Particle Dark Matter in the galactic halo: results from DAMA/LIBRA

R. Cerulli
INFN-LNGS

Rencontres de Moriond EW
La Thuile, Italy
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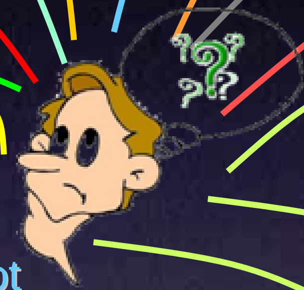
Relic DM particles from primordial Universe



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?

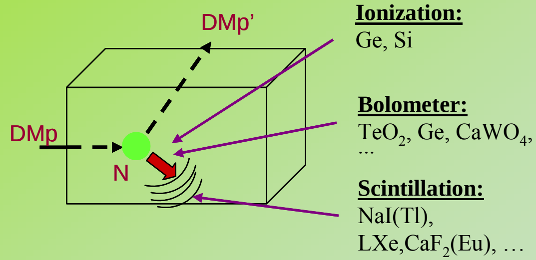
clumpiness?

etc… etc…

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



- 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

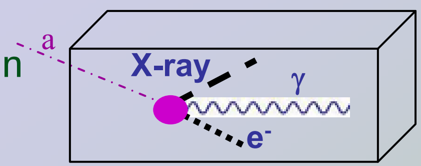
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

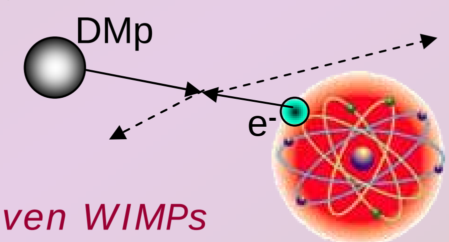
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

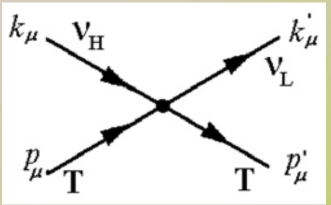
  → detection of e.m. radiation



… even WIMPs

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

  → detection of electron/nucleus recoil energy



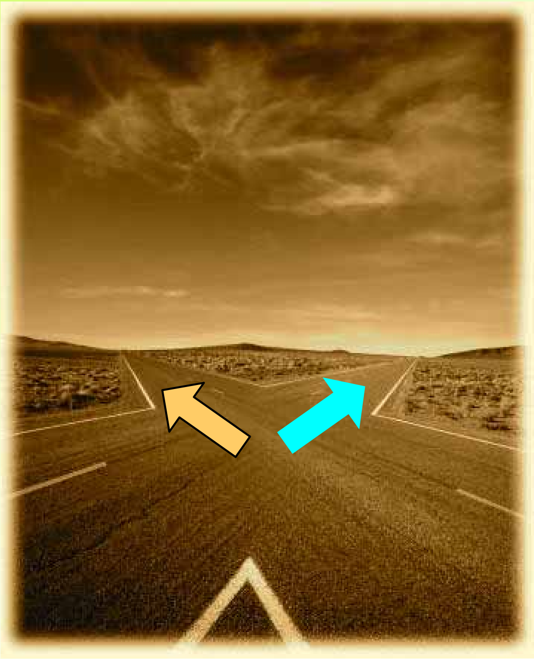
e.g. sterile ν

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

… also other ideas…

- **… and more**

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



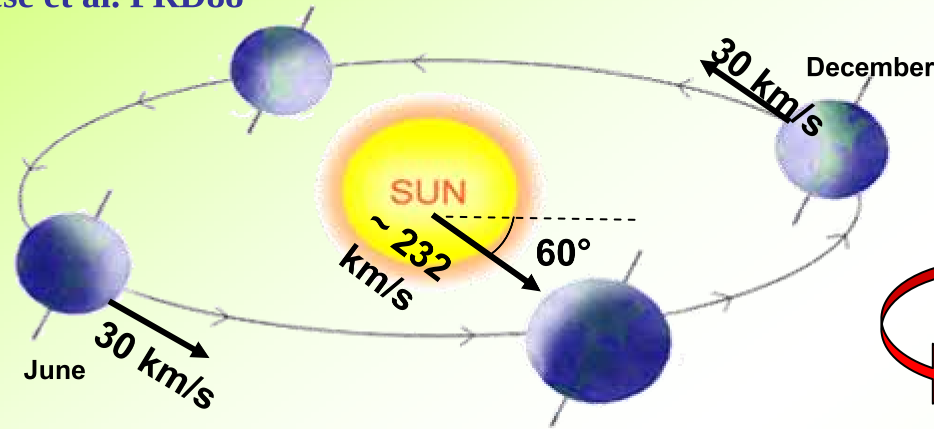
1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a "model-independent" signature

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

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

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence**.

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



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

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

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

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

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

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

Competitiveness of NaI(Tl) set-up

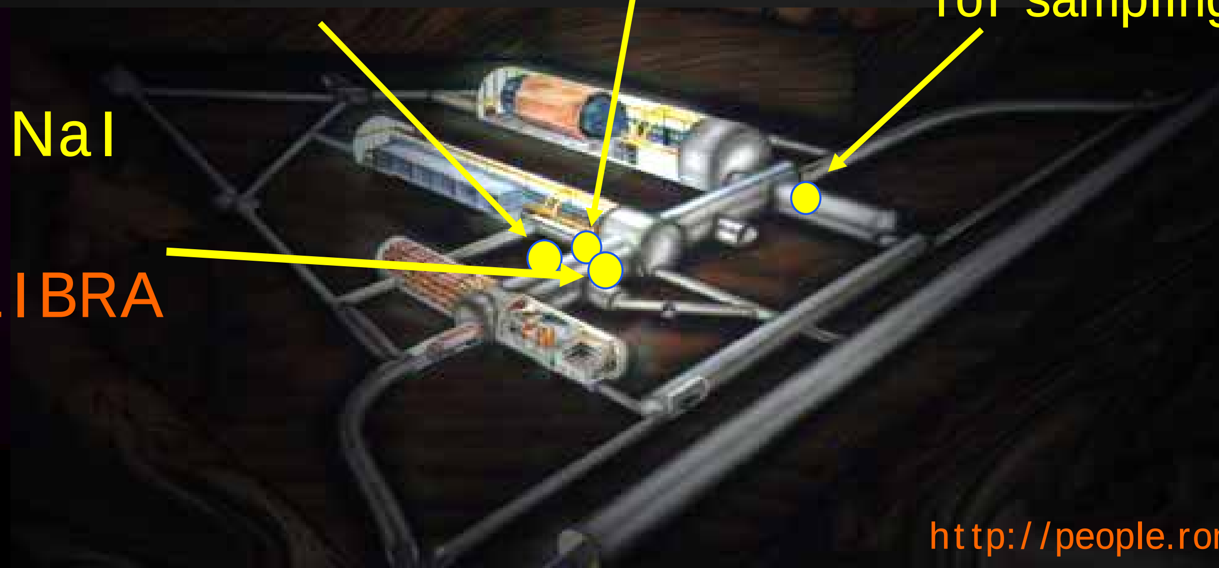
- **Well known technology**
- **High duty cycle**
- **Large mass possible**
- ***"Ecological clean"*** **set-up; no safety problems**
- **Cheaper than every other considered technique**
- **Small underground space needed**
- **High radiopurity by selections, chem./phys. purifications, protocols reachable**
- **Well controlled operational condition feasible**
- **Routine calibrations feasible down to keV range in the same conditions as the production runs**
- **Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)**
- **Absence of microphonic noise + effective noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)**
- **High light response (5.5 -7.5 ph.e./keV)**
- **Sensitive to SI, SD, SI&SD couplings and to other existing scenarios, on the contrary of many other proposed target-nuclei**
- **Sensitive to both high (by Iodine target) and low mass (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 such as: 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

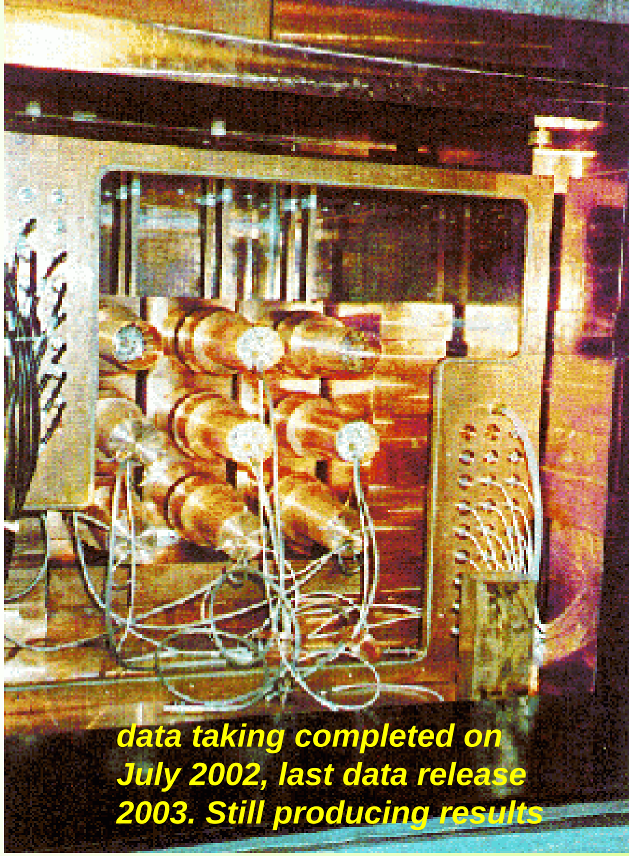
Roma2,Roma1,LNGS,IHEP/Beijing

DAMA: an observatory for rare processes @LNGS



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

DAMA/NaI : ≈100 kg 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.

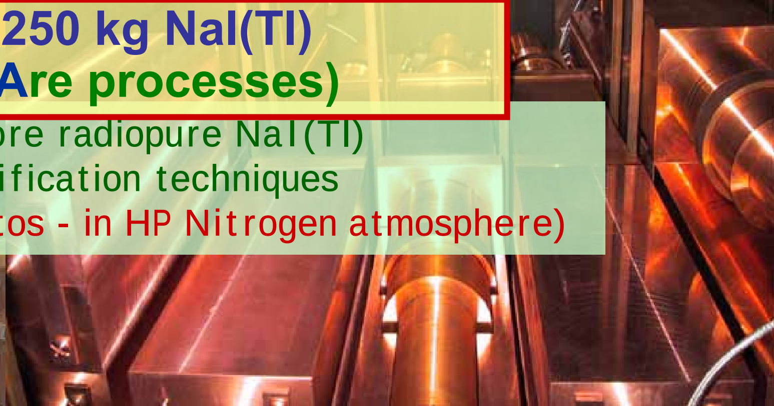
total exposure (7 annual cycles) 0.29 ton x yr

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

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

installing DAMA/LIBRA detectors

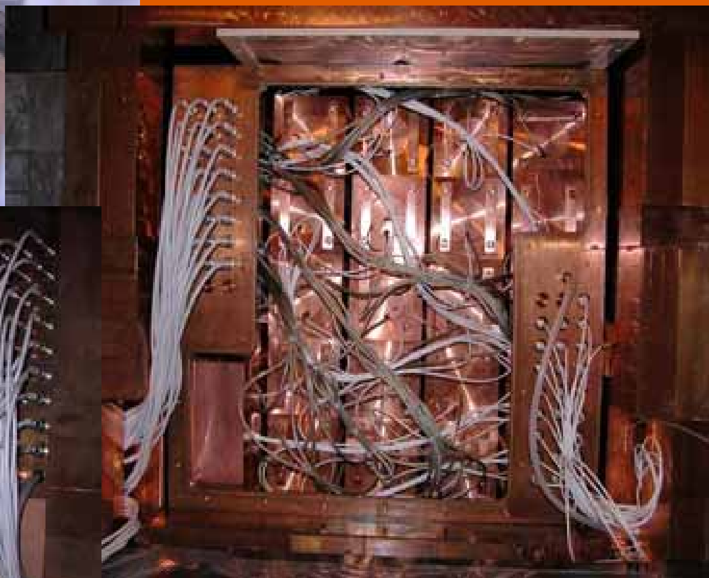
assembling a DAMA/ LIBRA detector



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



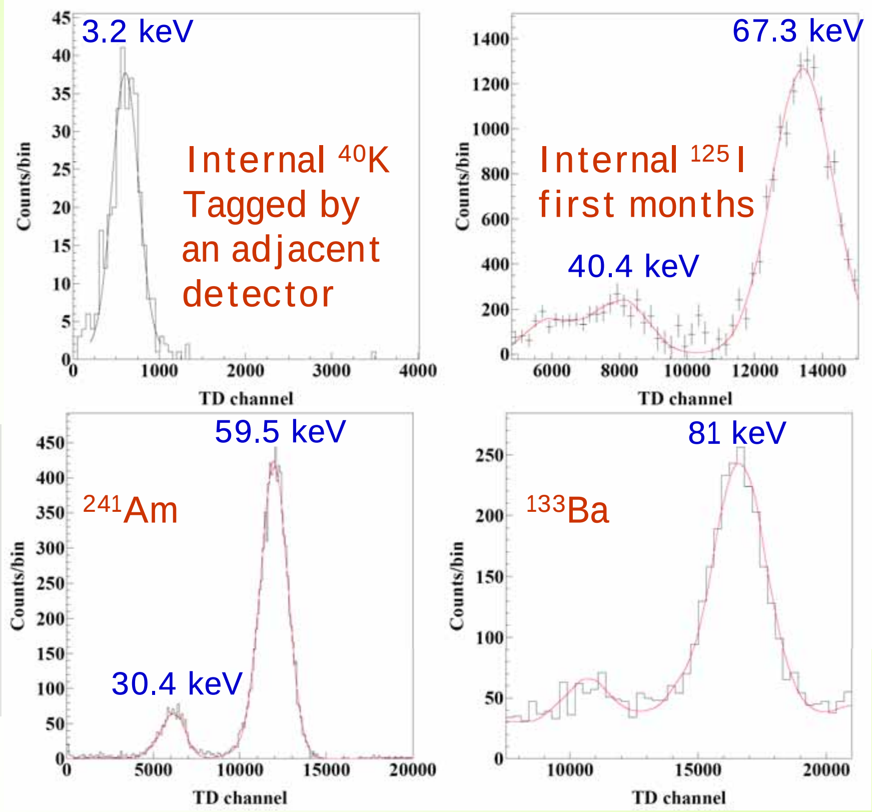
view at end of detectors' installation in the Cu box

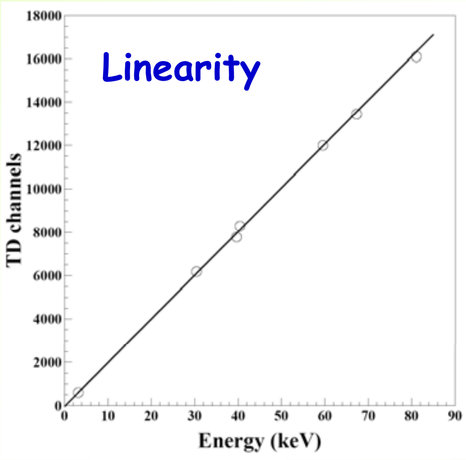
DAMA/LIBRA: calibrations at low energy

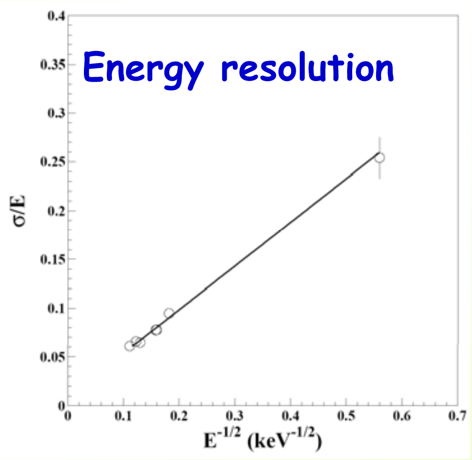
Studied by using various external gamma sources (^{241}Am, ^{133}Ba) and internal X-rays or gamma's (^{40}K, ^{125}I, ^{129}I)

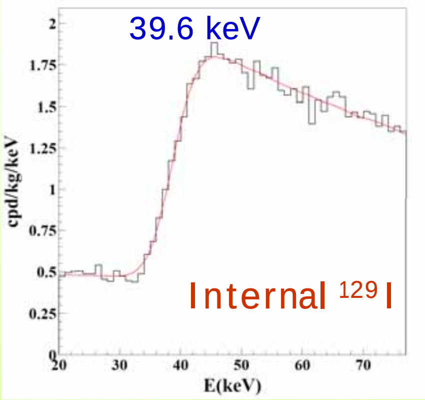
The curves superimposed to the experimental data have been obtained by simulations

- **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).







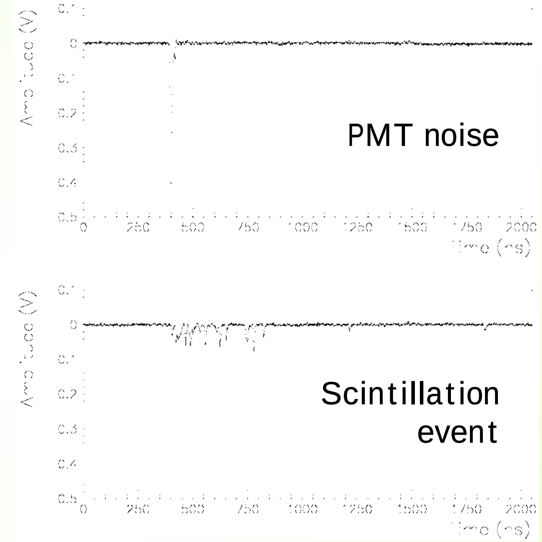


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

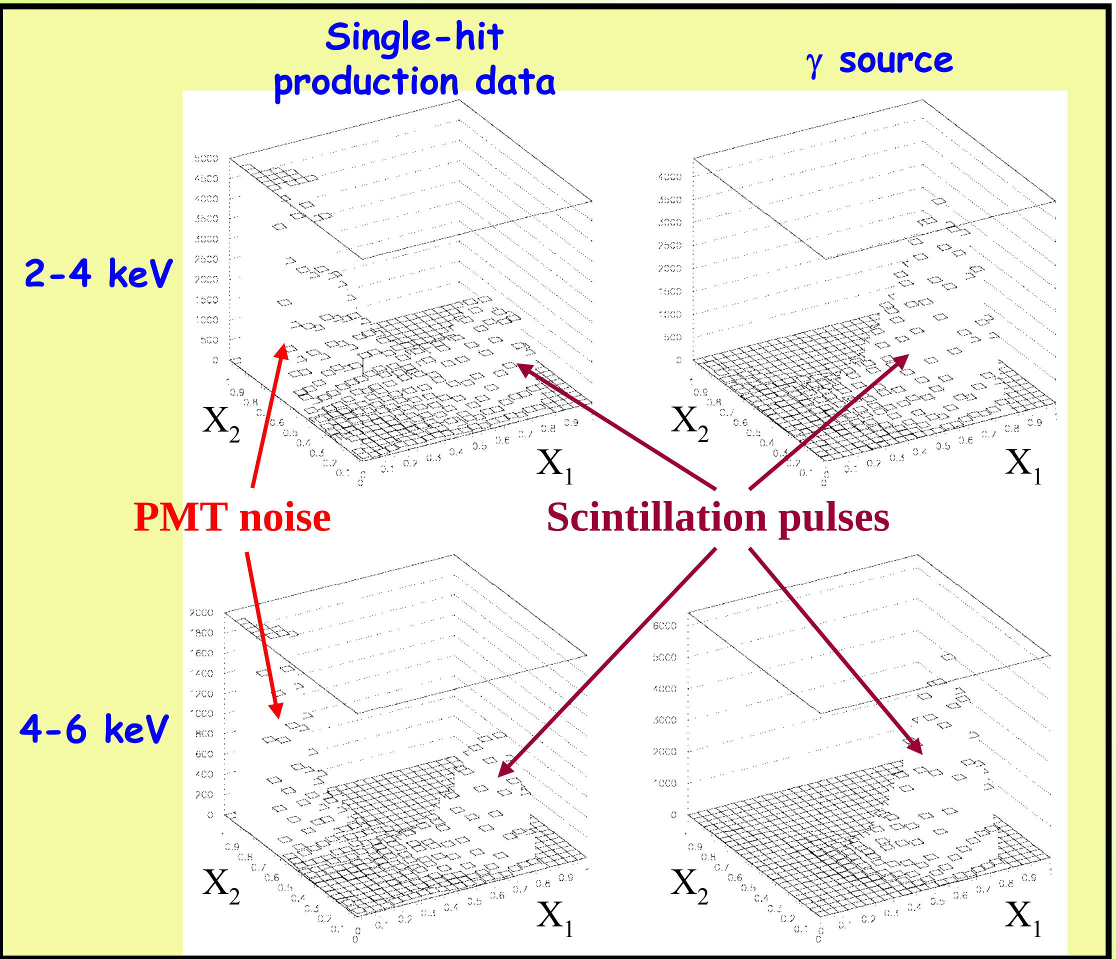
Routine calibrations with ^{241}Am

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

EPJC56(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

<u>Data released here:</u>

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

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

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

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

Two remarks:

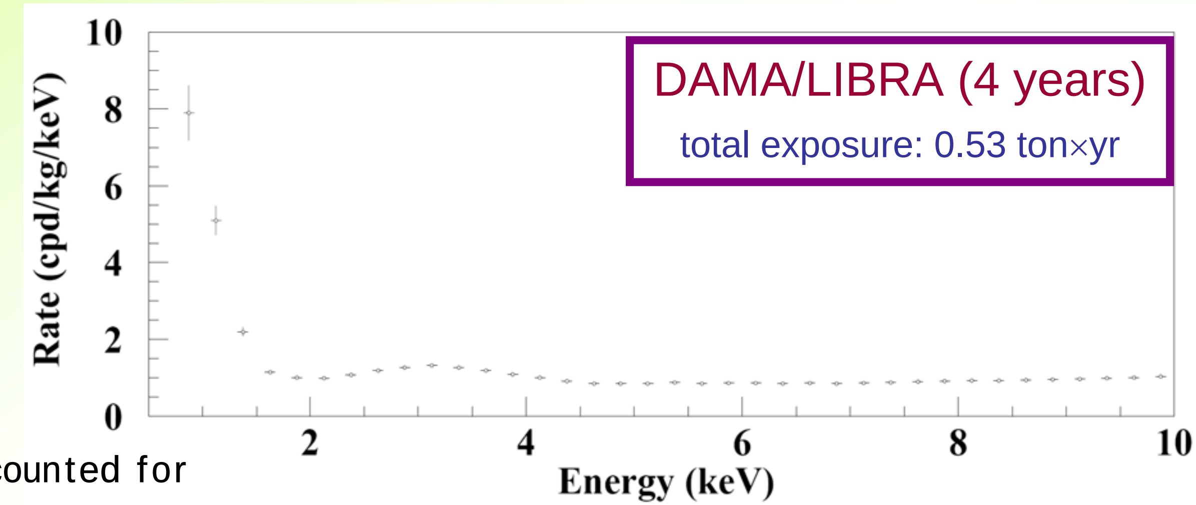
- One PMT problems after 6 months. Detector out of trigger since Sep. 2003 (it will be put again in operation at the 2008 upgrading)
- Residual cosmogenic ^{125}I presence in the first year in some detectors (this motivates the Sept. 2003 as starting time)

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

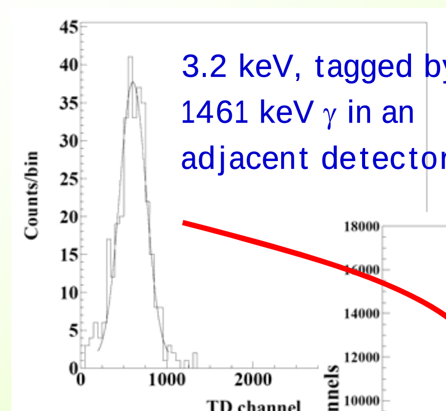
(Obviously differences among detectors are present depending e.g. on each specific level and location of residual contaminants, on the detector's location in the 5x5 matrix, etc.)

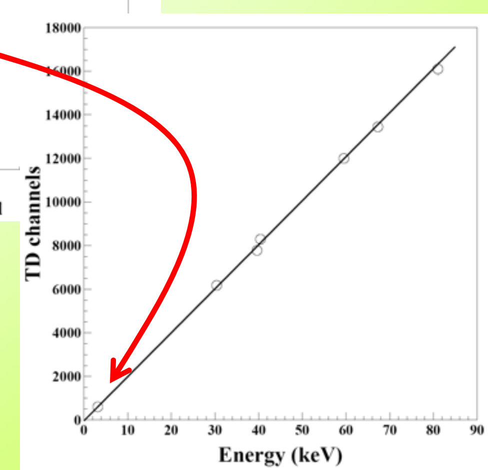


Efficiencies already accounted for

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.



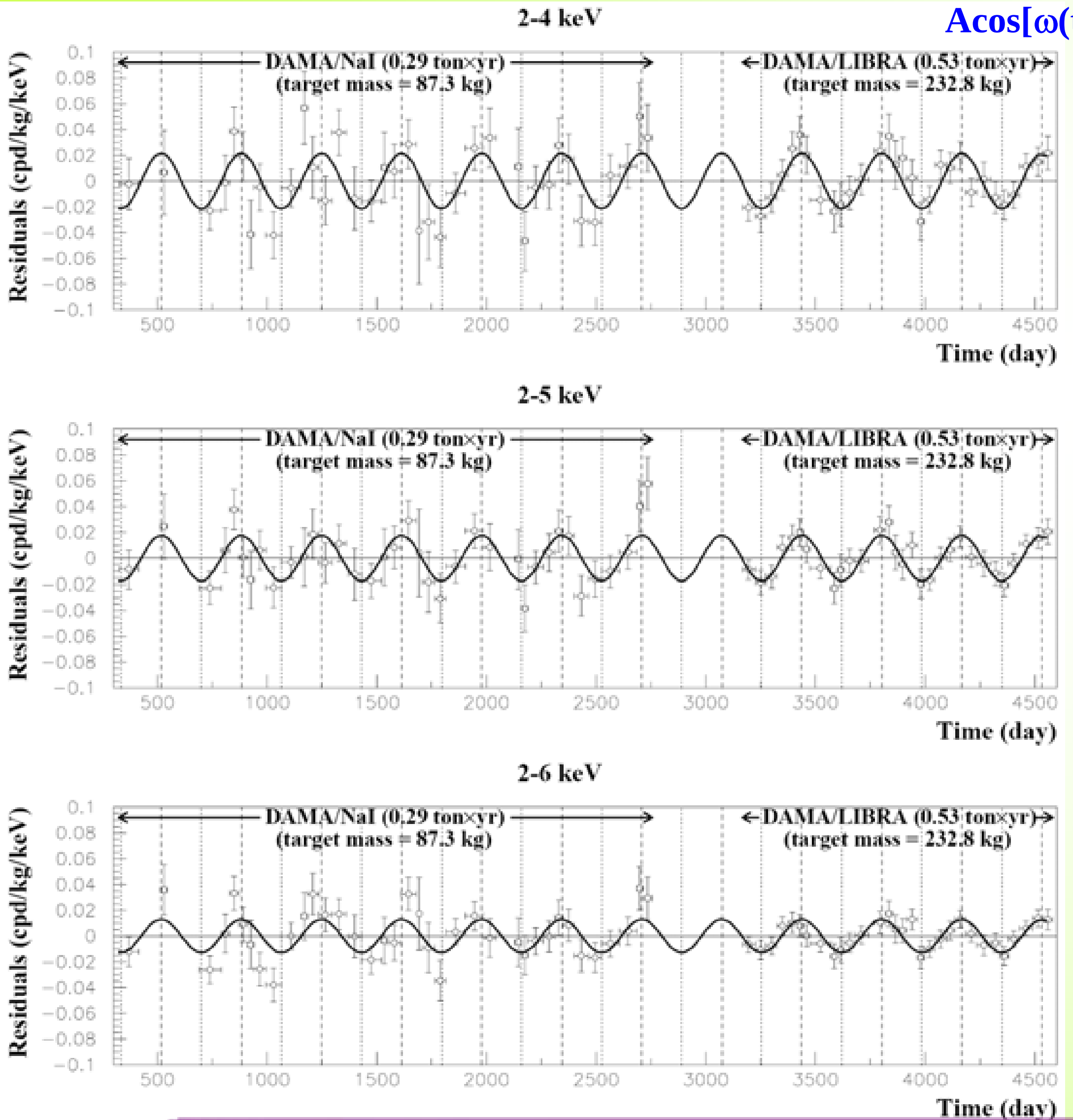


Model Independent Annual Modulation Result

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

EPJC56(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.

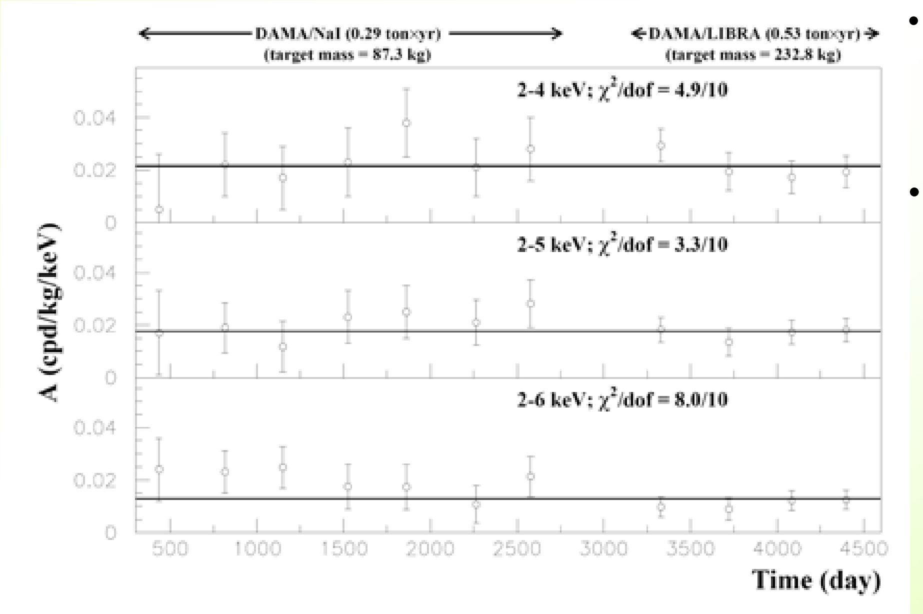
Model-independent residual rate for single-hit events

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 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 and (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.

χ^2 test (χ^2/dof = 4.9/10, 3.3/10 and 8.0/10) and *run test* (lower tail probabilities of 74%, 61% and 11%) accept at 90% C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.

Compatibility among the annual cycles

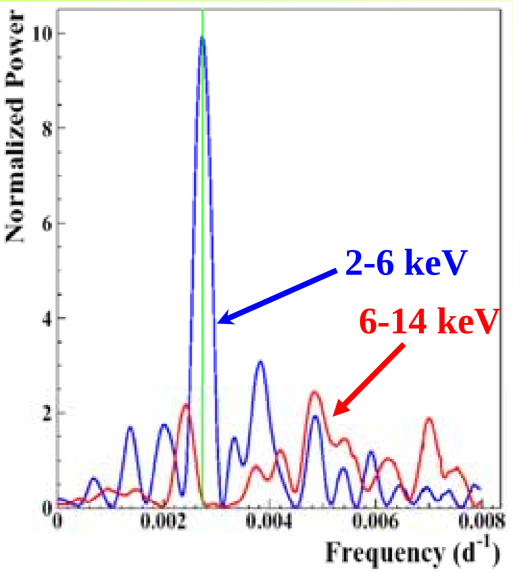
Power spectrum of single-hit residuals

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

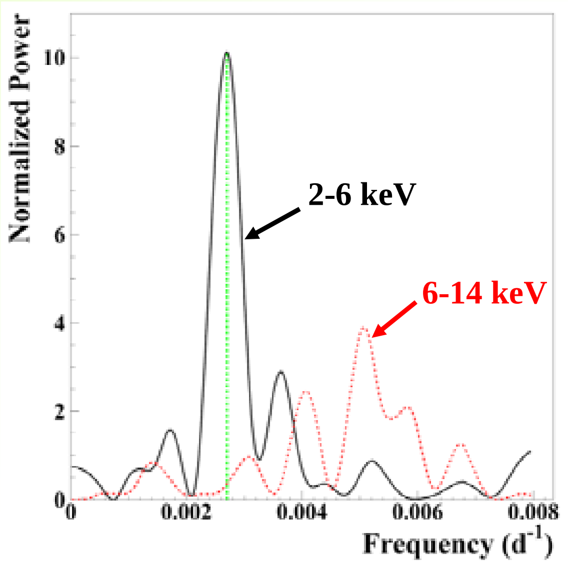
Treatment of the experimental errors and time binning included here

2-6 keV vs 6-14 keV

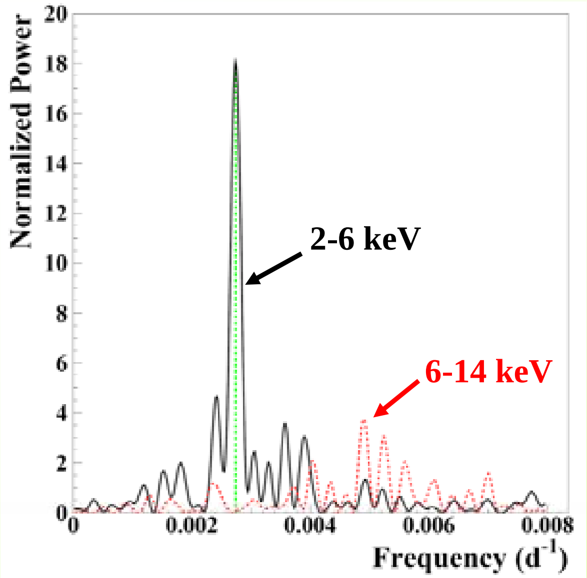
DAMA/NaI (7 years)
total exposure: 0.29 ton×yr



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}

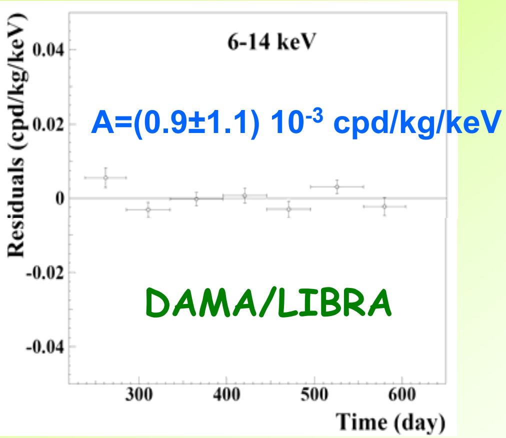
+

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**



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
→ statistically consistent with zero

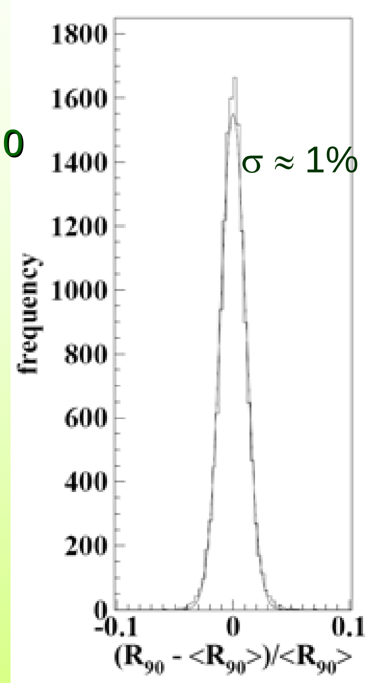
In the same energy region where the effect is observed: no modulation of the multiple-hits events (see next slide)

- **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 $\sigma \approx 1\%$, fully accounted by statistical considerations



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

+ 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

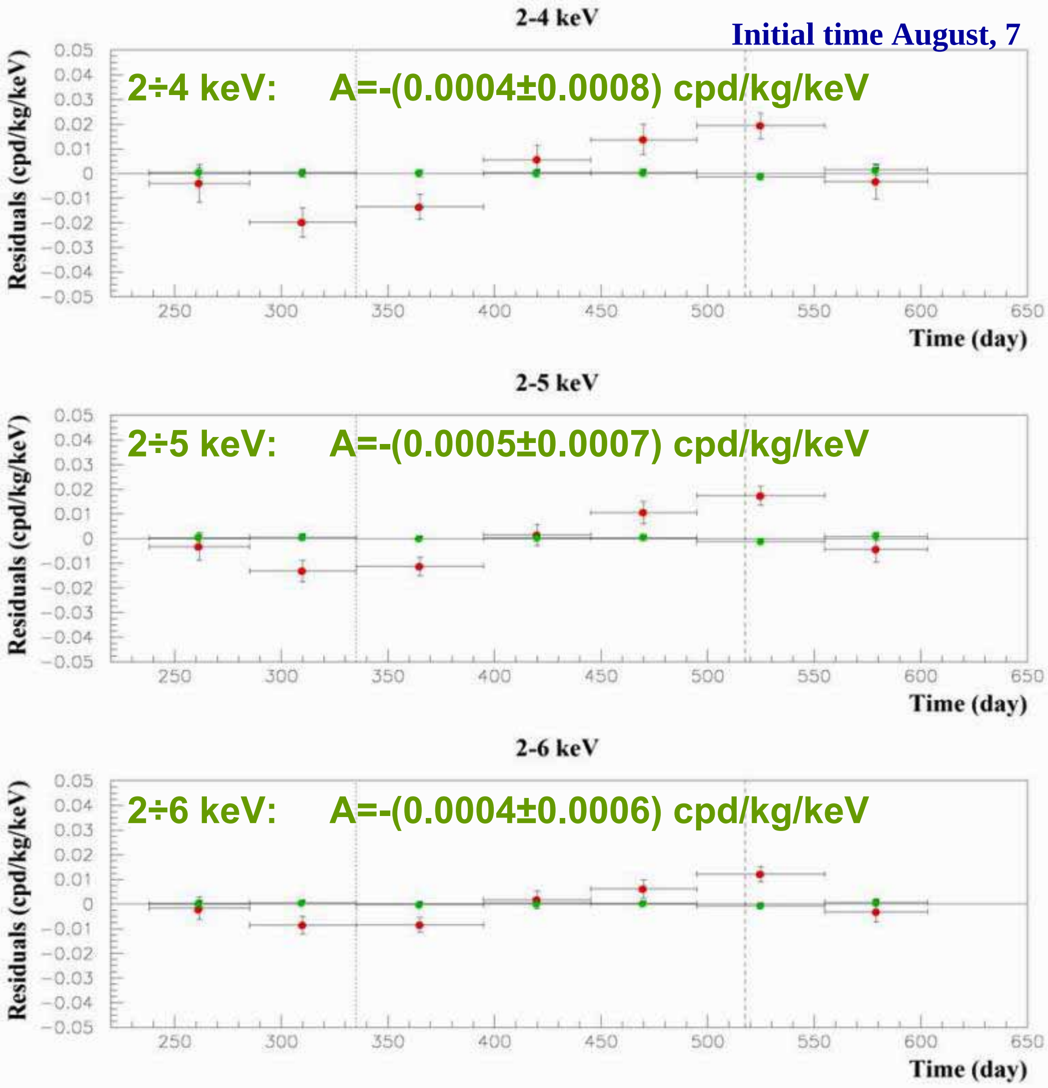
- **Each detector has its own TDs read-out → pulse profiles of multiple-hits events (multiplicity > 1) acquired (exposure: 0.53 ton×yr).**

- **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"

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

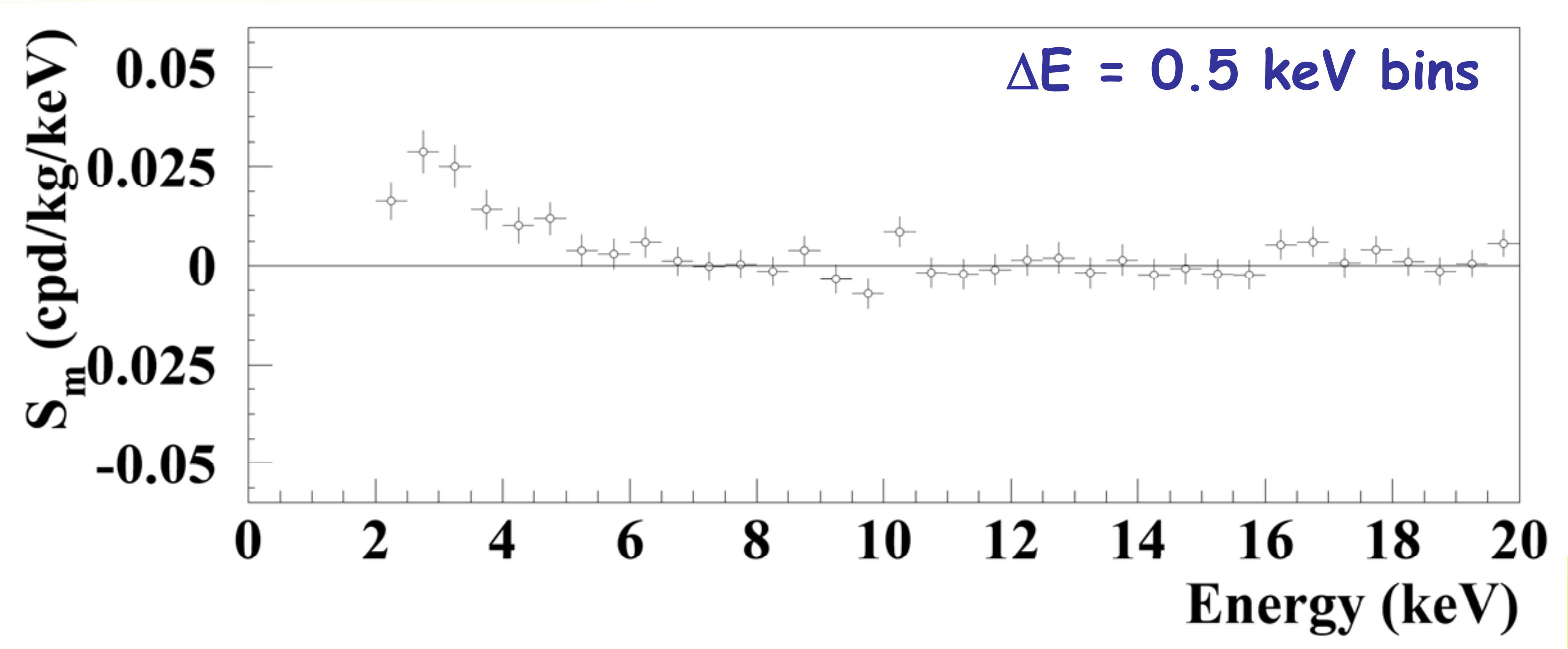
Energy distribution of the modulation amplitudes, S_m, for the total exposure

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

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)

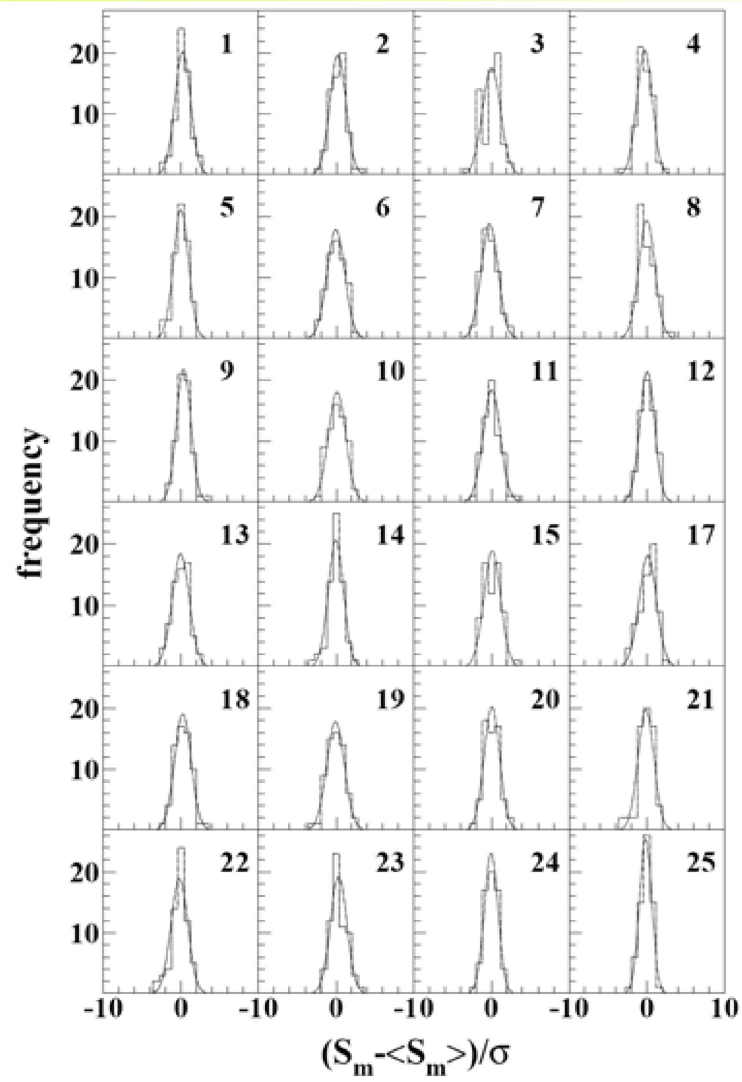
b) $\langle S_m \rangle$ = mean values over the detectors and the annual cycles for each energy bin; σ = errors associated to each S_m

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

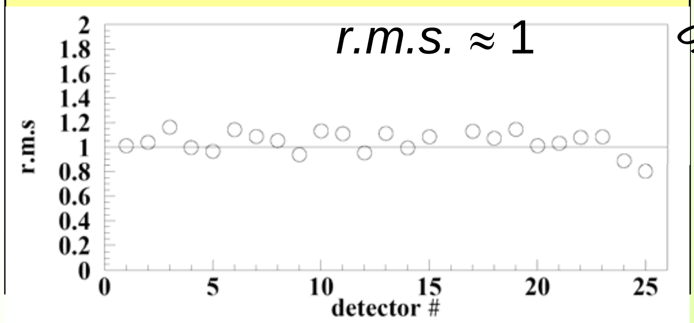
2-6 keV



Standard deviations of the variable

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

for the DAMA/LIBRA detectors



0.80 < r.m.s. < 1.16

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

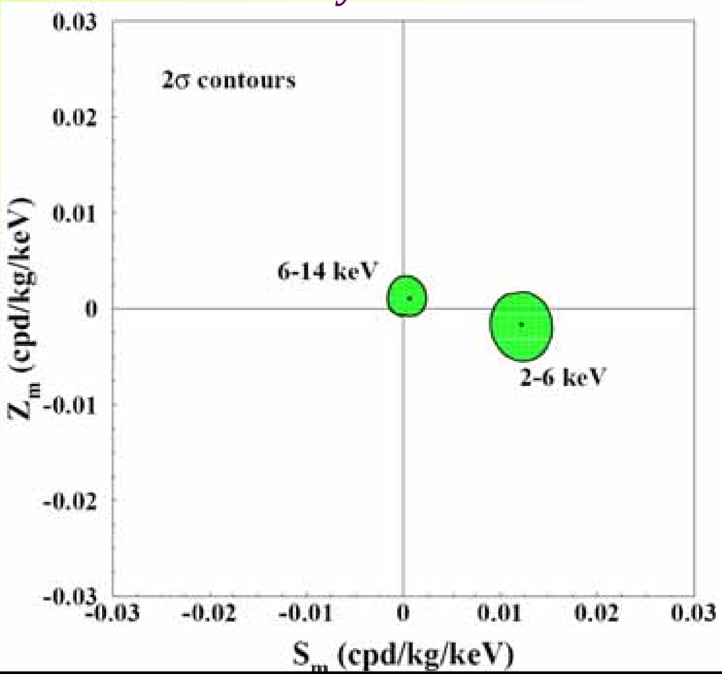
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

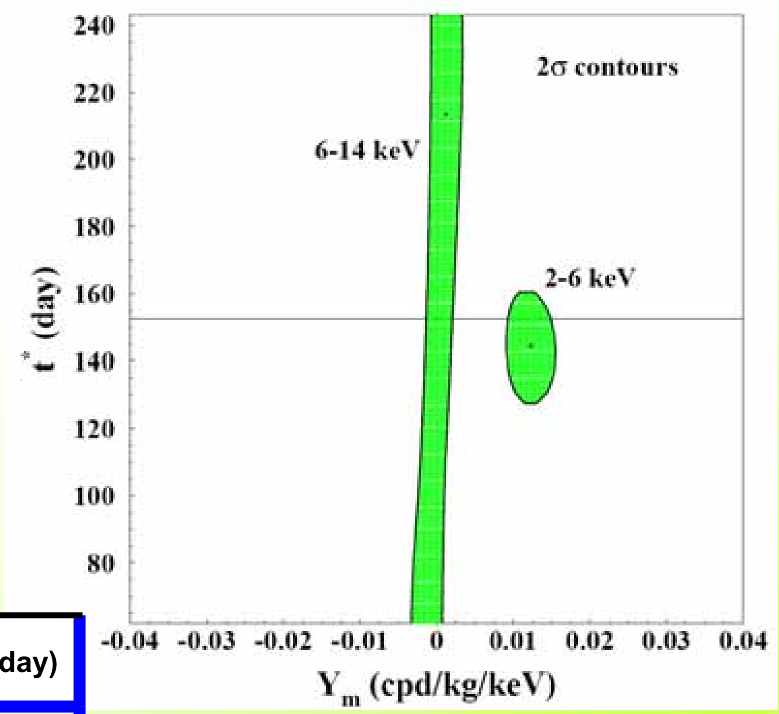
$$R(t) = S_0 + S_m \cos[\omega(t-t_0)] + Z_m \sin[\omega(t-t_0)] = S_0 + Y_m \cos[\omega(t-t^*)]$$

For Dark Matter signals:

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

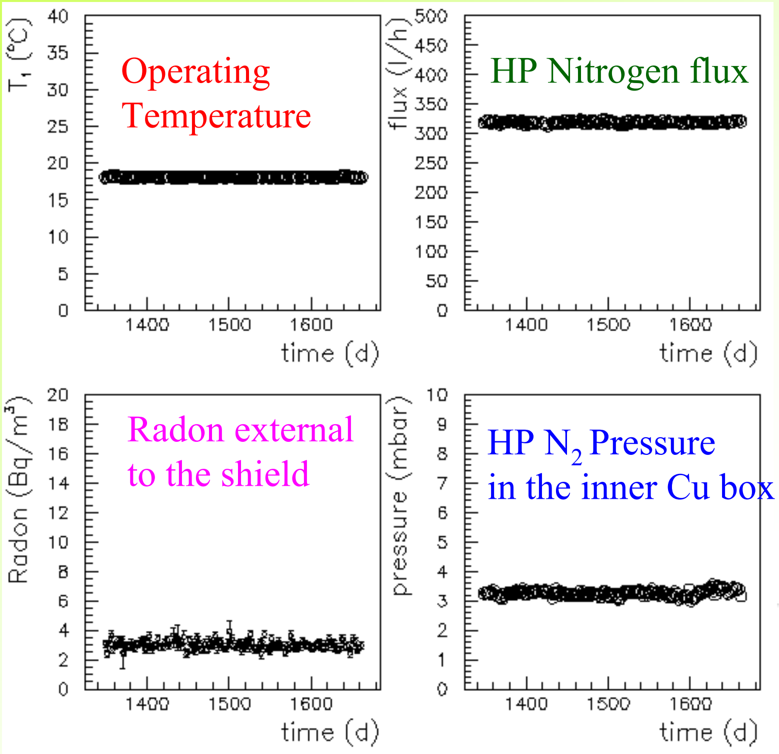
	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
Temperature	$-(0.0001 \pm 0.0061)$ °C	(0.0026 ± 0.0086) °C	(0.001 ± 0.015) °C	(0.0004 ± 0.0047) °C
Flux N_2	(0.13 ± 0.22) l/h	(0.10 ± 0.25) l/h	$-(0.07 \pm 0.18)$ l/h	$-(0.05 \pm 0.24)$ l/h
Pressure	(0.015 ± 0.030) mbar	$-(0.013 \pm 0.025)$ mbar	(0.022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

All the measured amplitudes well compatible with zero

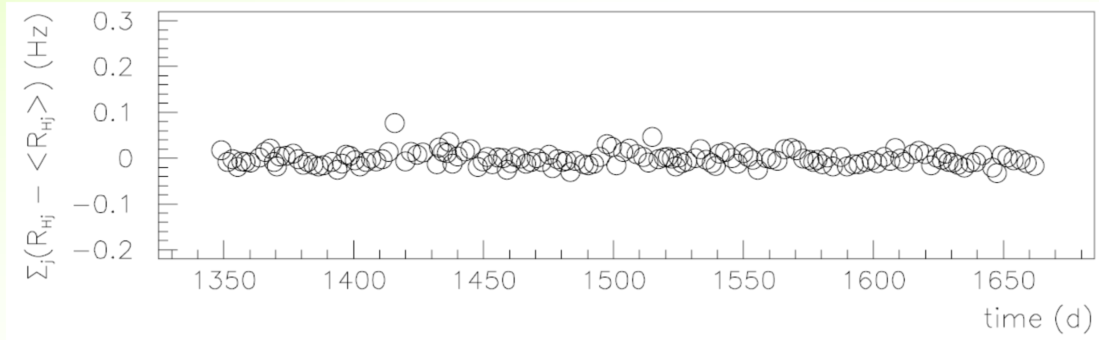
+none can account for the observed effect

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

Example of Stability Parameters: DAMA/LIBRA-1

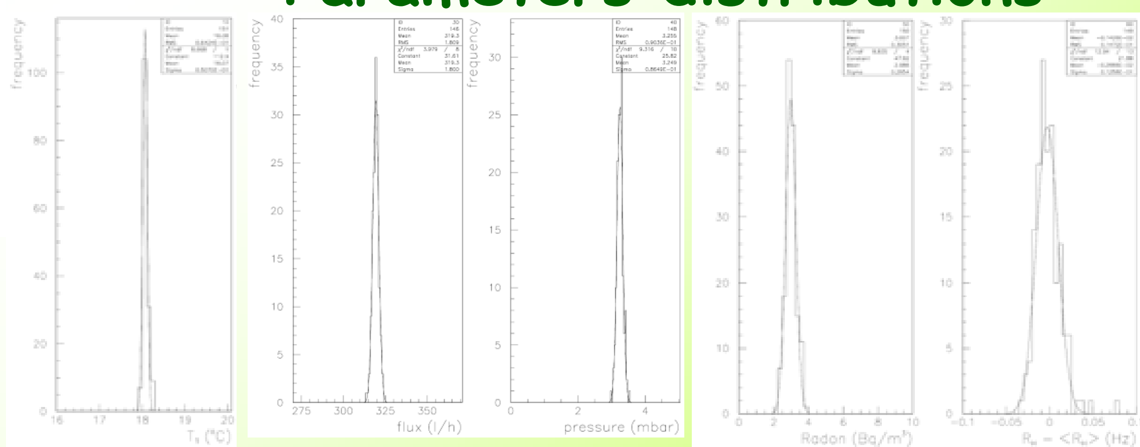


R_{Hj} = hardware rate of j-th detector above single photoelectron



Running conditions stable at level < 1%

Parameters distributions



All amplitudes well compatible with zero

+ no effect can mimic the annual modulation

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

(DAMA/LIBRA – NIMA592(2008)297, EPJC56(2008)333)

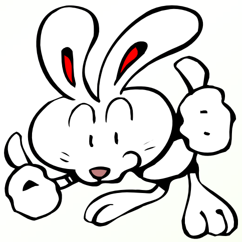
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<10^{-4} cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**<10^{-4} cpd/kg/keV**
ENERGY SCALE	Routine + instrinsic calibrations	**<1-2 $\times10^{-4}$ 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	**<3×10^{-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



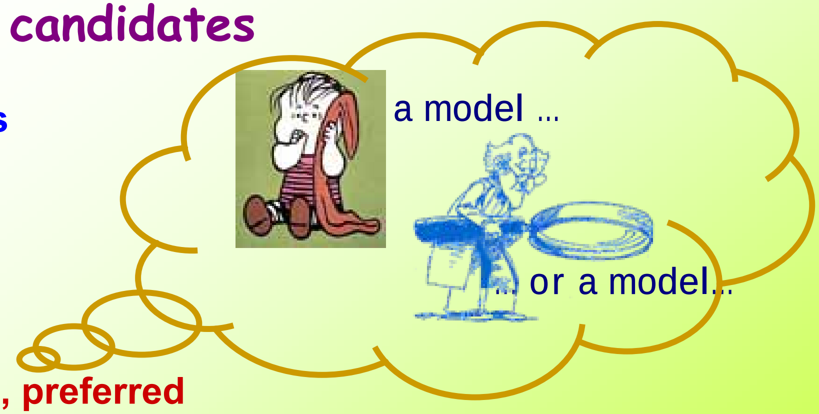
- Presence of modulation for 11 annual cycles at ~8.2σ C.L. with the proper distinctive features of the signature; all the features satisfied by the data over 11 independent experiments of 1 year each one
- Absence of known sources of possible systematics and side processes able to quantitatively account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

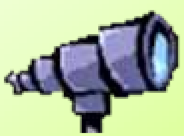
- **astrophysical models: ρ_{DM}, velocity distribution and its parameters**
- **nuclear and particle Physics models**
- **experimental parameters**



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

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

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

Neutralino as LSP in SUSY theories

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

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

Mirror Dark Matter

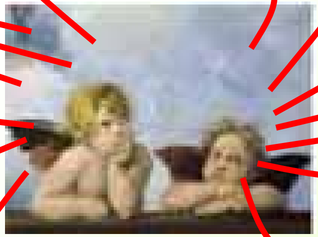
Light Dark Matter

Self interacting Dark Matter

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

Sterile neutrino

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



Elementary Black holes such as the Daemons

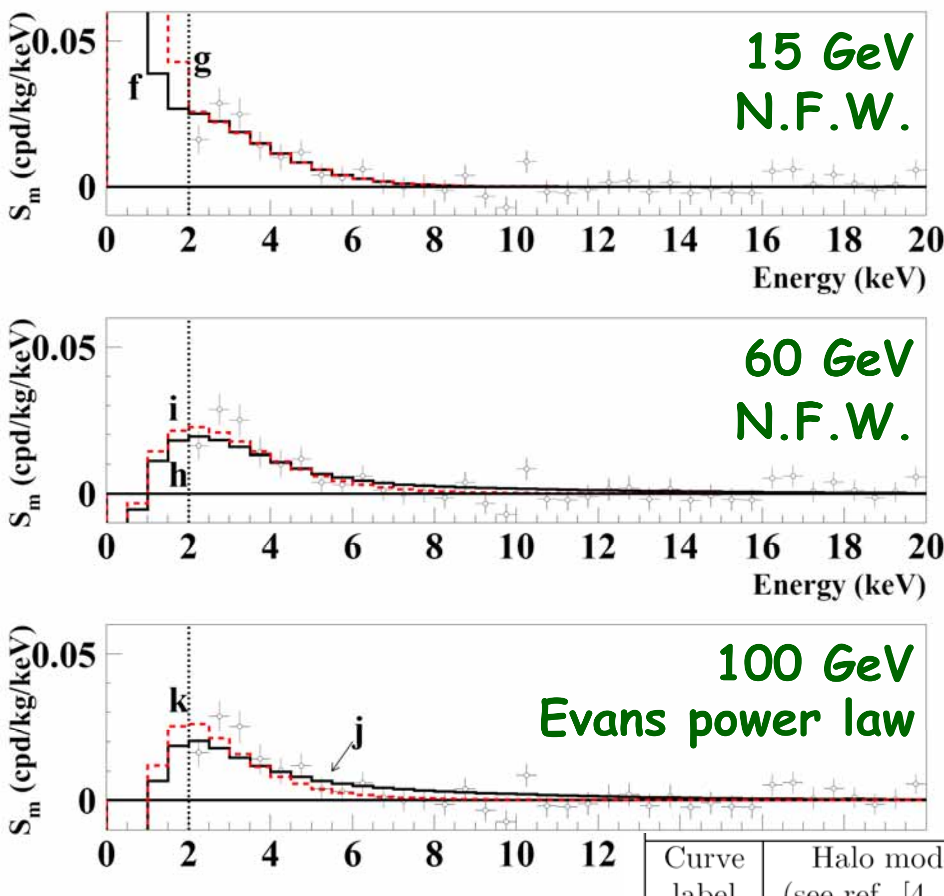
Kaluza Klein particles

... and more

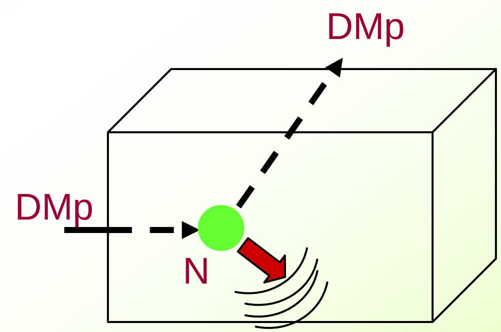
Possible model dependent positive hints from indirect searches not in conflict with DAMA results
(but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.)

Available results from direct searches using different target materials and approaches do not give any robust conflict

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

$$\theta = 2.435$$

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

where we are ...

- DAMA/LIBRA over 4 annual cycles (0.53 ton×yr) confirms the results of DAMA/NaI (0.29 ton×yr)
- The cumulative confidence level for the model independent evidence for presence of DM particle in the galactic halo is 8.2 σ (total exposure 0.82 ton × yr)

- **First upgrading of the experimental set-up in Sept. 2008**

Phase 1

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

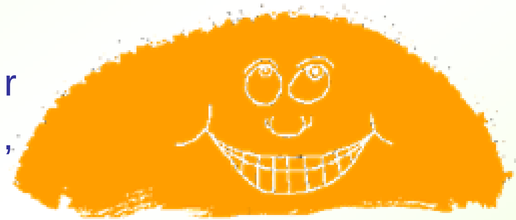
Phase 2

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

… since Oct. 2008 again in data taking

… and where we are going

- Continuing the data taking
- Update corollary analyses in some of the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc.. Consider further ones also on the basis of literature



- ***Next upgrading***: replacement of all the PMTs with higher Q.E. ones.
- Production of new high Q.E. PMTs in progress
- Goal: lowering the energy thresholds of the detectors

- Analyses/data taking to investigate also other rare processes in progress/foreseen

- Long term data taking to improve the investigation, to disentangle at least some of the many possibilities, to investigate other features of DM particle component(s) and second order effects, (& results on other processes with higher sensitivity), etc..

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

to deep investigate Dark Matter phenomenology at galactic scale

work is human only if it remains intelligent and free (Pope Paul VI , Populorum Progressio)