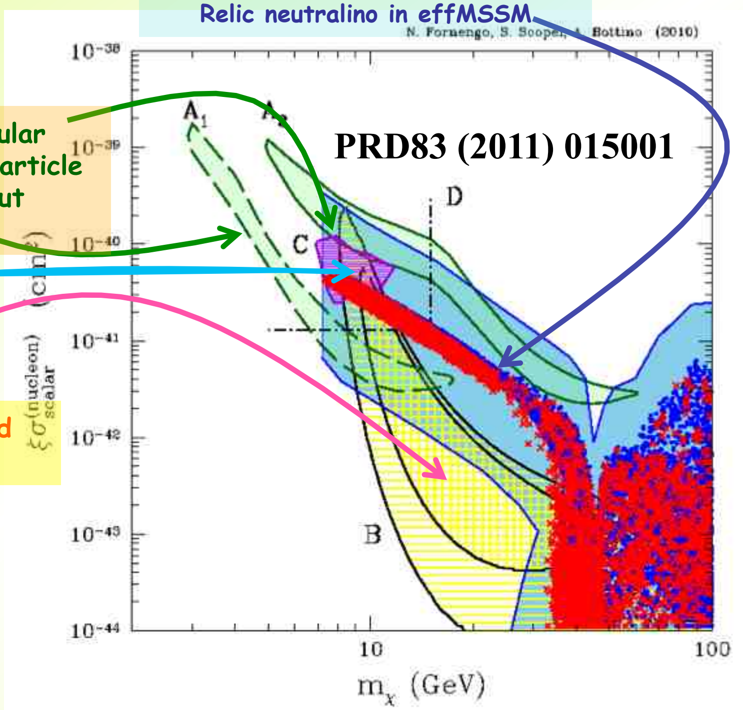
... an example in literature...

Supersymmetric expectations in MSSM

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

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

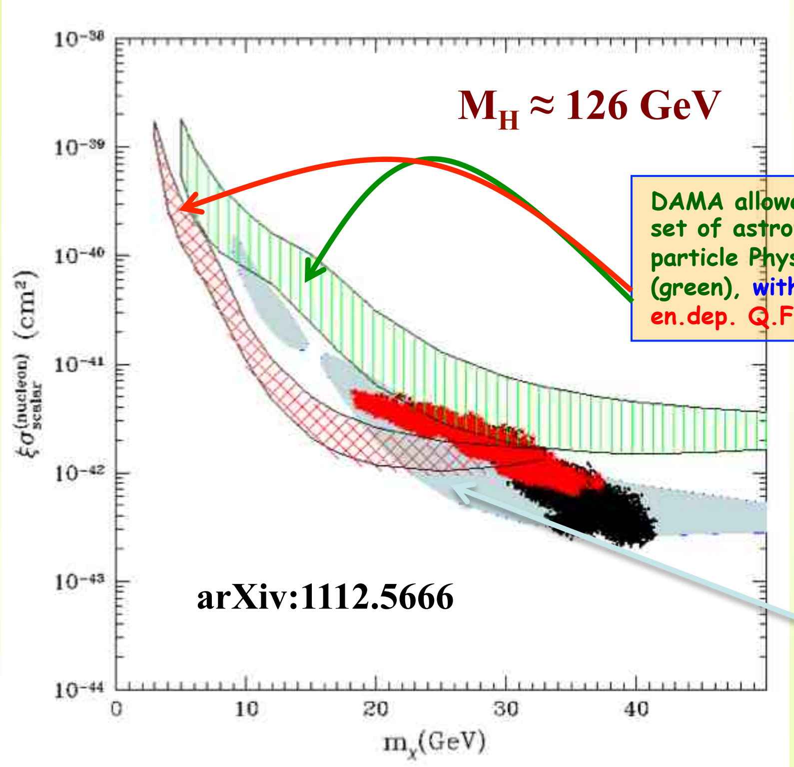
Relic neutralino in effMSSM



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

CoGeNT and CRESST

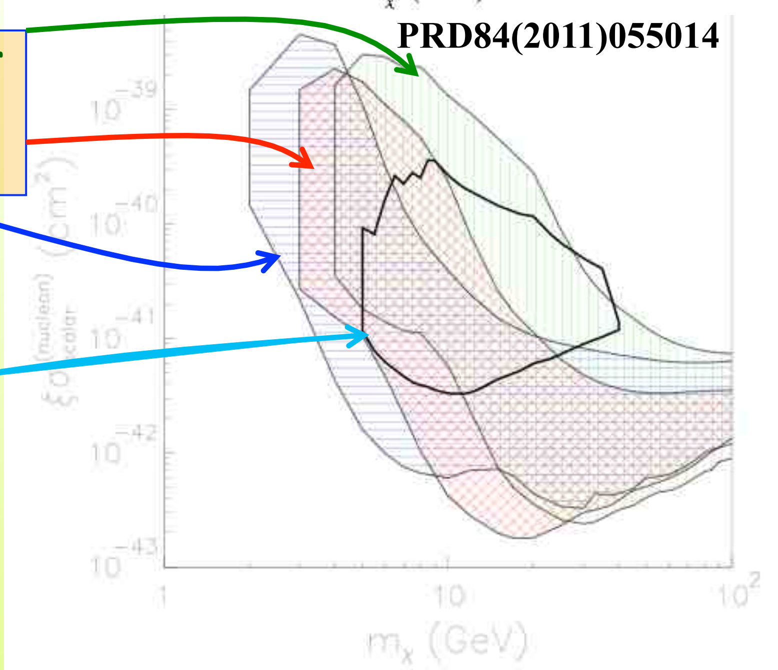
If the two CDMS events are interpreted as relic neutralino interactions



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

CoGeNT

CRESST



... examples in some given frameworks

DM particle with preferred inelastic interaction

- In the Inelastic DM (iDM) scenario, WIMPs scatter into an excited state, split from the ground state by an energy comparable to the available kinetic energy of a Galactic WIMP.

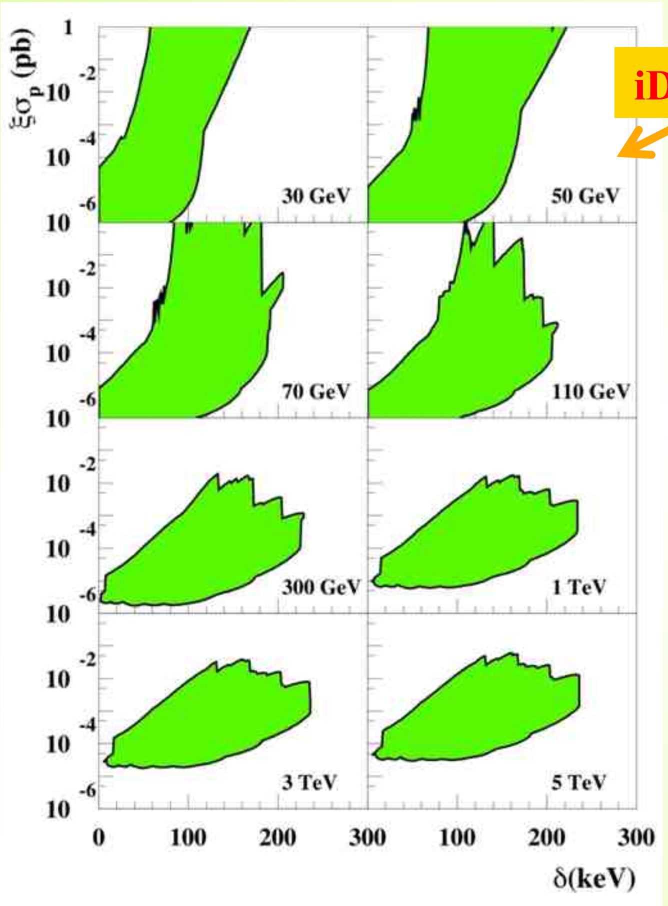
$$\chi^- + N \rightarrow \chi^+ + N$$

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

→ Kinematical constraint for iDM

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

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



iDM interaction on Iodine nuclei

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~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 with lower software energy threshold (below 2 keV).
- New preamplifiers and trigger modules realized to further implement low energy studies.
- Suitable exposure planned in the new configuration to deeper study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects.
- 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

- 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

Felix qui potuit rerum cognoscere causas

(Virgilio, Georgiche, II, 489)

Thank you a lot for your kind attention!