Signals from the Universe: the DAMA/LIBRA results

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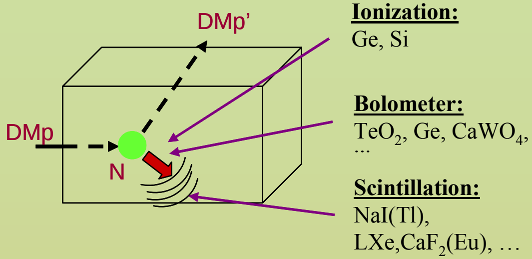
Direct, Indirect and Collider Signals of Dark Matter
KITP, Santa Barbara – December 2009

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



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

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

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

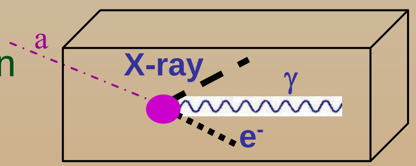
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

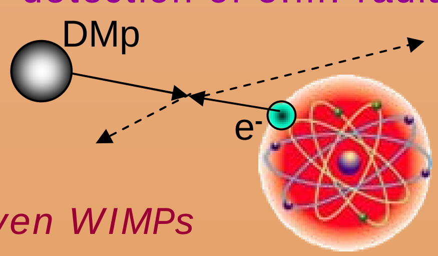
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

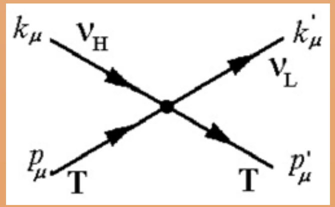
  → detection of e.m. radiation



… even WIMPs

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

  → detection of electron/nucleus recoil energy



e.g. sterile ν

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

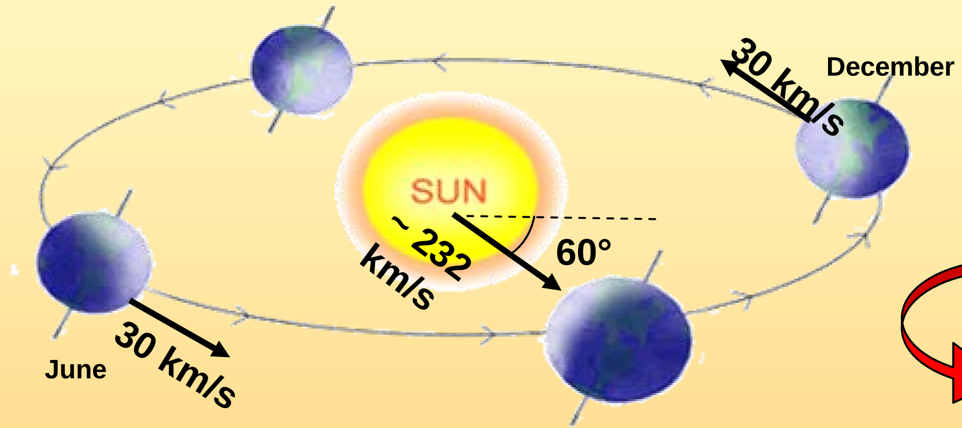
… also other ideas …

- **… and more**

The 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 = 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 the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

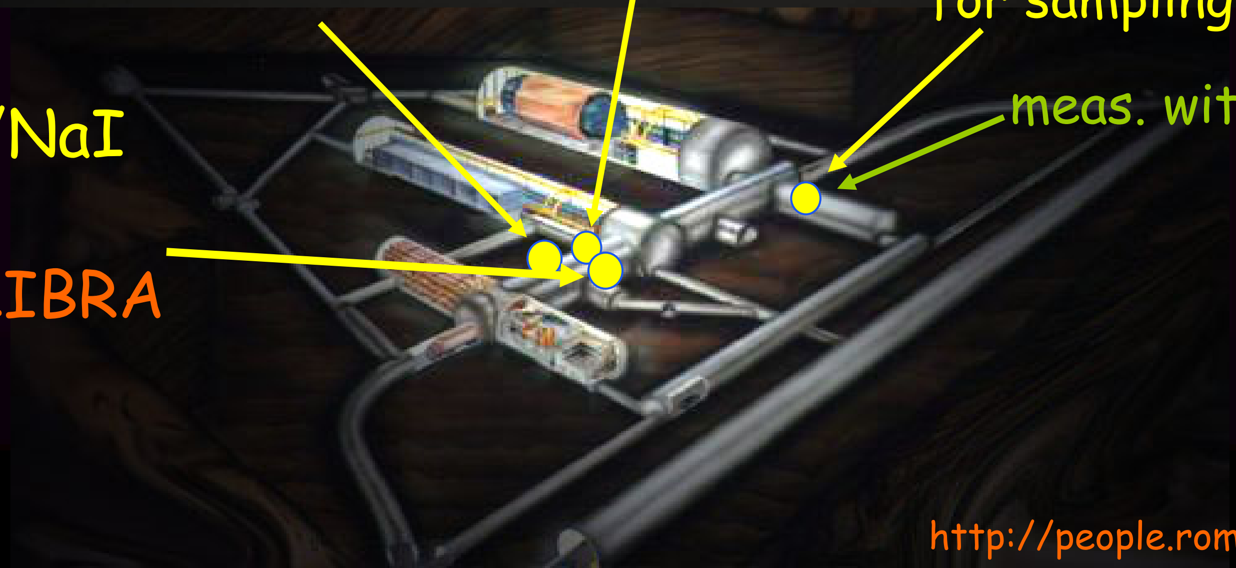
1) **Modulated rate according cosine**
2) **In a definite low energy range**
3) **With a proper period (1 year)**
4) **With proper phase (about 2 June)**
5) **For single hit events in a multi-detector set-up**
6) **With modulation amplitude in the region of maximal sensitivity must be <7% for usually 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

Roma2,Roma1,LNGS,IHEP/Beijing

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

DAMA: an observatory for rare processes @LNGS



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

DAMA/LXe: results on rare processes

NIMA482(2002)728

Dark Matter Investigation

- Limits on recoils investigating the DMp-^{129}Xe elastic scattering by means of PSD — PLB436(1998)379
- Limits on DMp-^{129}Xe inelastic scattering — PLB387(1996)222, NJP2(2000)15.1
- Neutron calibration — PLB436(1998)379, EPJdirectC11(2001)1
- ^{129}Xe *vs* ^{136}Xe by using PSD → SD *vs* SI signals to increase the sensitivity on the SD component — foreseen/in progress

Other rare processes:

- Electron decay into invisible channels — Astrop.P.5(1996)217
- Nuclear level excitation of ^{129}Xe during CNC processes — PLB465(1999)315
- N, NN decay into invisible channels in ^{129}Xe — PLB493(2000)12
- Electron decay: $e^- \rightarrow \nu_e \gamma$ — PRD61(2000)117301
- 2β decay in ^{136}Xe — Xenon01
- 2β decay in ^{134}Xe — PLB527(2002)182
- Improved results on 2β in ^{134}Xe, ^{136}Xe — PLB546(2002)23
- CNC decay ^{136}Xe → ^{136}Cs — Beyond the Desert (2003) 365
- N, NN, NNN decay into invisible channels in ^{136}Xe — EPJA27 s01 (2006) 35

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

- Particle Dark Matter search with CaF_2(Eu)

NPB563(1999)97,
Astrop.Phys.7(1997)73

- 2β decay in ^{136}Ce and in ^{142}Ce — Il Nuov.Cim.A110(1997)189
- 2EC2ν ^{40}Ca decay — Astrop. Phys. 7(1997)73
- 2β decay in ^{46}Ca and in ^{40}Ca — NPB563(1999)97
- $2\beta^+$ decay in ^{106}Cd — Astrop.Phys.10(1999)115
- 2β and β decay in ^{48}Ca — NPA705(2002)29
- 2EC2ν in ^{136}Ce, in ^{138}Ce and α decay in ^{142}Ce — NIMA498(2003)352
- $2\beta^+0\nu$, EC$\beta^+0\nu$ decay in ^{130}Ba — NIMA525(2004)535
- Cluster decay in $LaCl_3$(Ce) — NIMA555(2005)270
- CNC decay ^{139}La → ^{139}Ce — UJP51(2006)1037
- α decay of natural Eu — NPA789(2007)15
- β decay of ^{113}Cd — PRC76(2007)064603
- $\beta\beta$ decay of ^{64}Zn — PLB658(2008)193
- $\beta\beta$ decay of ^{108}Cd and ^{114}Cd — EPJA36(2008)167
- $2\varepsilon0\nu$ in ^{136}Ce; 2β in ^{136}Ce, ^{138}Ce — NPA824(2009)101
- 2β in ^{64}Zn, ^{70}Zn, ^{180}W, ^{186}W — NPA826(2009)256

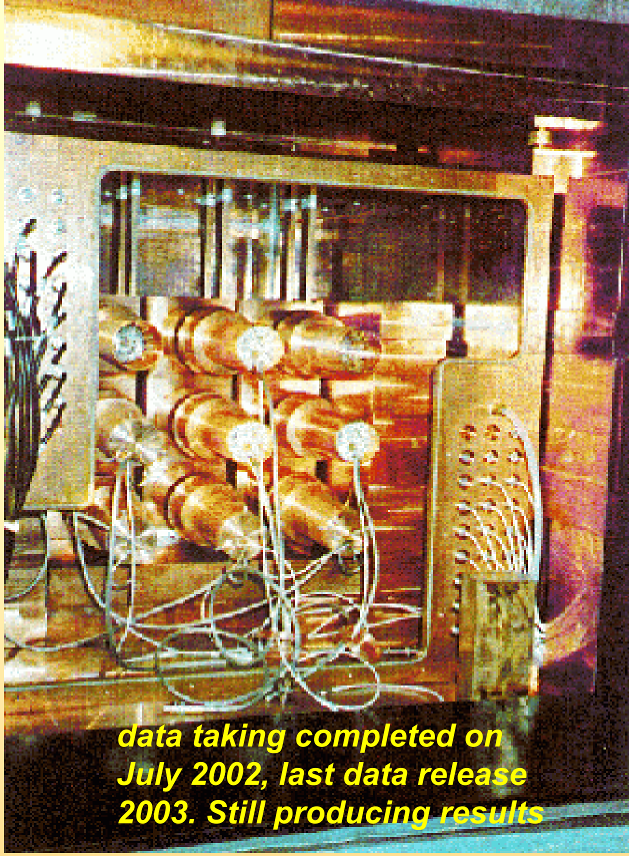
DAMA/Ge & LNGS Ge facility

- RDs on highly radiopure NaI(Tl) set-up;
- several RDs on low background PMTs;
- qualification of many materials
- measurements with a $Li_6Eu(BO_3)_3$ crystal (NIMA572(2007)734)
- measurements with ^{100}Mo sample investigating $\beta\beta$ decay in the 4π low-bckg HP Ge facility of LNGS (NPAE(2008)473)
- search for ^{7}Li solar axions (NPA806(2008)388)

+Many other meas. already scheduled for near future

DAMA/NaI : ≈100 kg NaI(Tl)

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



Results on rare processes:

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

Results on DM particles:

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

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

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

total exposure (7 annual cycles) 0.29 ton 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

filling the inner Cu box with further shield

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

- *Radiopurity,performances, procedures, etc.:* NIMA592(2008)297
- *Results on DM particles: Annual Modulation Signature:* EPJC56(2008)333
- *Results on rare processes: Possible processes violating the Pauli exclusion principle in Na and I:* EPJC62(2009)327

closing the Cu box housing the detectors

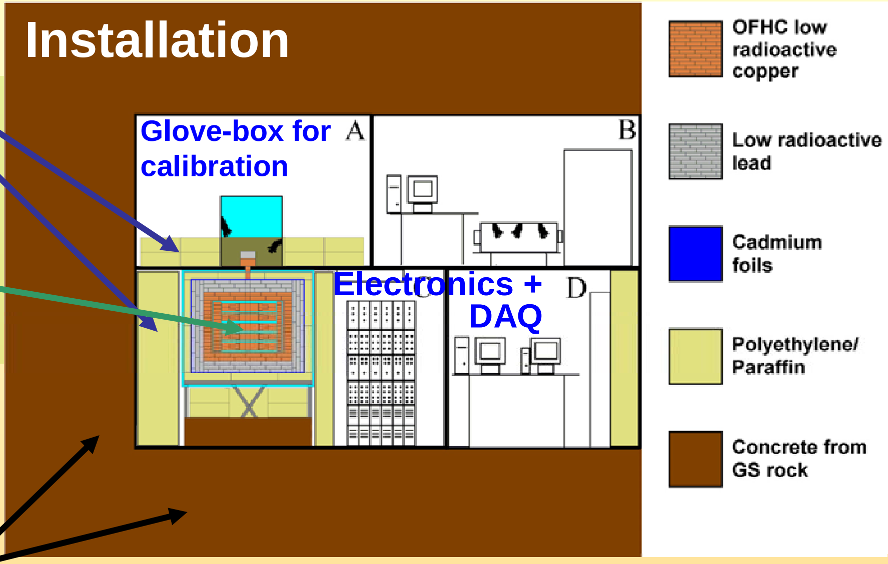
view at end of detectors' installation in the Cu box

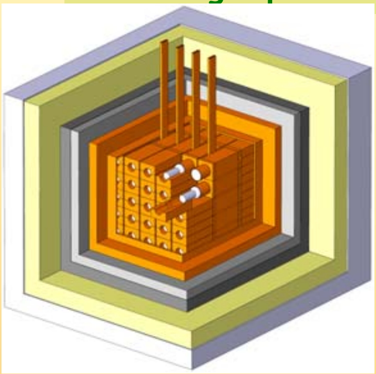
The DAMA/LIBRA set-up

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

Polyethylene/ paraffin

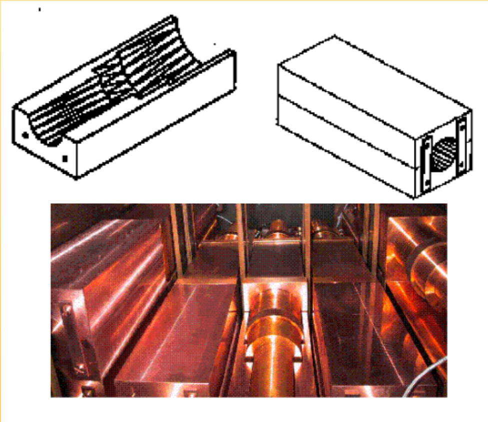
- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold



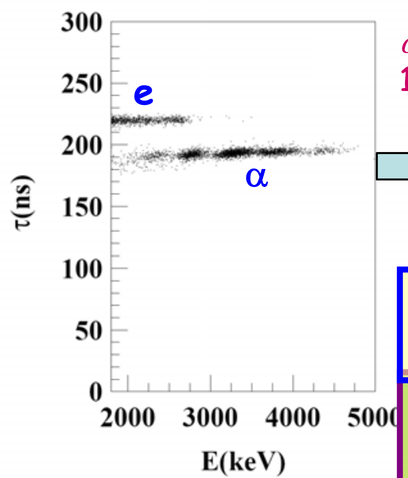


~ 1m concrete from GS rock

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waweform Analyzer *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

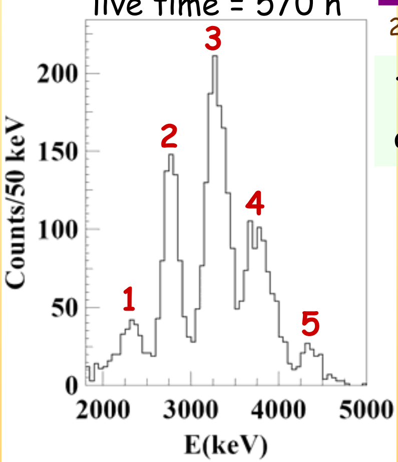
The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/day

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

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

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

live time = 570 h

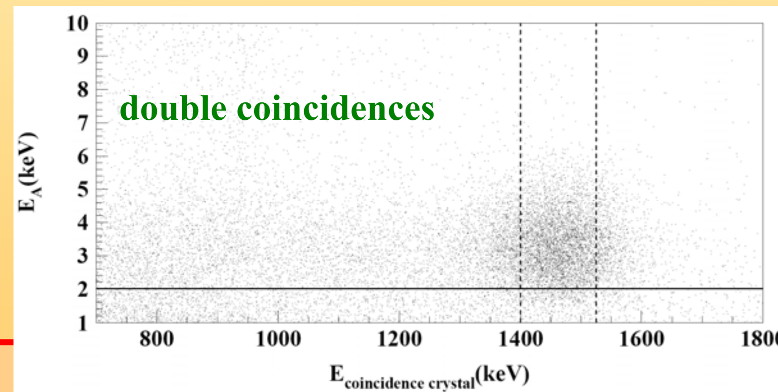


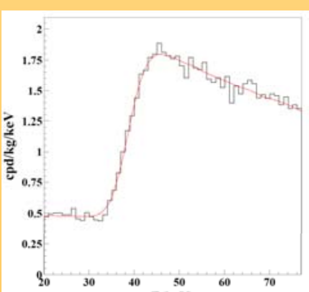
^{238}U chain splitted into 5 subchains: ^{238}U $\rightarrow$ ^{234}U $\rightarrow$ ^{230}Th $\rightarrow$ ^{226}Ra $\rightarrow$ ^{210}Pb $\rightarrow$ ^{206}Pb

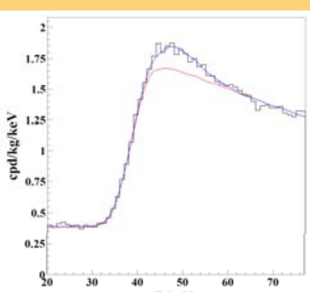
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U
and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{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

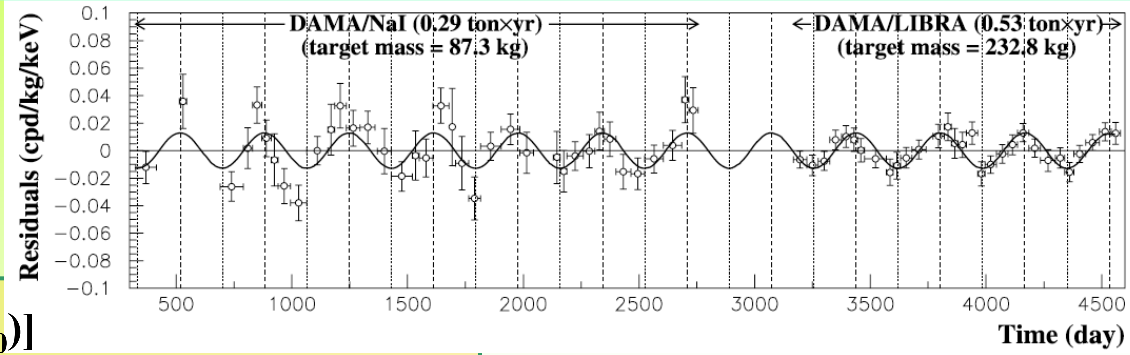
... more on NIMA592(2008)297

Model-independent annual modulation result

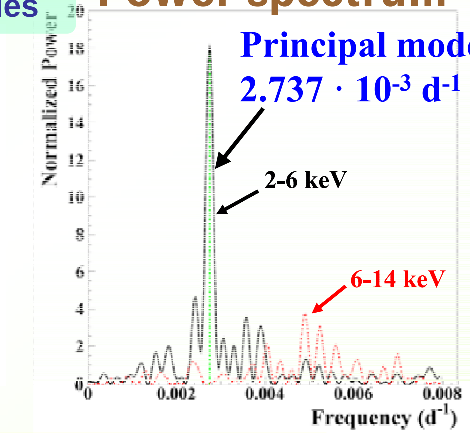
EPJC 56(2008)333

DAMA/NaI (7 years) + DAMA/LIBRA (4 years). Total exposure: 0.82 ton×yr

Experimental single-hit residuals rate vs time and energy in 2-6 keV over 11 annual cycles



Power spectrum



$A\cos[\omega(t-t_0)]$

continuous lines: t_0 = 152.5 d, T = 1.00 y

A=(0.0129±0.0016) cpd/kg/keV

χ^2/dof = 54.3/66 8.2σ C.L.

Absence of modulation? No

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

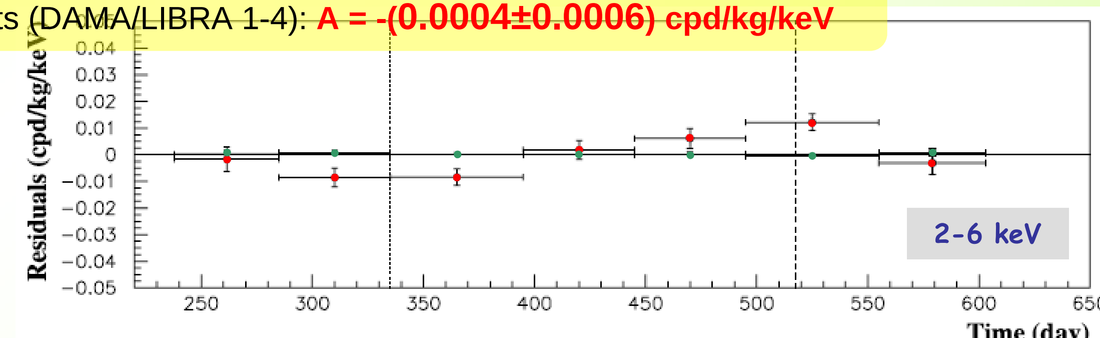
from the fit with all the parameters free:

A = (0.0131 ± 0.0016) cpd/kg/keV

t_0 = (144 ±8) d

T = (0.998±0.003) y

No modulation in the experimental residual rate of the multiple hit events (DAMA/LIBRA 1-4): **A = -(0.0004±0.0006) cpd/kg/keV**



Multiple hits events = Dark Matter particle "switched off"

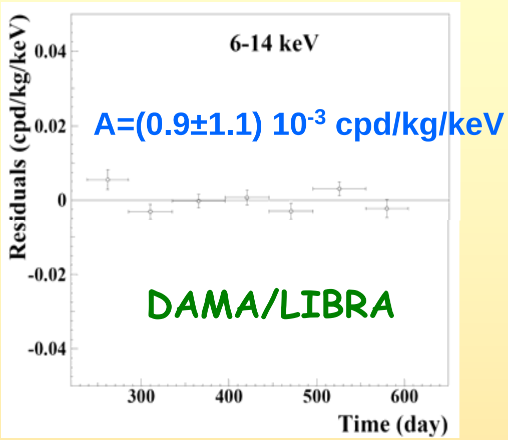
No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature have been found or suggested by any other over more than a decade

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

The data favor the presence of a modulated behavior with proper features for DM particles in the galactic halo at 8.2σ C.L.

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

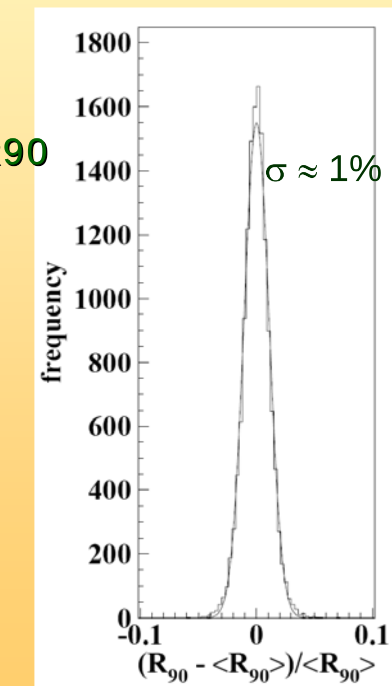
In the same energy region where the effect is observed: no modulation of the multiple-hits events

- **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:

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)

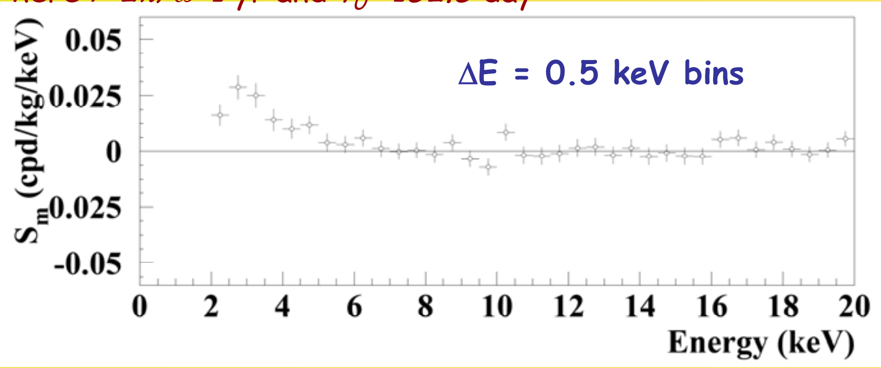
Model-independent annual modulation result

EPJC 56(2008)333

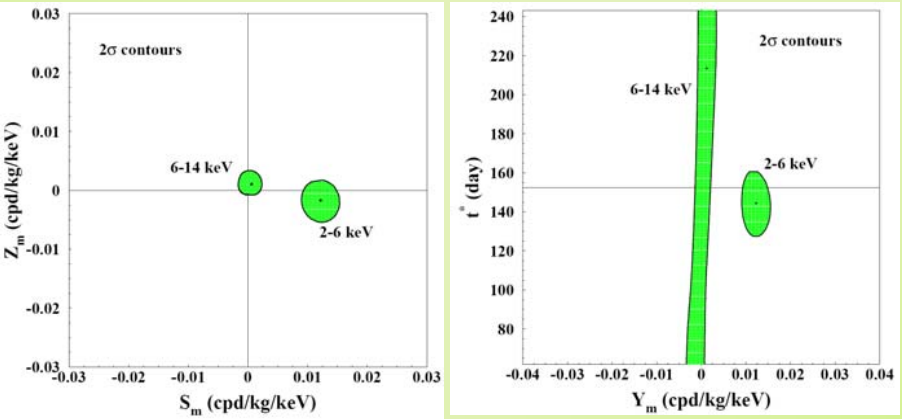
DAMA/NaI (7 years) + DAMA/LIBRA (4 years). Total exposure: 0.82 ton×yr
(the **largest** exposure ever collected in this field)

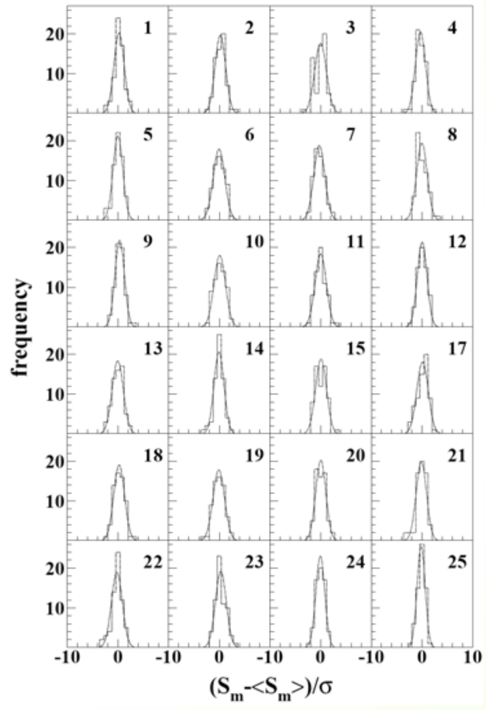
$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$

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



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





Phase from the best fit: t*=(144.0±7.5) day
(expected ≈152.5 day, slight differences from Jun 2 in case of contributions from non thermalized DM components, as e.g. the SagDEG stream)

- **Clear modulation in the (2-6) keV energy interval**
- **S_m values compatible with zero just above (χ^2/dof = 24.4/28 in (6–20) keV)**
- **No modulation above 6 keV**
- **No modulation in the multiple-hit events**
- **No modulation in the whole spectrum at higher energy**
- **S_m statistically well distributed in all the detectors and annual cycles**
- **Annual modulation is present in the outer and in the inner detectors**

From the analysis of the S_m distributions in all the detectors and in all the annual cycles, an upper limit of possible systematic effects can be derived as: ≤ 4.7% or ≤ 0.7% (if quadratically or linearly combined, respectively) of the DAMA/LIBRA modulation amplitude

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

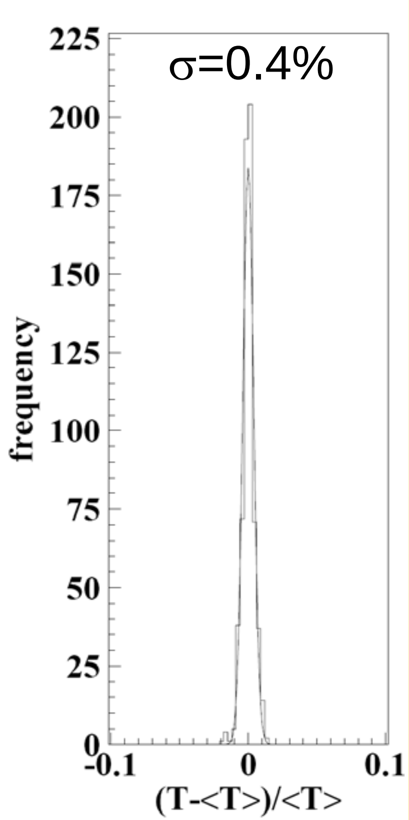
All the measured amplitudes well compatible with zero

+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)

Temperature

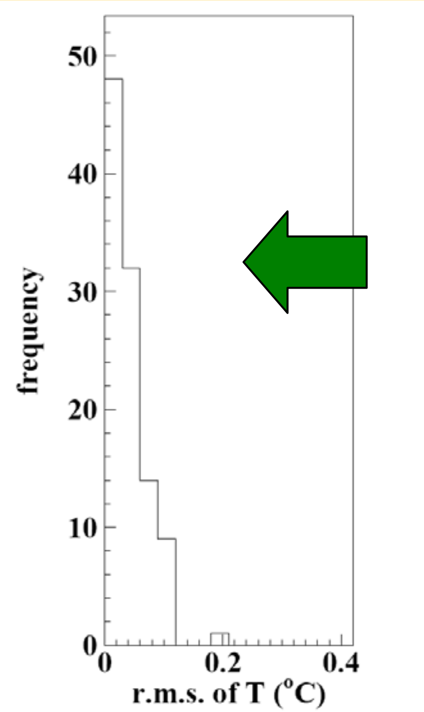
- **Detectors in Cu housings directly in contact with multi-ton shield $\rightarrow$huge heat capacity ($\approx 10^6$ cal/^{0}C)**
- **Experimental installation continuosly air conditioned (2 independent systems for redundancy)**
- **Operating T of the detectors continuously controlled**



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

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 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} :

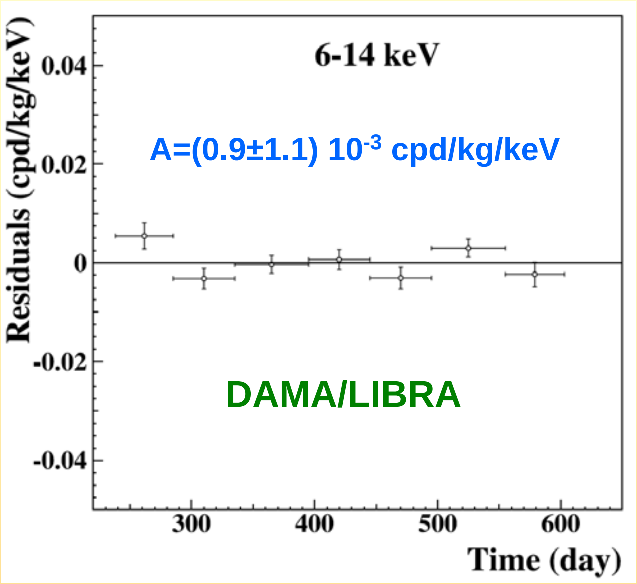
$<10^{-4}$ cpd/kg/keV (< 0.5% $S_m^{observed}$)

An effect from temperature can be excluded

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

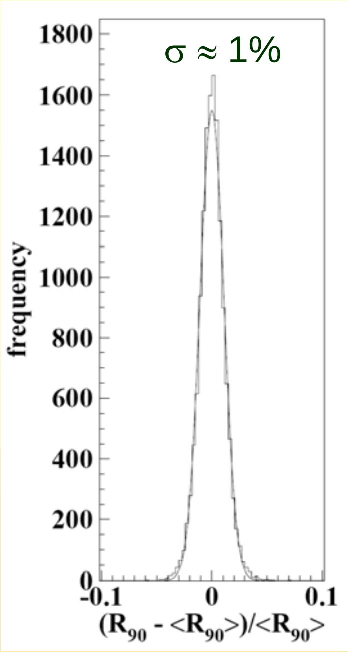
Summarizing on a hypothetical background modulation in DAMA/LIBRA 1-4

- **No Modulation above 6 keV**

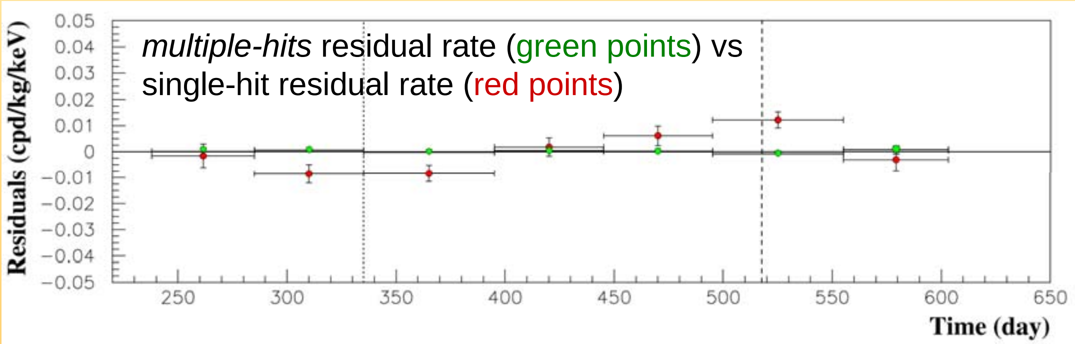


- **No modulation in the whole energy spectrum**

+ 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



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



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

Nevertheless, additional investigations performed ...

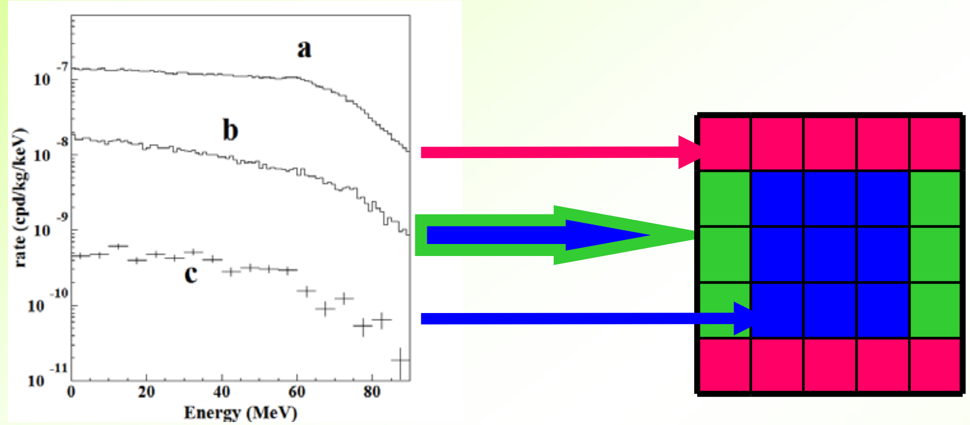
Three examples for specific cases in the following:

1. **The muon case**
2. **The ^{40}K case**
3. **The neutron case**

The μ case

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

events where just one detector fires



Case of fast neutrons produced by μ

Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±2% modulated)
Measured neutron Yield @ LNGS: $Y = 1 \div 7 \; 10^{-4}$ n/μ/(g/cm²)
R_n = (fast n by μ)/(time unit) = $\Phi_\mu \, Y \, M_{eff}$

Annual modulation amplitude at low energy due to μ modulation:

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

(g = geometrical factor; ε = detection effic. by elastic scattering
$f_{\Delta E}$ = energy window (E>2keV) effic.; f_{single} = single hit effic.)

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

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

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} + different phase, etc.

Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:
- only events at low energy,
- only *single-hit* events,
- no sizeable effect in the *multiple-hit* counting rate?

?

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

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

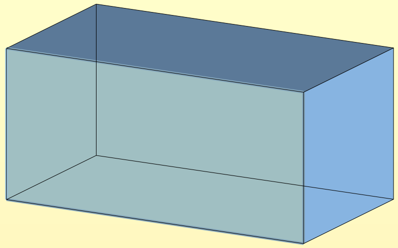
The muon flux at LNGS (≈ 20 μ m^{-2} d^{-1}) is yearly modulated (±2%) with phase roughly around middle of July and largely variable from year to year. Last meas. by LVD: 1.5% modulation and phase=July 5th ± 15 d.

→ DAMA/NaI + DAMA/LIBRA
measured a stable phase: May, 25th ± 7.5 days

NO

This phase is 6.9 σ far from July 15th and is 5.5 σ far from July 5th

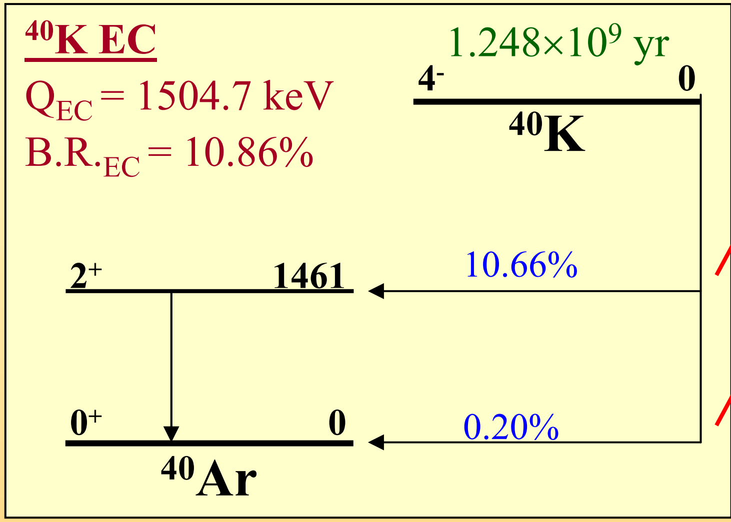
residual ^{nat}K



^{40}K: $\delta = 0.0117\ \%$

$T_{1/2} = 1.248 \times 10^9$ yr (EC = 10.86 %; $\beta^- = 89.14$ %)

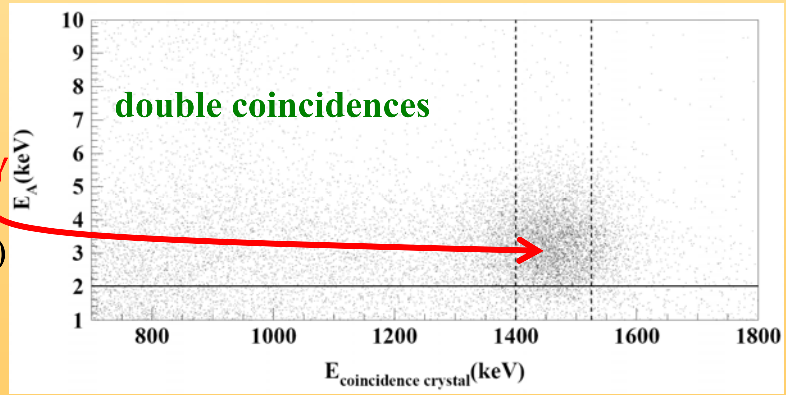
$$\Rightarrow \ 1\text{ppb}\ ^{nat}\text{K}: \quad a(^{40}\text{K}) = \frac{1000 \cdot 10^{-9} \cdot N_A}{39.1}\,\delta\,\frac{\ln 2}{T_{1/2}} = 31.7\ \mu\text{Bq/kg}$$



L1461: $EC_K = 76.3\%$; $EC_L = 20.9\%$; $EC_{M+} = 2.74\%$

L0: $EC_K = 87.9\%$; $EC_L = 8.6\%$; $EC_{M+} = 1.26\%$

The 1461 keV γ can escape from one detector (*A*) and hit another one causing a double coincidence. X-rays/Auger electrons give rise in *A* to a 3.2 keV peak

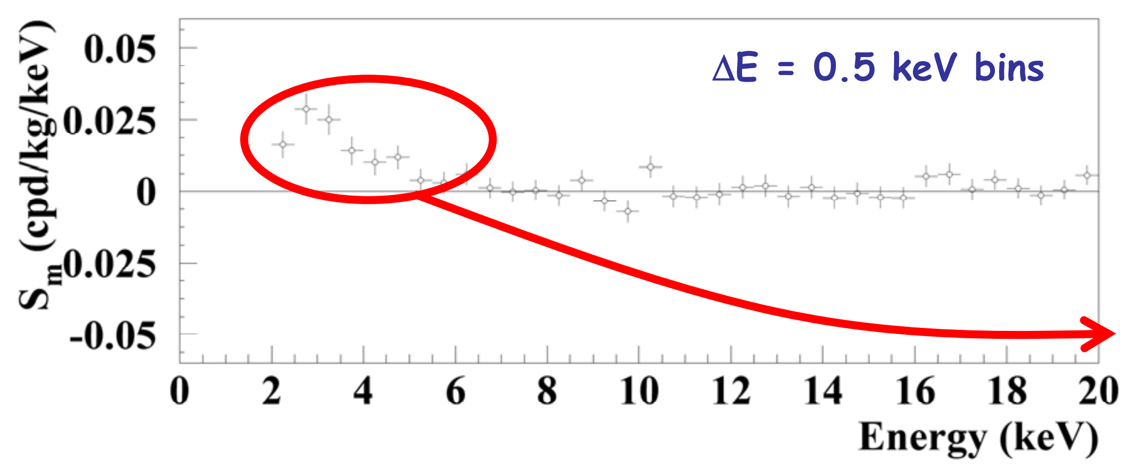


The probability for ^{40}K EC from shell K to the 1461 keV level of ^{40}Ar is: **$P_{40K\ EK \rightarrow 1461} = 10.66\% \times 76.3\% = 8.1\%$** in such a case a **1461 keV γ** is emitted together with the **3.2 keV X-rays/Auger electrons** from shell K of ^{40}Ar (this last is contained in the detector with efficiency ~ 1)

The 3.2 keV peak offers also the proof of the physical threshold of the detectors and an intrinsic calibration for each one in the lowest energy region

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

No role can be played by ^{40}K in the experimental S_m - 1



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

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

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

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

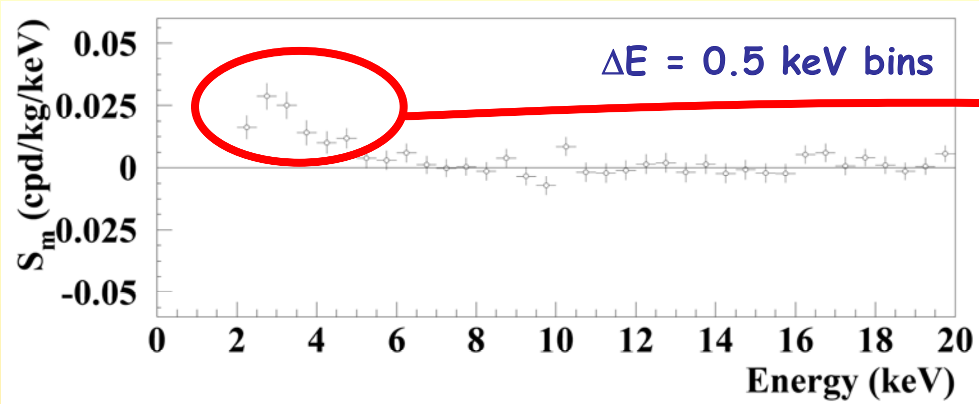
arXiv:0912.0660

1. Although the peak at 3 keV in the cumulative energy spectrum can be partially ascribed to ^{40}K decay, there is not evidence for any 3 keV peak in the S_m distribution (see above). At the present level of sensitivity the S_m behaviour is compatible within the uncertainties both with a monotonic behaviour and with a "kind" of structure, as expected for many Dark Matter candidates and also for WIMPs scenarios.
2. ^{40}K decay cannot give any modulation at all, as well known, unless evoking new exotic physics (see later)!?
3. No modulation has been observed in other energy regions where ^{40}K decay contributes.
4. No modulation has been observed in multiple-hit events (events where more than one detector fire) in the same energy region where DAMA observes modulation of the single-hit events (events where just one detector fires). In fact, ^{40}K can also give double events in two adjacent detectors and multi-site events due to Compton scatterings (thus, multiple-hit events) and these events are not modulated.
5. No modulation of the double coincidence events, 1461 keV-3 keV (see also later).
6. The annual modulation signal is present both in the outer and in the inner detectors.
7. The annual modulation signal is equally distributed over all the detectors.
8. Stability of efficiency (see e.g. EPJC56(2008)333).

(no dependence on the veto capability, that is different – by geometrical reasons – among the detectors)

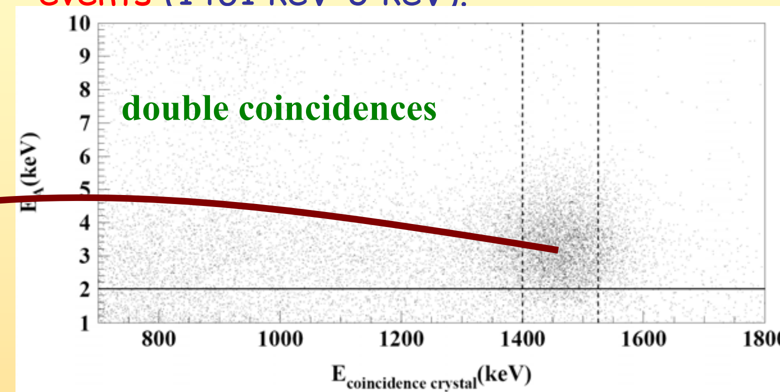
No role can be played by ^{40}K in the experimental S_m - 2

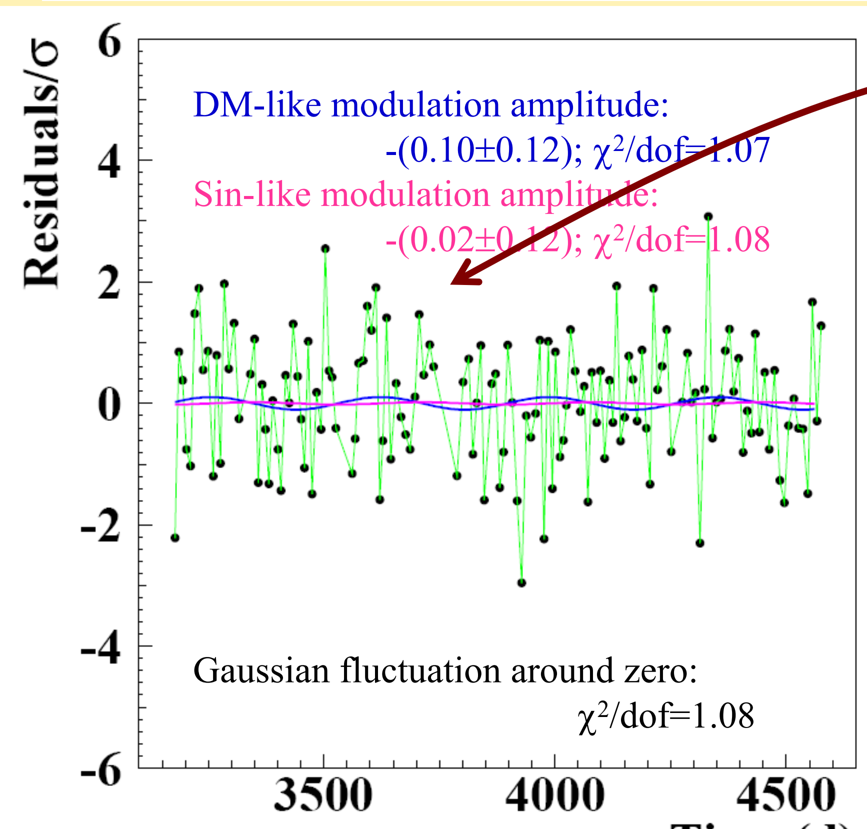
arXiv:0912.0660

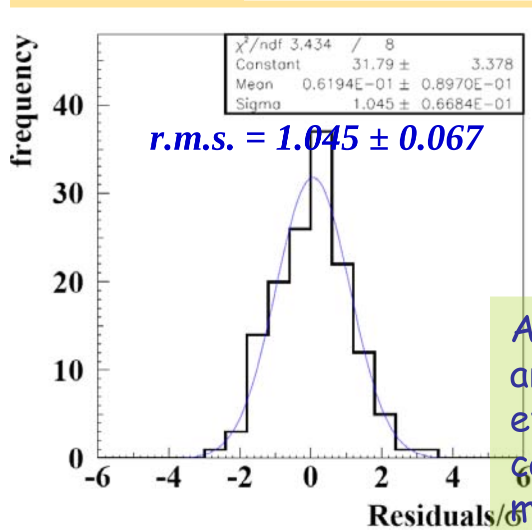


The experimental S_m cannot be due to ^{40}K for many reasons.

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







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

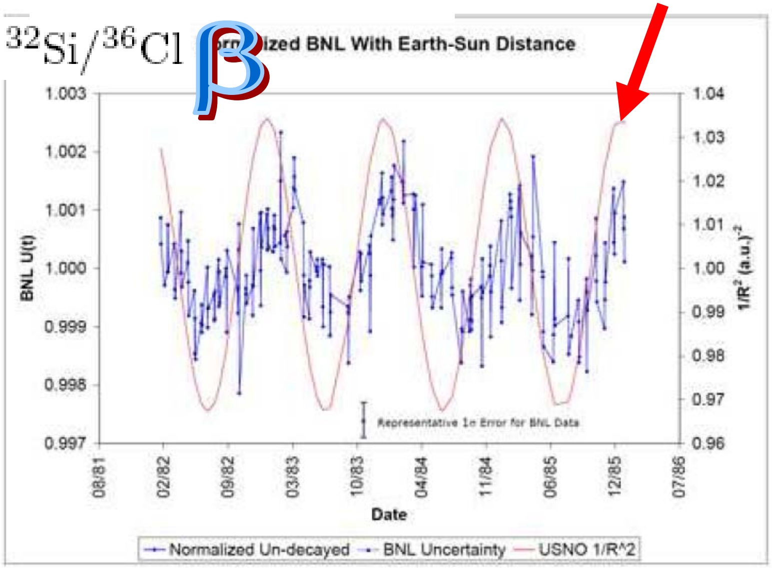
Any modulation contribution around 3 keV in the single-hit events from the hypothetical cases of: i) ^{40}K "exotic" modulated decay; ii) spill-out effects from double to single events and viceversa, are ruled out at more than 10 σ

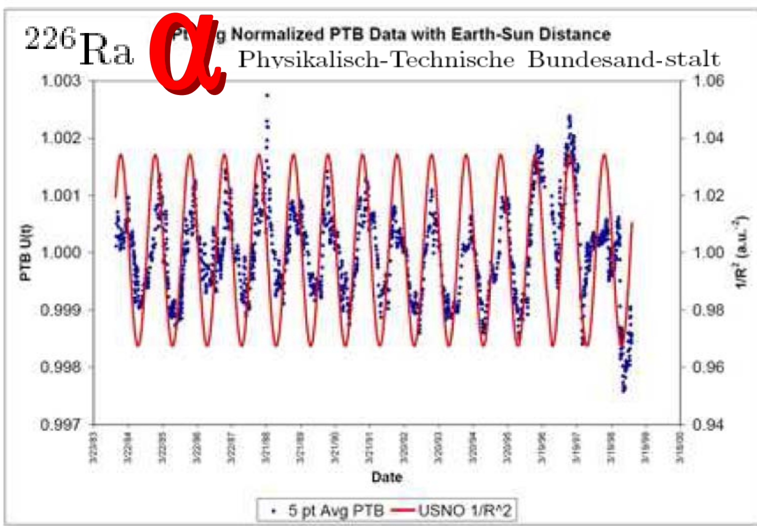
DAMA/LIBRA 0.53 ton×yr

Correlations Between Nuclear Decay Rates and Earth-Sun Distance?

arXiv:0808.3283v1

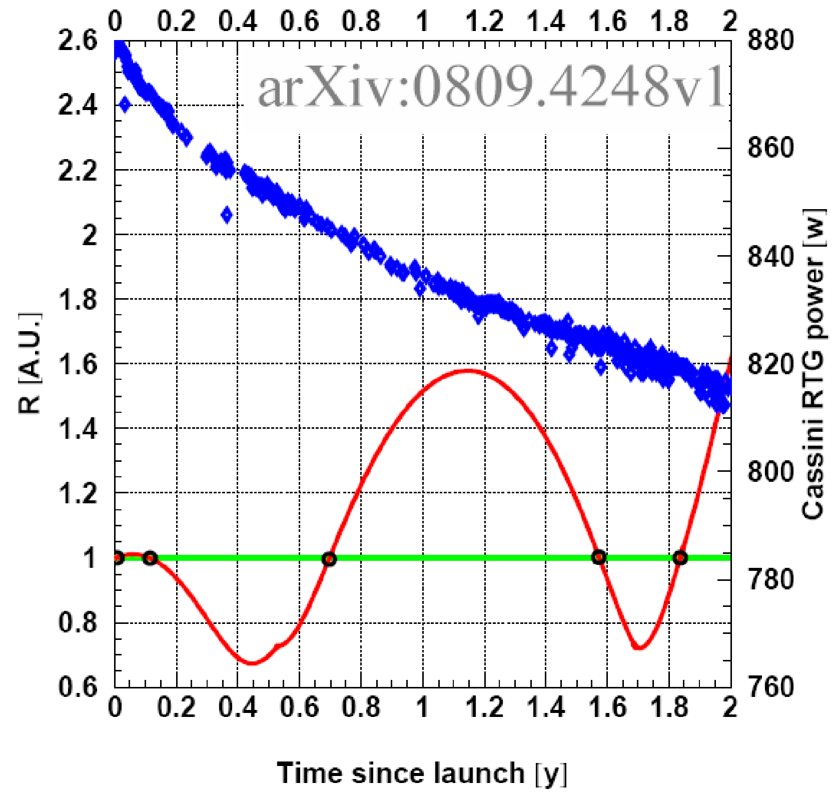
REMARK. Phase: 3 jan (perihelion) ≠ 2 jun (Dark Matter)





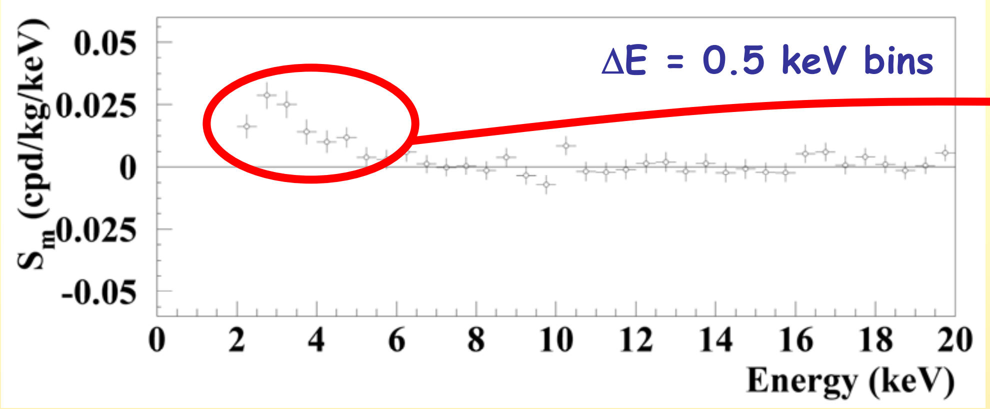
Attributed to effect of vacuum expectations of dilatonic field in proximity of the Sun on the electromagnetic fine structure constant α_{EM}

Cassini spacecraft had explored in a much wide range: 0.7 – 1.6 A.U. three Radioisotope Thermoelectric Generators RTGs, each of which is a very large (7.7Kg, 130KCu) ^{238}Pu radioactive source (α 87.7y half life)



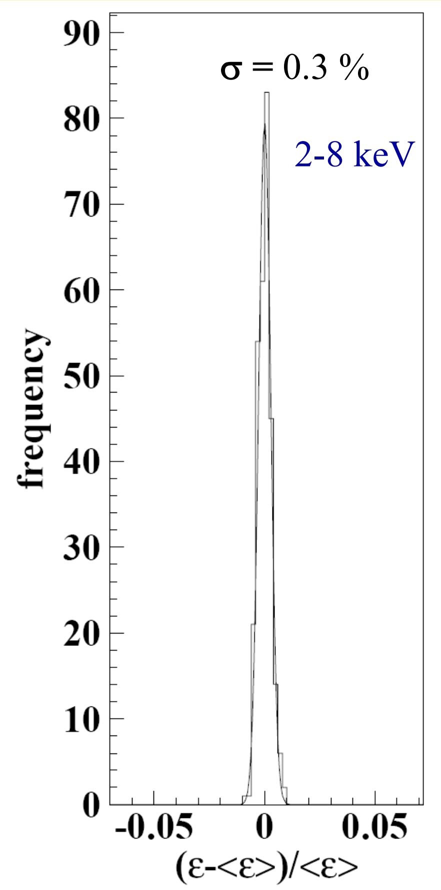
The analysis (arXiv:0809.4249) rules out the hypothesis that nuclear decay rate are correlated with the distance of the source from the Sun to a level 350× smaller than the effect reported by 0808.3283

No role can be played by ^{40}K in the experimental S_m - 3



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

8. Stability of efficiency.



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)

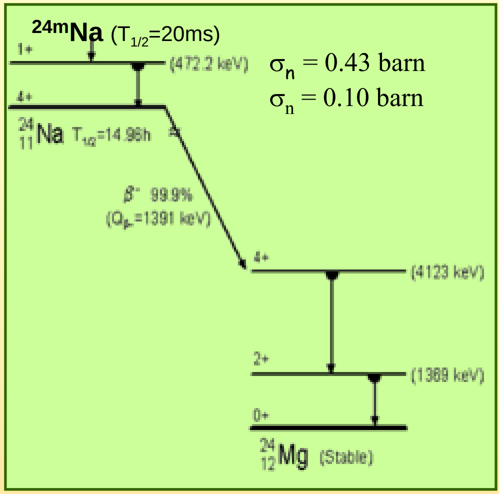
Amplitudes well compatible with zero
+ cannot mimic the signature

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

NO

- Thermal neutrons flux measured at LNGS :

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



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

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

- Two consistent upper limits on thermal neutron flux have been obtained with DAMA/NaI considering the same capture reactions and using different approaches.

Evaluation of the expected effect:

- Capture rate = $\Phi_n \, \sigma_n \, N_T$ < 0.022 captures/day/kg

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

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

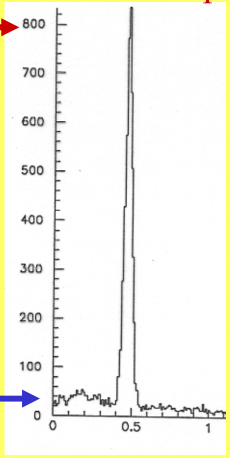
Already excluded also by R_{90} analysis

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: ⇒ $S_m^{(fast\ n)} < 10^{-4}$ cpd/kg/keV (< 0.5% $S_m^{observed}$)

- **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/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

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.	**$<2.5\times10^{-6}$ 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**

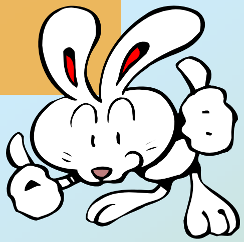
+ even if larger they cannot satisfy all the requirements of annual modulation signature

→ **Thus, they can not mimic the observed annual modulation effect**

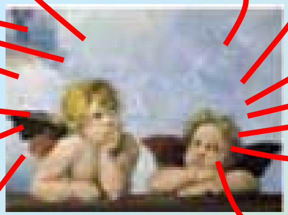
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

- Presence of modulation for 11 annual cycles at ~8.2σ C.L. with the proper distinctive features of the DM 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 modulation amplitude and to satisfy contemporaneously all the peculiarities of the signature

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



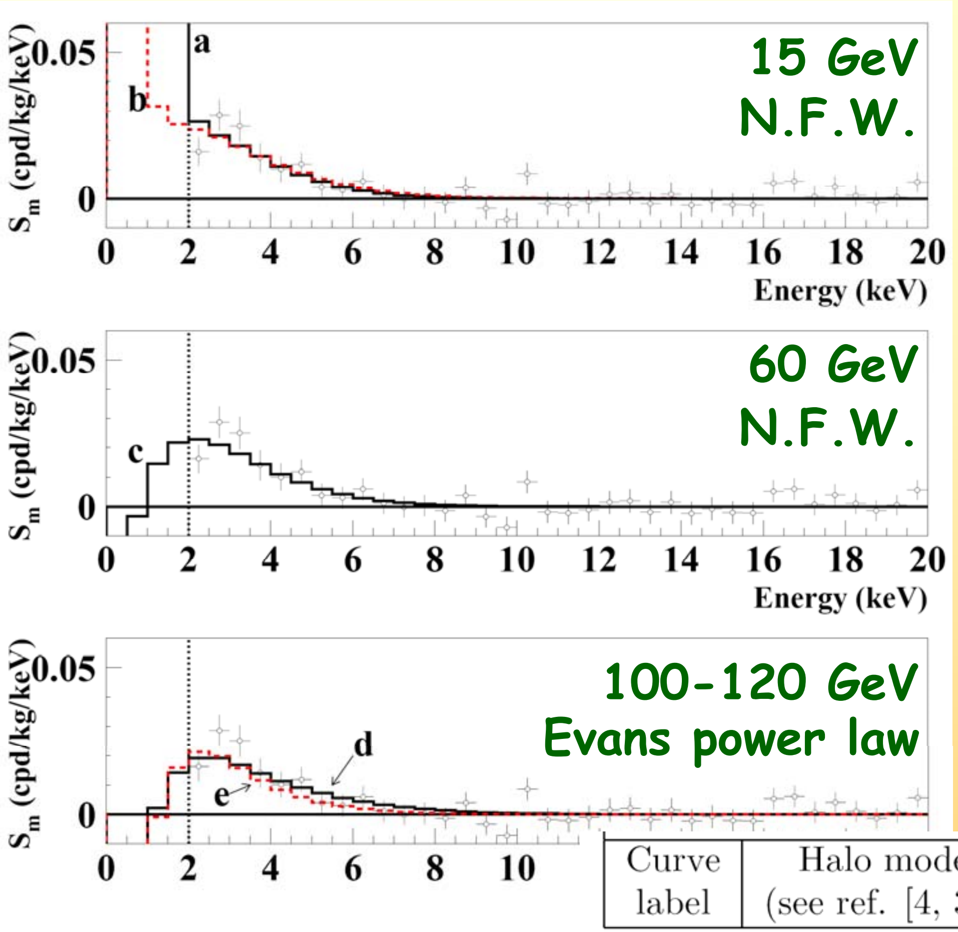
- Neutralino as LSP in SUSY theories
- Various kinds of WIMP candidates with several different kind of interactions Pure SI, pure SD, mixed + Migdal effect +channeling,... (from low to high mass)
- a heavy ν of the 4-th family
- Pseudoscalar, scalar or mixed light bosons with axion-like interactions
- 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



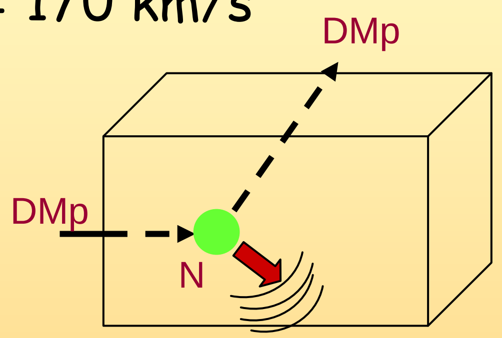
Possible model dependent positive hints from indirect searches not in conflict with DAMA results
(but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.)

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])
considering elastic scattering on nuclei
SI dominant coupling
v_0 = 170 km/s



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

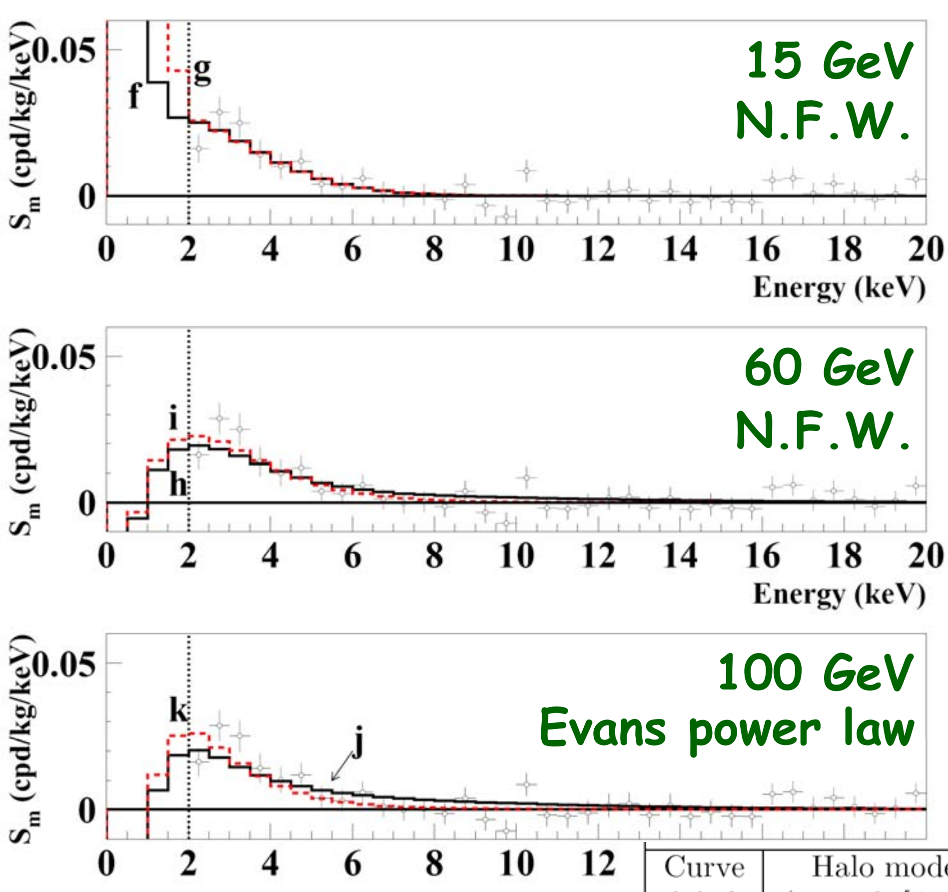
…scaling from NaI

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

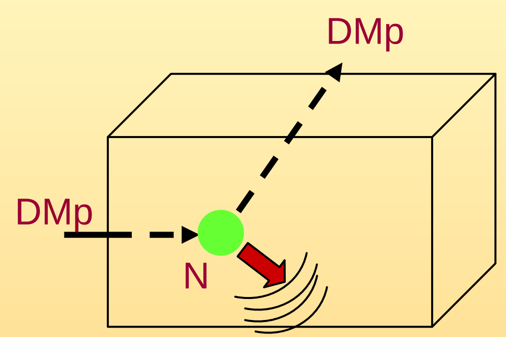
Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)
a	A5 (NFW)	0.2	A	15 GeV	3.1×10^{-4}
b	A5 (NFW)	0.2	A	15 GeV	1.3×10^{-5}
c	A5 (NFW)	0.2	B	60 GeV	5.5×10^{-6}
d	B3 (Evans power law)	0.17	B	100 GeV	6.5×10^{-6}
e	B3 (Evans power law)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



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

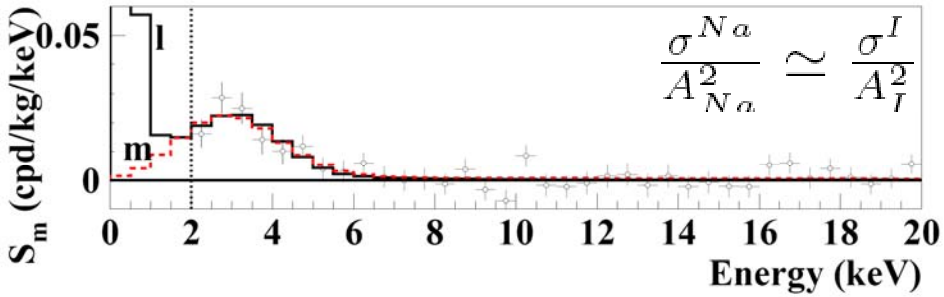
…scaling from NaI

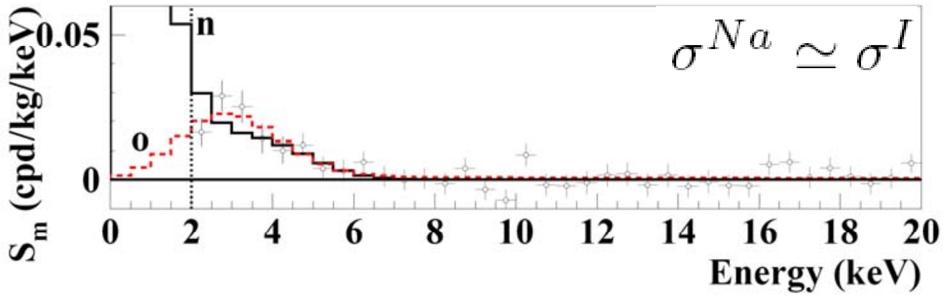
$\theta = 2.435$

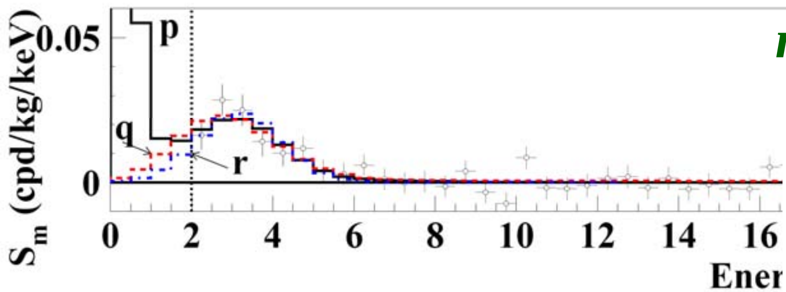
Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)	$\xi\sigma_{SD}$ (pb)
f	A5 (NFW)	0.2	A	15 GeV	10^{-7}	2.6
g	A5 (NFW)	0.2	A	15 GeV	1.4×10^{-4}	1.4
h	A5 (NFW)	0.2	B	60 GeV	10^{-7}	1.4
i	A5 (NFW)	0.2	B	60 GeV	8.7×10^{-6}	8.7×10^{-2}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

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

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



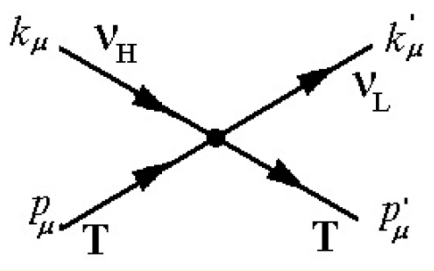




m_L=0

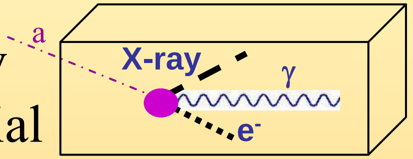
LDM candidate

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



Light bosonic candidate

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



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

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

Curve label	DM particle	Interaction	Set as in [4]	m_H	Δ	Cross section (pb)
l	LDM	coherent on nuclei	A	30 MeV	18 MeV	$\xi\sigma_m^{coh} = 1.8 \times 10^{-6}$
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}

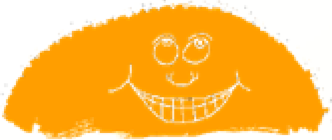
[4] RNC 26 (2003) 1; [34] PRD66 (2002) 043503

Where DAMA/LIBRA is ...

- **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)**

- DAMA/LIBRA in continuous data taking
- First upgrading of the experimental set-up in Sept. 2008
- Opening of the shield of DAMA/LIBRA set-up in HP N_2 atmosphere
- Replacement of some PMTs in HP N_2 atmosphere
- Dismounting of the Tektronix TDs and mounting of the new Acqiris TDs and of the new DAQ system with optical read-out
- ***Since Oct. 2008 again in data taking***

- Continuing the data taking
- Data of other 2 annual cycles at hand: one after the upgrading (increased mass, new TDs, new DAQ)
- Update corollary analyses in some possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..
- Analyses/data taking to investigate also other rare processes in progress/foreseen



... and where DAMA/LIBRA is going to

- Continuing the data taking
- Update corollary analyses in some of the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..
- *Next upgrading*: replacement of all the PMTs with higher Quantum Efficiency (Q.E.) PMTs.
  - New PMTs with higher Q.E.in production: 16 prototypes under tests

- **Goals:**
  - better separation under 2 keV in the rejection plane between noise and single-hit scintillation events
  - lowering the energy threshold (presently, at 2 keV)
  - improvement of the acceptance efficiency near energy threshold
  - increase the sensitivity in the *model independent* analysis (amplitude, phase, second order effects, …)
  - improvement of the sensitivity in the *model dependent* analyses, allowing to better disentangle several astrophysical, particle physics and nuclear physics scenarios

- 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), second order effects, etc..

to deep investigate Dark Matter phenomenology at galactic scale

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

Felix qui potuit rerum cognoscere causas *(Virgilio, Georgiche, II, 489)*