Particle Dark Matter in the galactic halo

Int. School of Nuclear Physics
32° Course Particle and Nuclear Astrophysics
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Erice (Italia)

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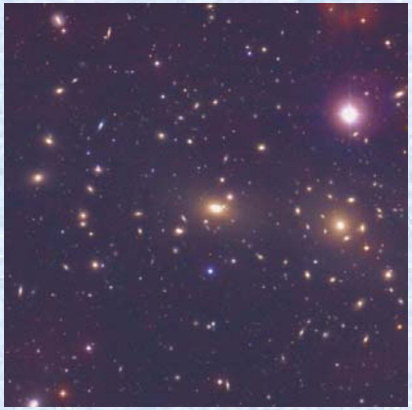
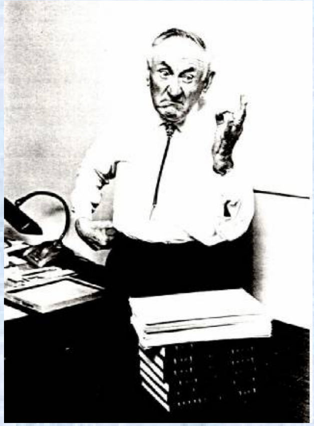
The Dark Side of the Universe: experimental evidences ...



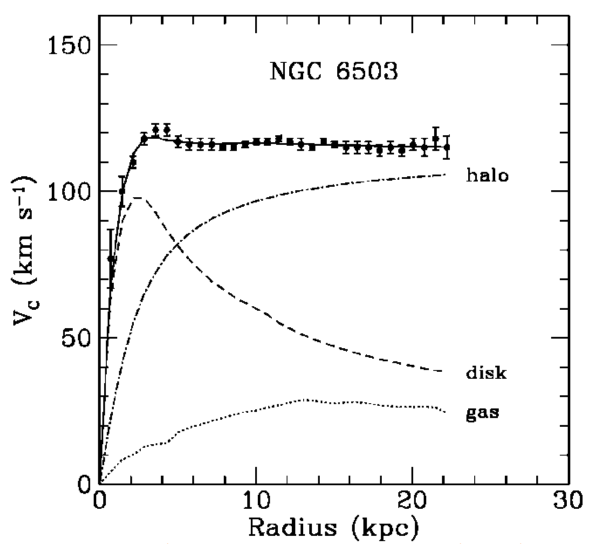
COMA Cluster

First evidence and confirmations:



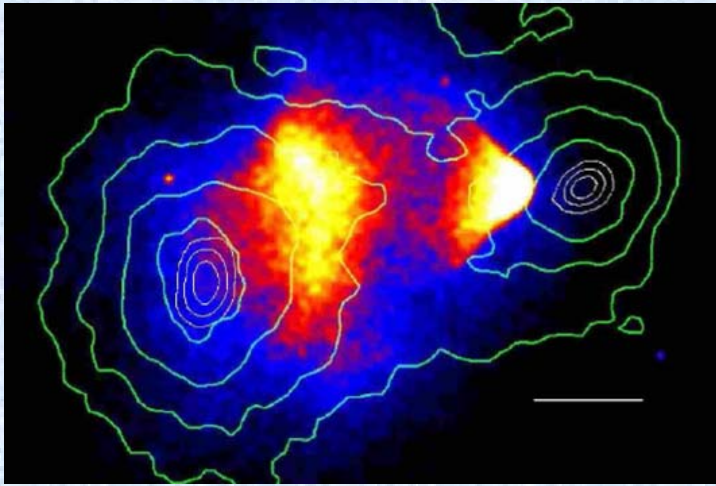
1933	**F. Zwicky:**	studying dispersion velocity of Coma galaxies
1936	**S. Smith:**	studying the Virgo cluster
1974	**two groups:**	systematical analysis of *mass density* vs *distance from center* in many galaxies

Other experimental evidences



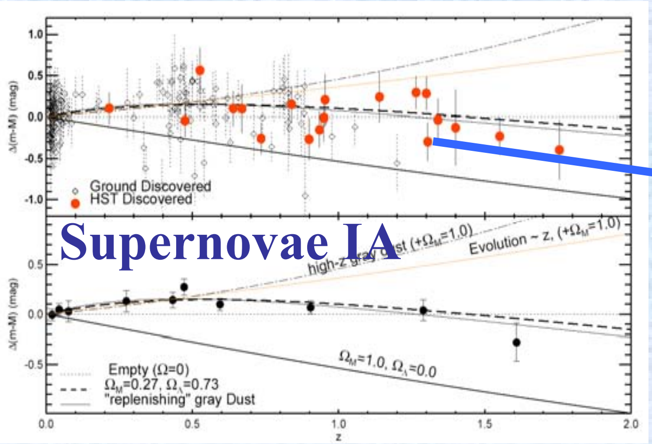
Rotational curve of a spiral galaxy

- ✓ from LMC motion around Galaxy
- ✓ from X-ray emitting gases surrounding elliptical galaxies
- ✓ from hot intergalactic plasma velocity distribution in clusters
- ✓ ...
- ✓ bullet cluster 1E0657-558

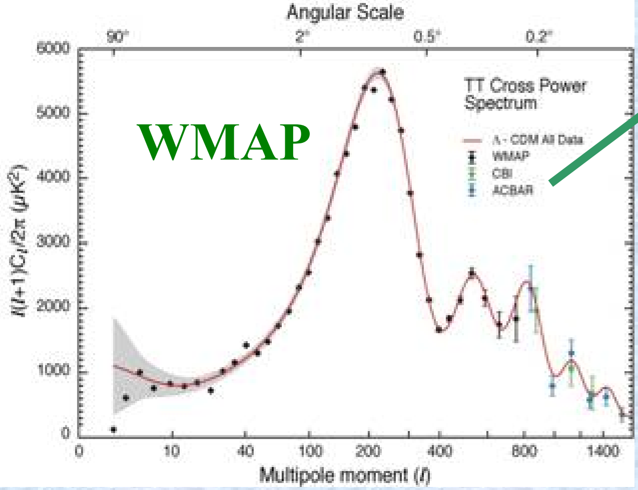


$M_{\text{visible Universe}} << M_{\text{gravitational effect}}$ ⇒ about 90% of the mass is DARK

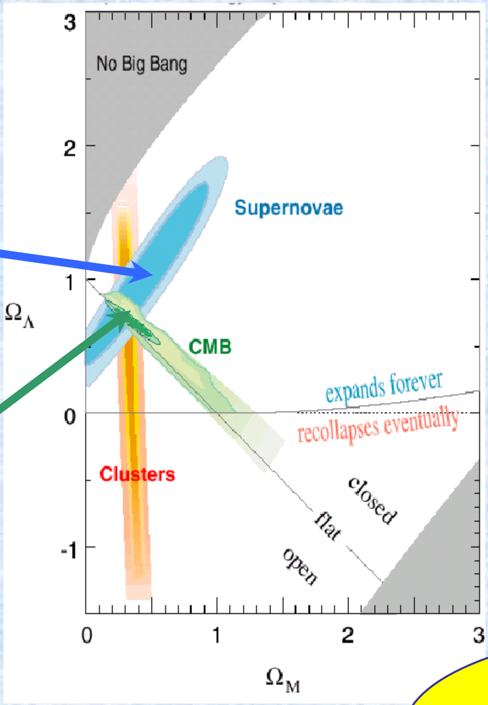
"Concordance model"



Supernovae IA



WMAP



$$\Omega = \Omega_\Lambda + \Omega_M =$$

close to 1

Ω = density/critical density

6 atoms of H/m³

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

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

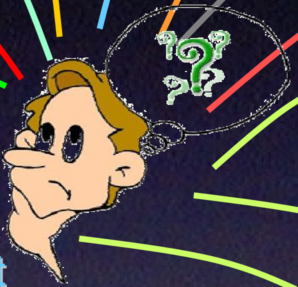
$\Omega_b \sim 4\%$

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?

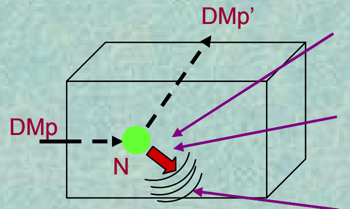
clumpiness?

etc… etc…

Some direct detection processes:

- Scatterings on nuclei

→ detection of nuclear recoil energy



Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, …

Scintillation:
NaI(Tl),
LXe, CaF_2(Eu), …

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

→ W has Two mass states $\chi+$, $\chi-$ with δ mass splitting

→ Kinematical constraint for the inelastic scattering of $\chi-$ on a nucleus

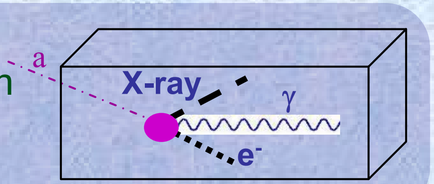
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

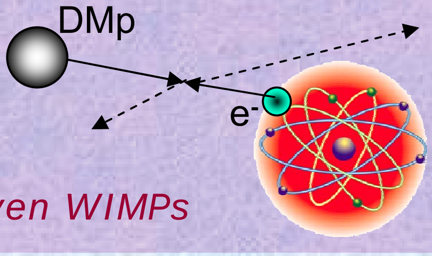
- Conversion of particle into e.m. radiation

→ detection of γ, X-rays, e^-



- Interaction only on atomic electrons

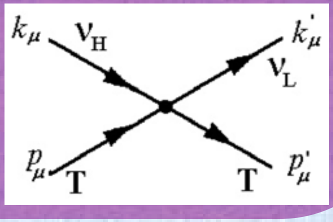
→ detection of e.m. radiation



… even WIMPs

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

→ detection of electron/nucleus recoil energy

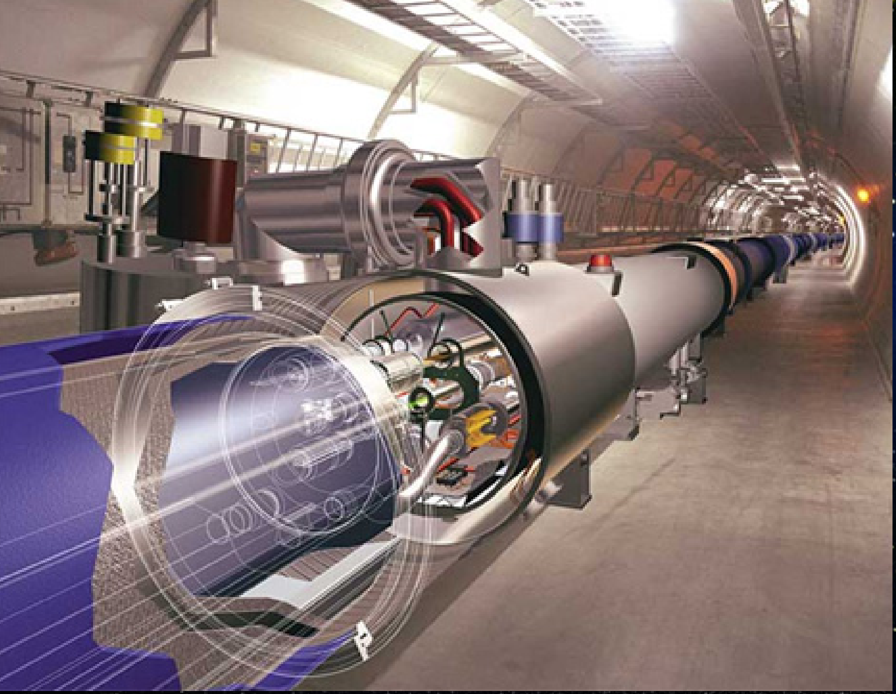


e.g. sterile ν

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 possibilities …

- **… and more**



accelerators can
prove the existence of some possible Dark Matter candidate particles

But accelerators cannot
credit that a certain particle is in the halo as the solution or the only solution for particle Dark Matter …

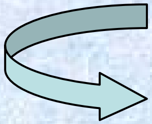
- Dark Matter candidate particles and scenarios (even for neutralino candidate) exist which cannot be investigated at accelerators

Direct detection with a model independent approach and a low background widely sensitive target material

2 different questions:

- Are there Dark Matter particles in the galactic halo?

The exploitation of the annual modulation DM signature with highly radiopure NaI(Tl) as target material can permit to answer to this question by direct detection and in a way largely independent on the nature of the candidate and on the astrophysical, nuclear and particle Physics assumptions



DAMA/NaI and DAMA/LIBRA

- Which are exactly the nature of the Dark Matter particle(s) and the related astrophysical, nuclear and particle Physics scenarios?

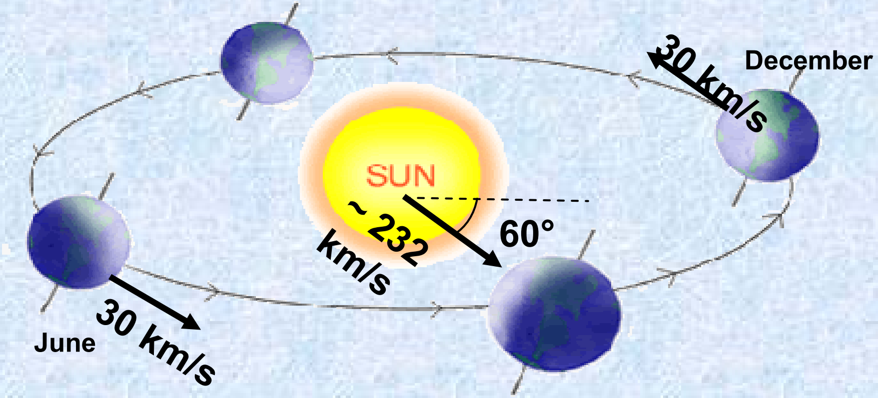
This requires subsequent model-dependent corollary analyses (see e.g. in recent DAMA – and other – literature;… and more)

N.B. It does not exist any approach to investigate the nature of the candidate in the direct and indirect DM searches, which can offer these latter information independently on assumed astrophysical, nuclear and particle Physics scenarios…

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

As a consequence of its annual revolution around the Sun, which is moving in the Galaxy, the Earth should be crossed by a larger flux of Dark Matter particles around 2 June (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around 2 December (when the two velocities are subtracted).

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



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

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

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

Expected rate in given energy bin changes because of the 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, systematics 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

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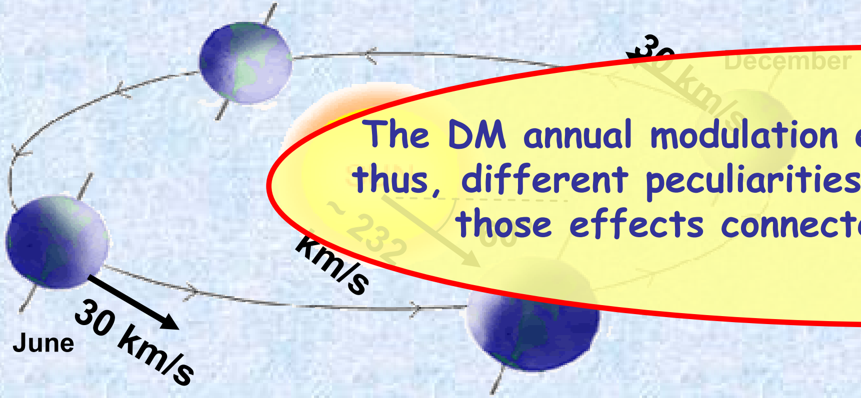

The DM annual modulation effect has different origins and, thus, different peculiarities (e.g. the phase) with respect to those effects connected instead with the seasons

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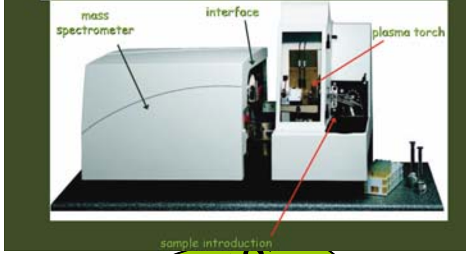
Competitiveness of ULB NaI(Tl) set-up

- Well known technology
- High duty cycle
- Large mass possible
- “Ecological clean” set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- High light response (5.5 -7.5 ph.e./keV)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios on the contrary of other proposed target-materials (and approaches)
- Sensitive to both high (mainly by Iodine target) and low mass (mainly by Na target) candidates
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up
- Etc.

A low background NaI(Tl) also allows the study of several other rare processes : possible processes violating the Pauli exclusion principle, CNC processes in ^{23}Na and ^{127}I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar axion search, ...

High benefits/cost

High radio-purity reachable?



- Identification of materials sources
- All involved materials selection whithin those potentially available at time of developments/production by:
  - Low background HPGe located deep underground
  - Mass and atomic spectrometry with high sensitivity
  - Neutron activation
- Devoted study of the presence of standard (U, Th, K) and non-standard contaminants
- Chemical/physical purification of the selected materials
- Selection of the more suitable growing process
- Additives selections
- Growing protocols
- Handling protocols
- Selection of the material other than crystal compounds
- Protocols for the assembling, the transport, the storage, the installation and maintenance in running conditions
- Prototypes tests deep underground

Necessary: many years,
many specific experience in the specific detecto
long dedicated time.
This kinds of development and measurements
themselves difficult experiments.

NO

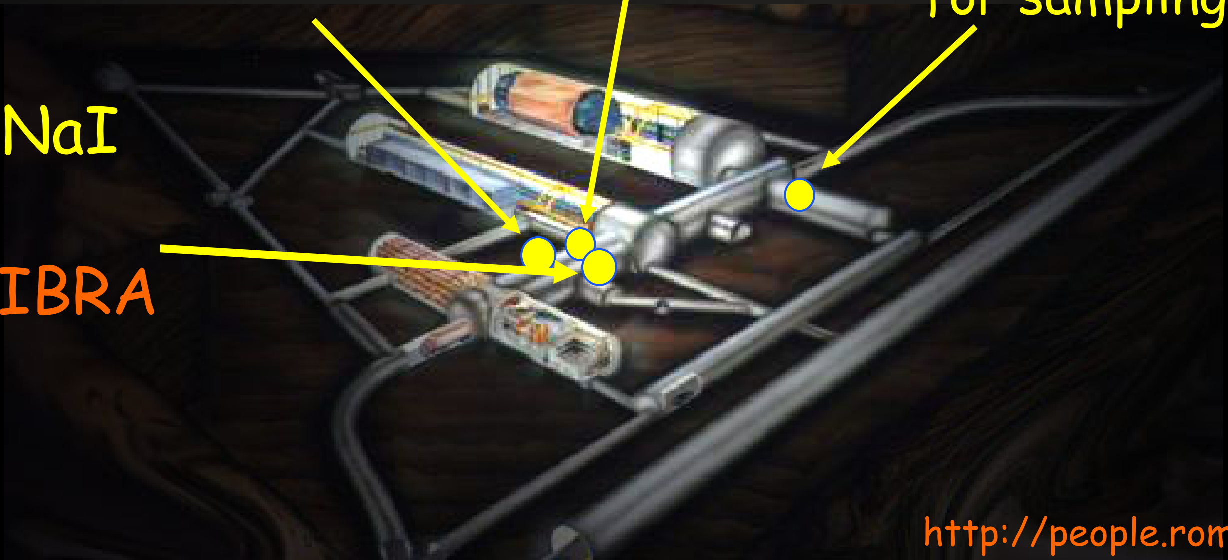
OK

Produce detectors for Physics and Astrophysics, but each one will have its own radio-purity + production differences....

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



DAMA/LXe

DAMA/R&D

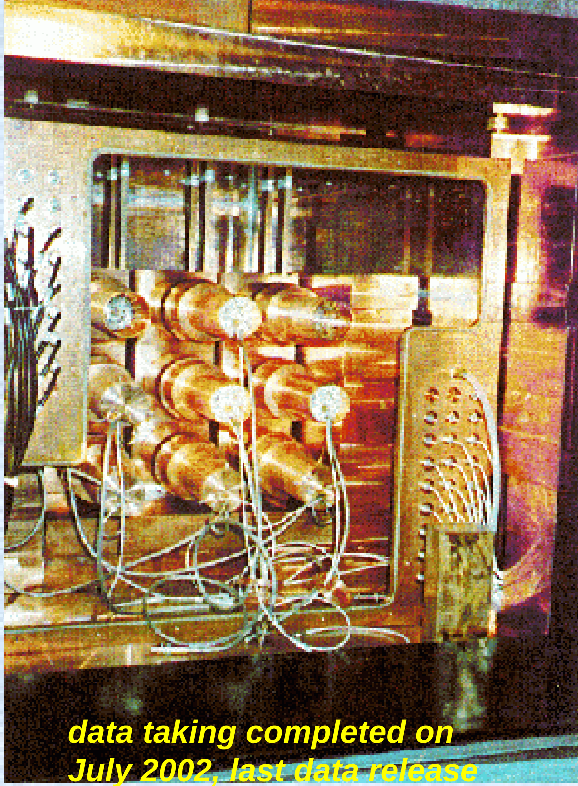
low bckg DAMA/Ge
for sampling meas.

DAMA/NaI

DAMA/LIBRA

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

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



data taking completed on July 2002, last data release 2003. Still producing results

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

Results on rare processes:

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

Results on DM particles:

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

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

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

total exposure (7 annual cycles) 0.29 ton x yr

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

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

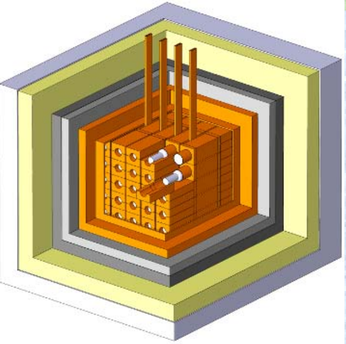
- *Radiopurity, performances, procedures, etc.:* NIMA592(2008)297
- *Results on DM particles:* EPJC56(2008)333, EPJC67(2010)39.
- *Results on rare processes:* EPJC62(2009)327

The DAMA/LIBRA set-up

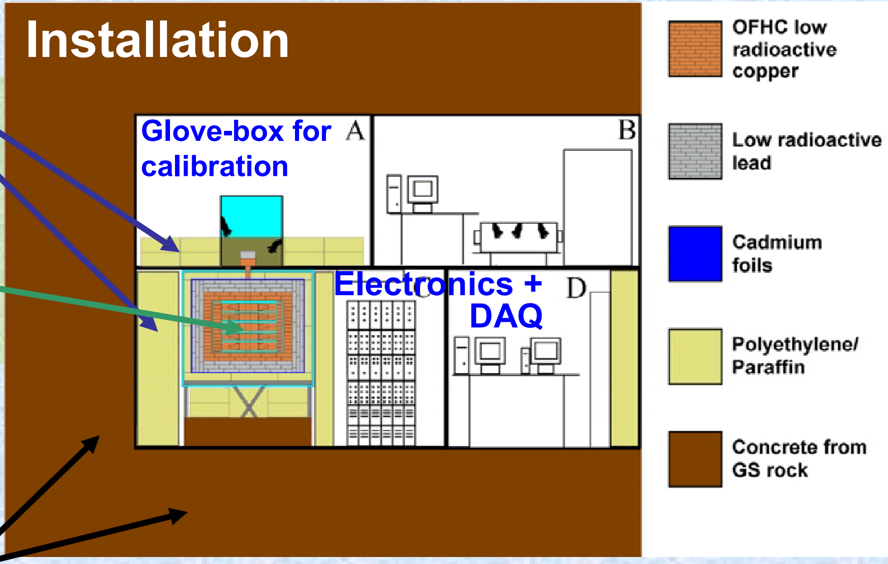
For details, radiopurity, performances, procedures, etc.
NIMA592(2008)297

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



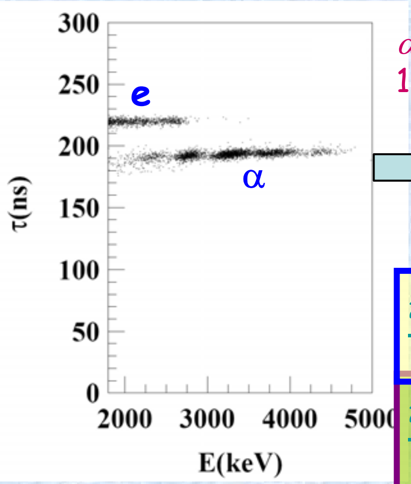
5.5-7.5 phe/keV



~ 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 Waveform 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

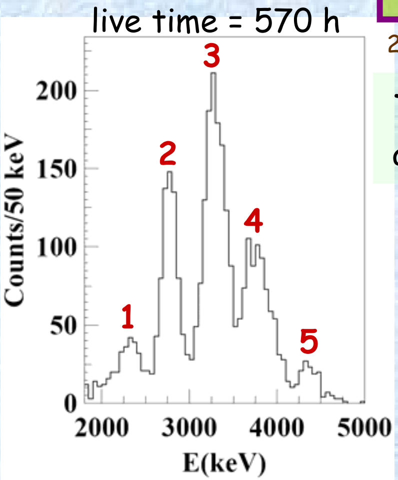


α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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 ⇒ ^{238}U contents in new detectors typically range from 0.7 to 10 ppt



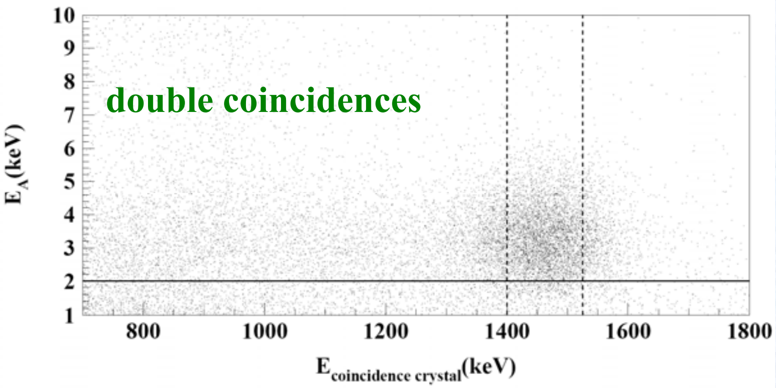
^{238}U chain splitted into 5 subchains: $^{238}\text{U} \rightarrow {}^{234}\text{U} \rightarrow {}^{230}\text{Th} \rightarrow {}^{226}\text{Ra} \rightarrow {}^{210}\text{Pb} \rightarrow {}^{206}\text{Pb}$

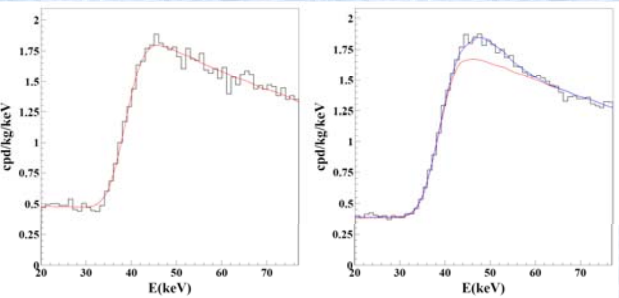
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{nat}K residual contamination

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





^{129}I and ^{210}Pb

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

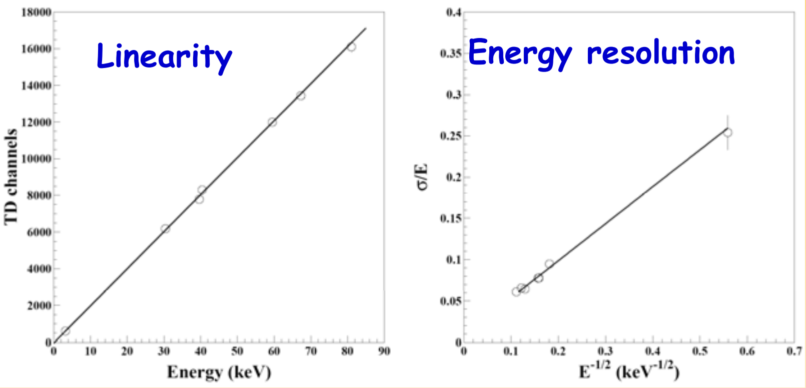
^{210}Pb in the new detectors: (5 – 30) μBq/kg.

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

... more on NIMA592(2008)297

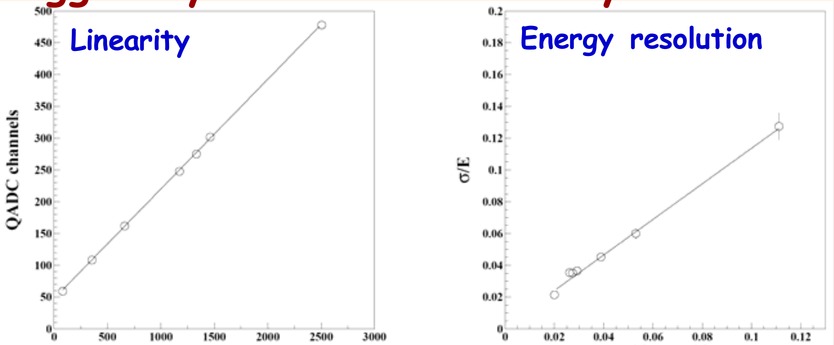
DAMA/LIBRA calibrations

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



$$\frac{\sigma_{LE}}{E} = \frac{(0.448\pm0.035)}{\sqrt{E(keV)}} + (9.1\pm5.1)\cdot10^{-3}$$

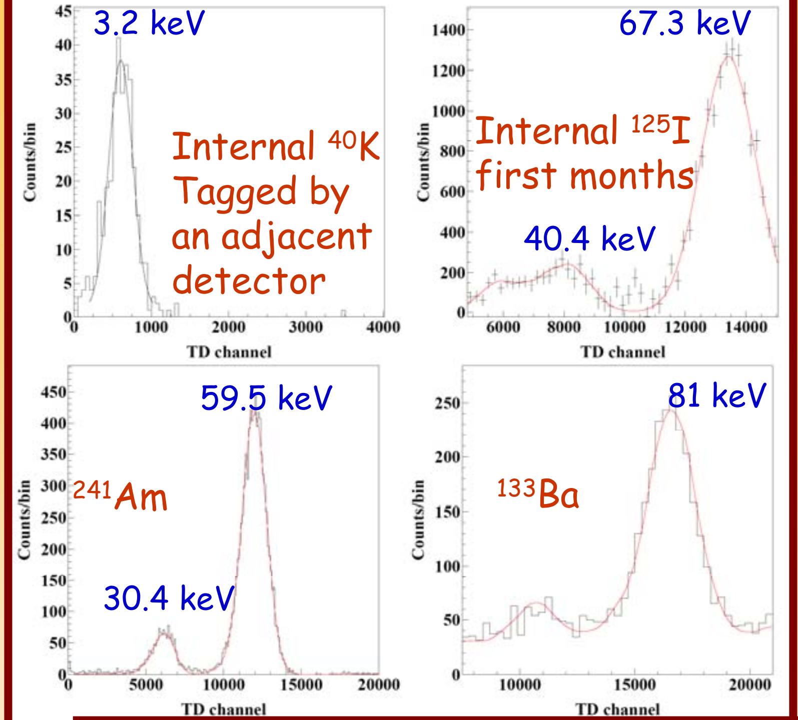
High energy: external sources of γ rays (e.g. ^{137}Cs, ^{60}Co and ^{133}Ba) and γ rays of 1461 keV due to ^{40}K decays in an adjacent detector, tagged by the 3.2 keV X-rays

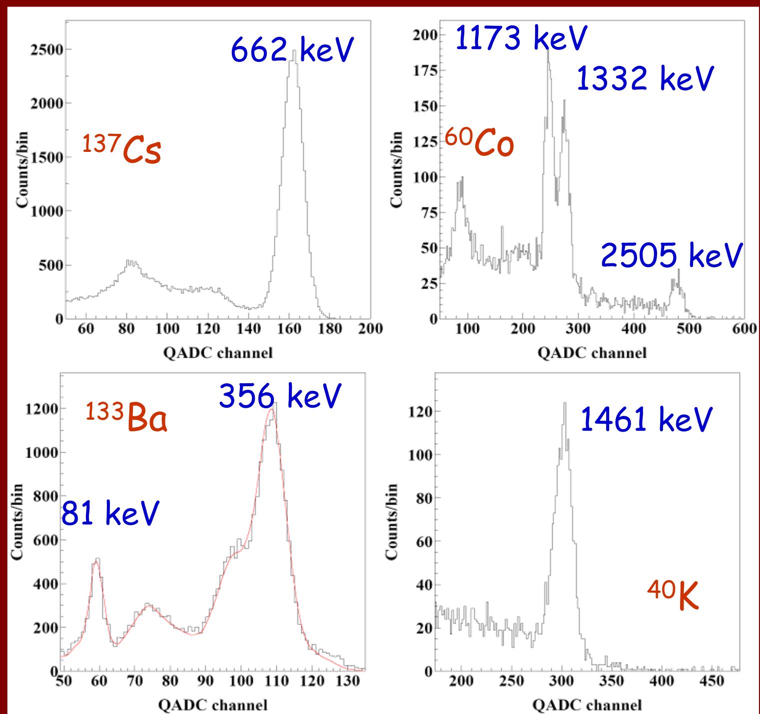


The signals (unlike low energy events) for high energy events are taken only from one PMT

$$\frac{\sigma_{HE}}{E} = \frac{(1.12\pm0.06)}{\sqrt{E(keV)}} + (17\pm23)\cdot10^{-4}$$

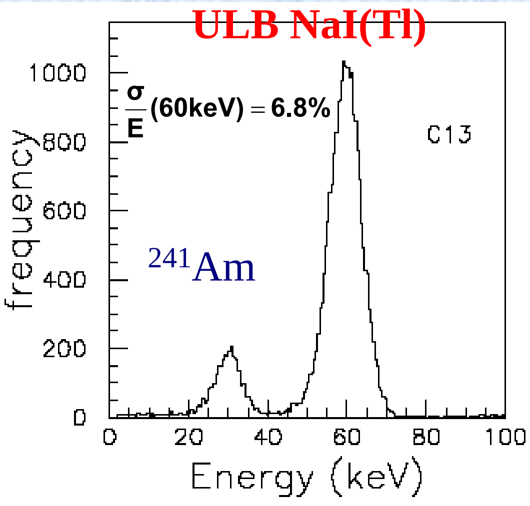
Thus, here and hereafter keV means keV electron equivalent





Examples of energy resolutions

DAMA/LIBRA
ULB NaI(Tl)



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σ/E @ 122 keV = 13%
at zero field

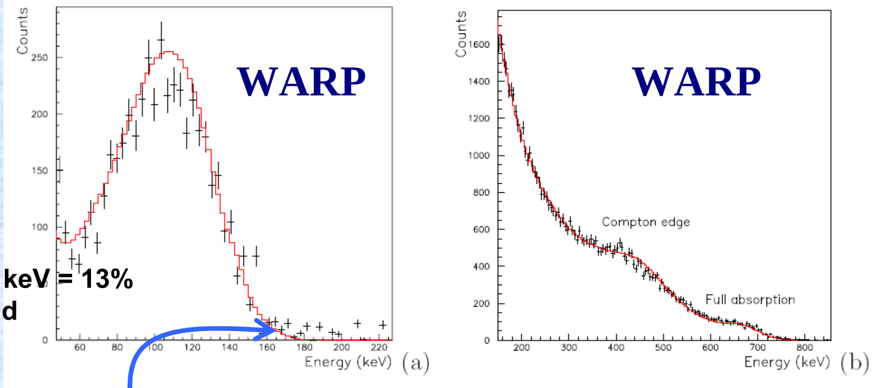
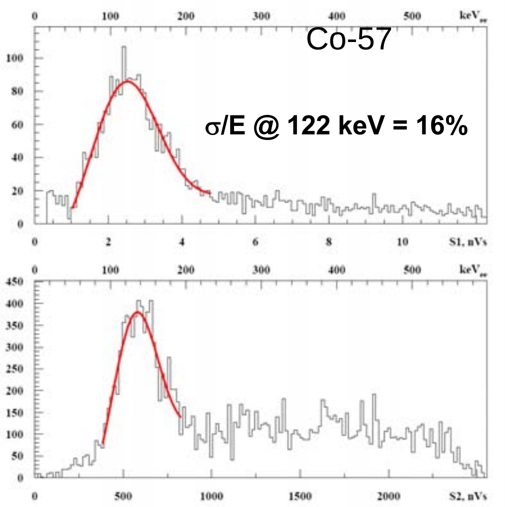


Fig. 2. Energy spectra taken with external γ-ray sources, superimposed with the corresponding Monte Carlo simulations. (a) ^{57}Co source ($E = 122$ keV, B.R. 85.6%, and 136 keV, B.R. 10.7%), (b) ^{137}Cs source ($E = 662$ keV).

subtraction of the spectrum ?

ZEPLIN-II

AP 28 (2007) 287



σ/E @ 122 keV = 16%

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%

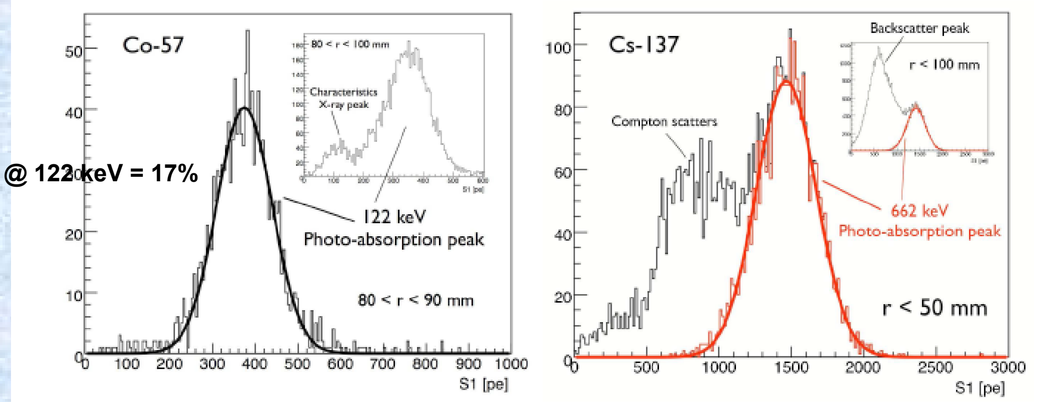
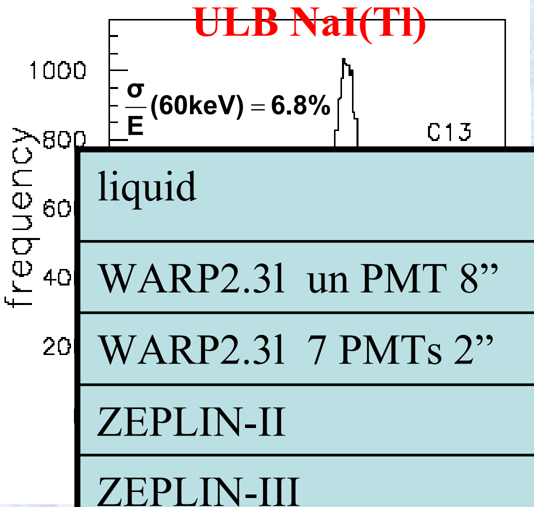


Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

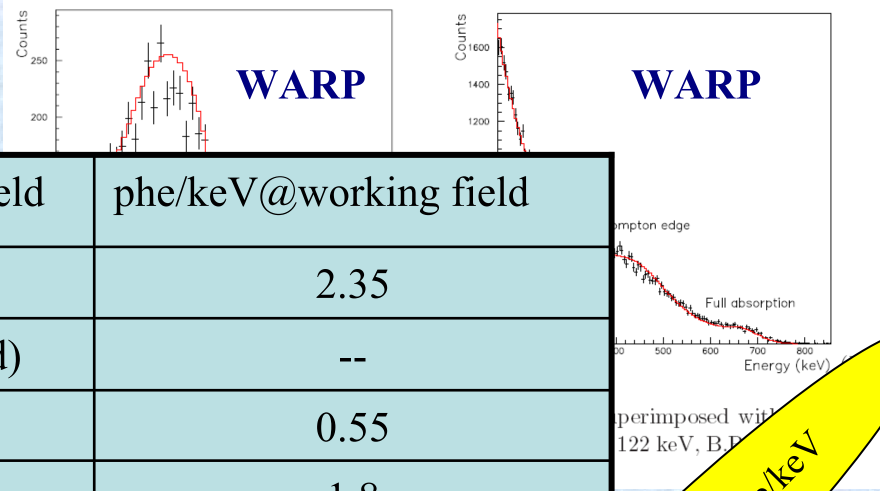
JoP: Conf. Ser. 65 (2007) 012015

Examples of energy resolutions

DAMA/LIBRA ULB NaI(Tl)



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 forese

DAMA/LIBRA : 5.5 – 7.5 phe/keV

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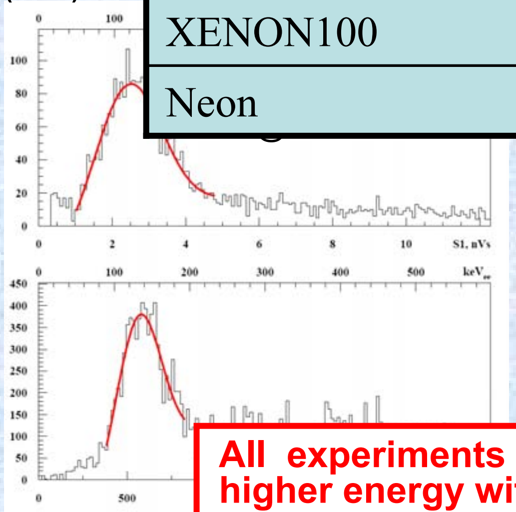
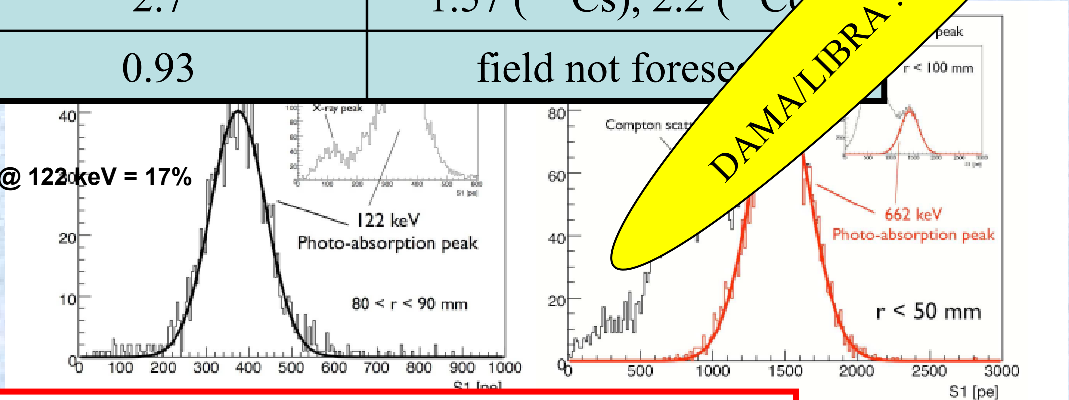


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of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



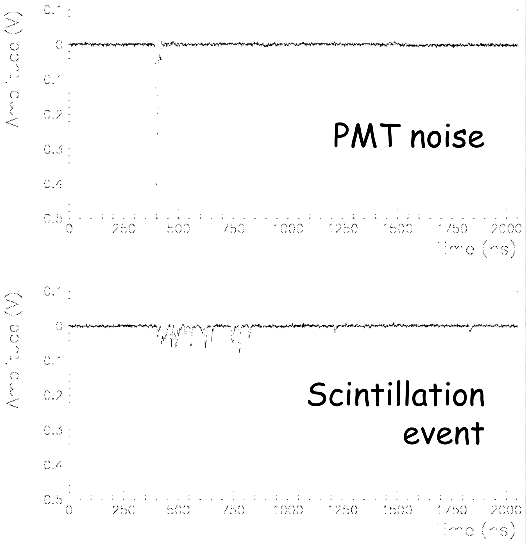
All experiments – except DAMA – use only calibration points at higher energy with “extrapolation” to low energy

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



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

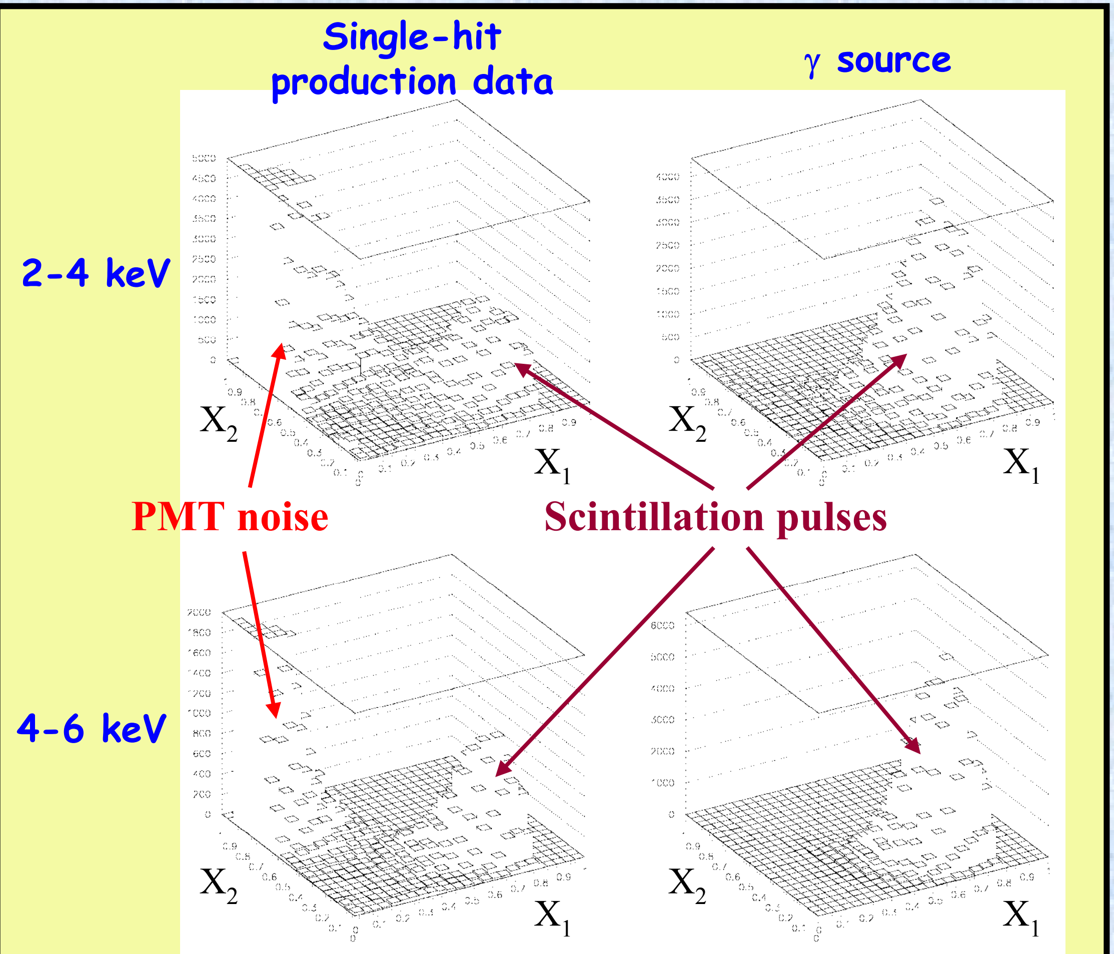
From the Waveform Analyser 2048 ns time window:

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

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

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

This is the only procedure applied to the analysed data



Infos about DAMA/LIBRA data taking

Period		Mass (kg)	Exposure (kg × day)	α-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**

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

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

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

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

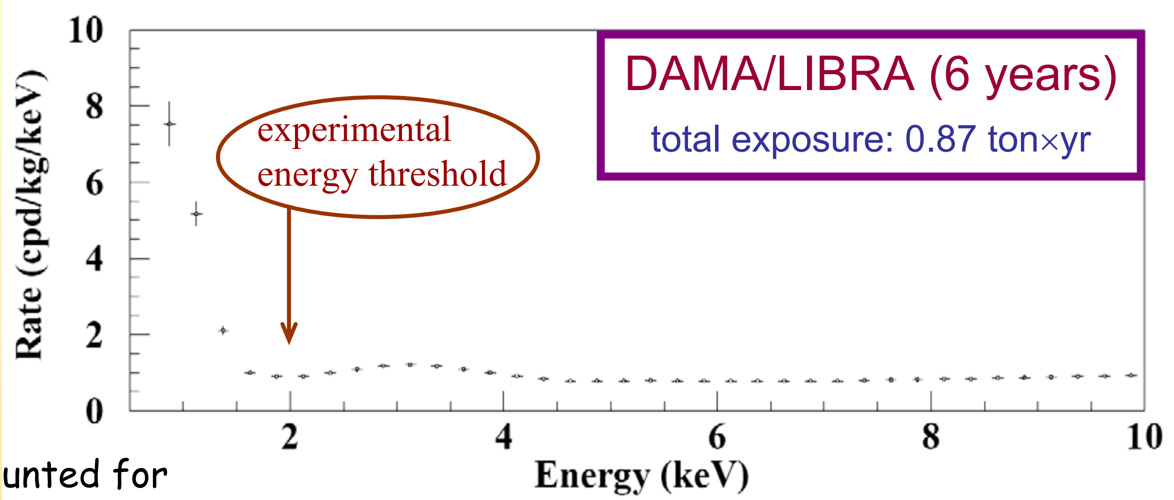
- **First upgrade on Sept 2008:**
  - replacement of some PMTs in HP N_2 atmosphere
  - restore 1 detector to operation
  - new Digitizers installed (U1063A Acqiris 1GS/s 8-bit High-Speed cPCI)
  - new DAQ system with optical read-out installed
- **New upgrade foreseen on fall 2010**

... continuously running

Cumulative low-energy distribution of the *single-hit* scintillation events

Single-hit events = each detector has all the others as anticoincidence

(Obviously differences among detectors are present depending e.g. on each specific level and location of residual contaminants, on the detector's location in the 5x5 matrix, etc.)



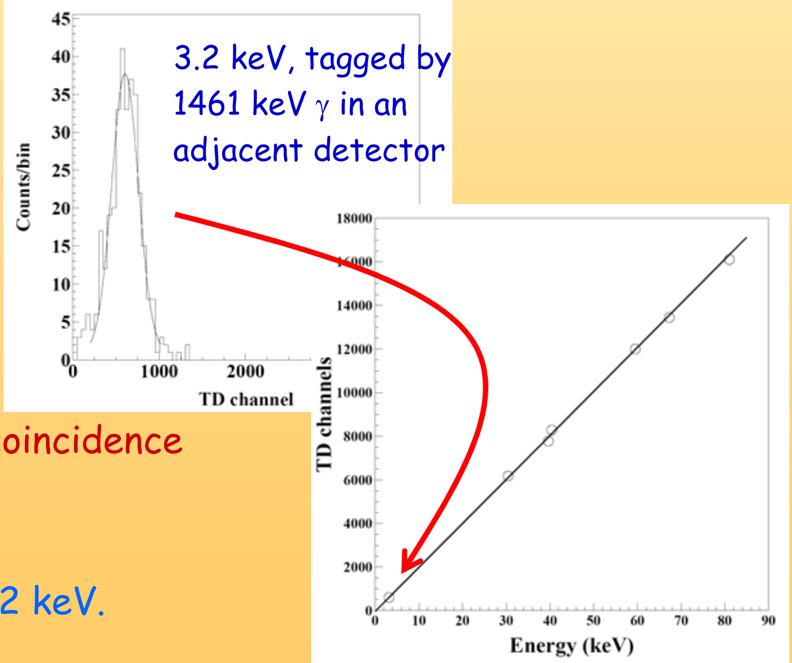
experimental energy threshold

DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr

Efficiencies already accounted for

About the energy threshold:



3.2 keV, tagged by 1461 keV γ in an adjacent detector

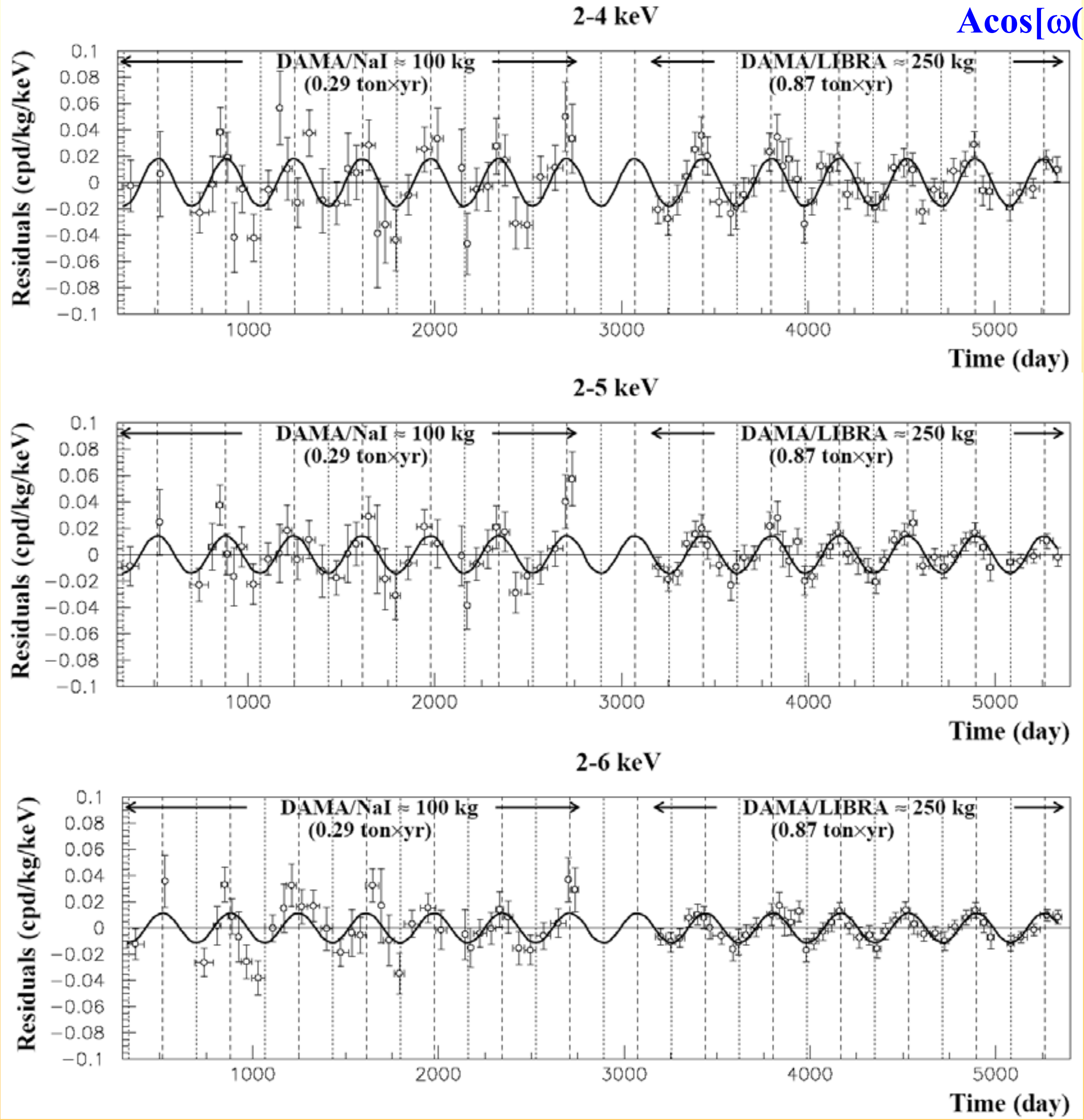
- The DAMA/LIBRA detectors have been calibrated down to the keV region. This assures a clear knowledge of the "physical" energy threshold of the experiment.
- It obviously profits of the relatively high number of available photoelectrons/keV (from 5.5 to 7.5).
- The two PMTs of each detector in DAMA/LIBRA work in coincidence with hardware threshold at single photoelectron level.
- Effective near-threshold-noise full rejection.
- The software energy threshold used by the experiment is 2 keV.

Model Independent Annual Modulation Result

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

EPJC67(2010)39 and refs. therein

experimental single-hit residuals rate vs time and energy



Acos[ω(t-t_0)] ; continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV

A=(0.0183±0.0022) cpd/kg/keV

χ^2/dof = 75.7/79 **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=147/80 ⇒ P(A=0) = 7×10^{-6}

2-5 keV

A=(0.0144±0.0016) cpd/kg/keV

χ^2/dof = 56.6/79 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=135/80 ⇒ P(A=0) = 1.1×10^{-4}

2-6 keV

A=(0.0114±0.0013) cpd/kg/keV

χ^2/dof = 64.7/79 **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=140/80 ⇒ P(A=0) = 4.3×10^{-5}

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

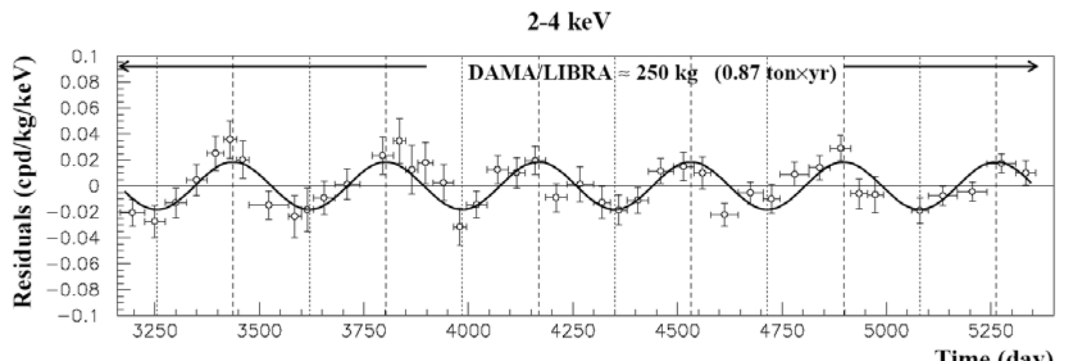
DAMA/LIBRA-1 to 6 Model Independent Annual Modulation Result

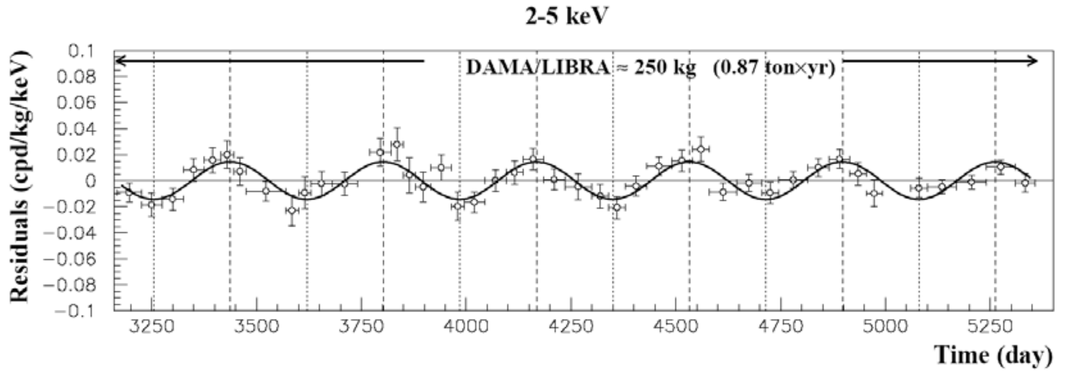
experimental single-hit residuals rate vs time and energy

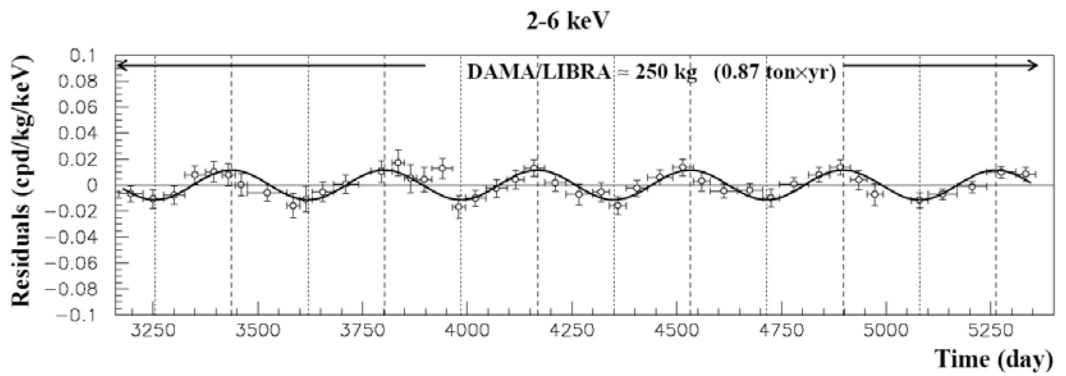
EPJC67(2010)39

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

DAMA/LIBRA-1,2,3,4,5,6 (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±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

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

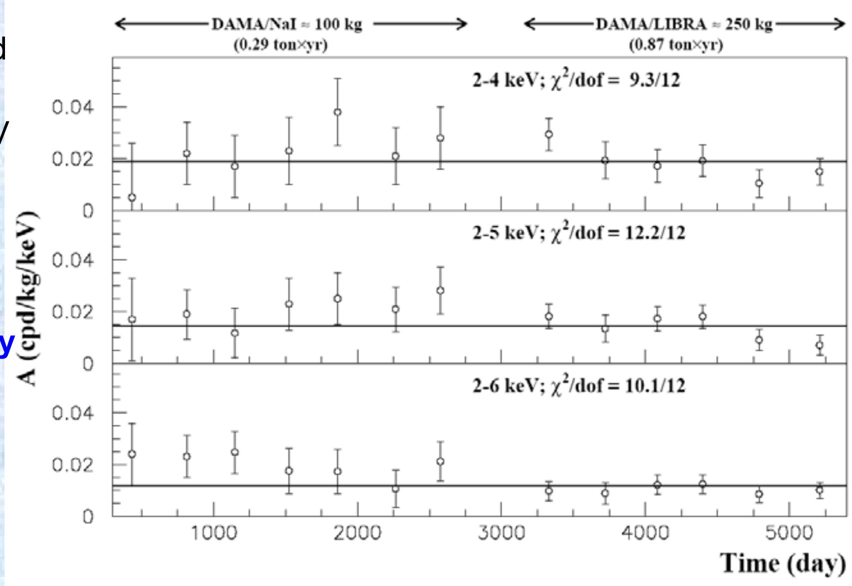
	A (cpd/kg/keV)	T= 2π/ω (yr)	t_0 (day)	C.L.
DAMA/NaI (7 years)				
(2÷4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2÷5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2÷6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA (6 years)				
(2÷4) keV	0.0180 ± 0.0025	0.996 ± 0.002	135 ± 8	7.2σ
(2÷5)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

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

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

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

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



Compatibility among the annual cycles

Power spectrum of single-hit residuals

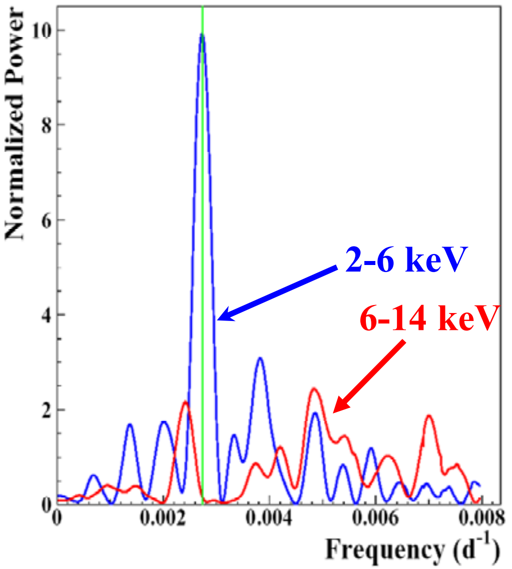
(according to Ap.J.263(1982)835; Ap.J.338(1989)277)

Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

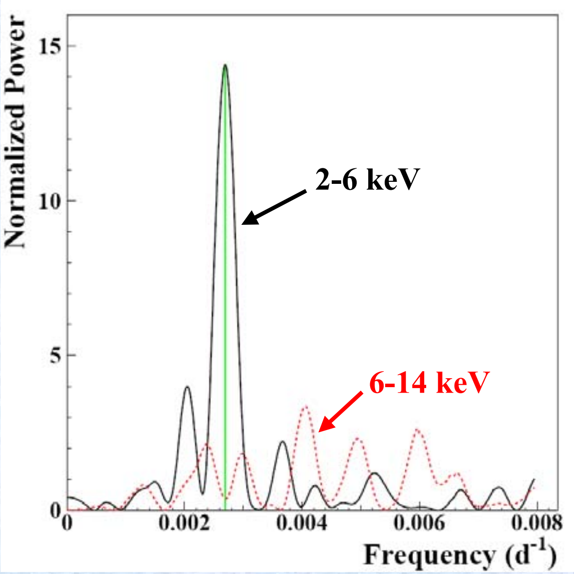
DAMA/NaI (7 years)

total exposure: 0.29 ton×yr



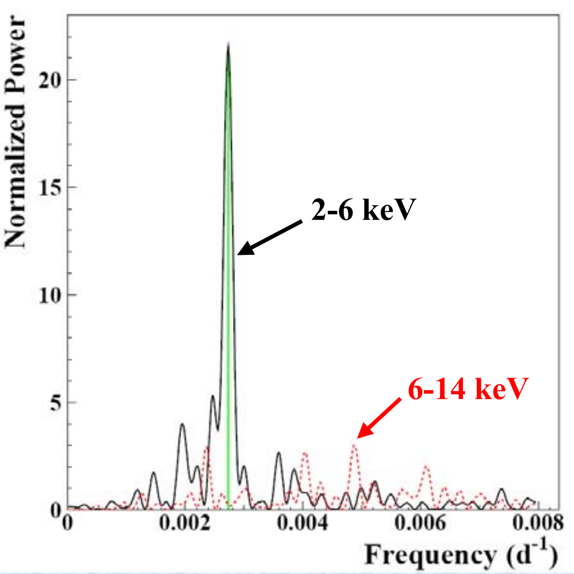
DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr



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

total exposure: 1.17 ton×yr



Principal mode in the 2-6 keV region:

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

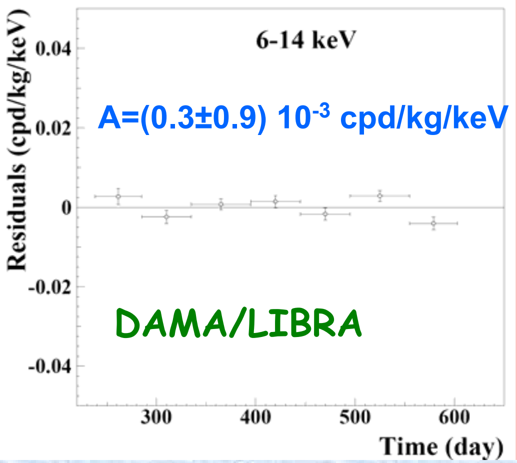
+

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

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

Rate behaviour above 6 keV

- **No Modulation above 6 keV**

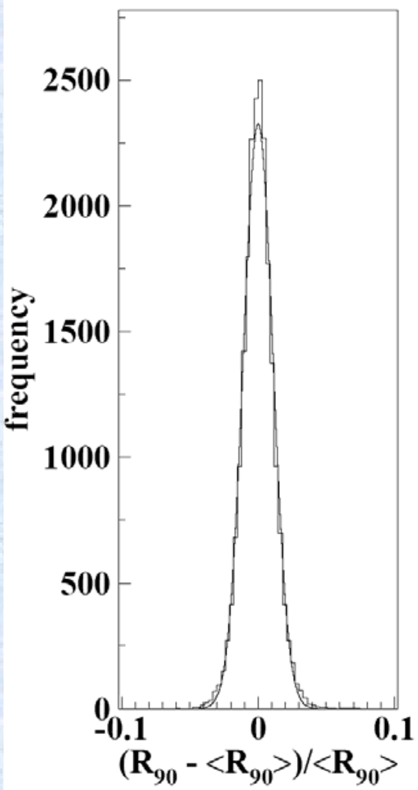


Mod. Ampl. (6-10 keV): cpd/kg/keV

(0.0016 ± 0.0031) DAMA/LIBRA-1
-(0.0010 ± 0.0034) DAMA/LIBRA-2
-(0.0001 ± 0.0031) DAMA/LIBRA-3
-(0.0006 ± 0.0029) DAMA/LIBRA-4
-(0.0021 ± 0.0026) DAMA/LIBRA-5
(0.0029 ± 0.0025) DAMA/LIBRA-6

→ statistically consistent with zero

DAMALIBRA-1 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

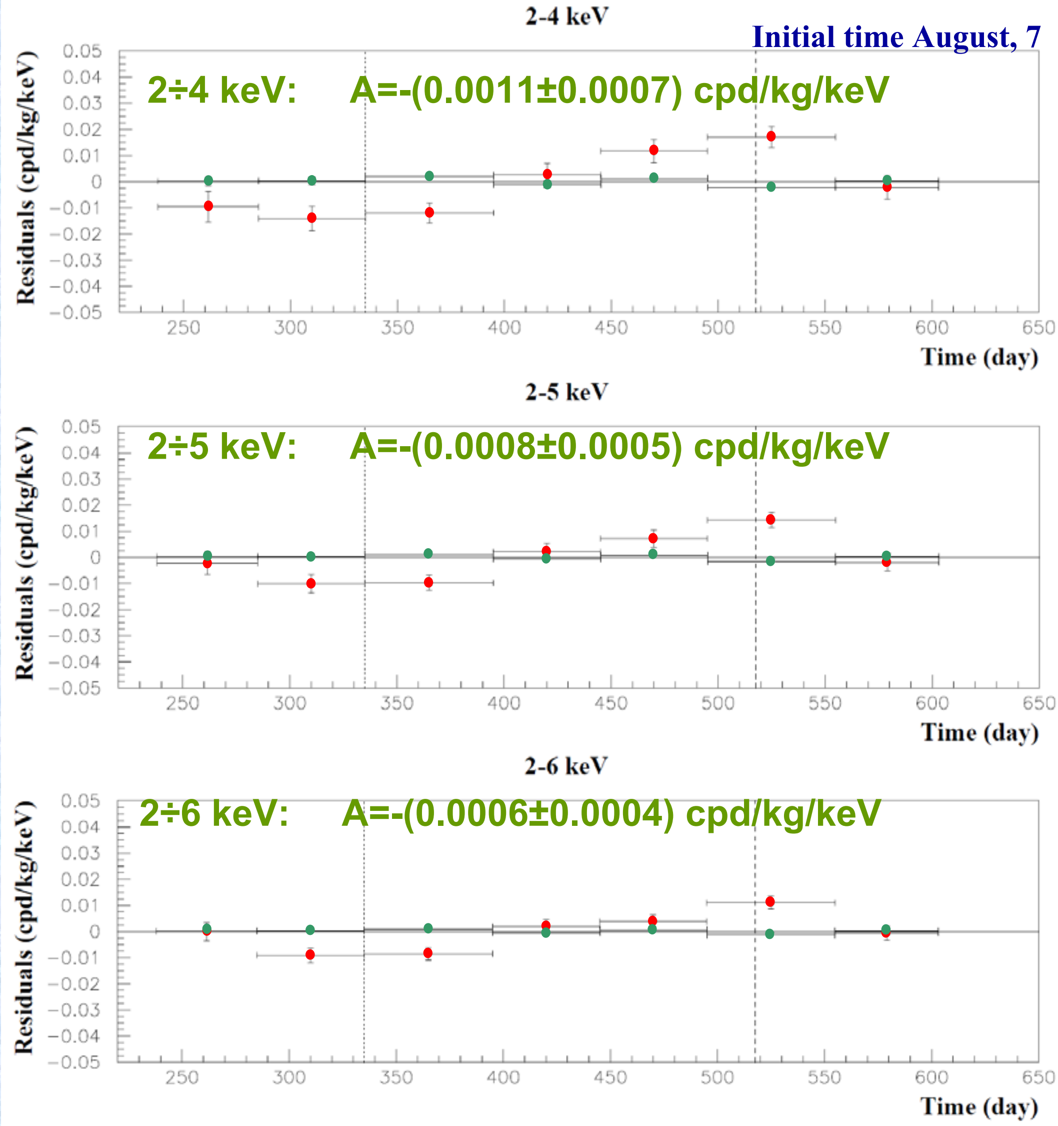
This accounts for all sources of bckg and is consistent with studies on the various components

Multiple-hits events in the region of the signal - DAMA/LIBRA 1-6

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

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

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



Evidence of annual modulation with proper features as required by the DM annual modulation signature is present in the *single-hit* residuals, while it is absent in the *multiple-hits* residual rate.

This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo

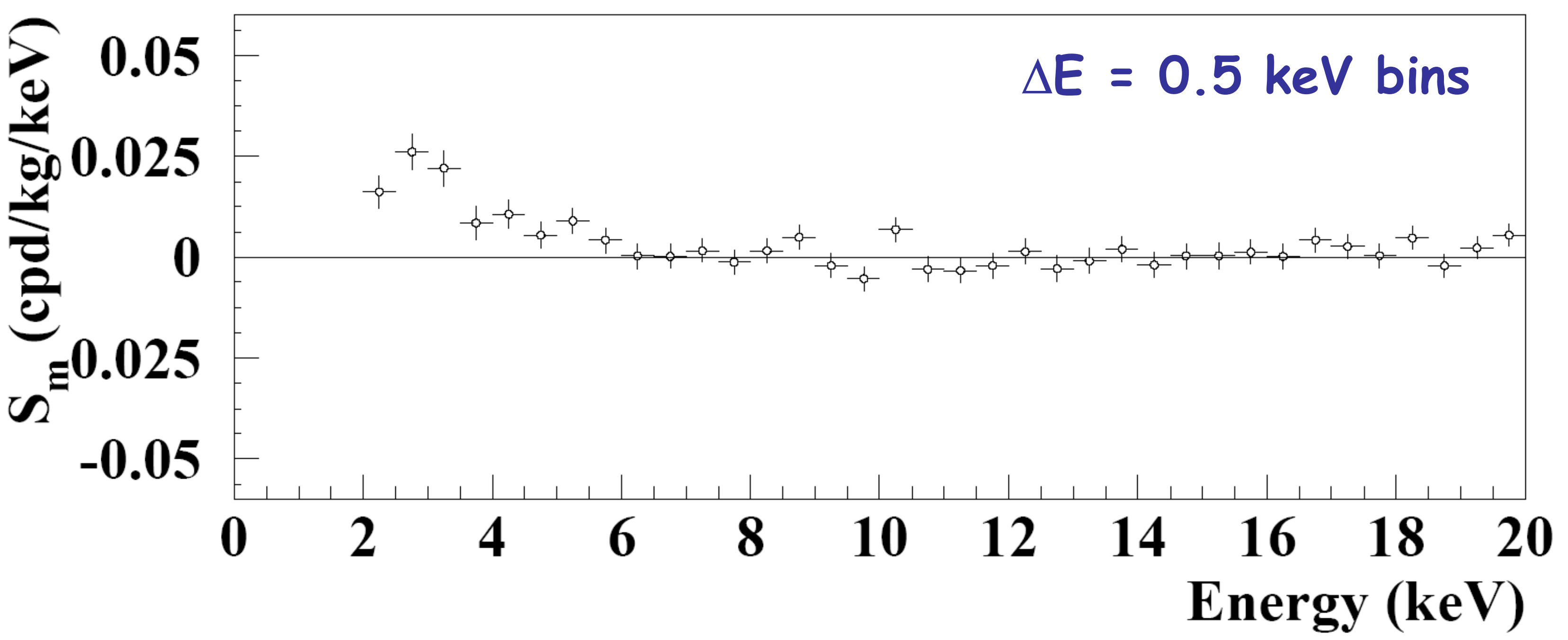
Energy distribution of the modulation amplitudes

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

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)

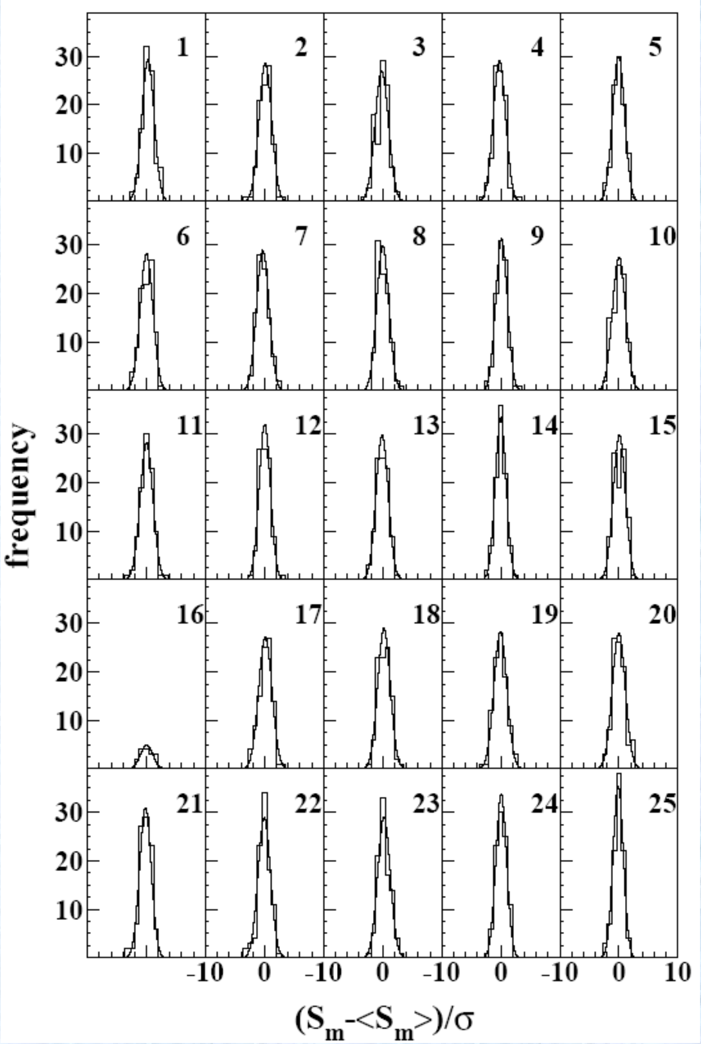
a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

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

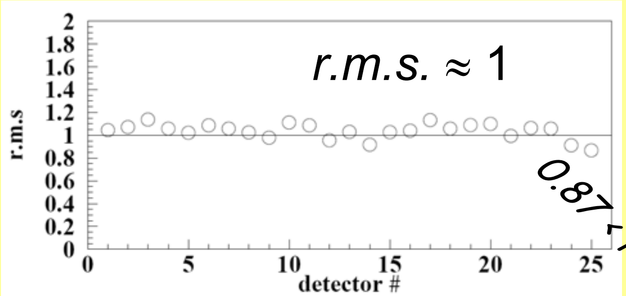


2-6 keV

Standard deviations of the variable

(Sm-⟨Sm⟩)/σ

for the DAMA/LIBRA 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)

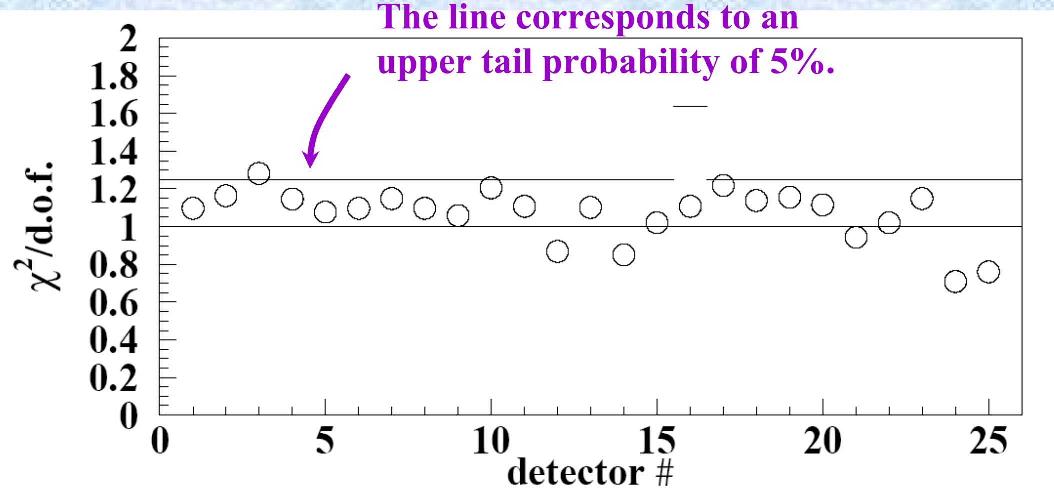
$x=(S_m-<S_m>)/\sigma$,

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

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

DAMA/LIBRA (6 years)

total exposure: 0.87 ton×yr



The line corresponds to an upper tail probability of 5%.

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.

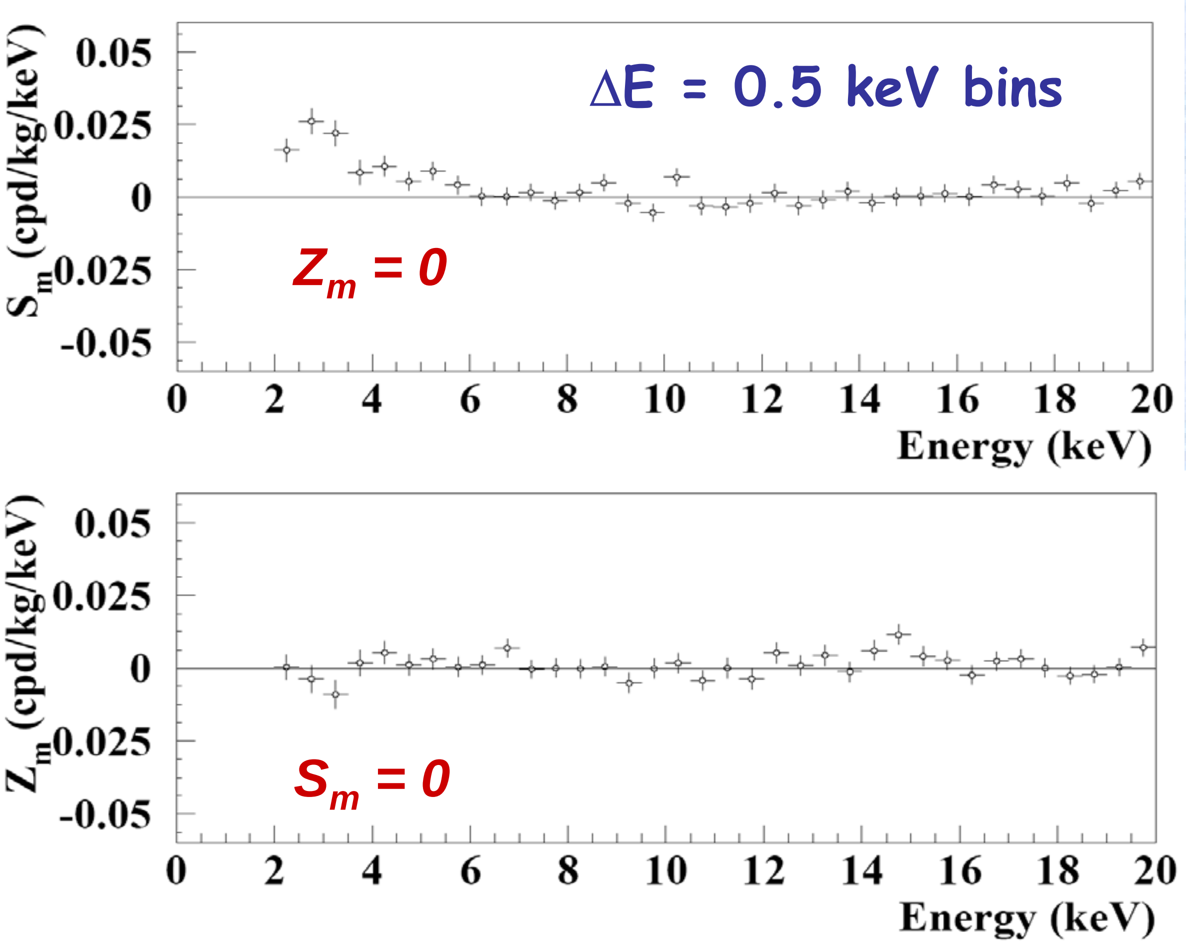
- The mean value of the twenty-five points is 1.066, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 4 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 5\times10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (**≤ 4 %** or **≤ 0.5%**, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

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)**

***phase at* 2° June**

as for DM particles

***phase 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)

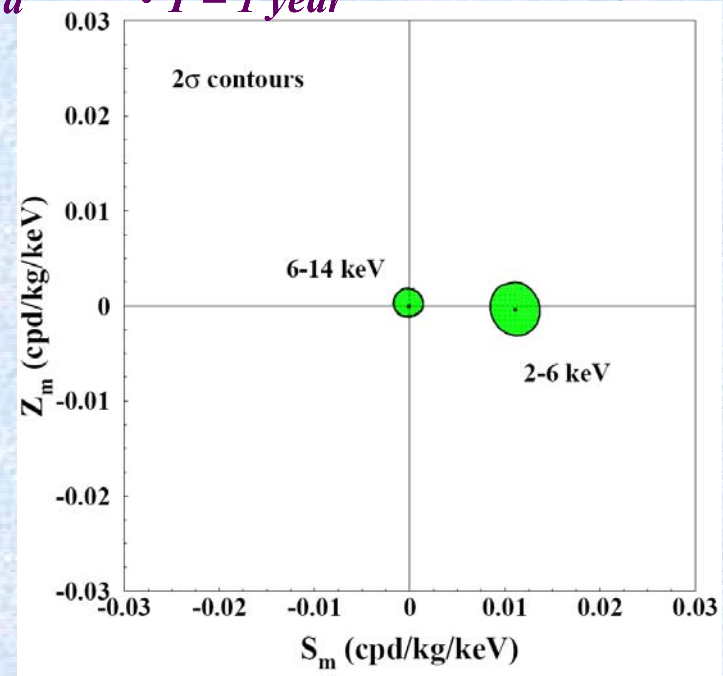
total exposure: 425428 kg×day = 1.17 ton×yr

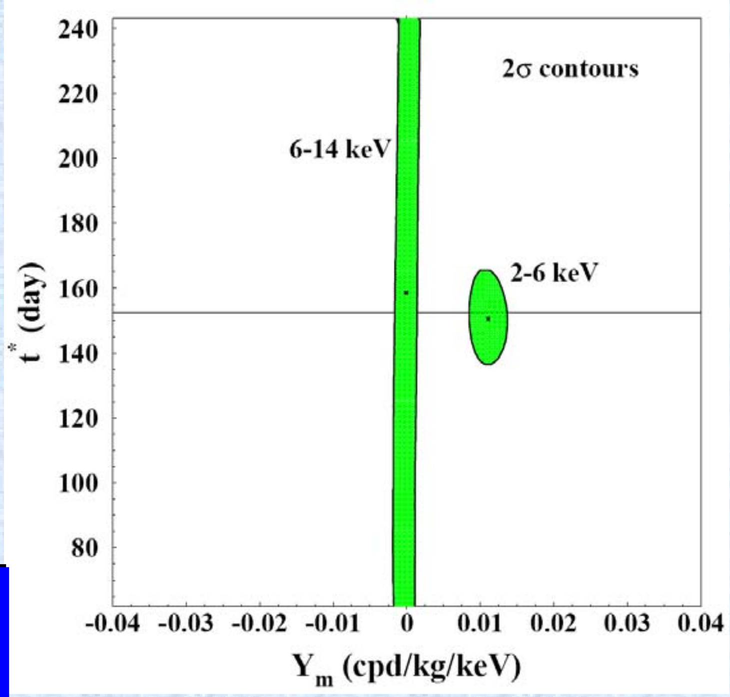
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

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)

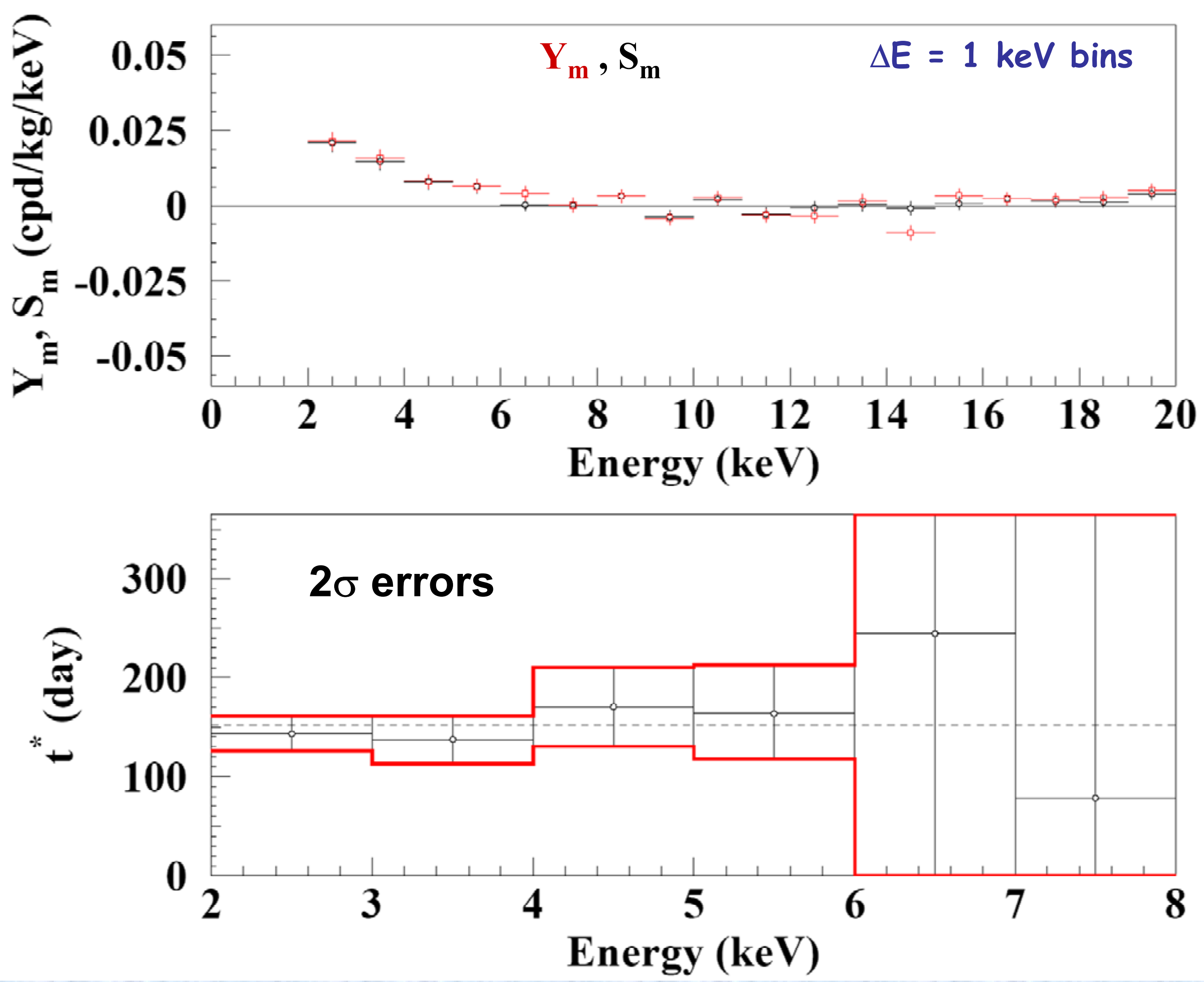
total exposure: 425428 kg×day = 1.17 ton×yr

For Dark Matter signals:

$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

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



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

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) × 10^{-2} Hz	(0.09 ± 0.17) × 10^{-2} Hz	-(0.03 ± 0.20) × 10^{-2} Hz	(0.15 ± 0.15) × 10^{-2} Hz	(0.03 ± 0.14) × 10^{-2} Hz	(0.08 ± 0.11) × 10^{-2} Hz

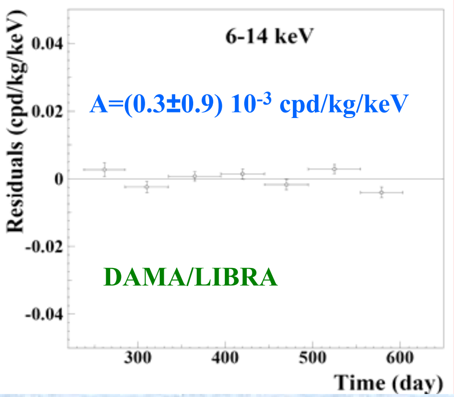
All the measured amplitudes well compatible with zero

+ 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)

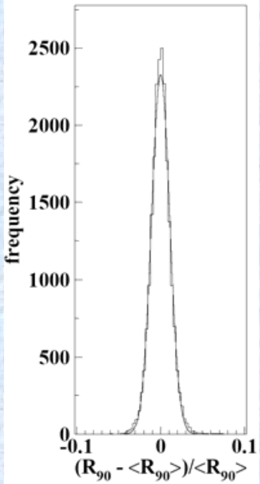
Summarizing on
a hypothetical background modulation in DAMA/LIBRA 1-6

- **No Modulation above 6 keV**



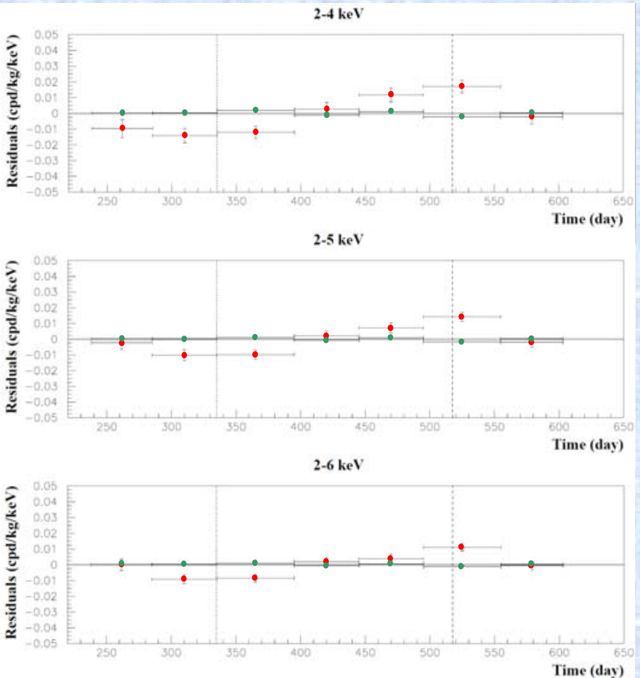
- **No modulation in the whole energy spectrum**

$\sigma \approx 1\%$



+ 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 in the 2-6 keV *multiple-hits* residual rate**



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

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

Nevertheless, additional investigations performed ...

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

NO

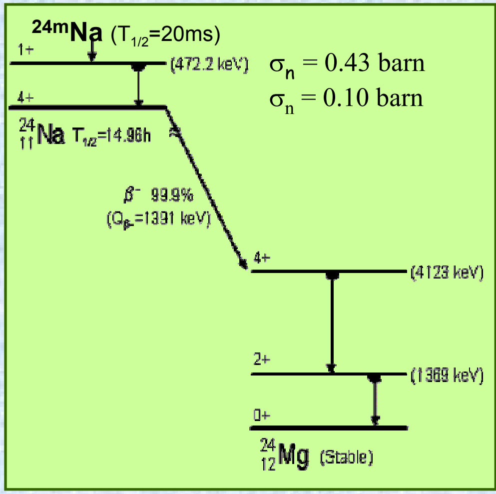
- Thermal neutrons flux measured at LNGS :

$\Phi_n = 1.08\ 10^{-6}$ 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:

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

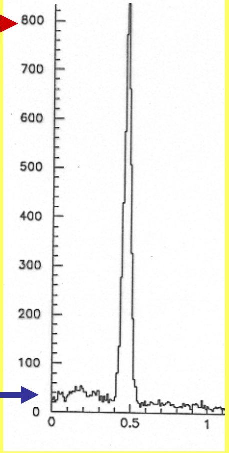
Already excluded also by R_{90} analysis

MC simulation of the process

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

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

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



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

NO

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield

Measured fast neutron flux @ LNGS:
$\Phi_n = 0.9 \, 10^{-7}$ n cm^{-2} s^{-1} (Astropart.Phys.4 (1995)23)

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

HYPOTHESIS: assuming - very cautiously - a 10% neutron modulation: ⇒ $S_m^{(\text{fast n})} < 10^{-4}$ 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}Na(n,n′)^{23}Na*(2076 keV) which produces two γ's in coincidence (1636 keV and 440 keV):

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

  - well compatible with the measured values at LNGS. This further excludes any presence of a fast neutron flux in DAMA/LIBRA significantly larger than the measured ones.

Moreover, a possible fast n modulation would induce:

- a variation in all the energy spectrum (steady environmental fast neutrons always accompained by thermalized component)

  already excluded also by R_{90}

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

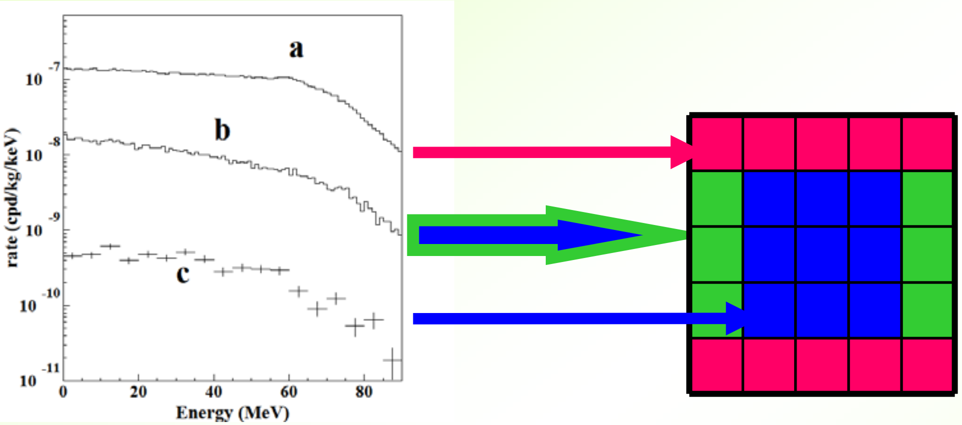
  already excluded by the multiple-hit events

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

The μ case

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

events where just one detector fires



Case of fast neutrons produced by μ

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

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

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.

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

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

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

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

- only events at low energy,
- only *single-hit* events,
- no sizable effect in the *multiple-hit* counting rate

?

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

- if τ<<T/2π: $t_{side} = t_\mu + \tau$
- if τ>>T/2π: $t_{side} = t_\mu + T/4$

It cannot mimic the signature, e.g.: 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 partially overlapped with DAMA/NaI and fully with DAMA/LIBRA: 1.5% modulation and phase=July 5th ± 15 d.

→

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

This phase is 7.3 σ far from July 15th and is 5.9 σ far from July 5th

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

NO

Summary of the results obtained in the additional investigations of possible systematics or side reactions: DAMA/LIBRA-1 to 6

(NIMA592(2008)297, EPJC56(2008)333, EPJC67(2010)39, arXiv:0912.0660, arXiv:1007.0595)

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 can not mimic the observed annual modulation effect

Summarizing

The new annual cycles DAMA/LIBRA-5,6 have further confirmed a peculiar annual modulation of the *single-hit* events in the (2-6) keV energy region which satisfies the many requests of the DM annual modulation signature.

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 the roughly about 152.5 days as expected for the DM signal

4)
The modulation is present only in the low energy (2—6) keV energy 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-hit* ones as expected for the DM signal

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

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

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

well compatible with several candidates (in several of the many possible astrophysical, nuclear and particle physics scenarios); other ones are open

Neutralino as LSP in various SUSY theories

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

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

Self interacting Dark Matter

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

Sterile neutrino

heavy exotic canditates, as “4th family atoms”, ...

Elementary Black holes such as the Daemons

Kaluza Klein particles

… and more

Possible model dependent positive hints from indire
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 of positive excess

- complete model dependent analyses require to apply maximum likelihood analysis in time and energy to the collected events of the cumulative exposure to derive allowed regions at given C.L., accounting both for all the info carried out by the data and for at least some of the many existing uncertainties in the field (as done by DAMA/NaI in **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**, and more)

- Just to offer some naive feeling on the complexity of the argument:

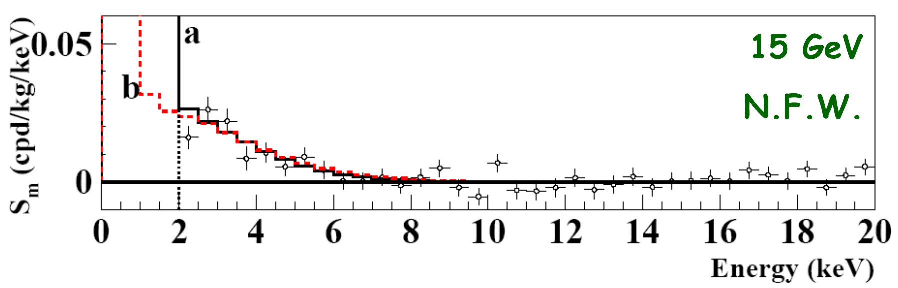
experimental S_m values vs expected behaviours

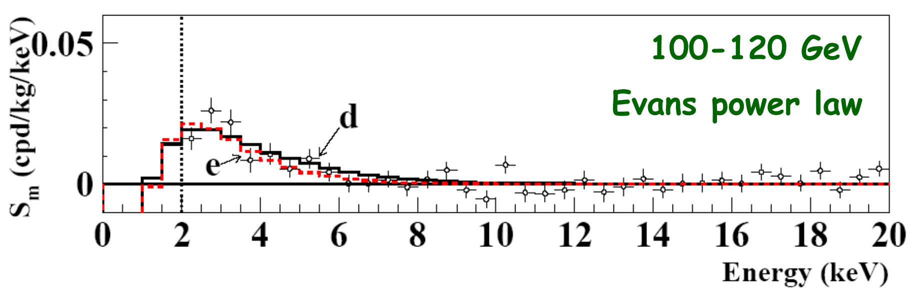
for some DM candidates in few of
the many possible astrophysical,
nuclear and particle physics
scenarios and parameters values

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

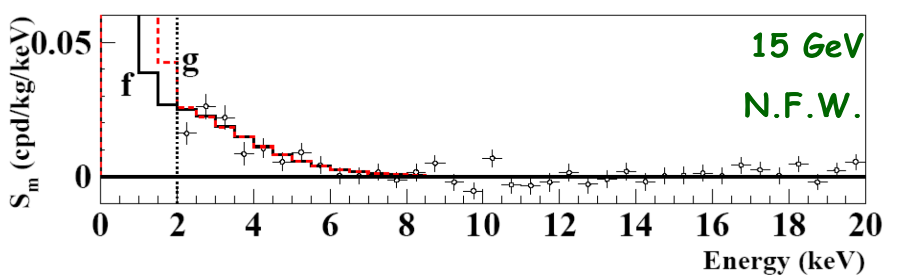
- Not best fit
- About the same C.L.,

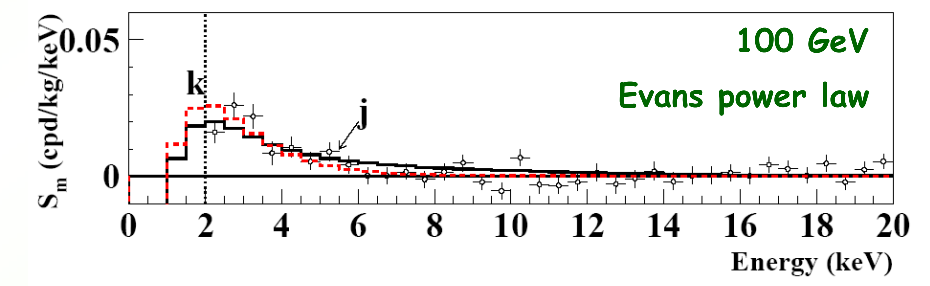
WIMP: SI



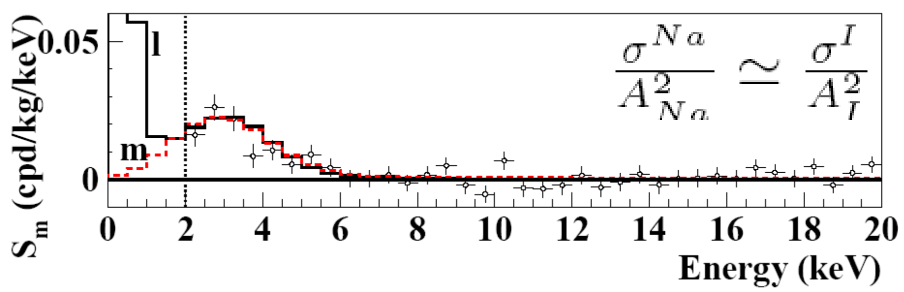


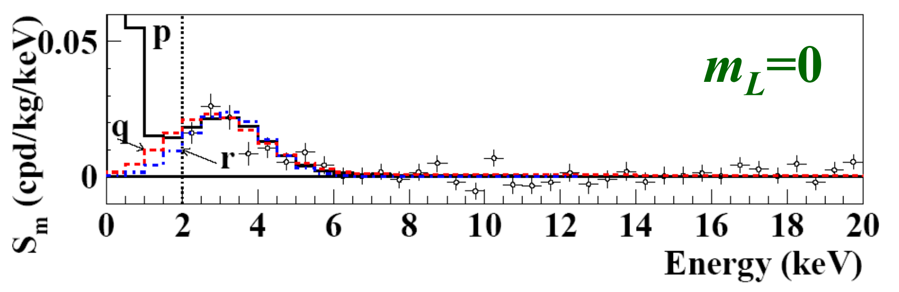
WIMP: SI & SD $\theta = 2.435$





LDM, bosonic DM





EPJC56(2008)333

Compatibility with several candidates; other ones are open

… other 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.

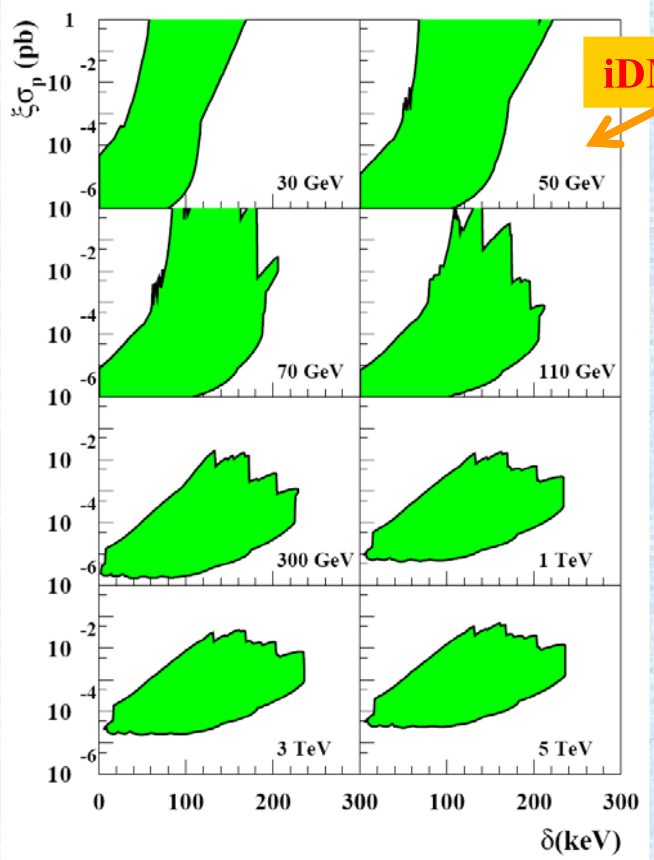
$$\chi^- + N \rightarrow \chi^+ + N$$

→ 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

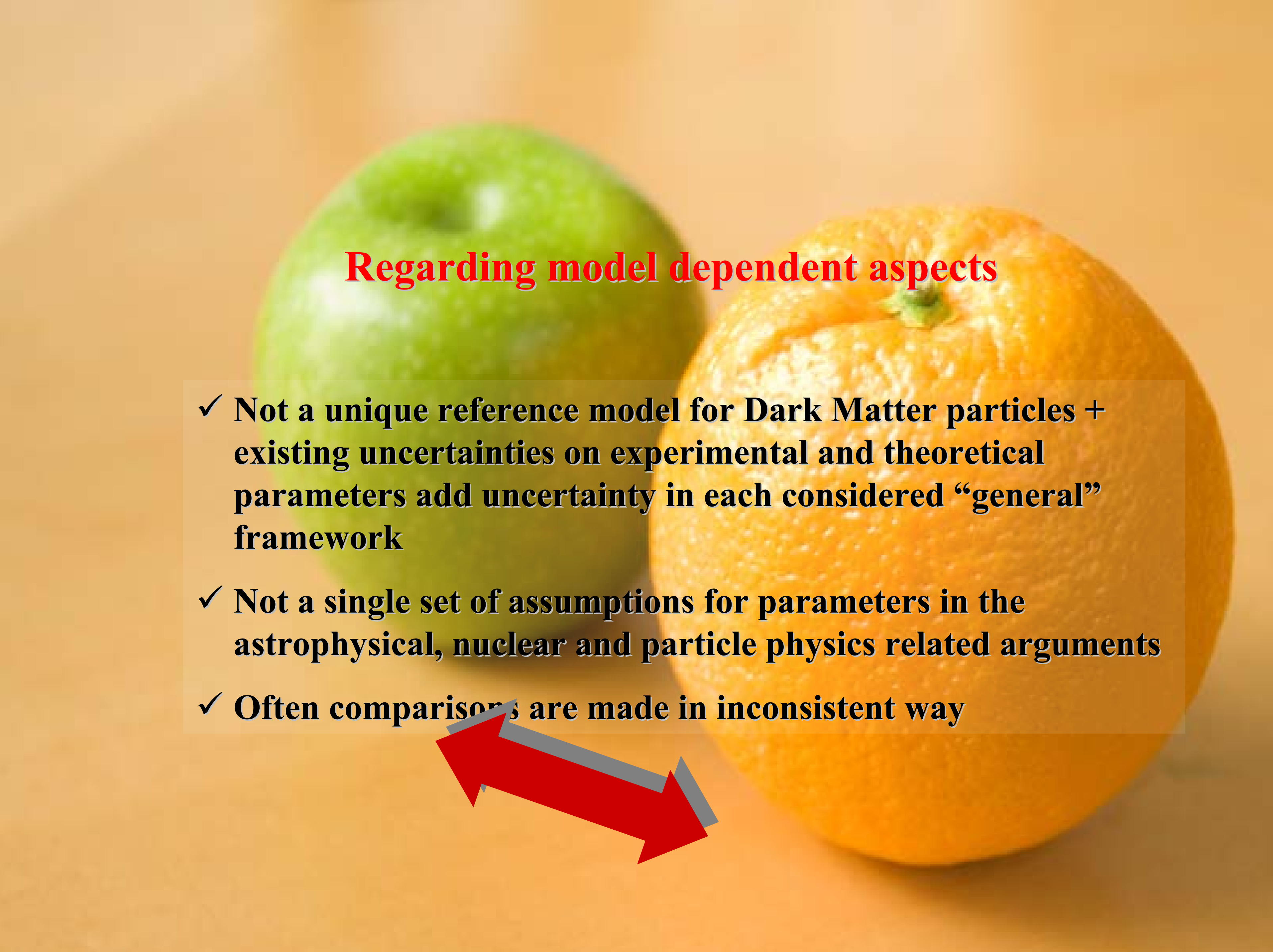
iDM interaction on Tl nuclei of the NaI(Tl) dopant?

- 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.
- Inelastic scattering WIMPs with **large splittings** do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

arXiv:1007.2688:

… and more considering experimental and theoretical uncertainties

Regarding model dependent aspects



- ✓ Not a unique reference model for Dark Matter particles + existing uncertainties on experimental and theoretical parameters add uncertainty in each considered “general” framework
- ✓ Not a single set of assumptions for parameters in the astrophysical, nuclear and particle physics related arguments
- ✓ Often comparisons are made in inconsistent way

About model dependent exclusion plots

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

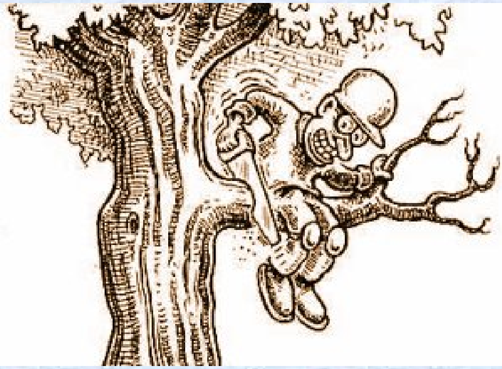
- *which particle?*
- *which couplings? which model for the coupling?*
- *which form factors for each target material and related parameters?*
- *which nuclear model framework for each target material?*
- *Which spin factor for each case?*
- *which scaling laws?*
- *which halo profile?*
- *which halo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

road sign or labyrinth?

and experimental aspects ,,,

- *marginal and "selected" exposures*
- *Threshold, energy scale and energy resolution when calibration in other energy region (& few phe/keV)? Stability? Too few calibration procedures and often not in the same running conditions*
- *Selections of detectors and of data*
- *handling of (many) "subtraction" procedures and stability in time of all the cuts windows and related quantities, etc.? Efficiencies?*
- *fiducial volume vs disuniformity of detector response in liquids?*
- *Used values in the calculation (q.f., etc)*
- *Used approximations*

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



+ no uncertainties accounted for

no sensitivity to DM annual modulation signature

Different target materials

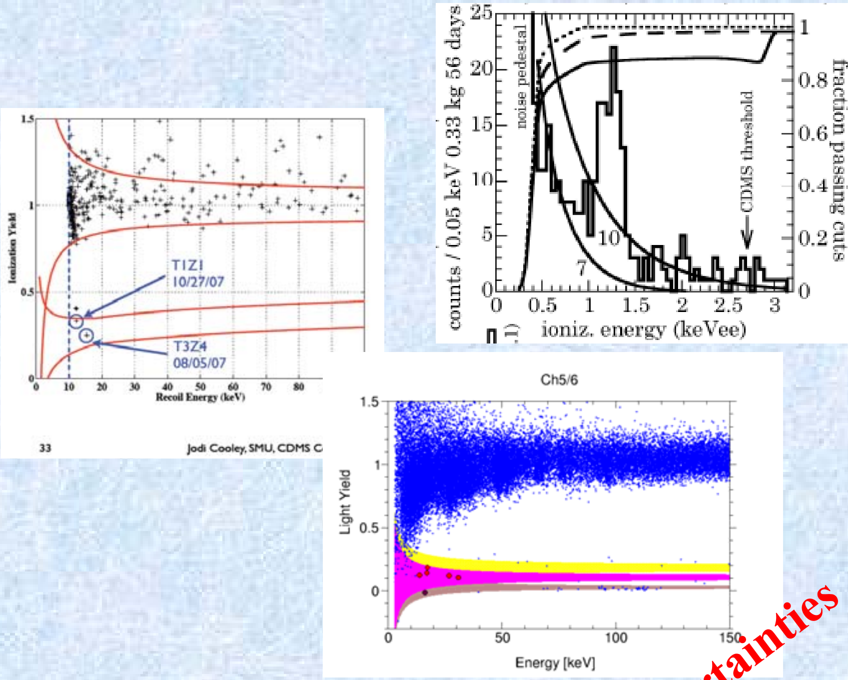
DAMA implications often presented in incorrect/incomplete/non-updated way

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

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

Example 2010 – Positive recoil-like excesses in different kinds of direct searches

- **CoGeNT**: low-energy rise in the spectrum (irriducible by the applied background reduction procedures)
- **CDMS**: after data selection and cuts, 2 Ge candidate recoils survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)
- **CRESST**: after data selection and cuts, 32 O candidate recoils survive in an exposure of ≈ 400 kg x day (8.7±1.2 estimated as expected from residual background)



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

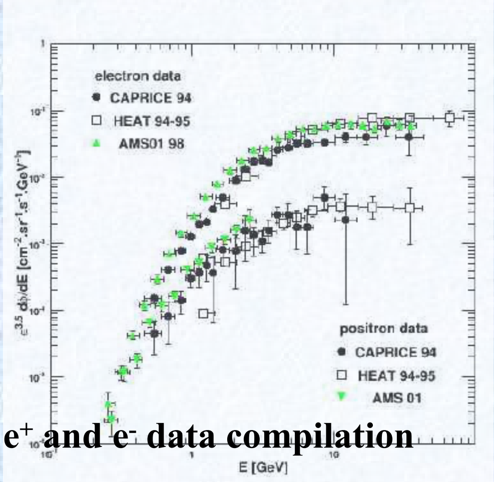
Some recent literature discussing compatibility in various frameworks e.g.:

- Light WIMP DM (arXiv:1003.0014,arXiv:1007.1005v2)
- Low mass neutralino in effMSSM (PRD81(2010)107302,arXiv:0912.4025)
- Inelastic DM (PRD79(2009)043513, arXiv:1007.2688)
- Mirror DM (arXiv:10010096)
- Resonant DM (arXiv:0909.2900)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Light Neutralino DM (arXiv:1009.0549)
- Composite DM (arXiv:1003.1144)
- Light scalar WIMP through Higgs portal (arXiv:1003.2595)
- SD Inelastic DM (arXiv:0912.4264)
- Complex Scalar Dark Matter (arXiv:1005.3328)
- Light Neutralinos (arXiv:1003.0682)
- ...

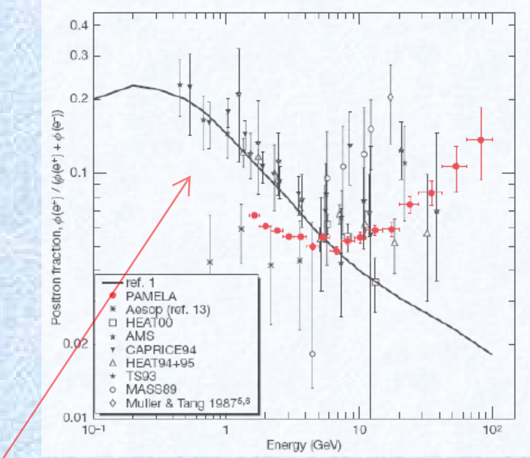
… and much more considering all the uncertainties

Local measurements of cosmic ray $e^{+/-}$

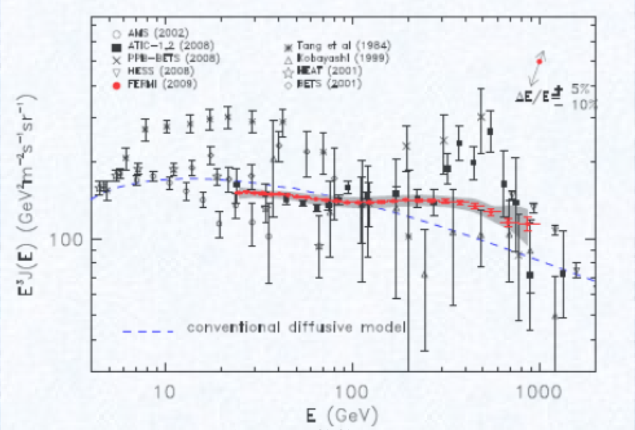
Some of the DM candidate particles might annihilate if certain conditions are assumed as fulfilled



e^+ and e^- data compilation



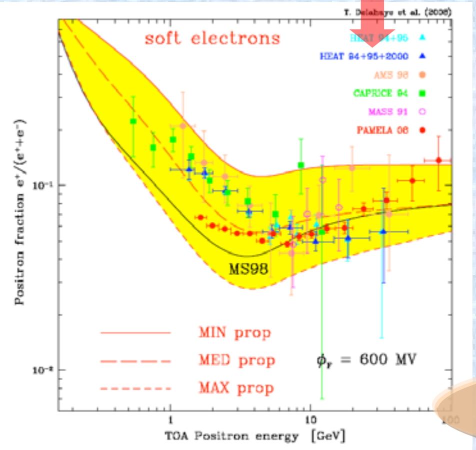
$e^+/(e^+ + e^-)$ PAMELA Adriani et al. (2009)



$(e^+ + e^-)$ HESS and FERMI Aharonian et al. (2009), Abdo et al. (2009)

Uncertainties are still large

Pamela positron fraction deviates from predictions of an assumed secondary production model (GALPROP); but, analogous models also exist with different secondary production giving no significant deviation, e.g.



arXiv:0809.5268

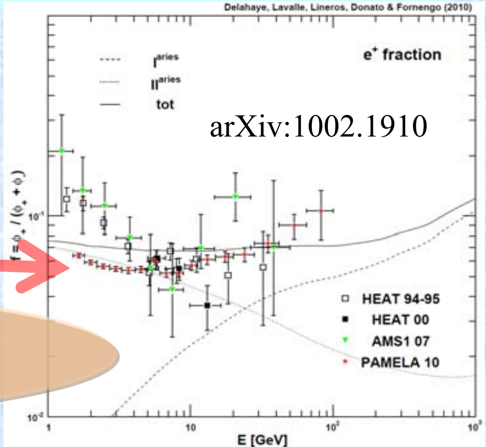
While PAMELA e^+ are well accounted by secondary e^+ expectations, a conventional secondary origin seems unlikely when FERMI data ($e^+ + e^-$) are included.

- Interpretation in terms of DM particle annihilation requires a very large **boost factor (≈ 400)**: i) boost the cross section, ii) play with the propagation parameters, iii) consider extra-source (subhalos, IMBHs). ***Unlikely***

+ no excess is observed in the anti-proton spectrum

- **Other well known sources** can account for a similar positron fraction (see literature): **pulsars**, **supernova** explosions near the Earth, **SNR**

Example



arXiv:1002.1910

Therefore, no constraint on direct detection phenomenology

Conclusions

- **Positive model independent evidence for the presence of DM particles in the galactic halo at 8.9 σ C.L. (cumulative exposure 1.17 ton × yr - 13 annual cycles DAMA/NaI & DAMA/LIBRA)**
- **Modulation parameters determined with better precision**
- **Full sensitivity to many kinds of DM candidates (both with high and low mass) and to many interaction types (both inducing recoils and/or e.m. radiation), many astrophysical scenarios, etc.**
- **No experiment exists whose result can be directly compared in a model independent way with those by DAMA/NaI & DAMA/LIBRA.**
- **Recent recoil-like excesses in direct searches above some estimates of residual background are - when interpreted as induced by some DM candidates - compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties.**
- **Indirect model dependent searches not in conflict.**
- **Investigations other than DM**

What next?

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

DAMA/LIBRA still the highest radiopure set-up in the field with the largest sensitive mass, the full controlled running conditions, the largest duty-cycle, exposure orders of magnitude larger than any other activity in the field, ecc., and the only one which effectively exploits a model independent DM signature