Signals from the Universe: from DAMA/NaI to DAMA/LIBRA

Desy, October 2008

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

COMA Cluster

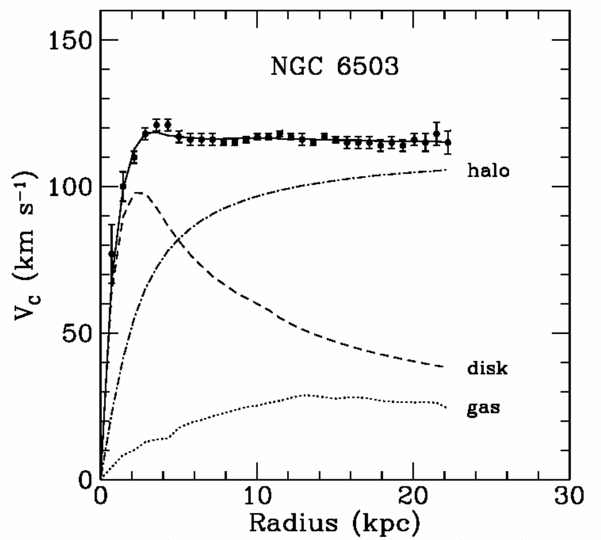
First evidence and confirmations:

1933 F. Zwicky: studying dispersion velocity of Coma galaxies

1936 S. Smith: studying the Virgo cluster

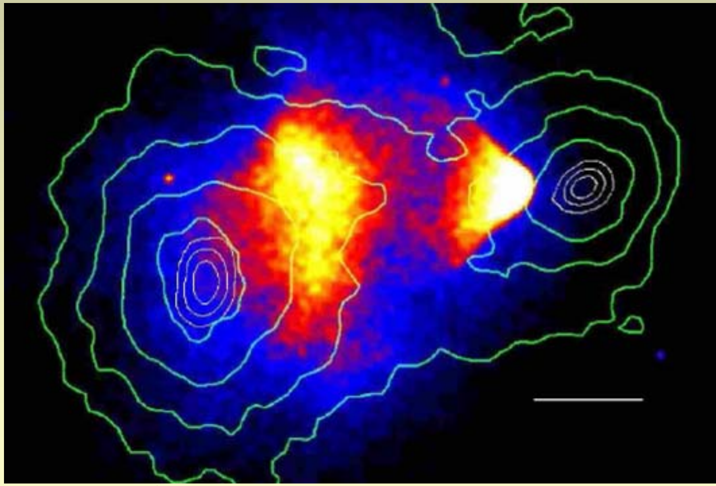
1974 two groups: systematical analysis of *mass density* vs *distance from center* in many galaxies

Other experimental evidences



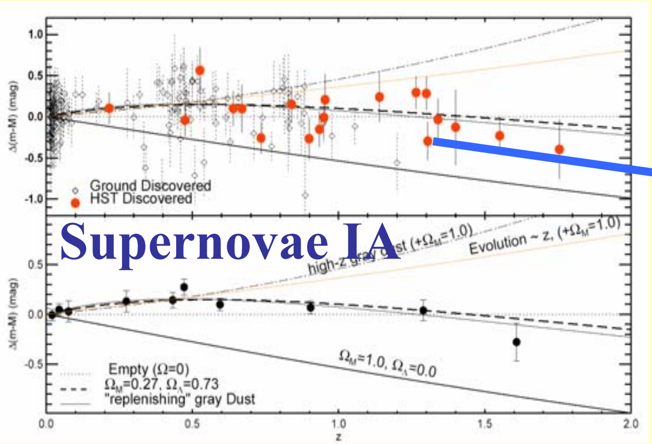
Rotational curve of a spiral galaxy

- ✓ 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

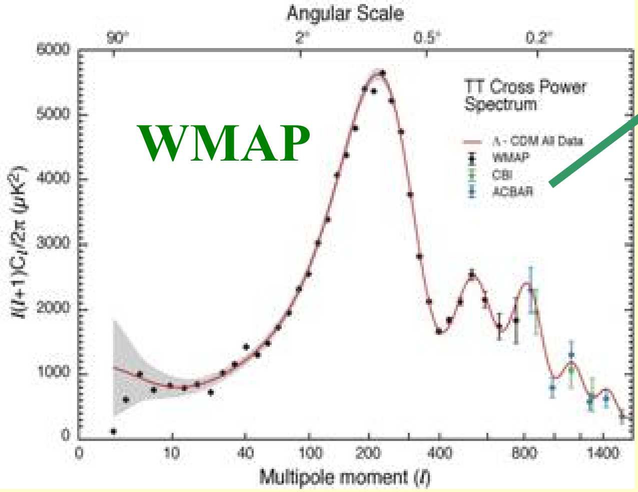


$M_{\text{visible Universe}} << M_{\text{gravitational effect}}$ ⇒ about 90% of the mass is DARK

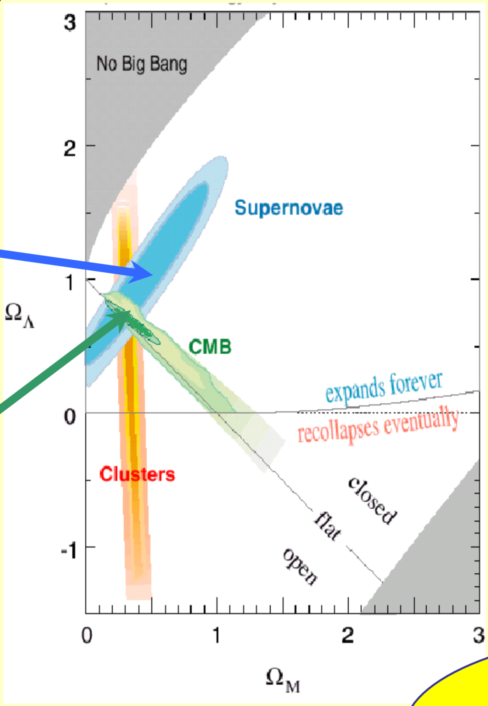
“Concordance model”



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

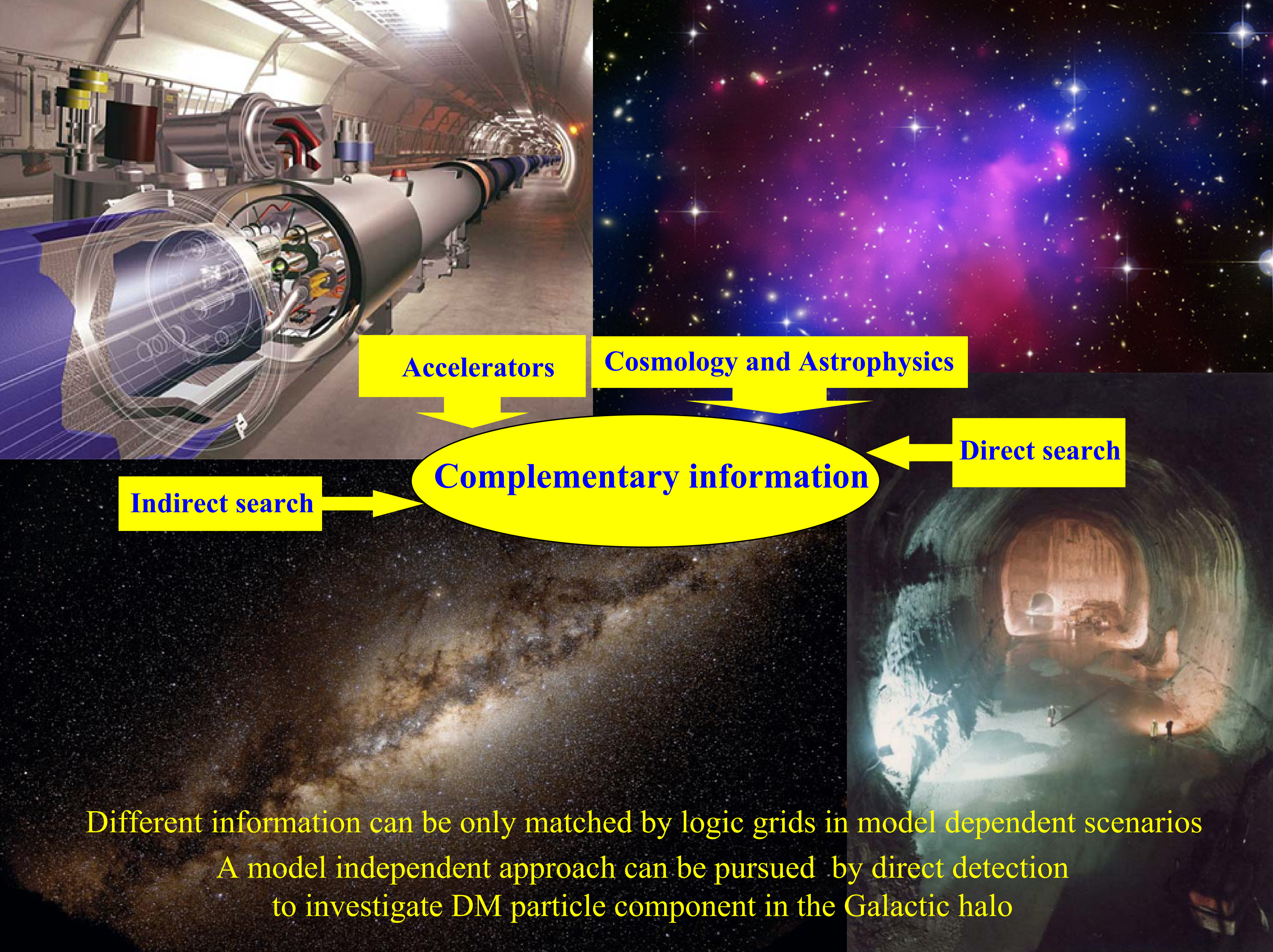
The baryons give “too small” contribution

$\Omega_b \sim 4\%$

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



Accelerators

Cosmology and Astrophysics

Direct search

Indirect search

Complementary information

Different information can be only matched by logic grids in model dependent scenarios

A model independent approach can be pursued by direct detection
to investigate DM particle component in the Galactic halo

Relic DM particles from primordial Universe

Heavy candidates:

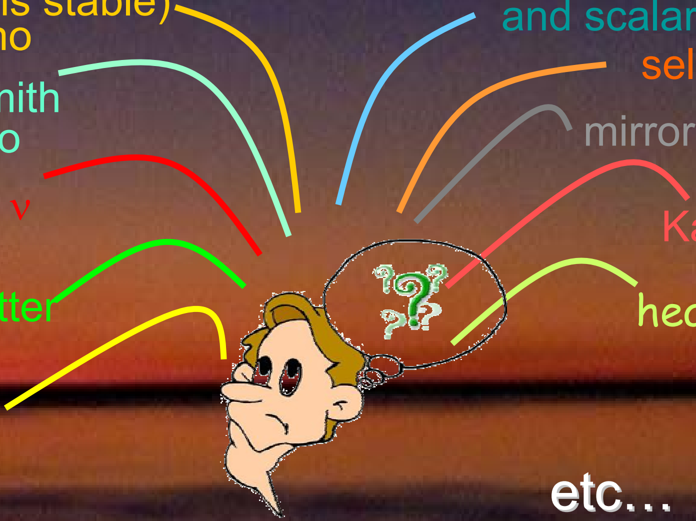
- In thermal equilibrium in the early stage of Universe
- Non relativistic at decoupling time:

  $<\sigma_{ann} \cdot v> \sim 10^{-26}/\Omega_{WIMP} h^2\ cm^3 s^{-1} \rightarrow \sigma_{ordinary\ matter} \sim \sigma_{weak}$
- Expected flux: $\Phi \sim 10^7 \cdot (GeV/m_W)\ cm^{-2}\ s^{-1}$ $(0.2 < \rho_{halo} < 1.7\ GeV\ cm^{-3})$
- Form a dissipationless gas trapped in the gravitational field of the Galaxy ($v \sim 10^{-3}c$)
- Neutral, massive, stable (or with half life ~ age of Universe) and weakly interacting

Light candidates:

axion, sterile neutrino, axion-like particles cold or warm DM

(no positive results from direct searches for relic axions with resonant cavity)



SUSY
(R-parity conserved → LSP is stable)
neutralino or sneutrino

the sneutrino in the Smith and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

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", ...

etc…

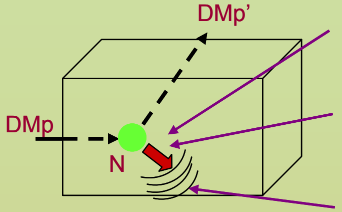
+ multi-component halo?

even a suitable particle not yet foreseen by theories

Some direct detection processes:

- Scattering 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 χ+ , χ- with δ mass splitting

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

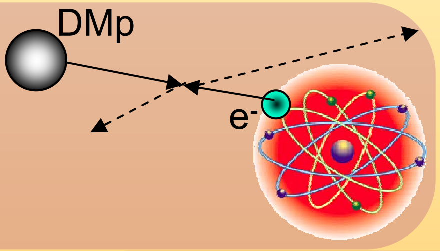
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

- Interaction only on atomic electrons

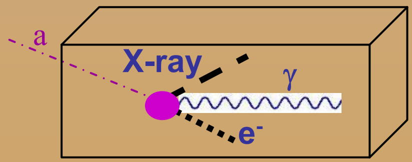
  → detection of e.m. radiation



… even WIMPs

- Conversion of particle into e.m. radiation

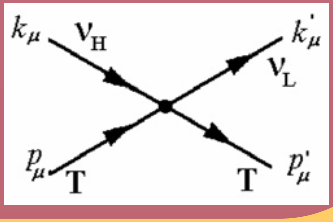
  → detection of γ, X-rays, e^-



- 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

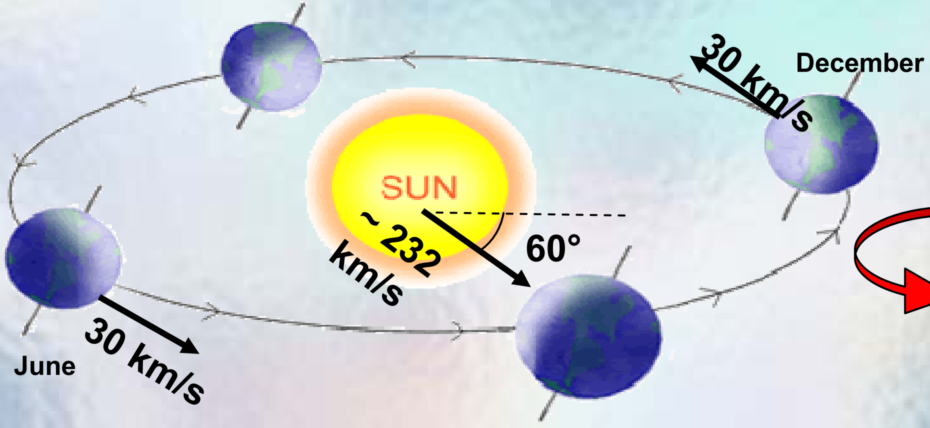


e.g. signals from these candidates are completely lost in experiments based on "rejection procedures" of the electromagnetic component of their counting rate

- **… and more**

Investigating the presence of a DM particle component in the galactic halo by the model independent annual modulation signature

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 Earth's motion around the Sun moving in the Galaxy

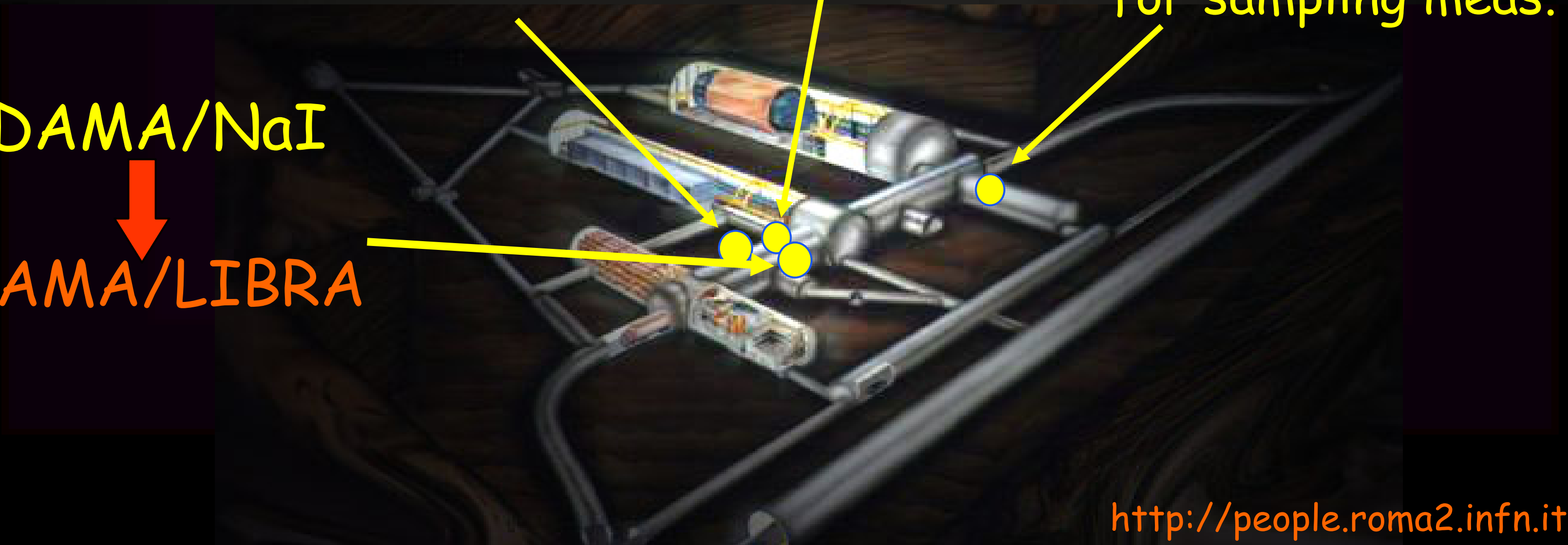
Requirements:

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2nd June)
5) For single hit in a multi-detector set-up
6) With modulated amplitude in the region of maximal sensitivity < 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 be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Roma2,Roma1,LNGS,IHEP/Beijing

DAMA: an observatory for rare processes @LNGS



DAMA/LXe

DAMA/R&D

low bckg DAMA/Ge
for sampling meas.

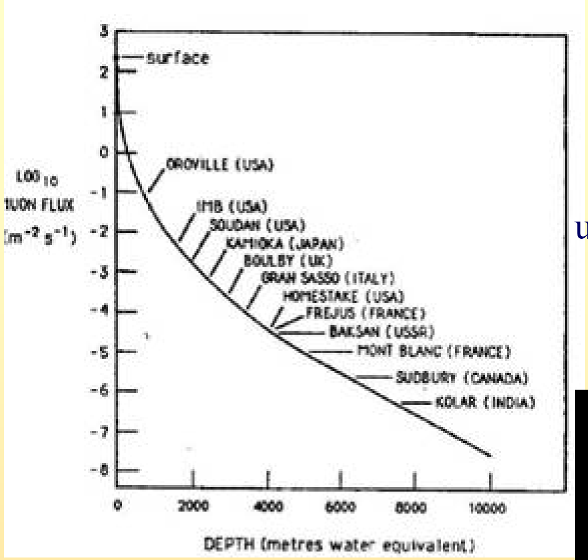
DAMA/NaI

DAMA/LIBRA

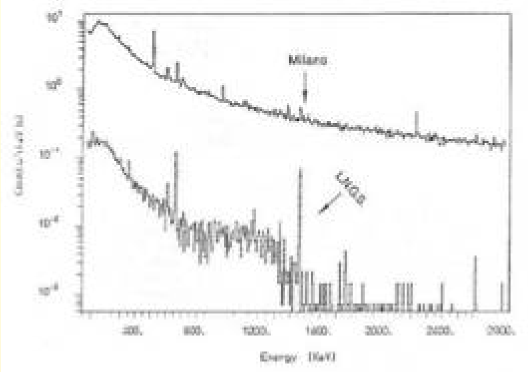
http://people.roma2.infn.it/dama

Main recipes for the Dark Matter particle direct detection

- Underground site
- Low bckg hard shields against γ's, neutrons
- Lowering bckg: selection of materials, purifications, growing techniques, ...
- Rn removal systems



Reduction from the underground site



Background sources

- LNGS:

muons → **0.6 μ/(m²h)**

neutrons → **$1.08\cdot10^{-6}$ n/(cm²s) thermal**

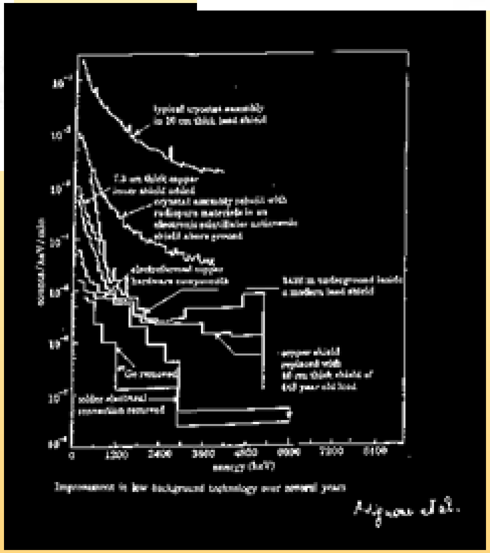
$1.98\cdot10^{-6}$ n/(cm²s) epithermal

$0.09\cdot10^{-6}$ n/(cm²s) fast (>2.5 MeV)

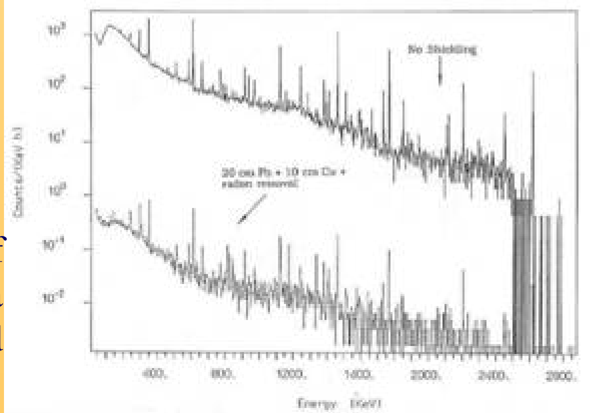
Radon in the hall → **≈30 Bq/m³**

- Internal Background:

selected materials (Ge, NaI, AAS, MS, ...)



Example of background reduction during many years of work



Example of the effect of a passive shield

Shielding

Passive shield: Lead (Boliden [< 30 Bq/kg from ^{210}Pb], LC2 [<0.3 Bq/kg from ^{210}Pb], lead from old roman galena), OFHC Copper, Neutron shield (low A materials, n-absorber foils)

Active shield: Low radio-activity NaI(Tl) surrounding the detectors

DAMA/NaI : ≈100 kg NaI(Tl)

data taking completed on July 2002, last data release 2003: total exposure (7 annual cycles) 0.29 ton x yr

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, other works in progress ...

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

DAMA/LIBRA ~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)

improving installation and environment

PMT +HV divider

storing new crystals

Cu etching with super- and ultra-pure HCl solutions, dried and sealed in HP N_2

etching staff at work in clean room

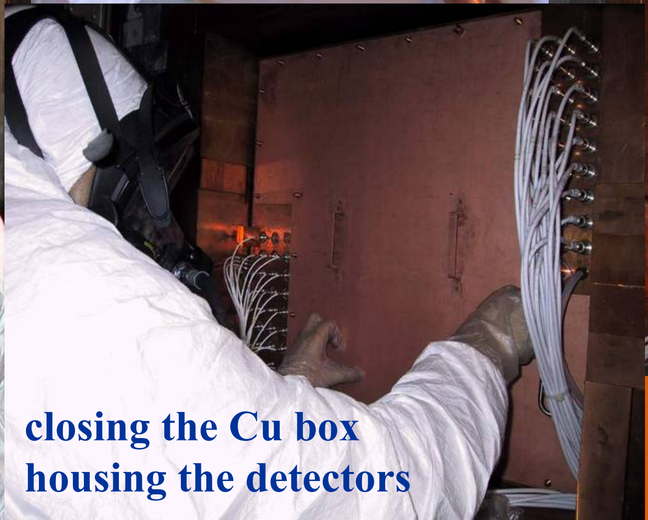
The new DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

installing DAMA/LIBRA detectors

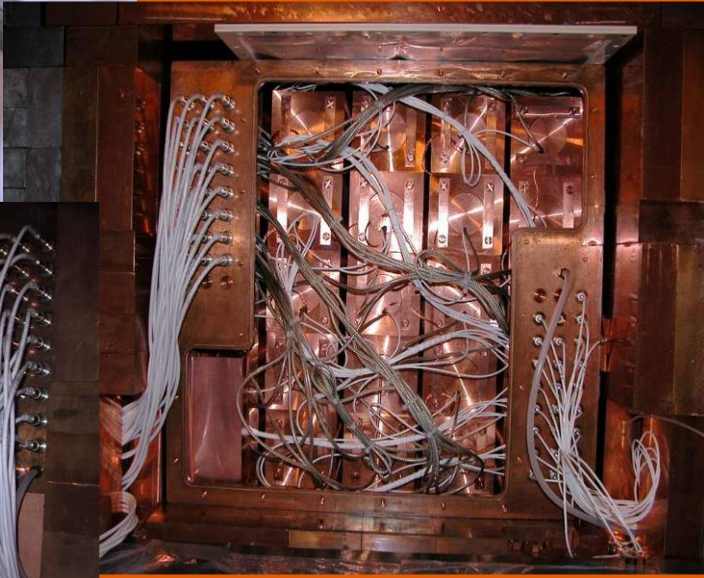
assembling a DAMA/ LIBRA detector

detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

filling the inner Cu box with further shield



closing the Cu box housing the detectors

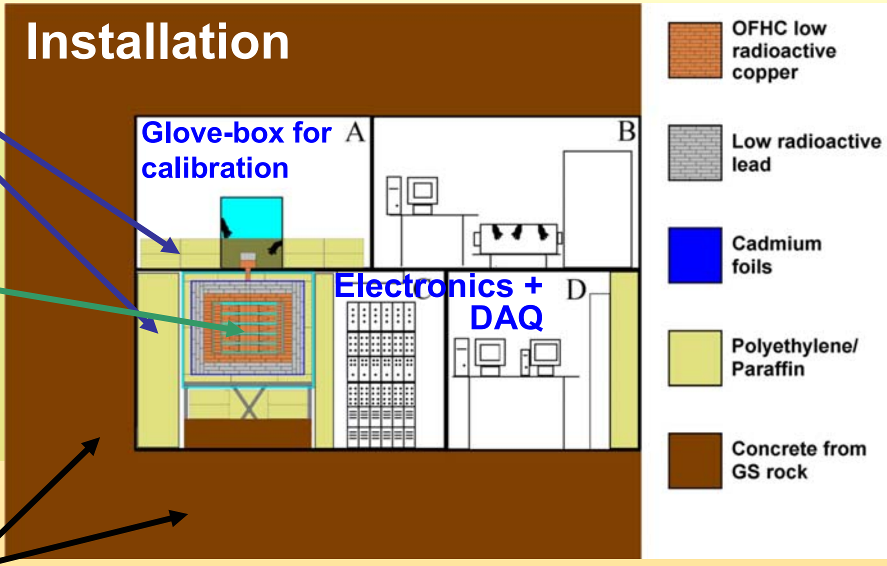


view at end of detectors' installation in the Cu box

The DAMA/LIBRA set-up

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

Polyethylene/
paraffin

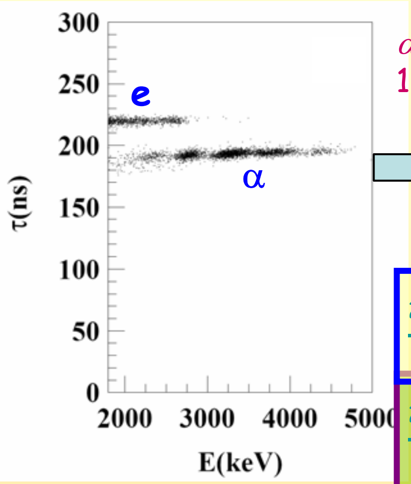


- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold

~ 1m concrete from GS rock

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield
- 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 *TVS641A* (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 NaI(Tl) detectors



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

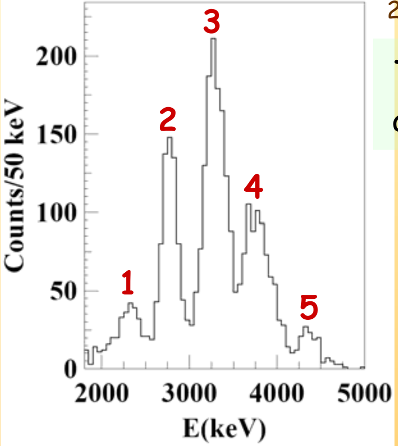
The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/keV

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

live time = 570 h



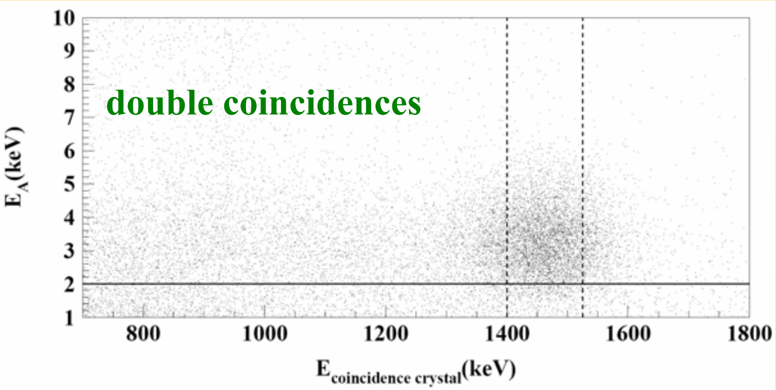
^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

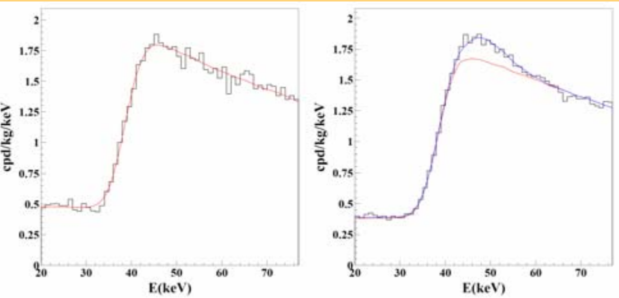
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

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

^{nat}K residual contamination

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





^{129}I and ^{210}Pb

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

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

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

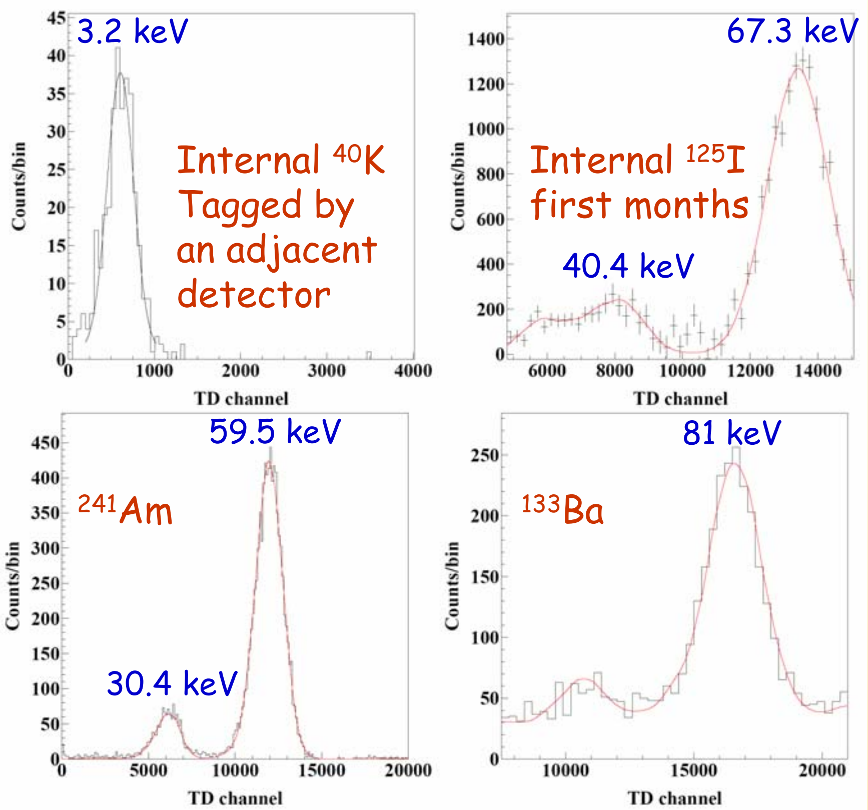
... more on NIMA592(2008)297

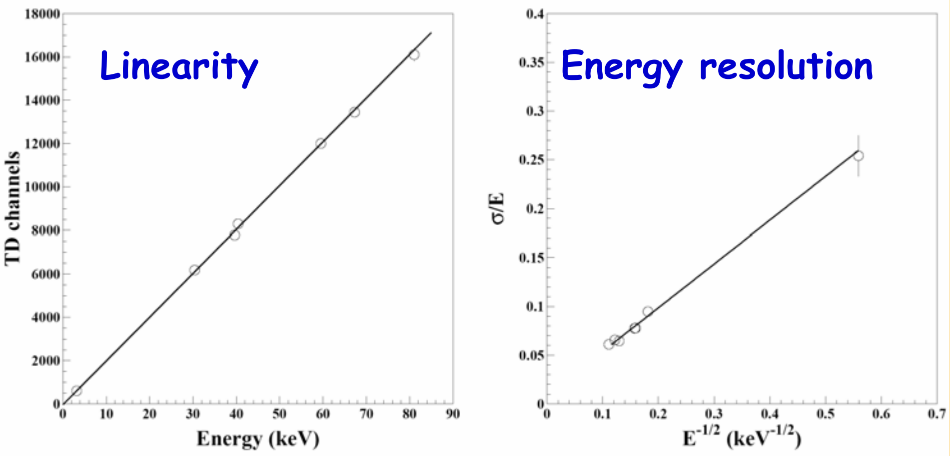
DAMA/LIBRA: calibrations at low energy

Studied by using various external gamma sources (^{241}Am, ^{133}Ba) and internal X-rays or gamma's (^{40}K, ^{125}I, ^{129}I)

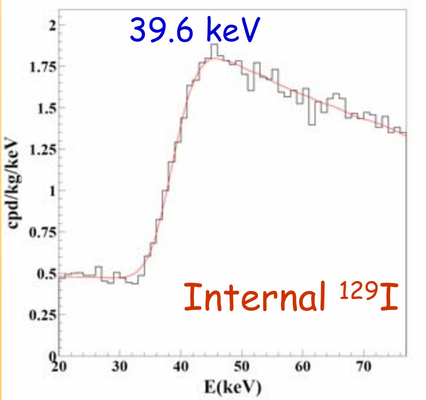
The curves superimposed to the experimental data have been obtained by simulations

- **Internal ^{40}K:** 3.2 keV due to X-rays/Auger electrons (tagged by 1461 keV γ in an adiacent detector).
- **Internal ^{125}I:** 67.3 keV peak (EC from K shell + 35.5 keV γ) and composite peak at 40.4 keV (EC from L,M,.. shells + 35.5 keV γ).
- **External ^{241}Am source:** 59.5 keV γ peak and 30.4 keV composite peak.
- **External ^{133}Ba source:** 81.0 keV γ peak.
- **Internal ^{129}I:** 39.6 keV structure (39.6 keV γ + β spectrum).





$$\frac{\sigma_{LE}}{E} = \frac{(0.448\pm0.035)}{\sqrt{E(keV)}} + (9.1\pm5.1)\cdot 10^{-3}$$

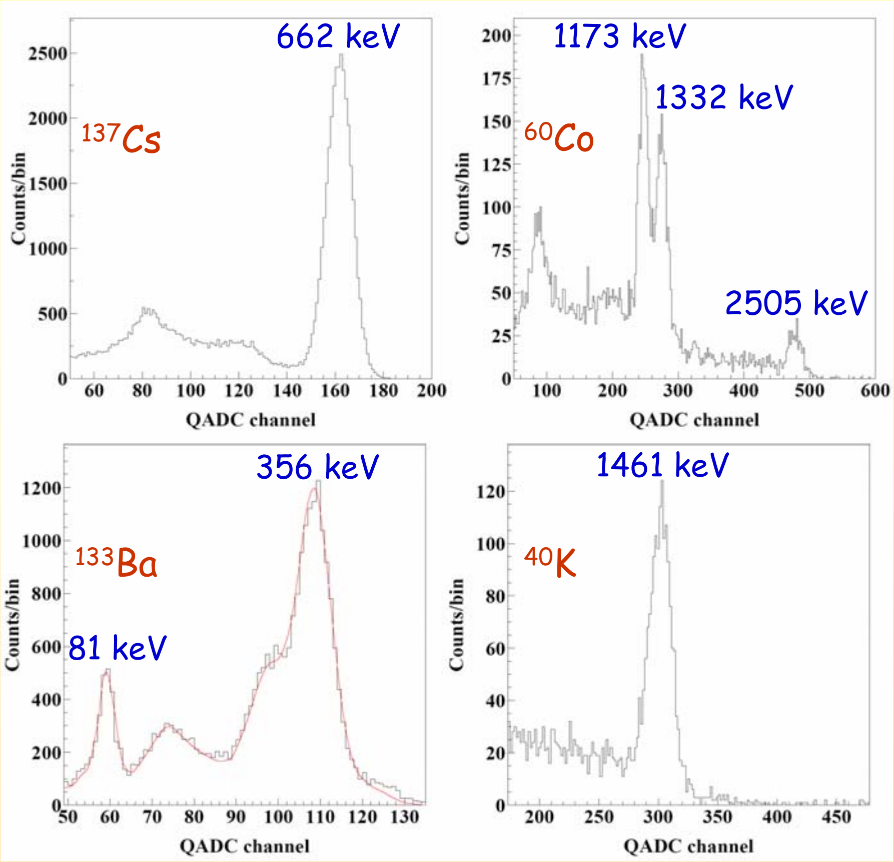


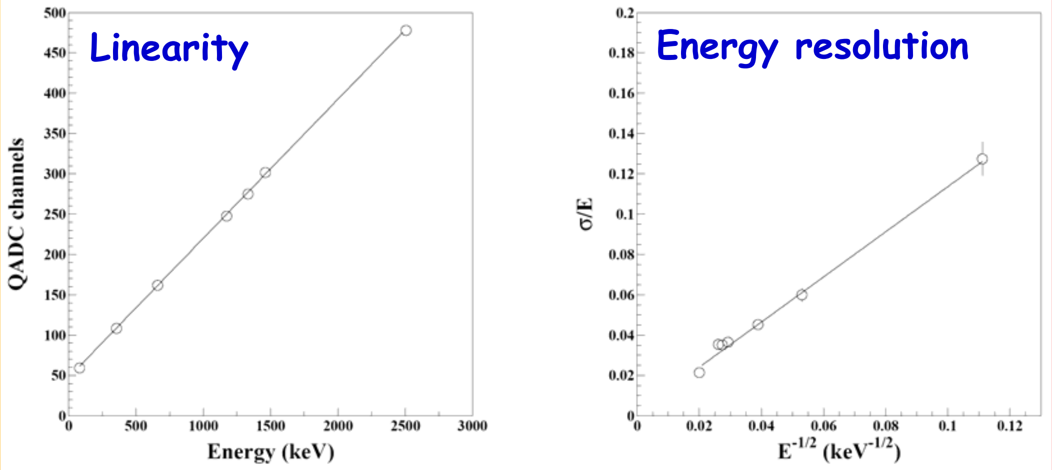
Routine calibrations with ^{241}Am

DAMA/LIBRA: calibrations at high energy

The data are taken on the full energy scale up to the MeV region by means QADC's

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





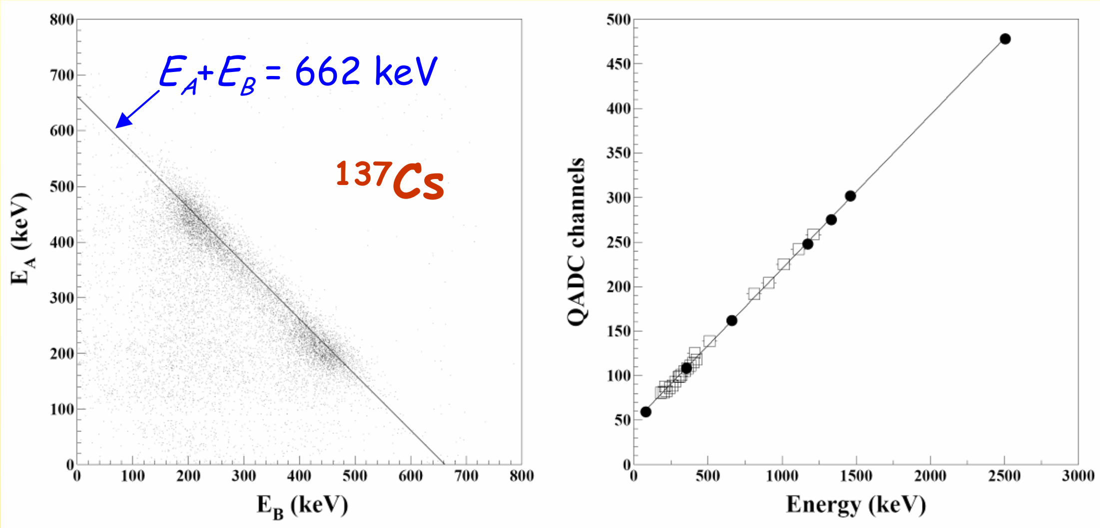
$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23) \cdot 10^{-4}$$

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

DAMA/LIBRA: another method to study linearity

Scatter plot of the energies, E_A and E_B, of two detectors *A* and *B* when using an external ^{137}Cs source placed in between

Solid line: E_A+E_B=662 keV. The data points around this line correspond to events where the γ has a Compton back-scattering in one detector and the scattered γ is completely absorbed in the other one.



E_A+E_B = 662 keV

^{137}Cs

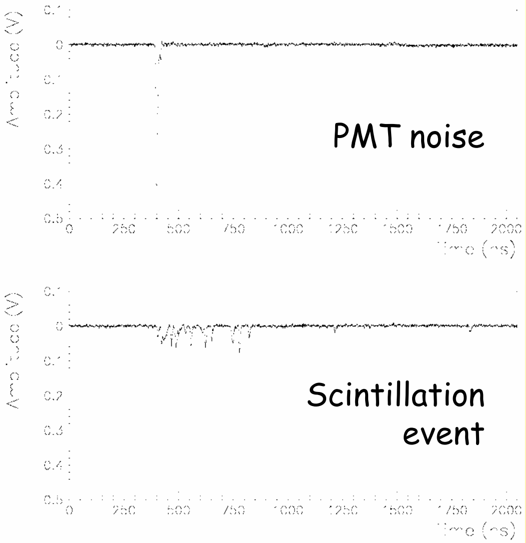
Fixing a slice – for example at a fixed E_B value – it is possible to extract the peak position on the E_A variable

Applying this procedure to the high energy calibration data from various sources other points can be added in the linearity plot (squared points)

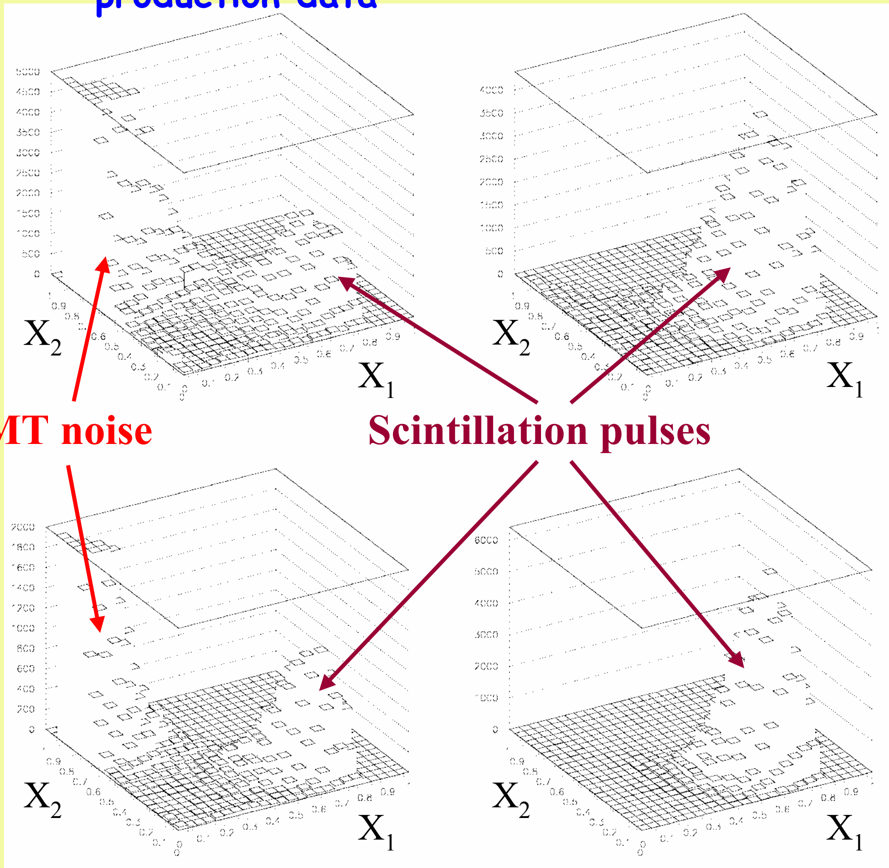
Black points: calibrations at the full-absorption photoelectric peaks

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



Single-hit production data

γ source

2-4 keV

4-6 keV

PMT noise

Scintillation pulses

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

EPJC 56 (2008) 333

DAMA/LIBRA test runs: from March 2003 to September 2003

DAMA/LIBRA normal operation: from September 2003 to August 2004

High energy runs for TDs: September 2004
to allow internal α's identification
(approximative exposure ≈ 5000 kg × d)

DAMA/LIBRA normal operation: from October 2004

Period		Exposure (kg×day)	$\alpha - \beta^2$
DAMA/LIBRA-1	Sept. 9, 2003 - July 21, 2004	51405	0.562
DAMA/LIBRA-2	July 21, 2004 - Oct. 28, 2005	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 - July 18, 2006	39445	0.591
DAMA/LIBRA-4	July 19, 2006 - July 17, 2007	49377	0.541
Total		192824 $\simeq$ 0.53 ton×yr	0.537

Data released here:

- four annual cycles: 0.53 ton × yr
- calibrations: acquired ≈ 44 M events from sources
- acceptance window eff: acquired ≈ 2 M events/keV

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

total exposure: 300555 kg×day = 0.82 ton×yr

Two remarks:

•One PMT problems after 6 months. Detector out of trigger since Sep. 2003 (since Sep. 2008 again in operation)

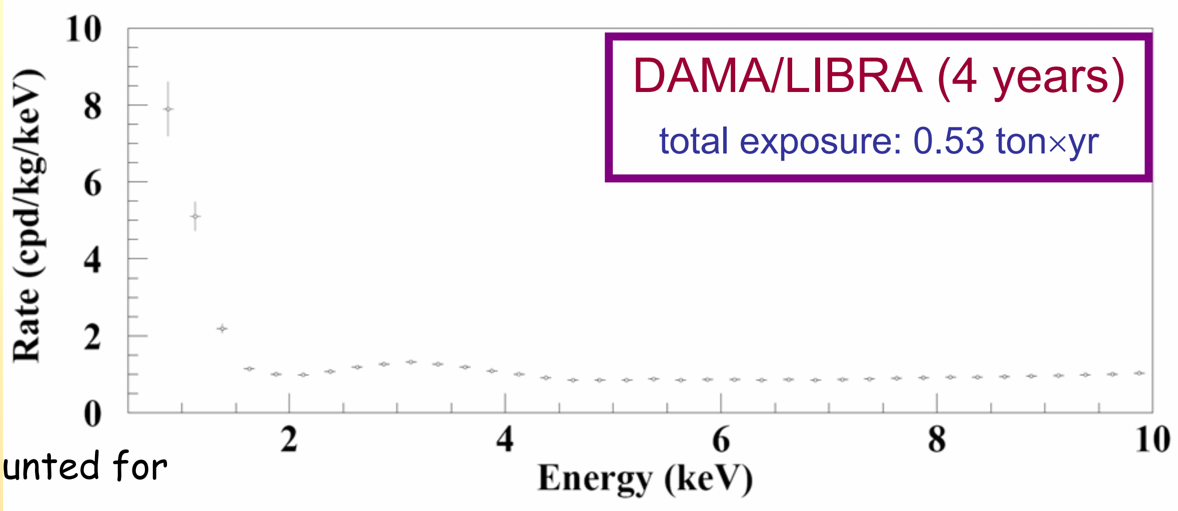
•Residual cosmogenic ^{125}I presence in the first year in some detectors (this motivates the Sept. 2003 as starting time)

DAMA/LIBRA is 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.)



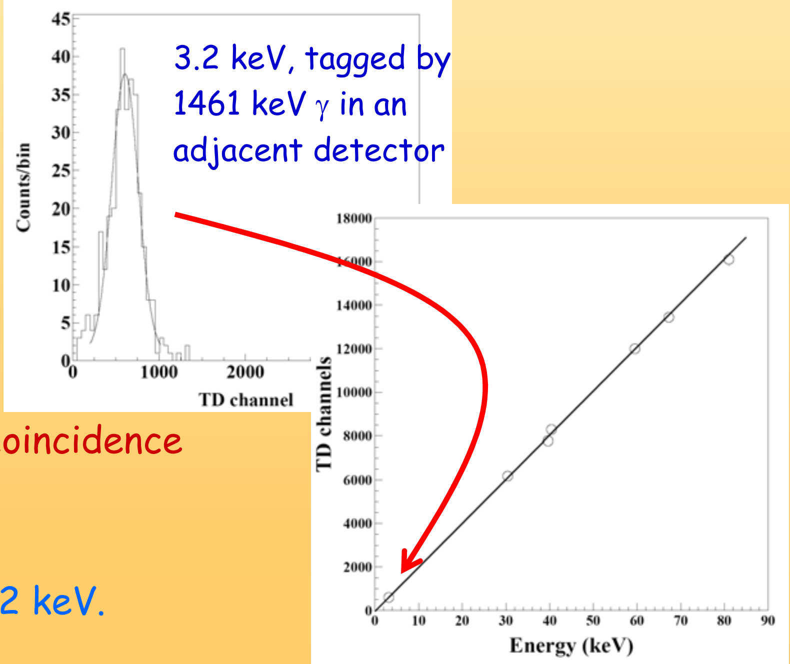
DAMA/LIBRA (4 years)

total exposure: 0.53 ton×yr

Efficiencies already accounted for

About the energy threshold:

- 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.

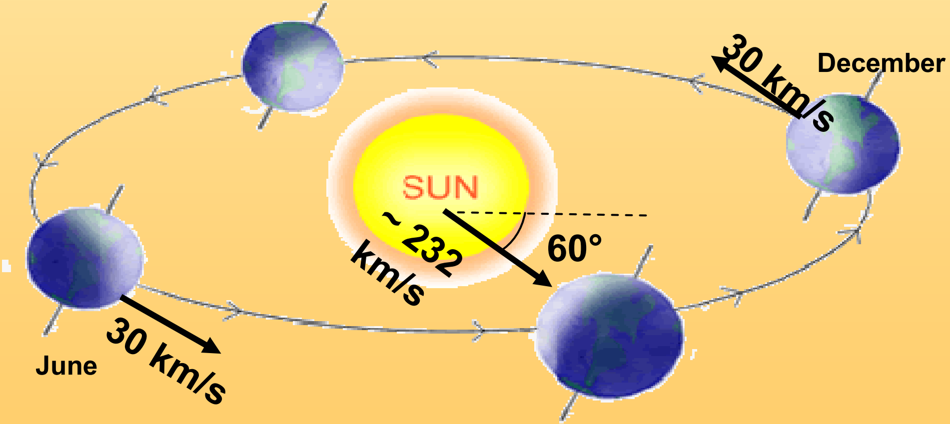


3.2 keV, tagged by 1461 keV γ in an adjacent detector

Experimental *single-hit* residuals rate vs time and energy

- Model-independent investigation of the annual modulation signature has been carried out by exploiting the time behaviour of the residual rates of the *single-hit* events in the lowest energy regions of the DAMA/LIBRA data.
- These residual rates are calculated from the measured rate of the *single-hit* events (already corrected for the overall efficiency and for the acquisition dead time) after subtracting the constant part:

$$\left\langle r_{ijk} - flat_{jk} \right\rangle_{jk}$$



- r_{ijk} is the rate in the considered *i-th* time interval for the *j-th* detector in the *k-th* energy bin
- $flat_{jk}$ is the rate of the *j-th* detector in the *k-th* energy bin averaged over the cycles.
- The average is made on all the detectors (*j* index) and on all the energy bins (*k* index)
- The weighted mean of the residuals must obviously be zero over one cycle.

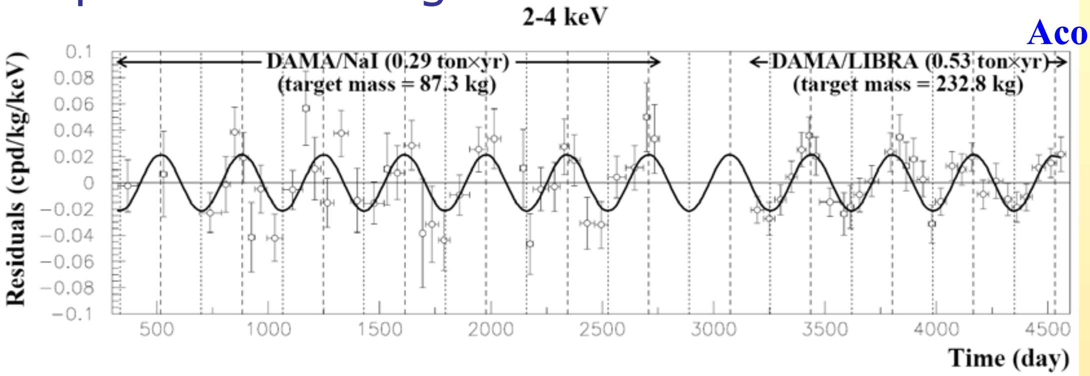
Model Independent Annual Modulation Result

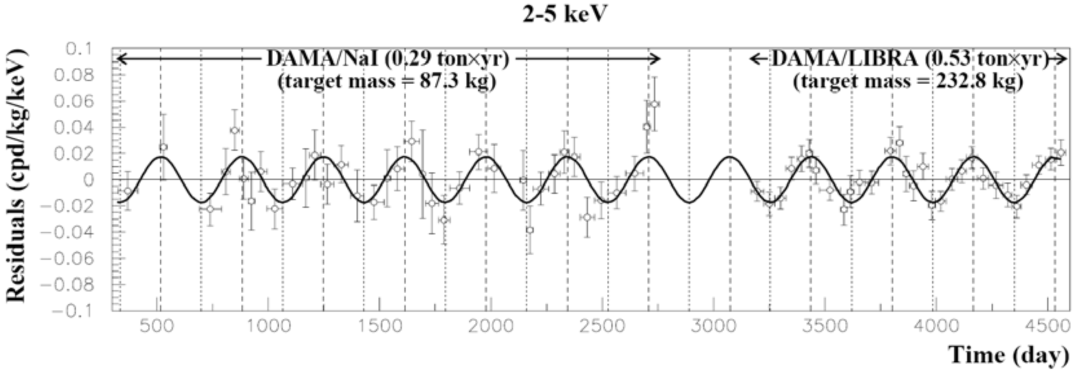
DAMA/NaI (7 years) + DAMA/LIBRA (4 years)   Total exposure: 300555 kg×day = 0.82 ton×yr

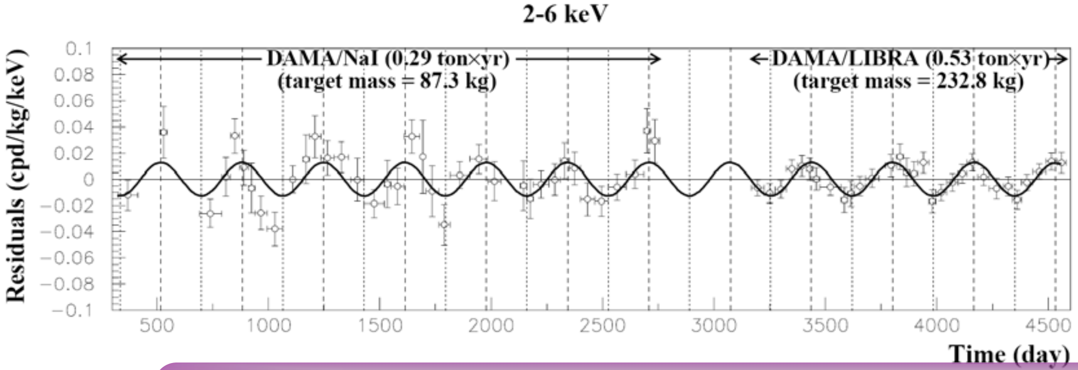
EPJC 56(2008)333

experimental single-hit residuals rate vs time and energy

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







2-4 keV

A=(0.0215±0.0026) cpd/kg/keV

χ^2/dof = 51.9/66   **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=117.7/67 ⇒ P(A=0) = 1.3×10^{-4}

2-5 keV

A=(0.0176±0.0020) cpd/kg/keV

χ^2/dof = 39.6/66   **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=116.1/67 ⇒ P(A=0) = 1.9×10^{-4}

2-6 keV

A=(0.0129±0.0016) cpd/kg/keV

χ^2/dof = 54.3/66 **8.2 σ C.L.**

Absence of modulation? No

χ^2/dof=116.4/67 ⇒ P(A=0) = 1.8×10^{-4}

The data favor the presence of a modulated behavior with proper features at 8.2σ C.L.

Model-independent residual rate for single-hit events

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

total exposure: 300555 kg×day = 0.82 ton×yr

Results of the fits keeping the parameters free:

	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 (4 years)				
(2÷4) keV	**0.0213 ± 0.0032**	**0.997 ± 0.002**	**139 ± 10**	**6.7σ**
(2÷5) keV	**0.0165 ± 0.0024**	**0.998 ± 0.002**	**143 ± 9**	**6.9σ**
(2÷6) keV	**0.0107 ± 0.0019**	**0.998 ± 0.003**	**144 ± 11**	**5.6σ**
DAMA/NaI + DAMA/LIBRA				
(2÷4) keV	**0.0223 ± 0.0027**	**0.996 ± 0.002**	**138 ± 7**	**8.3σ**
(2÷5) keV	**0.0178 ± 0.0020**	**0.998 ± 0.002**	**145 ± 7**	**8.9σ**
(2÷6) keV	**0.0131 ± 0.0016**	**0.998 ± 0.003**	**144 ± 8**	**8.2σ**

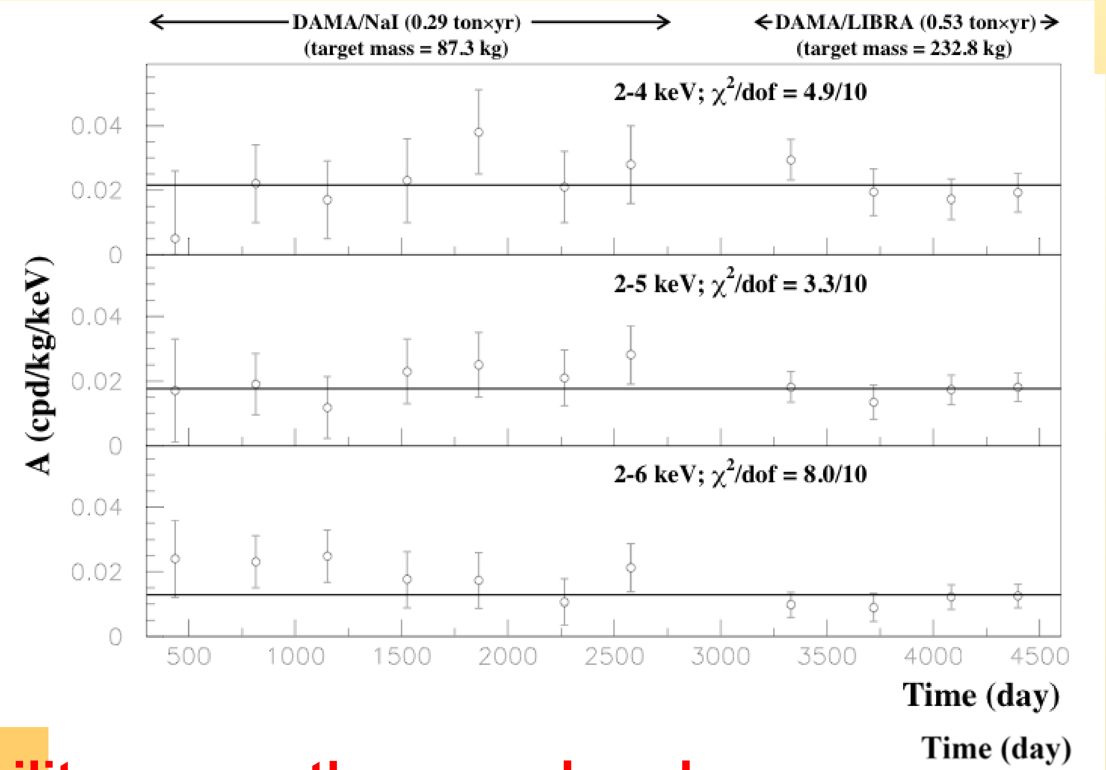
Modulation amplitudes, *A*, of single year measured in the 11 one-year experiments of DAMA (NaI + LIBRA)

- The difference in the (2 – 6) keV modulation amplitudes between DAMA/NaI and DAMA/LIBRA depends mainly on the rate in the (5 – 6) keV energy bin.

- The modulation amplitudes for the (2 – 6) keV energy interval, obtained when fixing exactly the period at 1 yr and the phase at 152.5 days, are: (0.019 ± 0.003) cpd/kg/keV for DAMA/NaI
(0.011 ± 0.002) cpd/kg/keV for DAMA/LIBRA.
- Thus, their difference: (0.008 ± 0.004) cpd/kg/keV is ≈ 2σ which corresponds to a modest, but non negligible probability.

Moreover:

The χ^2 test (χ^2 = 4.9, 3.3 and 8.0 over 10 *d.o.f.* for the three energy intervals, respectively) and the *run test* (lower tail probabilities of 74%, 61% and 11% 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

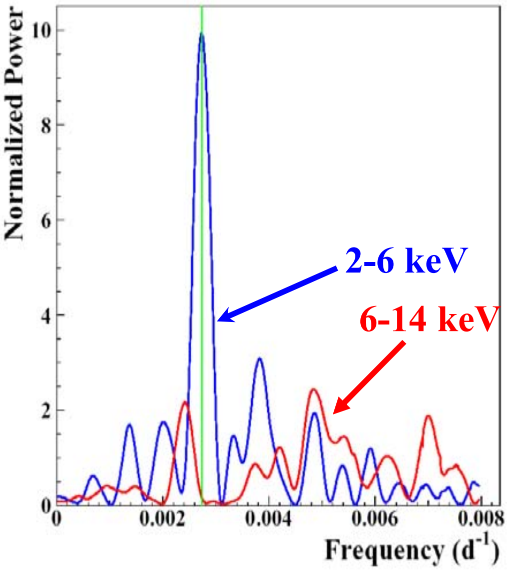
(according to Ap.J.263(1982)835; Ap.J.338(1989)277)

Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

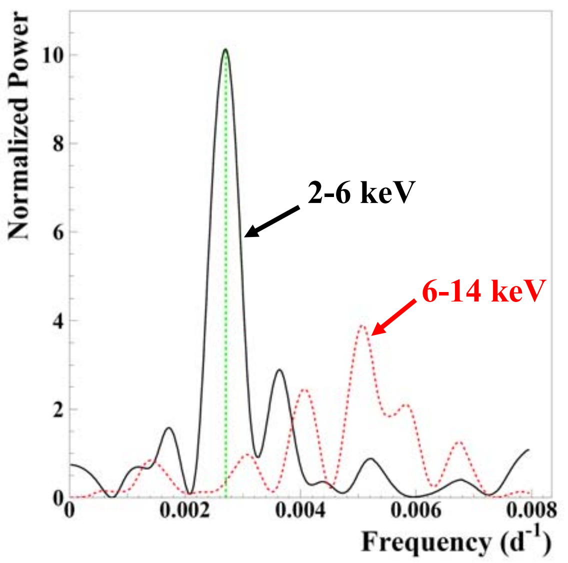
DAMA/NaI (7 years)

total exposure: 0.29 ton×yr



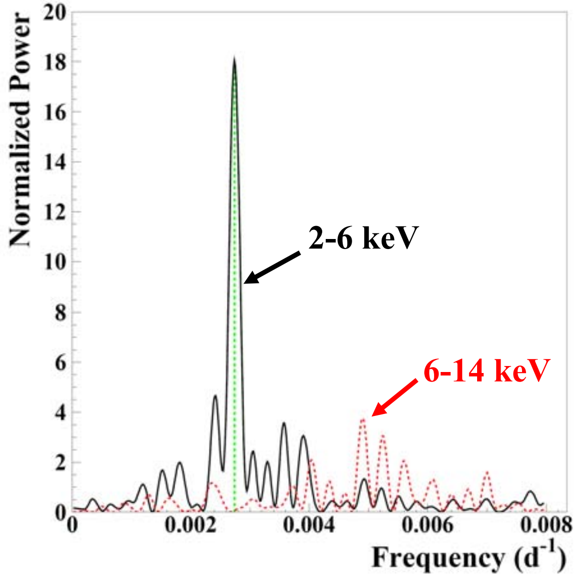
DAMA/LIBRA (4 years)

total exposure: 0.53 ton×yr



DAMA/NaI (7 years) +
DAMA/LIBRA (4 years)

total exposure: 0.82 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}	2.705×10^{-3} $d^{-1} \approx 1$ yr^{-1}	2.737×10^{-3} $d^{-1} \approx 1$ yr^{-1}

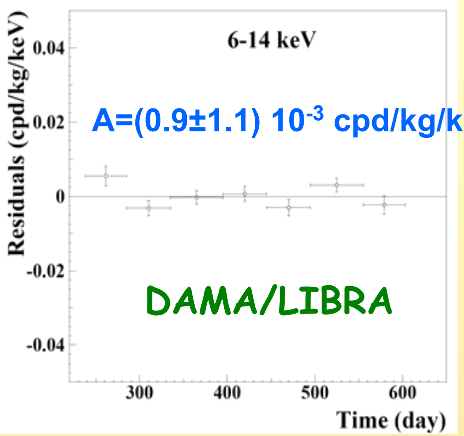
+

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

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

Can a hypothetical background modulation account for the observed effect?

- **No Modulation above 6 keV**



A=(0.9±1.1) 10^{-3} cpd/kg/keV

Mod. Ampl. (6-10 keV): (0.0016 ± 0.0031), -(0.0010 ± 0.0034), -(0.0001 ± 0.0031) and -(0.0006 ± 0.0029) cpd/kg/keV for DAMA/LIBRA-1, DAMA/LIBRA-2, DAMA/LIBRA-3, DAMA/LIBRA-4; → they can be considered statistically consistent with zero

+

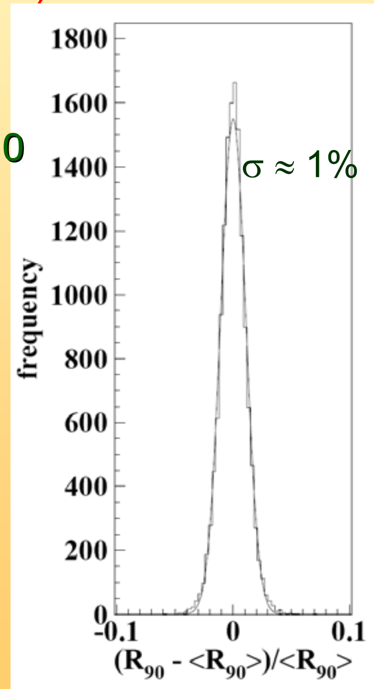
In the same energy region where the effect is observed: no modulation of the multiple-hits events (see next slide)

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

studying integral rate at higher energy, R90

- R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA-1,2,3,4 running periods

→ cumulative gaussian behaviour with σ ≈ 1%, fully accounted by statistical considerations



σ ≈ 1%

- Fitting the behaviour with time, adding a term modulated according period and phase expected for Dark Matter particles:

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

consistent with zero

+ 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

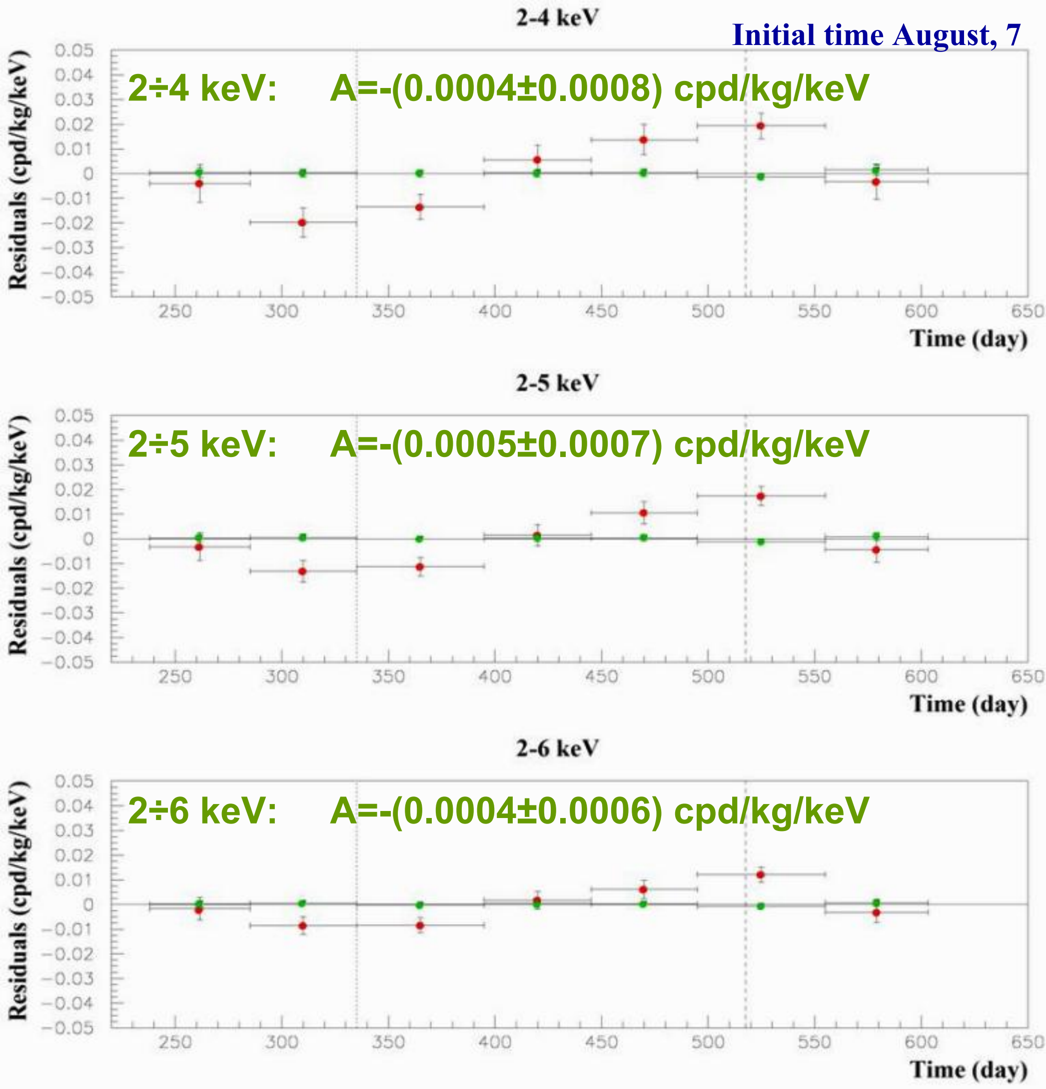
No modulation in the background:
these results account for all sources of bckg (+ see later)

Multiple-hits events in the region of the signal - DAMA/LIBRA 1-4

- **Each detector has its own TDs read-out → pulse profiles of multiple-hits events (multiplicity > 1) acquired (exposure: 0.53 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"



2÷4 keV: A=-(0.0004±0.0008) cpd/kg/keV

2÷5 keV: A=-(0.0005±0.0007) cpd/kg/keV

2÷6 keV: A=-(0.0004±0.0006) cpd/kg/keV

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 further excluding any side effect either from hardware or from software procedures or from background

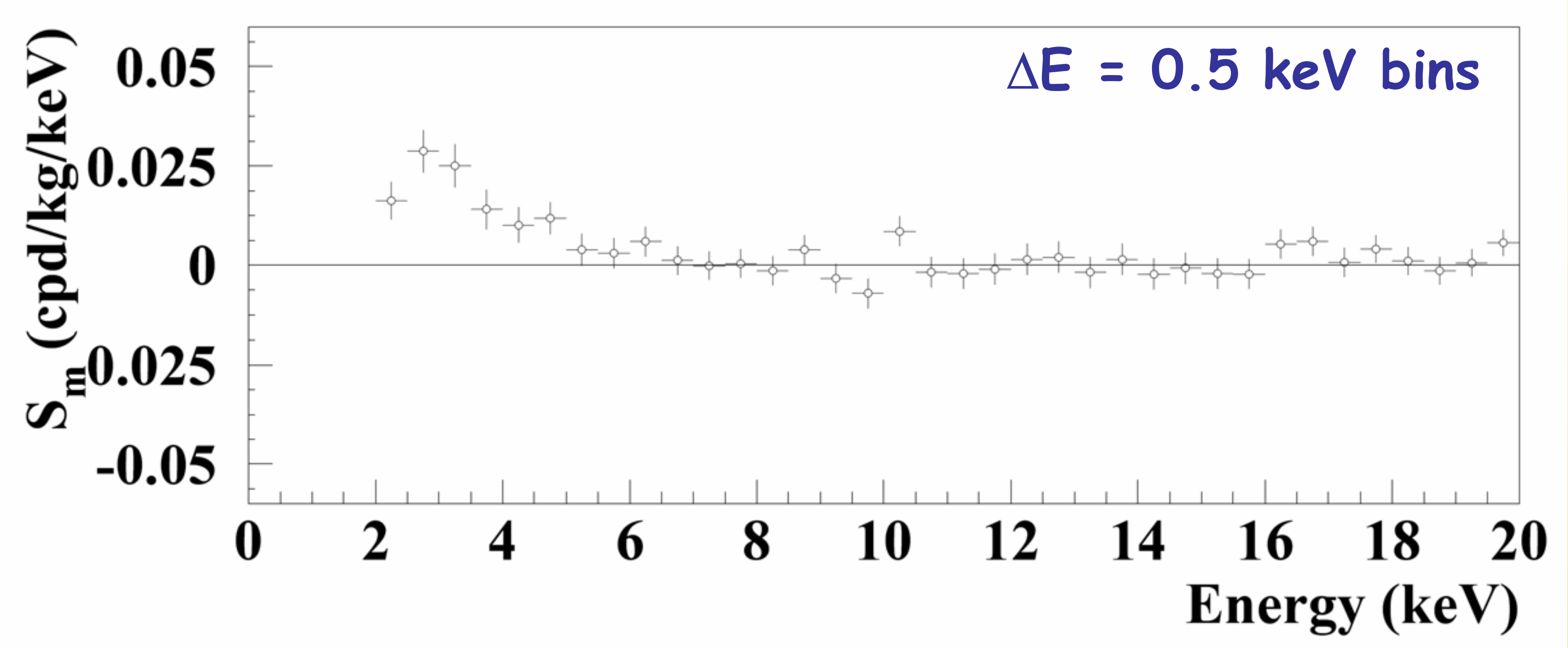
Energy distribution of the modulation amplitudes, S_m, for the total exposure

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

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)

total exposure: 300555 kg×day = 0.82 ton×yr

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



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

In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 24.4 for 28 degrees of freedom

Statistical distributions of the modulation amplitudes (S_m)

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

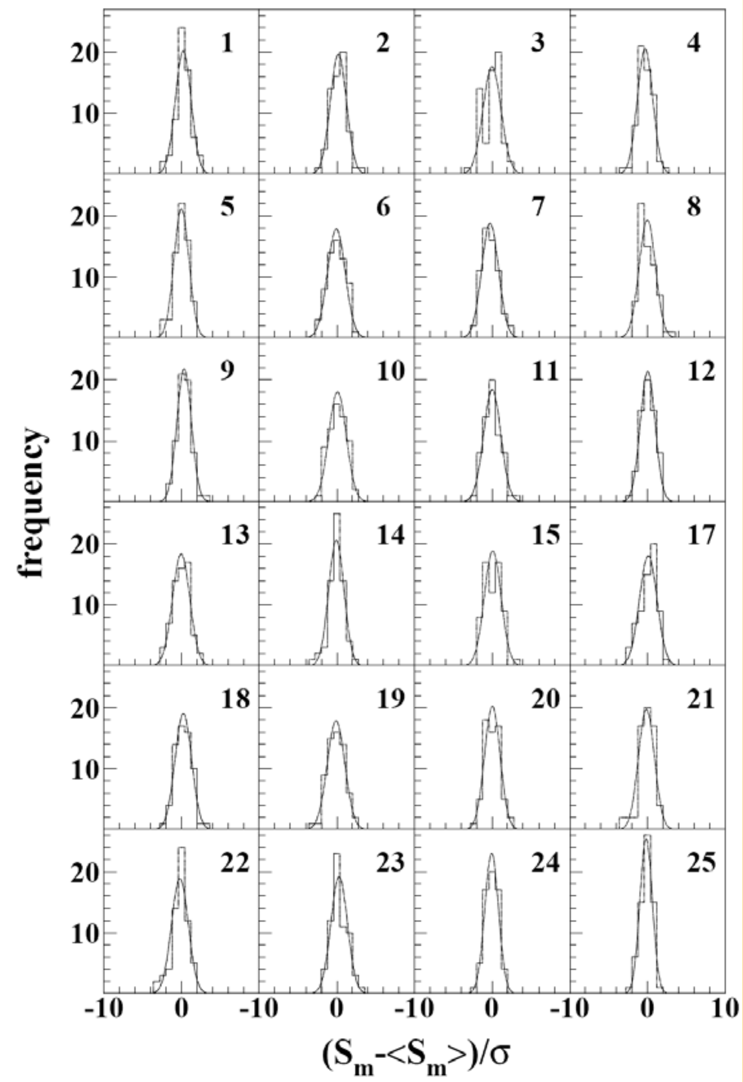
b) $<S_m>$ = mean values over the detectors and the annual cycles for each energy bin; σ = errors associated to each S_m

DAMA/LIBRA (4 years)

total exposure: 0.53 ton×yr

Each panel refers to each detector separately; 64 entries = 16 energy bins in 2-6 keV energy interval × 4 DAMA/LIBRA annual cycles

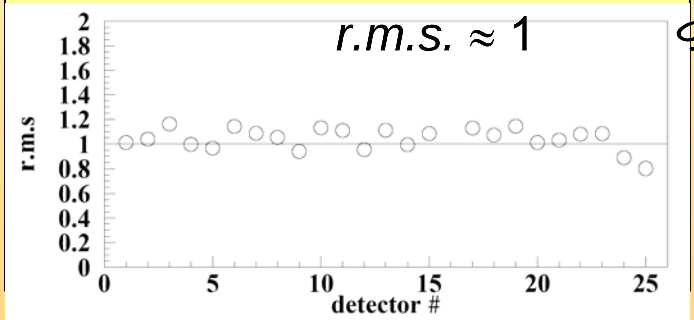
2-6 keV



Standard deviations of the variable

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

for the DAMA/LIBRA detectors



$0.80 < \text{r.m.s.} < 1.16$

Individual S_m values follow a normal distribution since $(S_m - <S_m>)/\sigma$ 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)

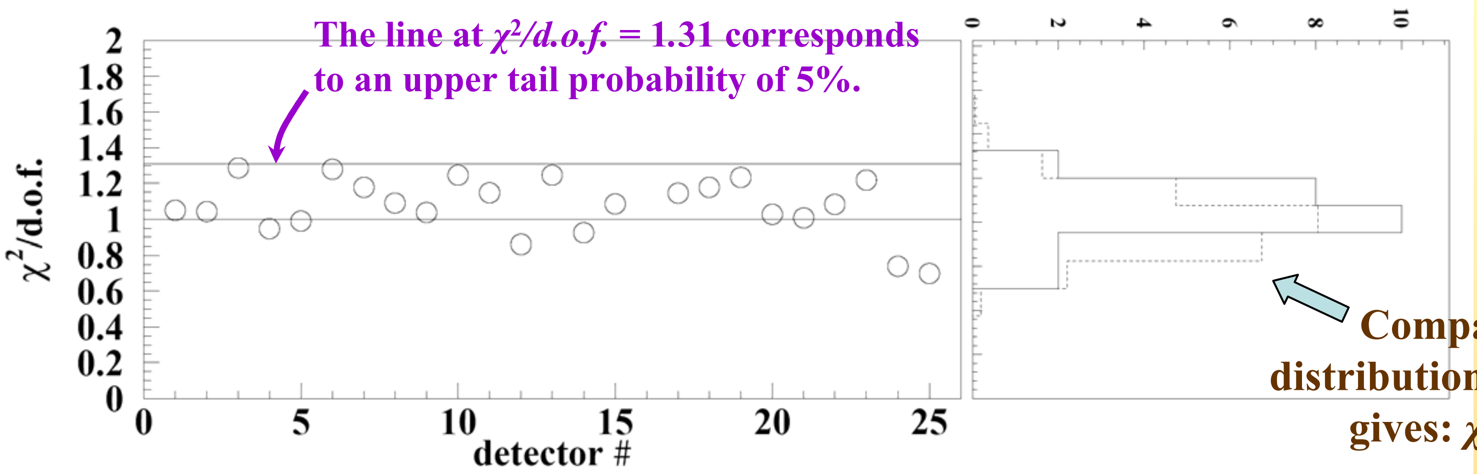
$x=(S_m-<S_m>)/\sigma,$

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

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

DAMA/LIBRA (4 years)

total exposure: 0.53 ton×yr



The line at $\chi^2/d.o.f.$ = 1.31 corresponds to an upper tail probability of 5%.

Comparison with χ^2 distribution with 64 d.o.f. gives: $\chi^2/d.o.f.$ = 8.1/7

The $\chi^2/d.o.f.$ values range from 0.7 to 1.28 (64 *d.o.f.* = 16 energy bins × 4 annual cycles)

⇒ at 95% C.L. the observed annual modulation effect is well distributed in all the detectors.

- The mean value of the twenty-four points is 1.072, 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 $\leq 5 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 7\times10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (**≤ 4.7%** or **≤ 0.7%**, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

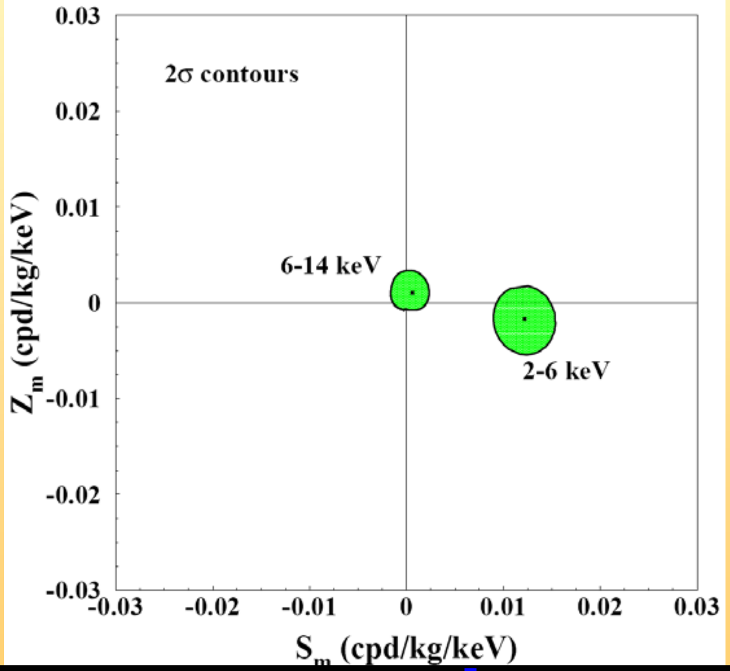
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

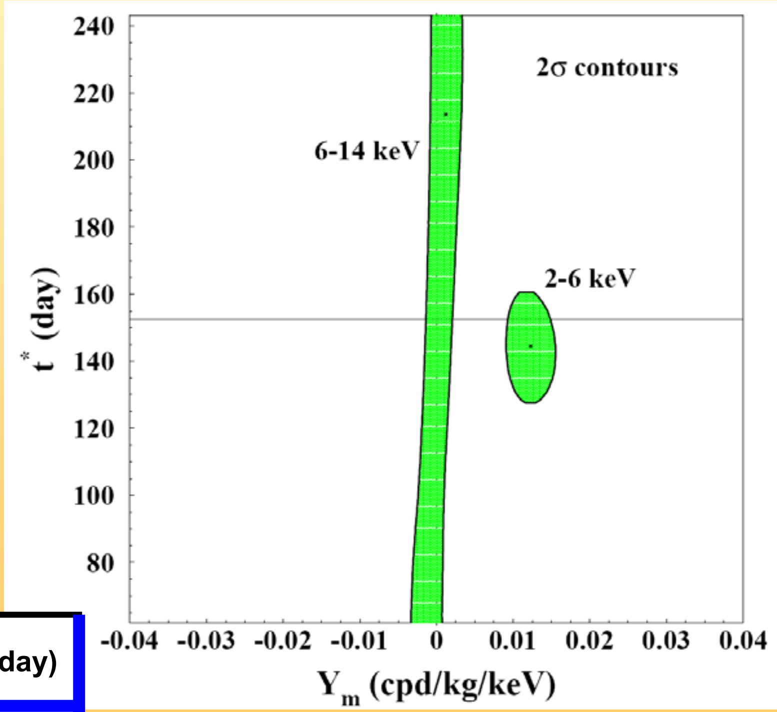
$$R(t) = S_0 + S_m \cos[\omega(t-t_0)] + Z_m \sin[\omega(t-t_0)] = S_0 + Y_m \cos[\omega(t-t^*)]$$

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	0.0122 ± 0.0016	-0.0019 ± 0.0017	0.0123 ± 0.0016	144.0 ± 7.5
6-14	0.0005 ± 0.0010	0.0011 ± 0.0012	0.0012 ± 0.0011	--

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

Additional investigations

The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about S_m already exclude any sizeable 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%

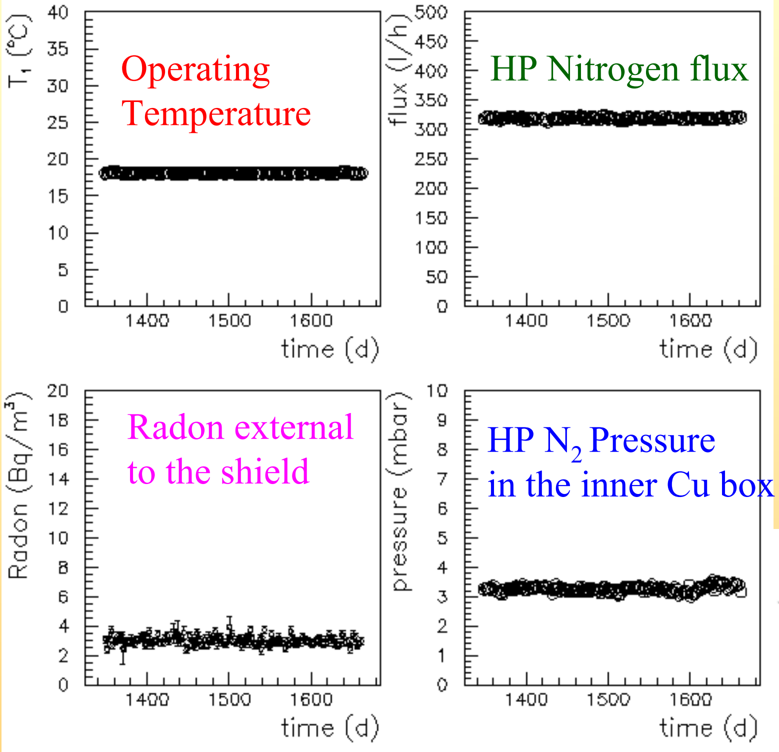
	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
Temperature	-(0.0001 ± 0.0061) °C	(0.0026 ± 0.0086) °C	(0.001 ± 0.015) °C	(0.0004 ± 0.0047) °C
Flux N_2	(0.13 ± 0.22) l/h	(0.10 ± 0.25) l/h	-(0.07 ± 0.18) l/h	-(0.05 ± 0.24) l/h
Pressure	(0.015 ± 0.030) mbar	-(0.013 ± 0.025) mbar	(0.022 ± 0.027) mbar	(0.0018 ± 0.0074) 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
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

All the measured amplitudes well compatible with zero

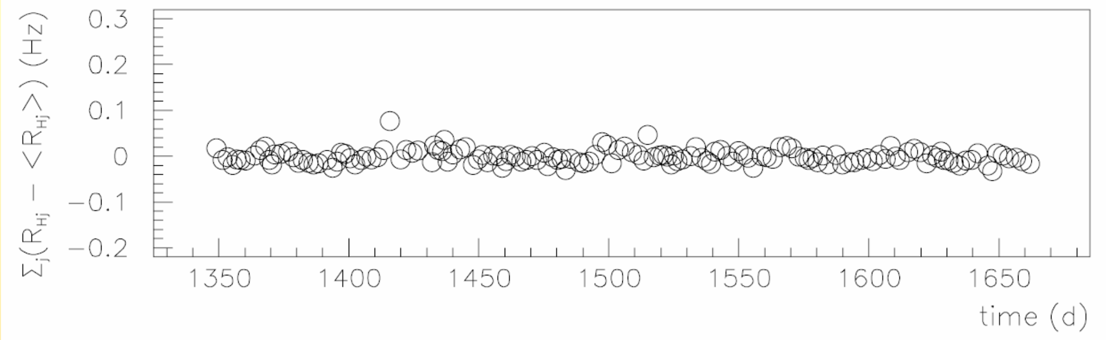
+none can account for the observed effect

(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)

Example of Stability Parameters: DAMA/LIBRA-1

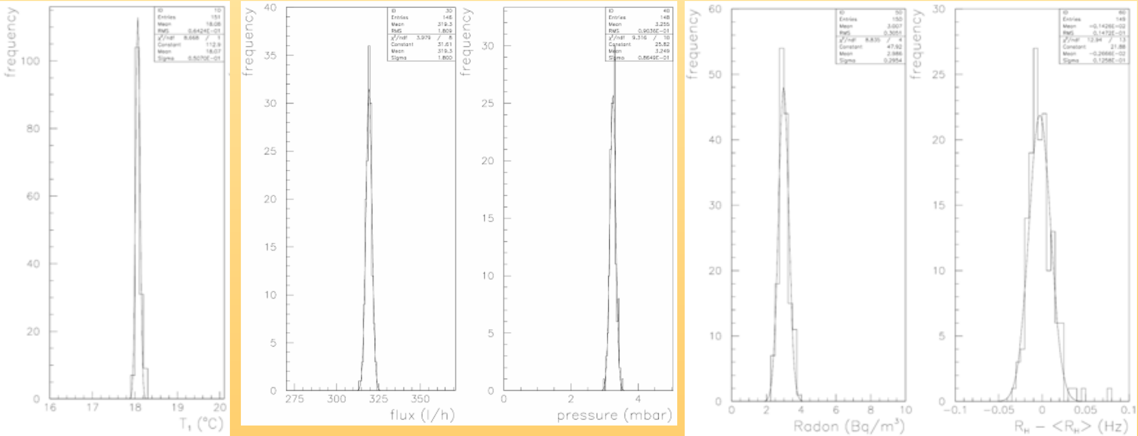


R_{Hj} = hardware rate of j-th detector above single photoelectron



Running conditions stable at level < 1%

Parameters distributions



All amplitudes well compatible with zero

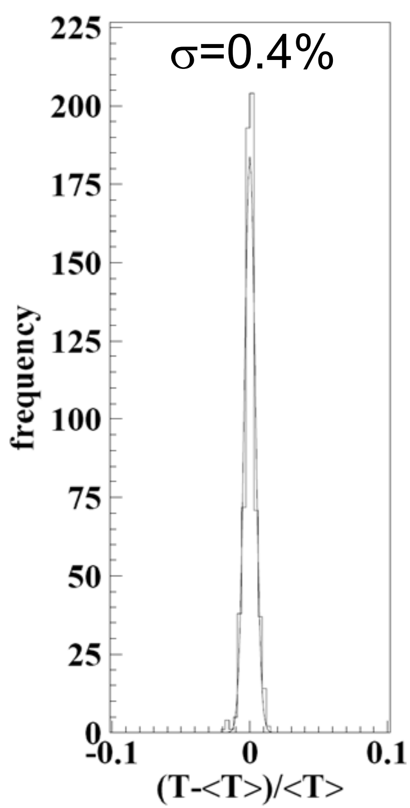
+ no effect can mimic the annual modulation

Temperature

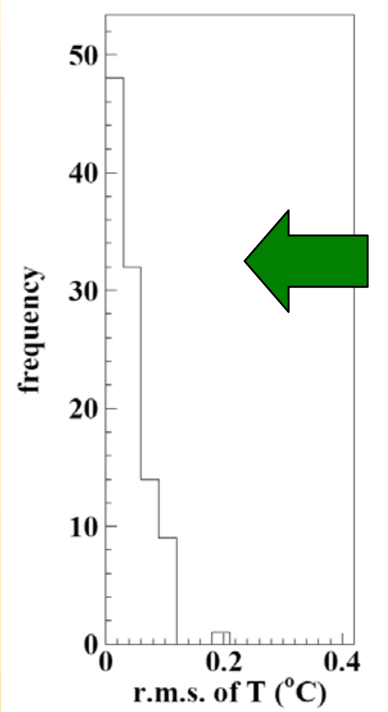
- **Detectors in Cu housings directly in contact with multi-ton shield →huge heat capacity (≈10^6 cal/^{0}C)**
- **Experimental installation continuosly air conditioned (2 independent systems for redundancy)**
- **Operating T of the detectors continuously controlled**

Amplitudes for annual modulation in the operating T of the detectors **well compatible with zero**

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
T (°C)	-(0.0001 ± 0.0061)	(0.0026 ± 0.0086)	(0.001 ± 0.015)	(0.0004 ± 0.0047)



Distribution of the relative variations of the operating T of the detectors



Distribution of the root mean square values of the operating T within periods with the same calibration factors (typically ≈7days):

mean value ≈ 0.04°C

Considering the slope of the light output ≈ -0.2%/ °C: relative light output variation < 10^{-4} :

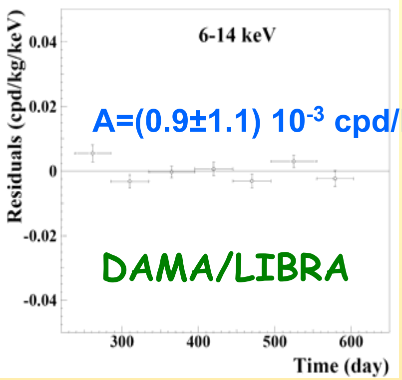
$<10^{-4}$ cpd/kg/keV (< 0.5% $S_m^{observed}$)

An effect from temperature can be excluded

+ Any possible modulation due to temperature would always fail some of the peculiarities of the signature

Summarizing on
a hypothetical background modulation in DAMA/LIBRA 1-4

- **No Modulation above 6 keV**

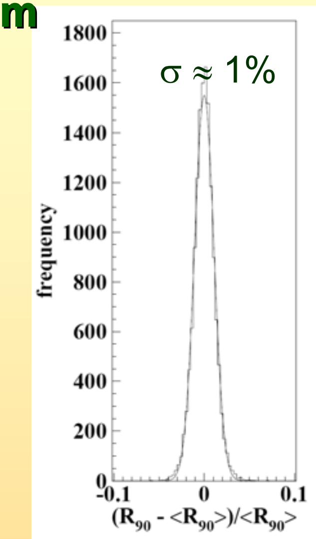


A=(0.9±1.1) 10^{-3} cpd/kg/keV

DAMA/LIBRA

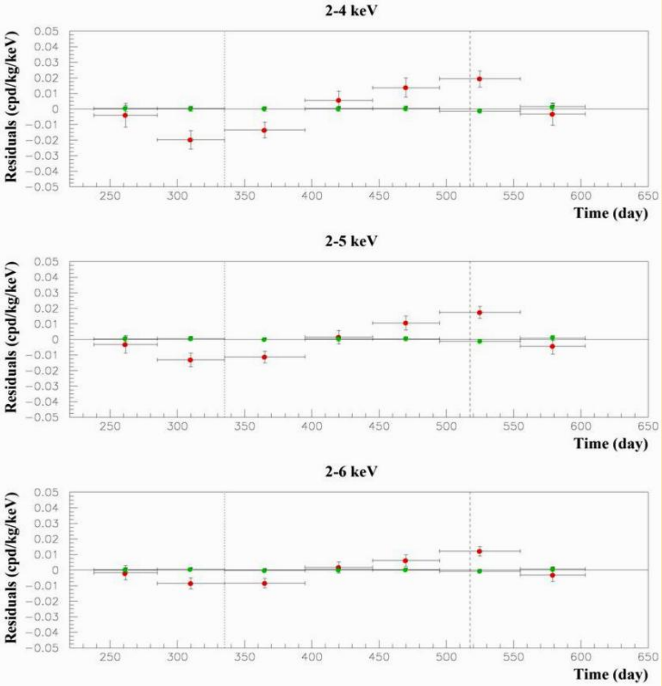
- **No modulation in the whole energy spectrum**

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



σ ≈ 1%

- **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

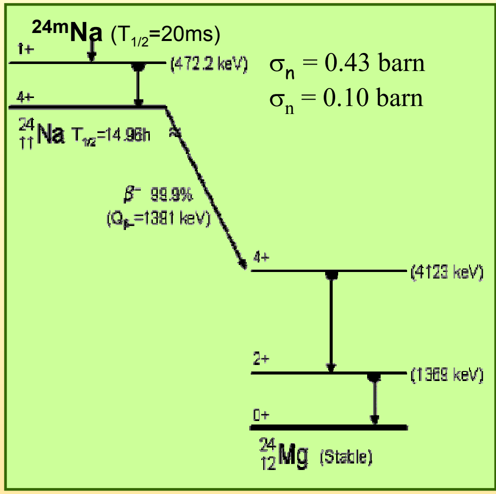
Nevertheless, additional investigations performed ...

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)



σ_n = 0.43 barn
σ_n = 0.10 barn

- 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^{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

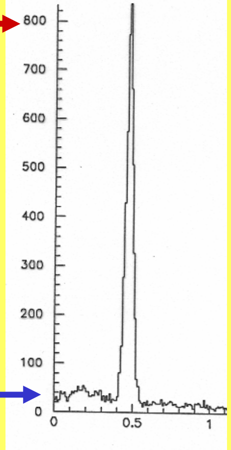
Already excluded also by R_{90} analysis

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



E (MeV)

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

NO

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

Measured fast neutron flux @ LNGS:
$\Phi_n = 0.9 \ 10^{-7}$ 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):

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

  - 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

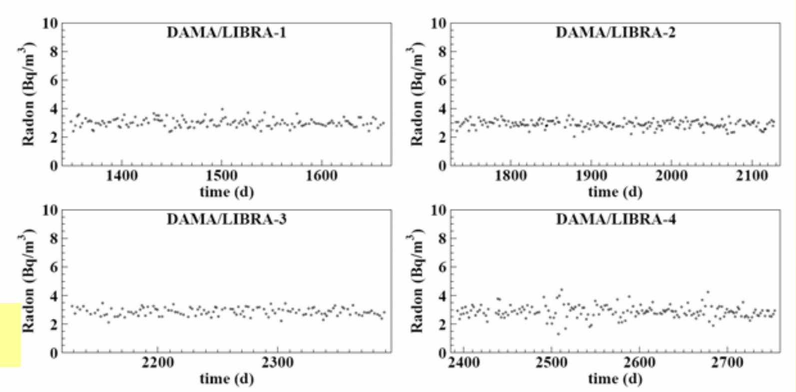
  already excluded by the multiple-hit events

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

Radon

- **Three-level system to exclude Radon from the detectors:**
- **Walls and floor of the inner installation sealed in Supronyl (2×10^{-11} cm^2/s permeability).**
- **Whole shield in plexiglas box maintained in HP Nitrogen atmosphere in slight overpressure with respect to environment**
- **Detectors in the inner Cu box in HP Nitrogen atmosphere in slight overpressure with respect to environment continuously since several years**

measured values at level of sensitivity of the used radonmeter



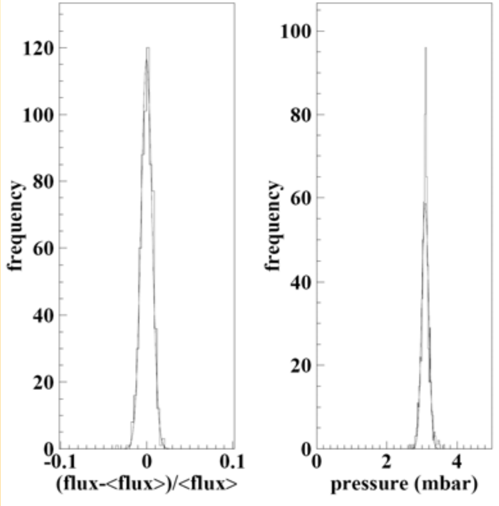
Time behaviours of the environmental radon in the installation (i.e. after the Supronyl), from which in addition the detectors are excluded by other two levels of sealing!

Amplitudes for annual modulation of Radon external to the shield:

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
Radon (Bq/m^3)	**-(0.029 ± 0.029)**	**-(0.030 ± 0.027)**	**(0.015 ± 0.029)**	**-(0.052 ± 0.039)**

<flux> ≈ 320 l/h

Over pressure ≈ 3.1 mbar



NO DM-like modulation amplitude in the time behaviour of external Radon (from which the detectors are excluded), of HP Nitrogen flux and of Cu box pressure

Investigation in the HP Nitrogen atmosphere of the Cu-box

- **Study of the double coincidences of γ's (609 & 1120 keV) from ^{214}Bi Radon daughter**
- **Rn concentration in Cu-box atmosphere <$5.8 \cdot 10^{-2}$ Bq/m^3 (90% C.L.)**
- **By MC: <$2.5 \cdot 10^{-5}$ cpd/kg/keV @ low energy for *single-hit* events**(enlarged matrix of detectors and better filling of Cu box with respect to DAMA/NaI)
- **An hypothetical 10% modulation of possible Rn in Cu-box:**

<2.5×10^{-6} cpd/kg/keV (<0.01% S_m^{observed})

An effect from Radon can be excluded

+ any possible modulation due to Radon would always fail some of the peculiarities of the signature and would affect also other energy regions

Can the μ modulation measured by MACRO account for the observed effect?

Case of fast neutrons produced by muons

Φ_μ @ LNGS $\approx 20\ \mu\ m^{-2}\ d^{-1}$ **(±2% modulated)**

Neutron Yield @ LNGS: $Y = 1 \div 7\ 10^{-4}\ n/\mu/(g/cm^2)$ **(hep-ex/0006014)**

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

Annual modulation amplitude at low energy due to μ modulation:

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

where:

g = geometrical factor

ε = detection efficiency by elastic scattering

$f_{\Delta E}$ = energy window (E>2keV) efficiency

f_{single} = single hit efficiency

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 $\Delta E = 4$keV

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

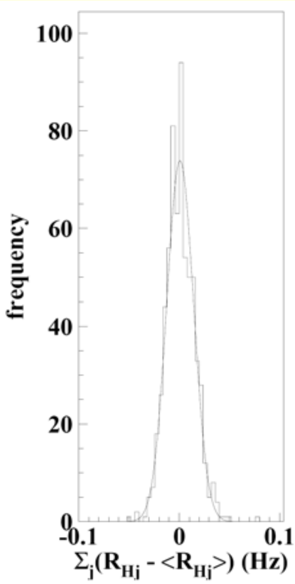
NO

Moreover, this modulation also induces a variation in other parts of the energy spectrum

It cannot mimic the signature: already excluded also by R_{90}

Noise

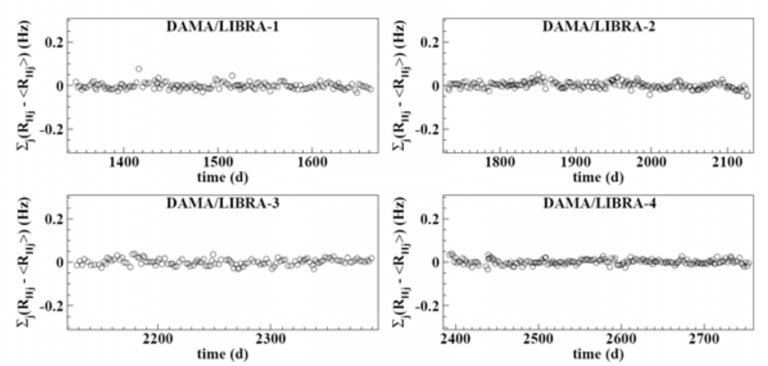
Distribution of variations of total hardware rates of the crystals over the single ph.el. threshold (that is from noise to "infinity") during DAMA/LIBRA-1,2,3,4 running periods



cumulative gaussian behaviour fully accounted by expected statistical spread arising from the sampling time used for the rate evaluation

R_{Hj} = hardware rate of j-th detector above single photoelectron

$\langle R_{Hj}\rangle$ = mean of R_{Hj} in the corresponding annual cycle



Amplitudes for annual modulation well compatible with zero:

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
Hardware rate (Hz)	$-(0.20 \pm 0.18) \times 10^{-2}$	$(0.09 \pm 0.17) \times 10^{-2}$	$-(0.03 \pm 0.20) \times 10^{-2}$	$(0.15 \pm 0.15) \times 10^{-2}$

Can a noise tail account for the observed modulation effect?

Despite the good noise identification near energy threshold and the used very stringent acceptance window for scintillation events (this is only procedure applied to the data), the role of an hypothetical noise tail in the scintillation events has even been quantitatively investigated.

The modulation amplitude of the "Hardware Rate" (period and phase as for DM particles) is compatible with zero: $(0.03 \pm 0.09) \times 10^{-2}$ Hz → $< 1.8 \times 10^{-3}$ Hz (90% CL)

Hardware Rate = noise +bckg [up to ≈MeV]+signal [up to ≈6keV]

- noise/crystal ≈ 0.10 Hz
- relative modulation amplitude from noise $< 1.8\ 10^{-3}$ Hz/2.5 Hz $\approx 7.2 \times 10^{-4}$ (90%CL)

even in the *worst hypothetical* case of 10% residual tail of noise in the data → **relative modulation amplitude from noise at low energy $< 7.2 \times 10^{-5}$** → **$< 10^{-4}$ cpd/kg/keV**

NO

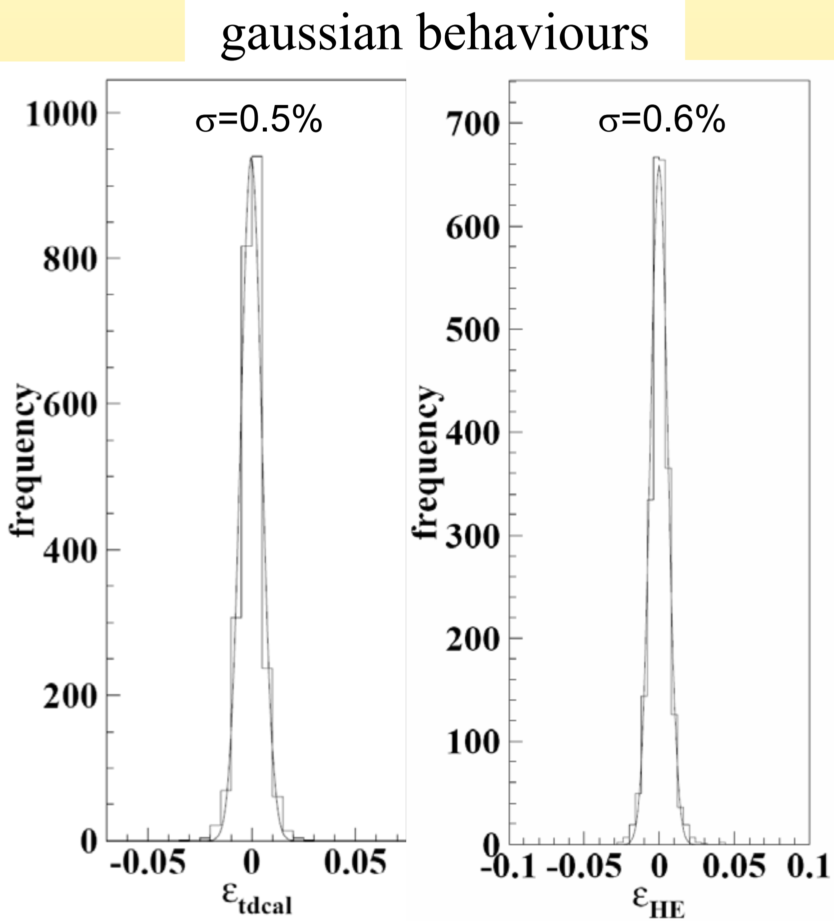
The calibration factors

DAMA/LIBRA-1,2,3,4

- Distribution of the percentage variations (ε_{tdcal}) of each energy scale factor ($tdcal_k$) with respect to the value measured in the previous calibration ($tdcal_{k-1}$) for the DAMA/LIBRA-1 to -4 annual cycles.

$$\varepsilon_{tdcal} = \frac{tdcal_k - tdcal_{k-1}}{tdcal_{k-1}}$$

- Distribution of the percentage variations (ε_{HE}) of the high energy scale factor with respect to the mean values for the DAMA/LIBRA-1 to -4 annual cycles.



gaussian behaviours

Low-Energy calibration factors (ε_{tdcal}) **High-Energy calibration factors (ε_{HE})**

the low energy calibration factor for each detector is known with an uncertainty <<1% during the data taking periods: **additional energy spread σ_{cal}**

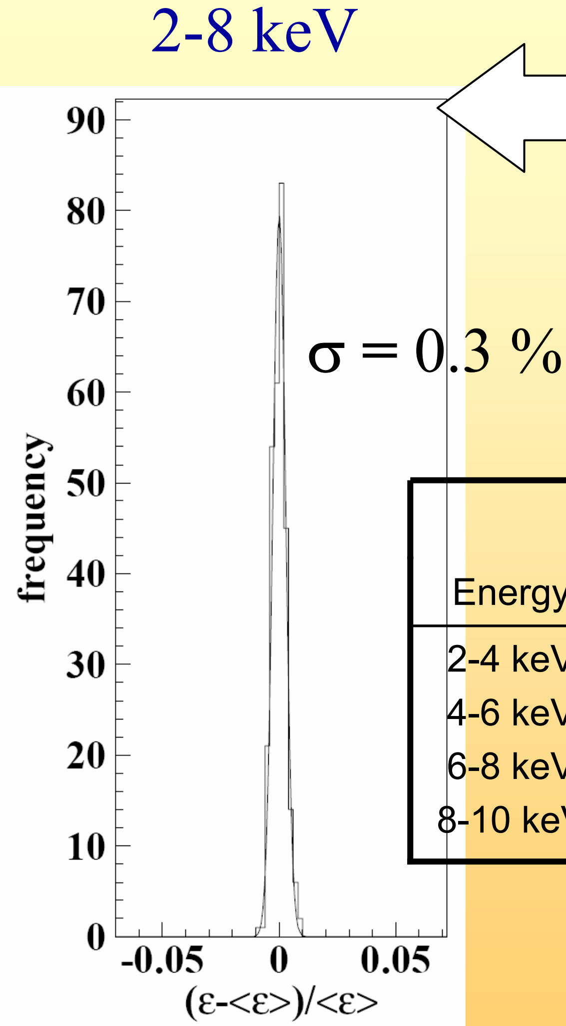
$$\sigma = \sqrt{\sigma_{res}^2 + \sigma_{cal}^2} \approx \sigma_{res} \cdot \left[1 + \frac{1}{2}\left(\frac{\sigma_{cal}}{\sigma_{res}}\right)^2\right]; \quad \frac{1}{2}\left(\frac{\sigma_{cal}/E}{\sigma_{res}/E}\right)^2 \leq 7.5 \cdot 10^{-4} \frac{E}{20keV}$$

Negligible effect considering routine calibrations and energy resolution at low energy

Confirmation from MC: maximum relative contribution < 1 – 2 × 10^{-4} cpd/kg/keV

No modulation in the energy scale
+ cannot mimic the signature

The efficiencies



Distribution of variations of the efficiency values with respect to their mean values during DAMA/LIBRA running periods

Time behaviour: modulation amplitudes obtained by fitting the time behaviours of the efficiencies including a WIMP-like cosine modulation for DAMA/LIBRA running periods

	Amplitudes ($\times 10^{-3}$)			
Energy	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
2-4 keV	(0.3±0.6)	(0.1±0.6)	-(0.4±1.1)	-(0.4±1.0)
4-6 keV	(0.0±0.6)	-(0.7±0.6)	-(0.3±1.0)	-(0.7±1.0)
6-8 keV	-(0.3±0.6)	-(1.0±0.7)	-(0.2±0.8)	-(1.0±0.8)
8-10 keV	-(0.5±0.5)	-(0.5±0.5)	-(0.2±0.6)	(0.7±0.6)

Energy	**Modulation amplitudes (DAMA/LIBRA)**
2-4 keV	**(0.1±0.4) × 10^{-3}**
4-6 keV	**-(0.4±0.4) × 10^{-3}**

Amplitudes well compatible with zero
+ cannot mimic the signature

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

EPJC 56(2008)333

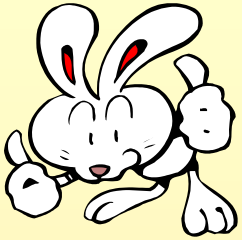
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously 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 by MACRO	**$<3\times10^{-5}$ cpd/kg/keV**

+ even if larger they cannot satisfy all the requirements of annual modulation signature

Thus, they can not mimic the observed annual modulation effect

... about the interpretation of the direct DM experimental results

The positive and model independent result of DAMA/NaI + DAMA/LIBRA

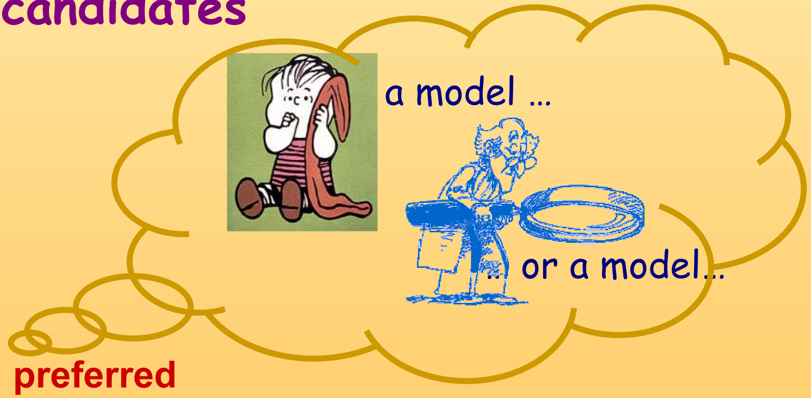


- Presence of modulation for 11 annual cycles at ~8.2σ C.L. with the proper distinctive features of the signature; all the features satisfied by the data over 11 independent experiments of 1 year each one
- Absence of known sources of possible systematics and side processes able to quantitatively account for the observed effect and to contemporaneously satisfy the many peculiarities of the signature

No other experiment whose result can be directly compared in model independent way is available so far

To investigate the nature and coupling with ordinary matter of the possible DM candidate(s), effective energy and time correlation analysis of the events has to be performed within given model frameworks

Corollary quests for candidates

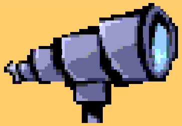


- **astrophysical models: ρ_{DM}, velocity distribution and its parameters**
- **nuclear and particle Physics models**
- **experimental parameters**

e.g. for WIMP class particles: SI, SD, mixed SI&SD, preferred inelastic, scaling laws on cross sections, form factors and related parameters, spin factors, halo models, etc.

+ different scenarios

+ multi-component halo?



THUS
uncertainties on models and comparisons

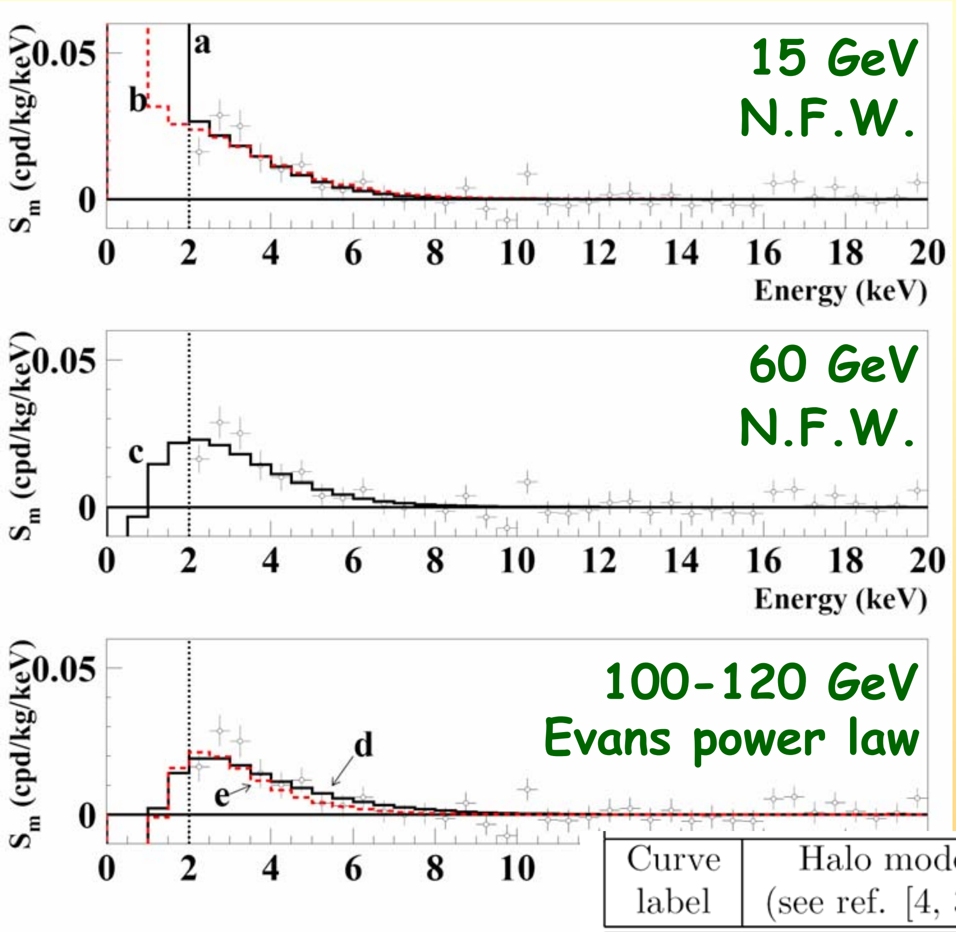
- In progress complete model dependent analyses by applying maximum likelihood analysis in time and energy accounting for at least some of the many existing uncertainties in the field (as done by DAMA/NaI in **Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125**), and to enlarge the investigations to other scenarios

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

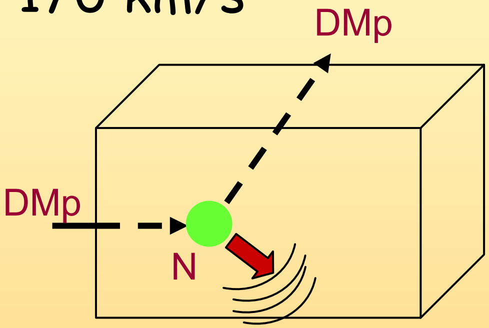
experimental S_m values vs expected behaviours

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

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.

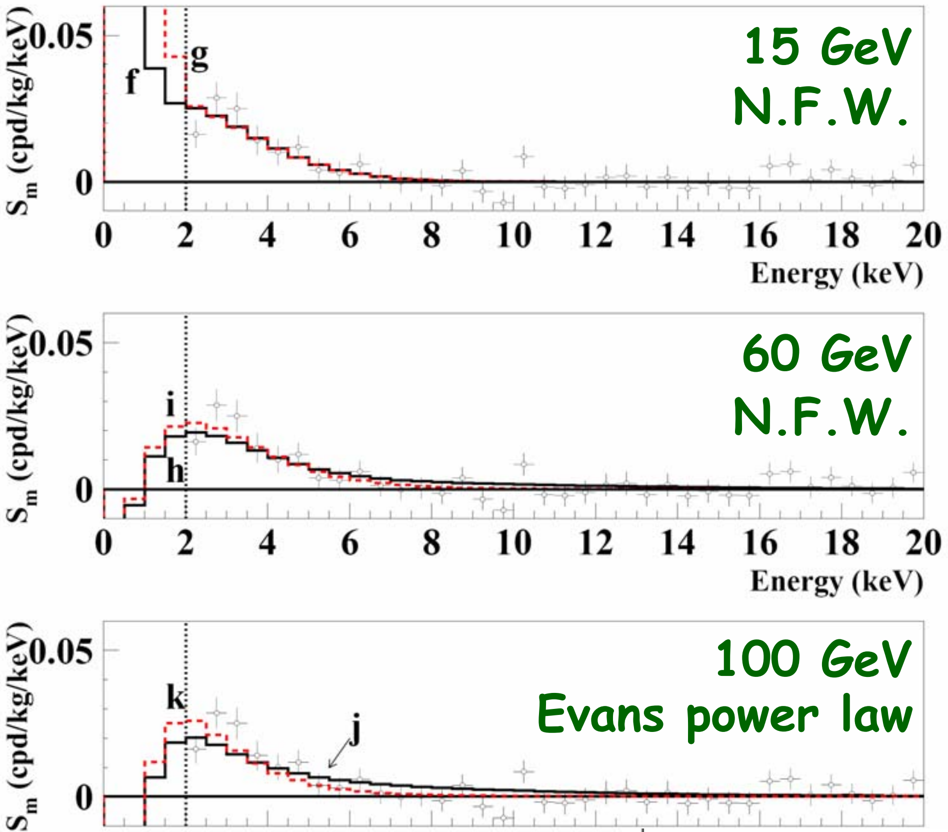
...scaling from NaI

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

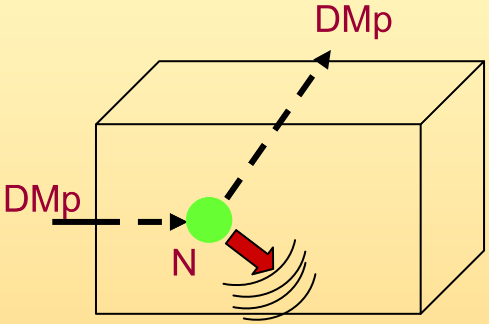
Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)
a	A5 (NFW)	0.2	A	15 GeV	3.1×10^{-4}
b	A5 (NFW)	0.2	A	15 GeV	1.3×10^{-5}
c	A5 (NFW)	0.2	B	60 GeV	5.5×10^{-6}
d	B3 (Evans power law)	0.17	B	100 GeV	6.5×10^{-6}
e	B3 (Evans power law)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

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

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



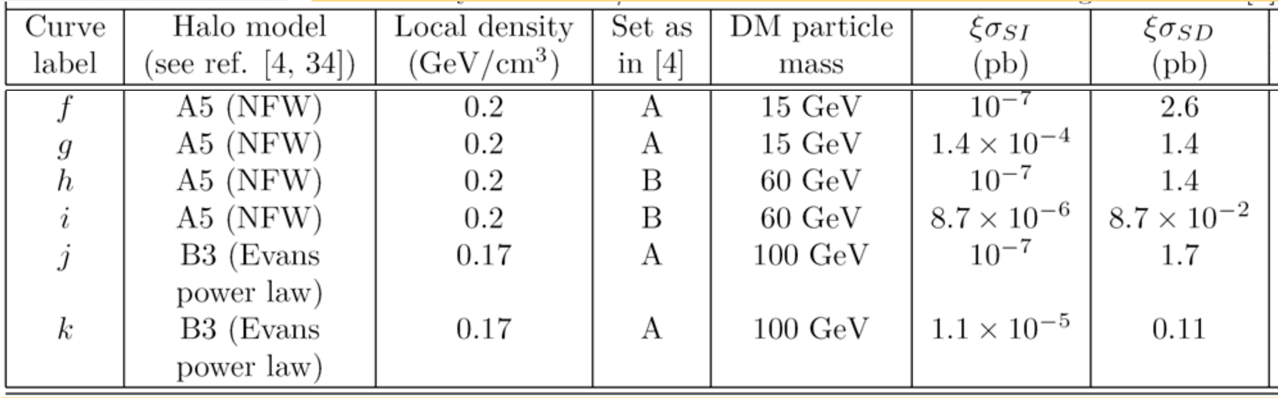
WIMP DM candidate (as in [4])
Elastic scattering on nuclei
SI & SD mixed coupling
v_0 = 170 km/s



About the same C.L.

...scaling from NaI

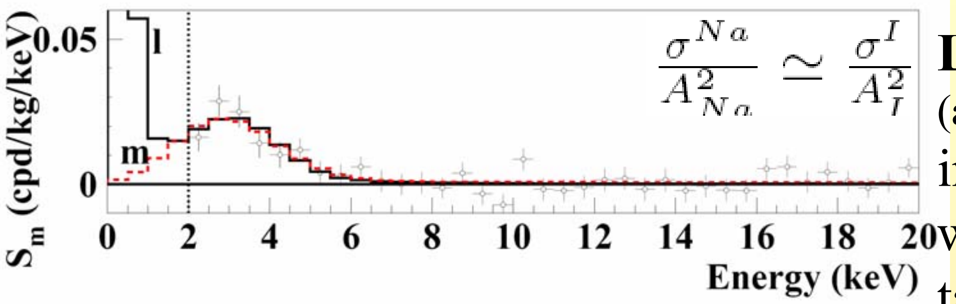
$$\boxed{\theta = 2.435}$$

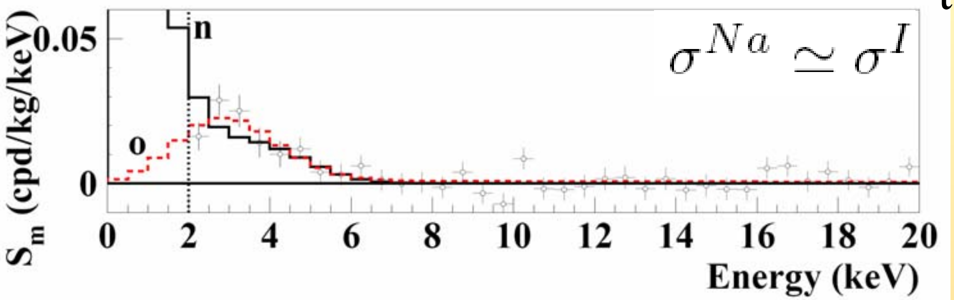


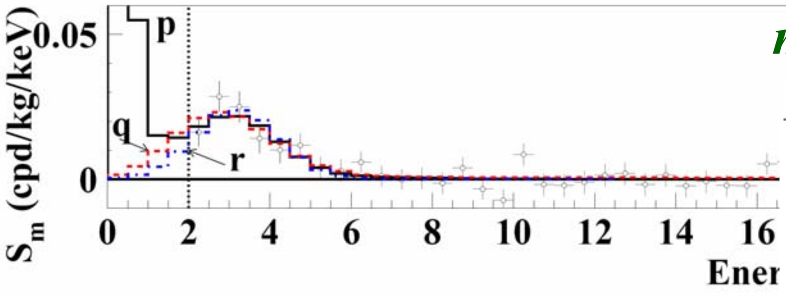
Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)	$\xi\sigma_{SD}$ (pb)
f	A5 (NFW)	0.2	A	15 GeV	10^{-7}	2.6
g	A5 (NFW)	0.2	A	15 GeV	1.4×10^{-4}	1.4
h	A5 (NFW)	0.2	B	60 GeV	10^{-7}	1.4
i	A5 (NFW)	0.2	B	60 GeV	8.7×10^{-6}	8.7×10^{-2}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





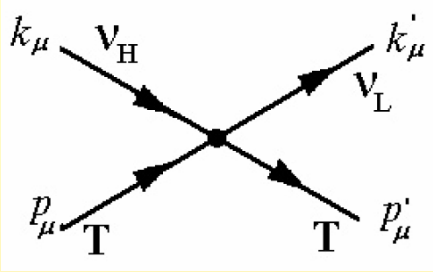


m_L=0

LDM candidate

(as in arXiv:0802.4336):

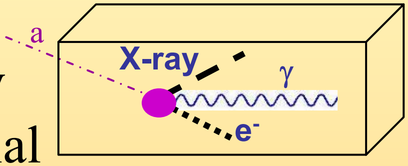
inelastic interaction with electron or nucleus targets



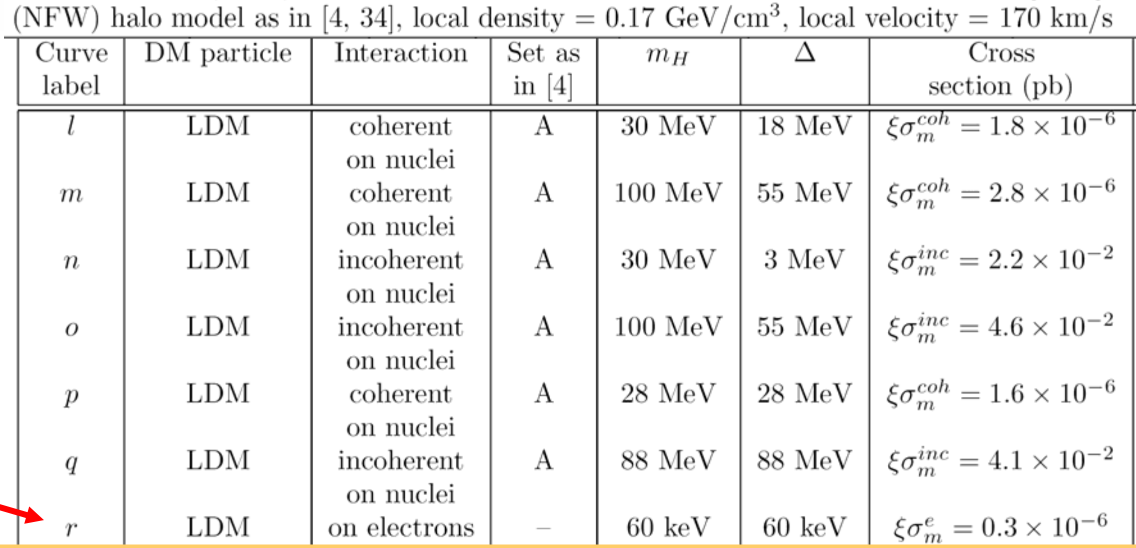
Light bosonic candidate

(as in IJMPA21(2006)1445):

axion-like particles totally absorbed by target material



About the same C.L.



(NFW) halo model as in [4, 34], local density = 0.17 GeV/cm³, 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	$\xi\sigma_m^{coh} = 1.8 \times 10^{-6}$
m	LDM	coherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{coh} = 2.8 \times 10^{-6}$
n	LDM	incoherent on nuclei	A	30 MeV	3 MeV	$\xi\sigma_m^{inc} = 2.2 \times 10^{-2}$
o	LDM	incoherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{inc} = 4.6 \times 10^{-2}$
p	LDM	coherent on nuclei	A	28 MeV	28 MeV	$\xi\sigma_m^{coh} = 1.6 \times 10^{-6}$
q	LDM	incoherent on nuclei	A	88 MeV	88 MeV	$\xi\sigma_m^{inc} = 4.1 \times 10^{-2}$
r	LDM	on electrons	–	60 keV	60 keV	$\xi\sigma_m^{e} = 0.3 \times 10^{-6}$

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

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

Conclusions

- *DAMA/LIBRA over 4 annual cycles (0.53 ton x yr) confirms the results of DAMA/NaI (0.29 ton x yr)*
- *The cumulative C.L. for the model independent evidence for presence of DM particle in the galactic halo is 8.2 σ (0.82 ton x yr)*
- *Updating of corollary analyses in some of the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc. is in progress.*
- *First upgrading of the experimental set-up occurred in September 2008.*
- *Analyses/data taking to investigate other rare processes in progress/foreseen*

A possible highly radiopure NaI(Tl) multi-purpose set-up DAMA/1 ton (proposed by DAMA in 1996) is at present at R&D phase