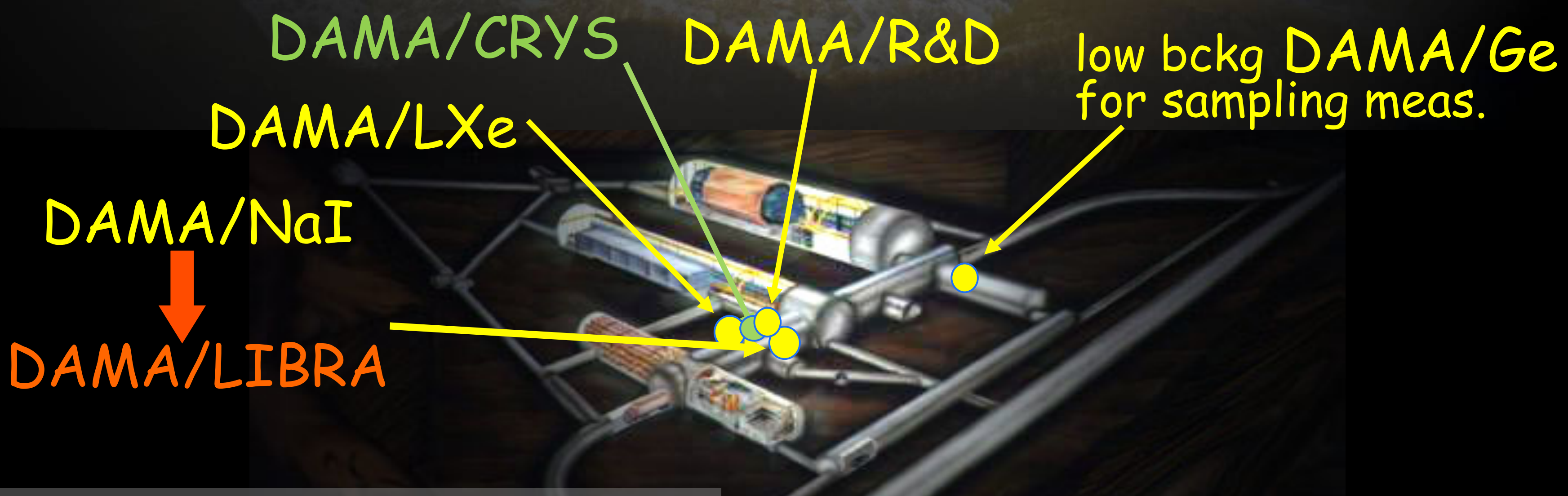
New results from DAMA/LIBRA

(Final model independent results of DAMA/LIBRA-phase1 and perspectives of phase2)

Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev and others
+ some studies on ββ decays(DST-MAE, inter-univ. agreem.): IIT Kharagpur/ Ropar, India

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



Frontier Objects in Astrophysics and Particle Physics, Vulcano, May 18 – 24, 2014

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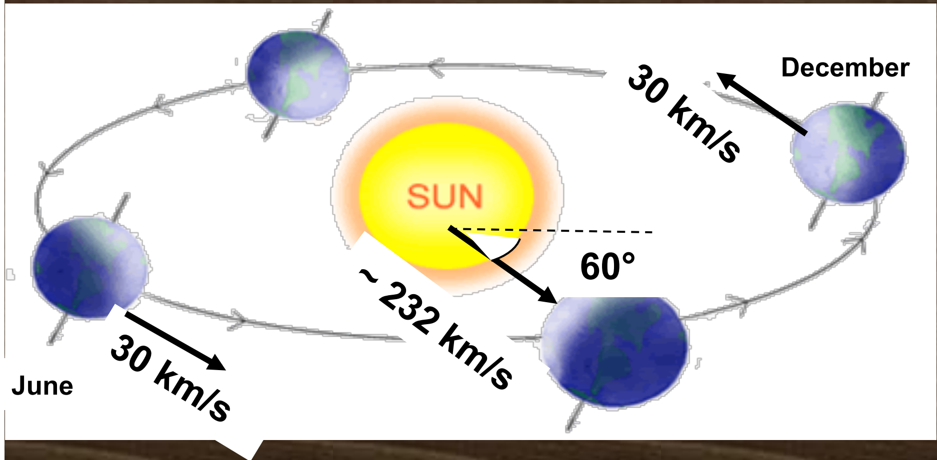
The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

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 can 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 revolution motion of the Earth around the Sun, which is moving in the Galaxy

Requirements of the annual modulation

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

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

The DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with seasons

- The investigated experimental observable in DAMA/LIBRA is the modulated component of the signal in NaI(Tl) target and not the constant part of it as in other approaches and/or targets where many (largely uncertain) subtractions are applied

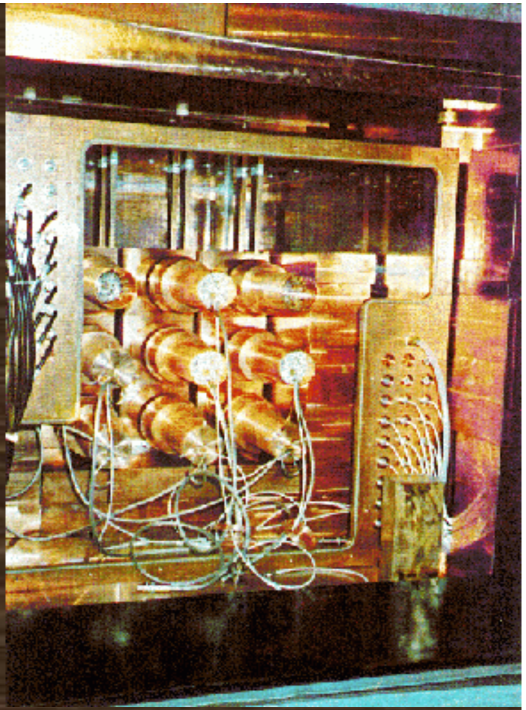
- The only bckg of interest are those able to mimic the signature (i.e.able to account for the whole observed modulation amplitude and to simultaneoulsy satisfy all its many peculiarities) → none able to simultaneously satisfy all the many requirements of the signature has been found or suggested by anyone from middle '80 (when Drukier, Freese et al. discussed this signature) to today 2014

- The signature itself acts as a strong background reduction as pointed out since the Freese et al. papers in the '80

- No direct model independent comparison is possible in the field when different target materials and/or approaches are used

- Many candidates, interactions, halo models, etc. are possible, while a "heavy cooking" of experimental and theoretical assumptions is generally adopted in a single arbitrary scenario without accounting neither for existing uncertainties nor for alternative possible scenarios and assuming a priori a particular interaction type, etc.

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



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

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

Results on rare processes:

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

Results on DM particles:

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

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

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

total exposure (7 annual cycles) 0.29 ton × yr

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

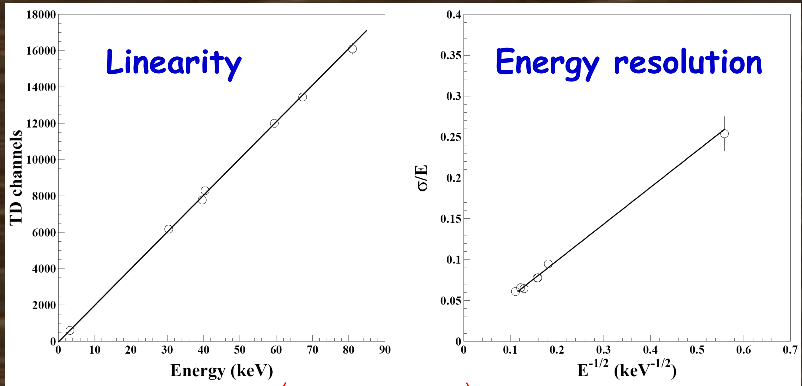
As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

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

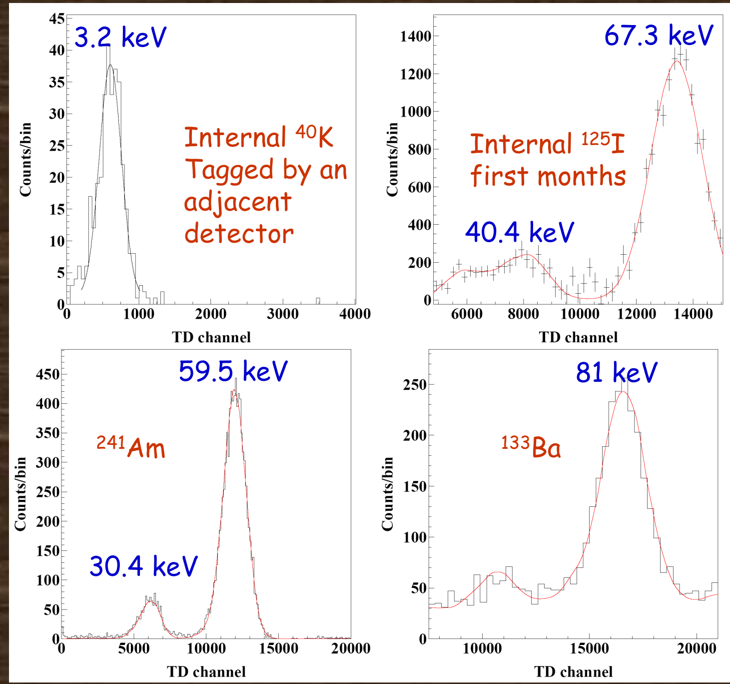
- *Radiopurity, performances, procedures, etc.:* NIMA592(2008)297, JINST 7 (2012) 03009
- *Results on DM particles: Ann. Mod. Signature:* EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648
- *related results:* PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827
- *Results on rare processes: PEP violation in Na, I:* EPJC62(2009)327, *CNC in I:* EPJC72(2012)1920
  IPP in ^{241}Am: EPJA49(2013)64

DAMA/LIBRA calibrations

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

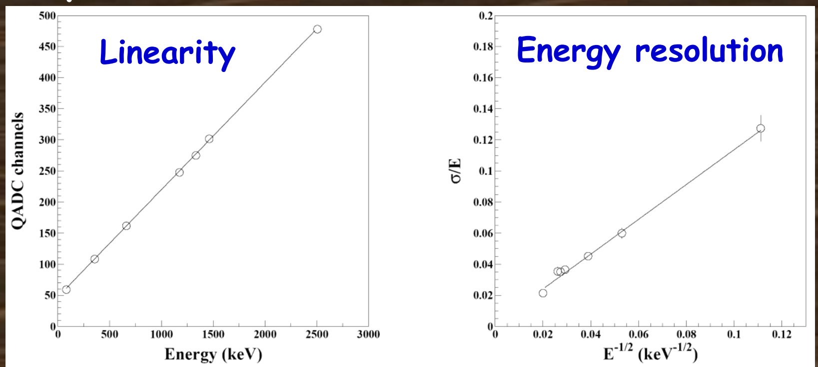


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$



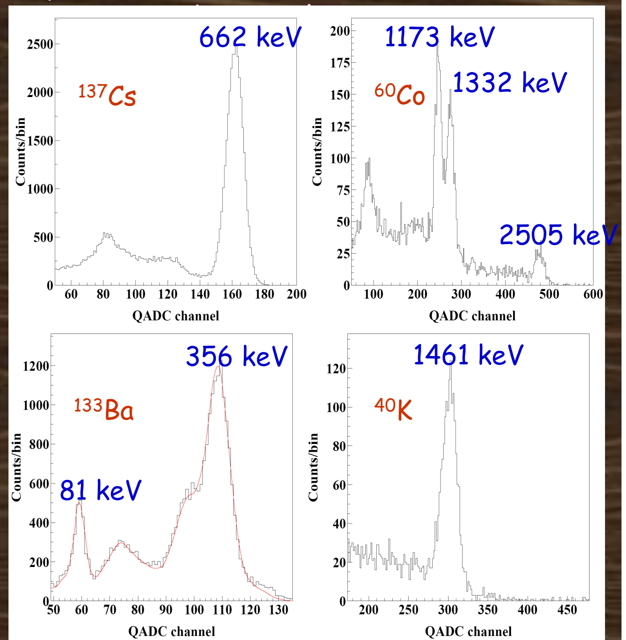
The curves superimposed to the experimental data have been obtained

High energy: 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



Thus, here and hereafter keV means keV electron equivalent

Complete DAMA/LIBRA-phase1: a ton x yr experiment? done

EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648

	Period	Mass (kg)	Exposure (kg$\times$day)	$(\alpha - \beta^2)$
DAMA/LIBRA-1	Sept. 9, 2003 - July 21, 2004	232.8	51405	0.562
DAMA/LIBRA-2	July 21, 2004 - Oct. 28, 2005	232.8	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 - July 18, 2006	232.8	39445	0.591
DAMA/LIBRA-4	July 19, 2006 - July 17, 2007	232.8	49377	0.541
DAMA/LIBRA-5	July 17, 2007 - Aug. 29, 2008	232.8	66105	0.468
DAMA/LIBRA-6	Nov. 12, 2008 - Sept. 1, 2009	242.5	58768	0.519
DAMA/LIBRA-7	Sep. 1, 2009 - Sept. 8, 2010	242.5	62098	0.515
DAMA/LIBRA–phase1	Sept. 9, 2003 - Sept. 8, 2010		379795 $\simeq$ 1.04 ton$\times$yr	0.518
DAMA/NaI + DAMA/LIBRA–phase1:			1.33 ton$\times$yr	

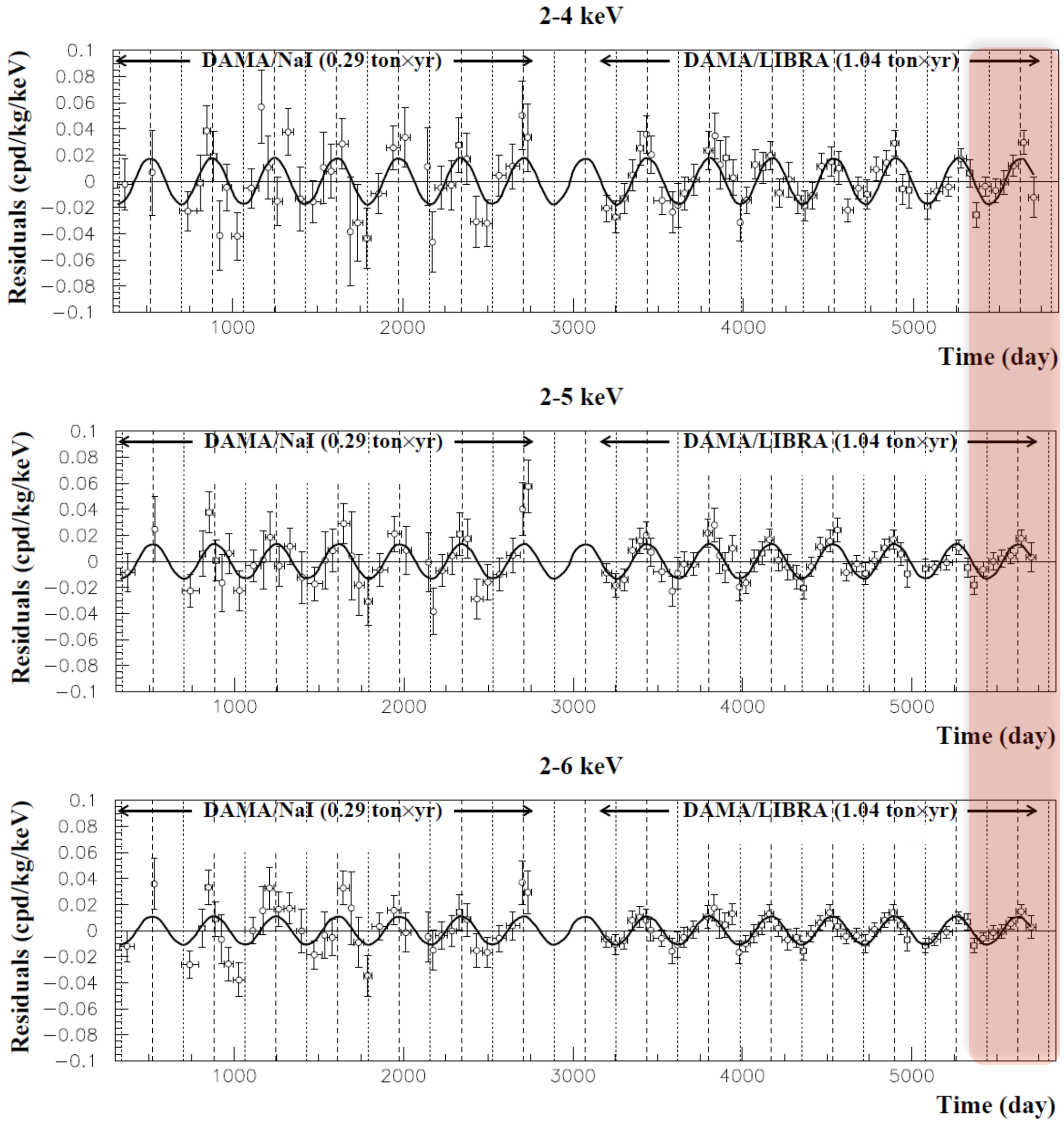
- **calibrations: $\approx$ 9.6 x 10^7 events from sources**
- **acceptance window eff**:

95 M events ($\approx$3.5M events/keV)

Model Independent DM Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = 1.33 ton×yr

experimental residuals of the single-hit scintillation events rate vs time and energy



EPJC73(2013)2648

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

2-4 keV

A=(0.0179±0.0020) cpd/kg/keV

χ^2/dof = 87.1/86 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=169/87 ⇒ P(A=0) = 3.7×10^{-7}

2-5 keV

A=(0.0135±0.0015) cpd/kg/keV

χ^2/dof = 68.2/86 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=152/87 ⇒ P(A=0) = 2.2×10^{-5}

2-6 keV

A=(0.0110±0.0012) cpd/kg/keV

χ^2/dof = 70.4/86 **9.2 σ C.L.**

Absence of modulation? No

χ^2/dof=154/87 ⇒ P(A=0) = 1.3×10^{-5}

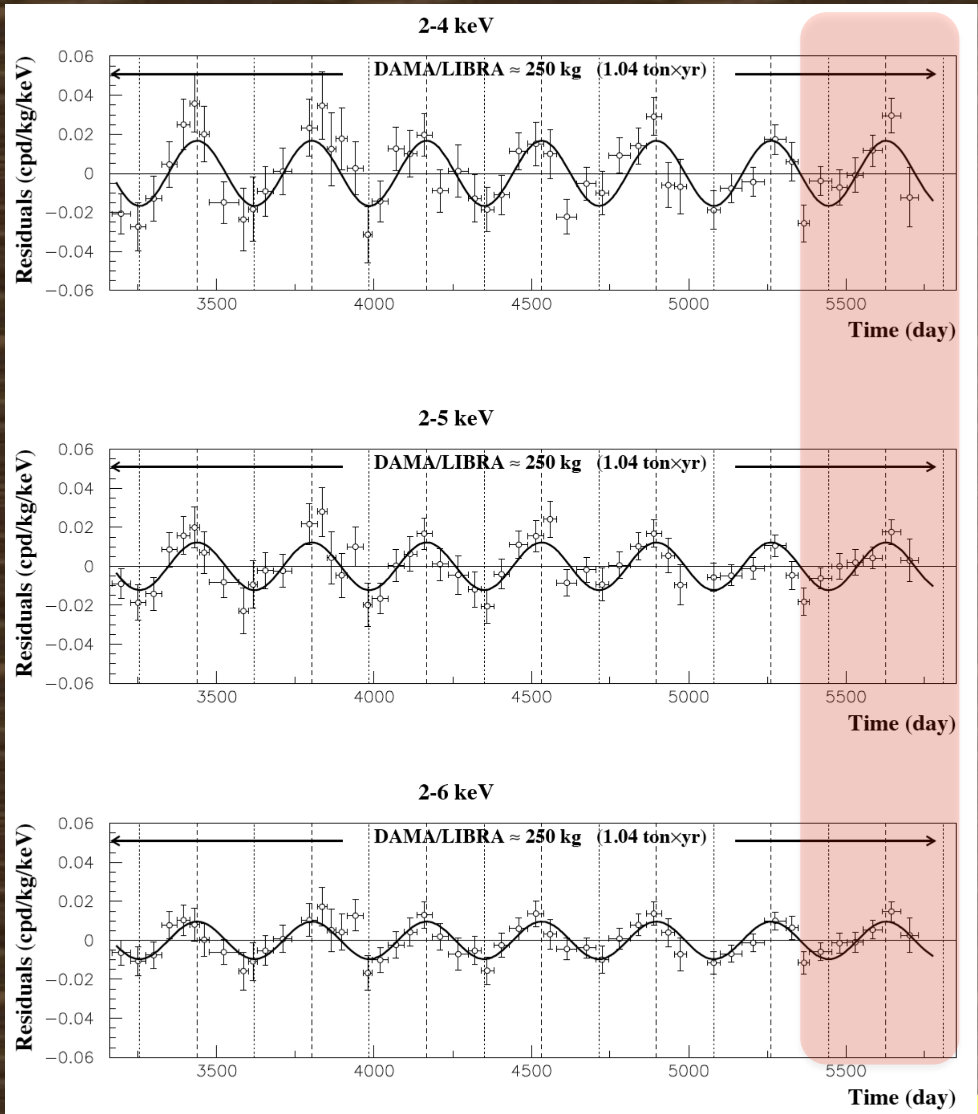
The data favor the presence of a modulated behavior with proper features at 9.2σ C.L.

Model Independent DM Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/LIBRA-phase1 (1.04 ton×yr)

EPJC73(2013)2648



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

2-4 keV

A=(0.0167±0.0022) cpd/kg/keV

χ^2/dof = 52.3/49 **7.6 σ C.L.**

Absence of modulation? No

χ^2/dof=111.2/50 ⇒ P(A=0) = 1.5×10^{-6}

2-5 keV

A=(0.0122±0.0016) cpd/kg/keV

χ^2/dof = 41.4/49 **7.6 σ C.L.**

Absence of modulation? No

χ^2/dof=98.5/50⇒ P(A=0) = 5.2×10^{-5}

2-6 keV

A=(0.0096±0.0013) cpd/kg/keV

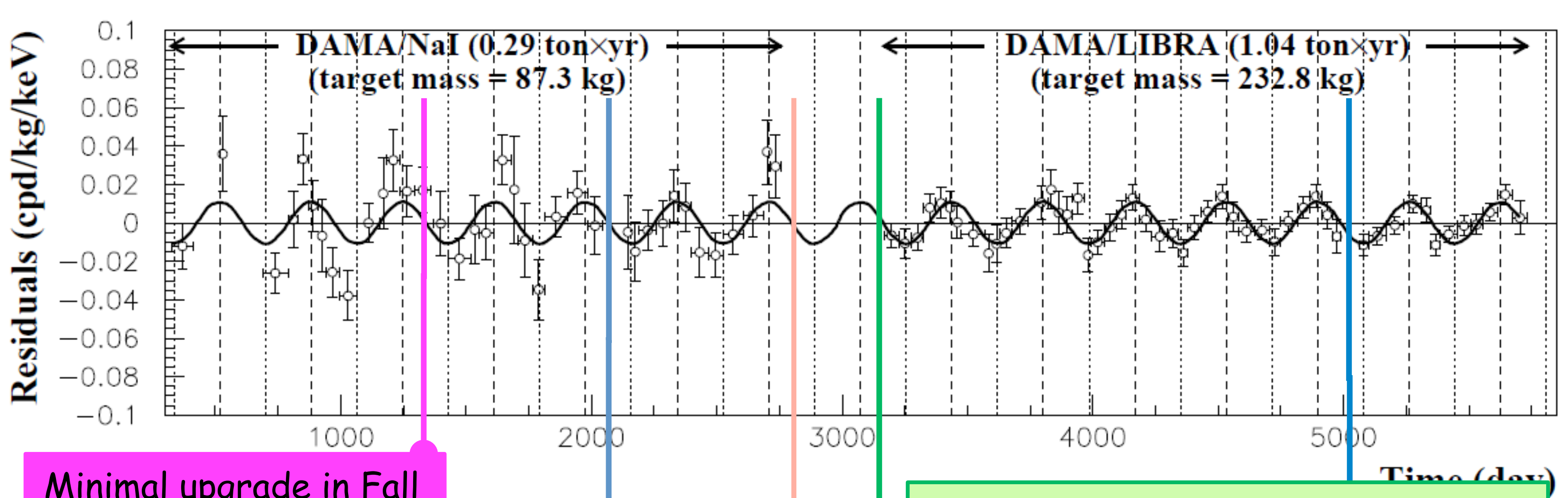
χ^2/dof = 29.3/49 **7.4 σ C.L.**

Absence of modulation? No

χ^2/dof=83.1/50 ⇒ P(A=0) = 2.2×10^{-3}

The data of DAMA/NaI + DAMA/LIBRA-phase1 favor the presence of a modulated behavior with proper features at 9.2σ C.L.

DAMA/NaI & DAMA/LIBRA main upgrades and improvements



PHASE2

Minimal upgrade in Fall

July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector): (i) TD VXI Tektronix; (ii) Digital Unix DAQ system; (iii) GPIB-CAMAC.

July 2002 DAMA/NaI taking completed

On 2003 DAMA/LIBRA has begun first operations (one TD channel for each PMT; two for each detector)

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:
(i) one detector has been recovered by replacing a broken PMT
(ii) new optimization of some PMTs and HVs performed
(iii) All TD replaced with new ones
(iv) new DAQ with optical read-out installed

The second DAMA/LIBRA upgrade in Fall 2010: replacement of all the PMTs with higher Q.E. ones
(+ new preamplifiers in fall 2012 & other developments in progress)

DAMA/LIBRA-phase2 *in data taking*

Modulation amplitudes (A), period (T) and phase (t_0) measured in DAMA/NaI and DAMA/LIBRA-phase1

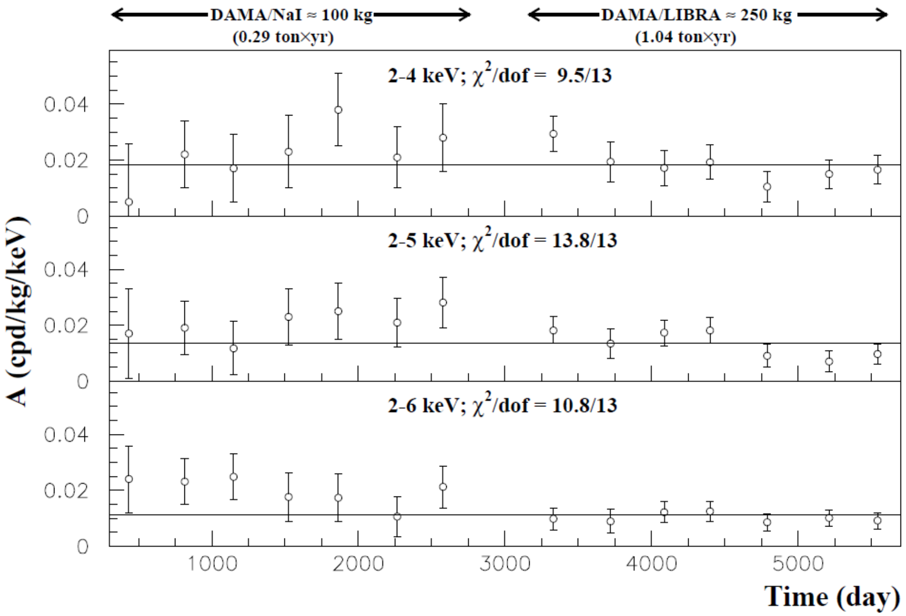
	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/NaI				
(2-4) keV	0.0252 ±0.0050	1.01 ±0.02	125 ±30	5.0σ
(2-5) keV	0.0215 ±0.0039	1.01 ±0.02	140 ±30	5.5σ
(2-6) keV	0.0200 ±0.0032	1.00 ±0.01	140 ±22	6.3σ
DAMA/LIBRA-phase1				
(2-4) keV	0.0178 ±0.0022	0.996 ±0.02	134 ± 7	8.1σ
(2-5) keV	0.0127 ±0.0016	0.996 ±0.02	137 ± 8	7.9σ
(2-6) keV	0.0097 ±0.0013	0.998 ±0.02	144 ± 8	7.5σ
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	0.0190 ±0.0020	0.996 ±0.0002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.0002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.0002	144 ± 7	9.3σ

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

DAMA/NaI (0.29 ton x yr) + DAMA/LIBRA-phase1 (1.04 ton x yr)

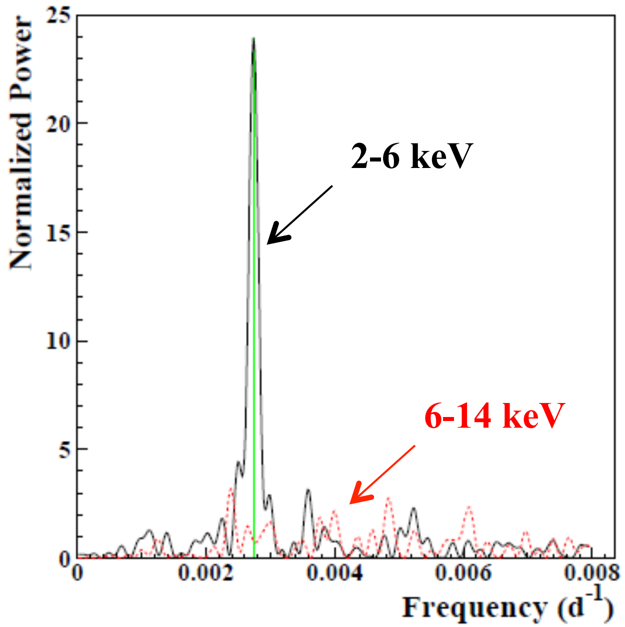
total exposure:
487526 kg×day = 1.33 ton×yr

χ^2 test (χ^2 = 9.5, 13.8 and 10.8 over 13 *d.o.f.* for the three energy intervals, respectively; upper tail probability 73%, 39%, 63%) and *run test* (lower tail probabilities of 41%, 29% and 23% 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



DAMA/NaI (7 years) + DAMA/LIBRA-phase1 (7 years)
total exposure: 1.33 ton×yr

Principal mode in the 2-6 keV region: $2.737 \times 10^{-3}\ d^{-1} \approx 1\ yr^{-1}$

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

The Lomb-Scargle periodogram, as reported in DAMA papers, always according to Ap.J. 263 (1982) 835, Ap.J. 338 (1989) 277 with the treatment of the experimental errors and of the time binning:

Given a set of data values r_i, $i = 1, \ldots N$ at respective observation times t_i, the Lomb-Scargle periodogram is:

$$P_N(\omega) = \frac{1}{2\sigma^2}\left\{ \frac{\left[\sum_i (r_i - \bar{r})\cos\omega(t_i - \tau)\right]^2}{\sum_i \cos^2\omega(t_i - \tau)} + \frac{\left[\sum_i (r_i - \bar{r})\sin\omega(t_i - \tau)\right]^2}{\sum_i \sin^2\omega(t_i - \tau)} \right\}$$

where: $\bar{r} = \frac{1}{N}\sum_1^N r_i \qquad \sigma^2 = \frac{1}{N-1}\sum_1^N (r_i - \bar{r})^2$

and, for each angular frequency $\omega = 2\pi f > 0$ of interest, the time-offset τ is:

$$\tan(2\omega\tau) = \frac{\sum_i \sin(2\omega t_i)}{\sum_i \cos(2\omega t_i)}$$

In order to take into account the different time binning and the residuals' errors we have to rewrite the previous formulae replacing:

$$\sum_i \;\rightarrow\; \sum_i \frac{\frac{N}{\Delta r_i^2}}{\sum_j \frac{1}{\Delta r_j^2}} = \frac{N}{\sum_j \frac{1}{\Delta r_j^2}} \cdot \sum_i \frac{1}{\Delta r_i^2}$$

$$\sin\omega t_i \;\rightarrow\; \frac{1}{2\Delta t_i}\int_{t_i-\Delta t_i}^{t_i+\Delta t_i} \sin\omega t \, dt$$

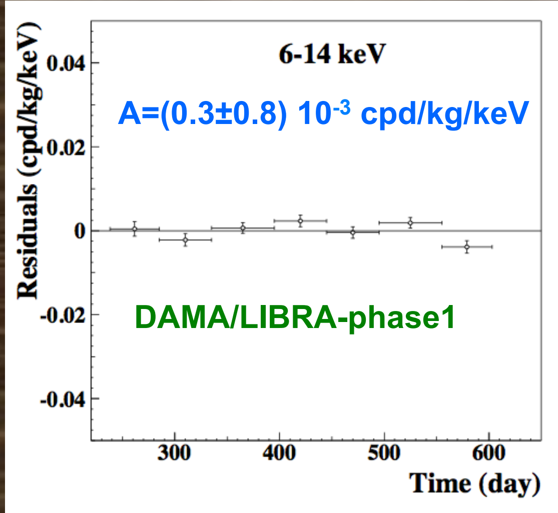
$$\cos\omega t_i \;\rightarrow\; \frac{1}{2\Delta t_i}\int_{t_i-\Delta t_i}^{t_i+\Delta t_i} \cos\omega t \, dt$$

The Nyquist frequency is ≈3 y^{-1} (≈0.008 d^{-1}); meaningless higher frequencies, washed off by the integration over the time binning.

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

Rate behaviour above 6 keV

- **No Modulation above 6 keV**

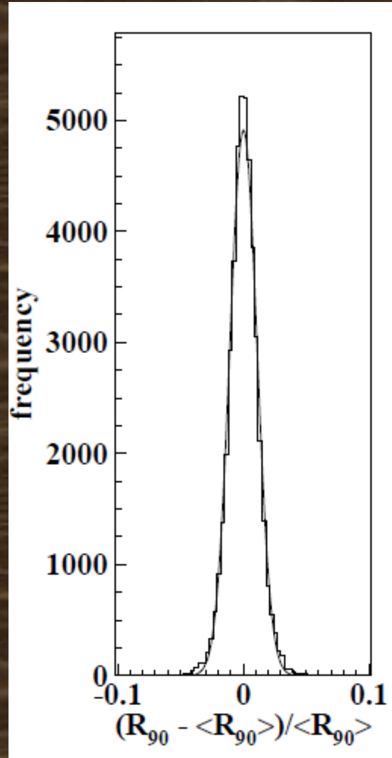


Mod. Ampl. (6-10 keV): cpd/kg/keV

(0.0016 ± 0.0031) DAMA/LIBRA-1
-(0.0010 ± 0.0034) DAMA/LIBRA-2
-(0.0001 ± 0.0031) DAMA/LIBRA-3
-(0.0006 ± 0.0029) DAMA/LIBRA-4
-(0.0021 ± 0.0026) DAMA/LIBRA-5
(0.0029 ± 0.0025) DAMA/LIBRA-6
-(0.0023 ± 0.0024) DAMA/LIBRA-7

→ statistically consistent with zero

DAMA/LIBRA-phase1



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

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

Period	Mod. Ampl.
DAMA/LIBRA-1	-(0.05±0.19) cpd/kg
DAMA/LIBRA-2	-(0.12±0.19) cpd/kg
DAMA/LIBRA-3	-(0.13±0.18) cpd/kg
DAMA/LIBRA-4	(0.15±0.17) cpd/kg
DAMA/LIBRA-5	(0.20±0.18) cpd/kg
DAMA/LIBRA-6	-(0.20±0.16) cpd/kg
DAMA/LIBRA-7	-(0.28±0.18) cpd/kg

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

consistent with zero

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

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

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

Multiple-hits events in the region of the signal

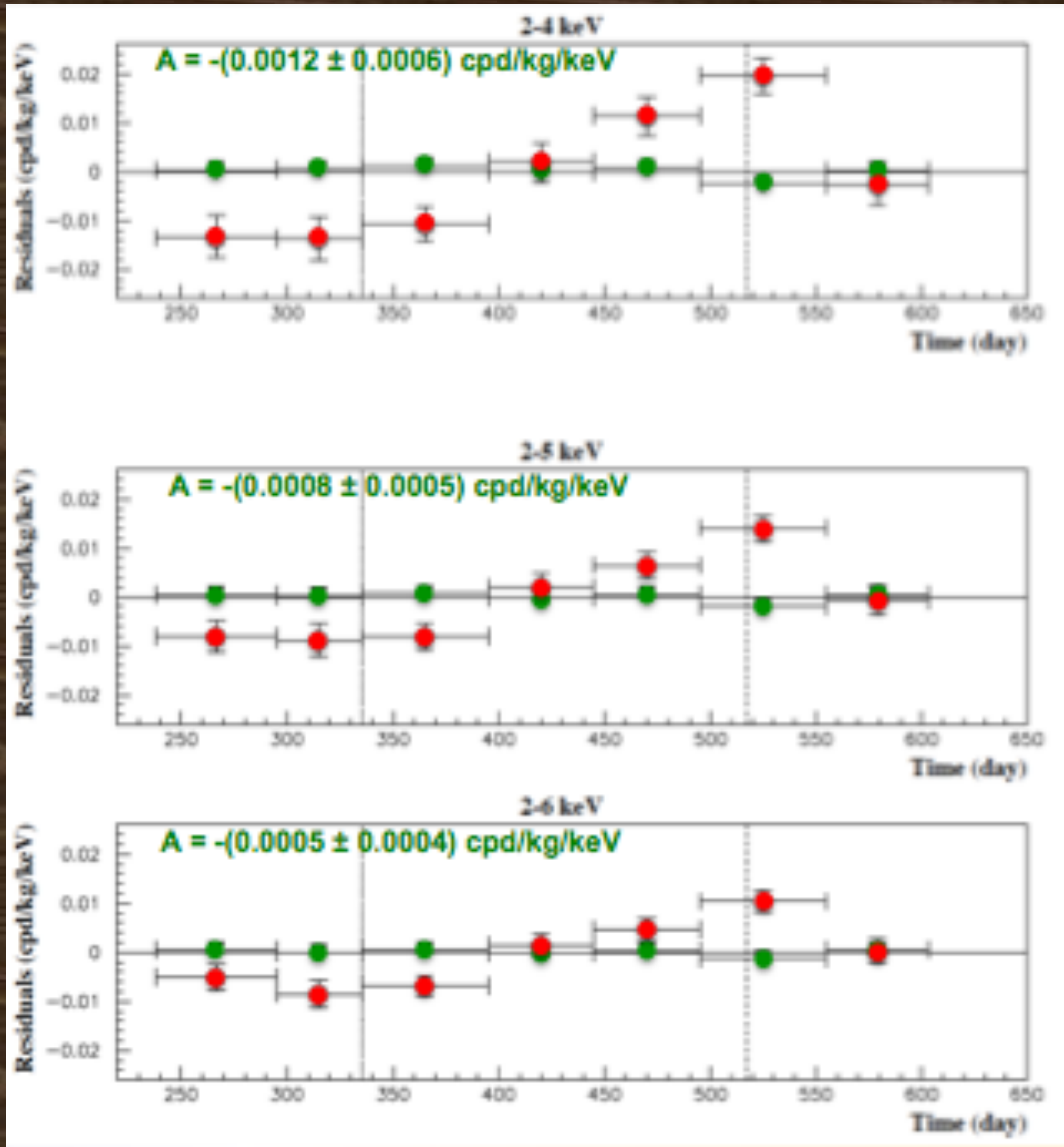
DAMA/LIBRA-phase1 (7 annual cycles)

- Each detector has its own TDs read-out → pulse profiles of *multiple-hits* events (multiplicity > 1) acquired (exposure: 1.04 ton×yr).
- The same hardware and software procedures as those followed for *single-hit* events

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

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

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



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

Energy distribution of the modulation amplitudes

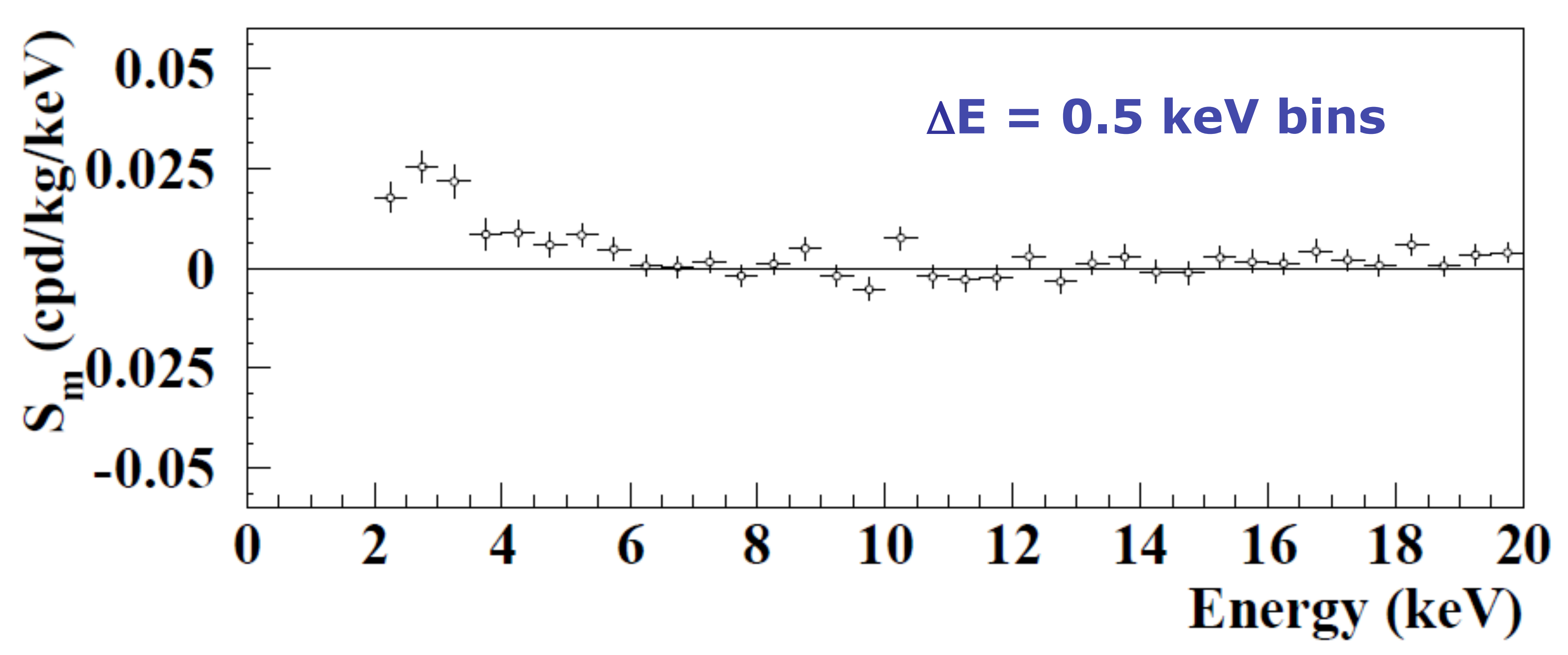
Max-likelihood analysis of the single-hit scintillation events

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

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

DAMA/NaI + **DAMA/LIBRA-phase1**

total exposure: 487526 kg×day ≈**1.33 ton×yr**



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

The S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability 15%)

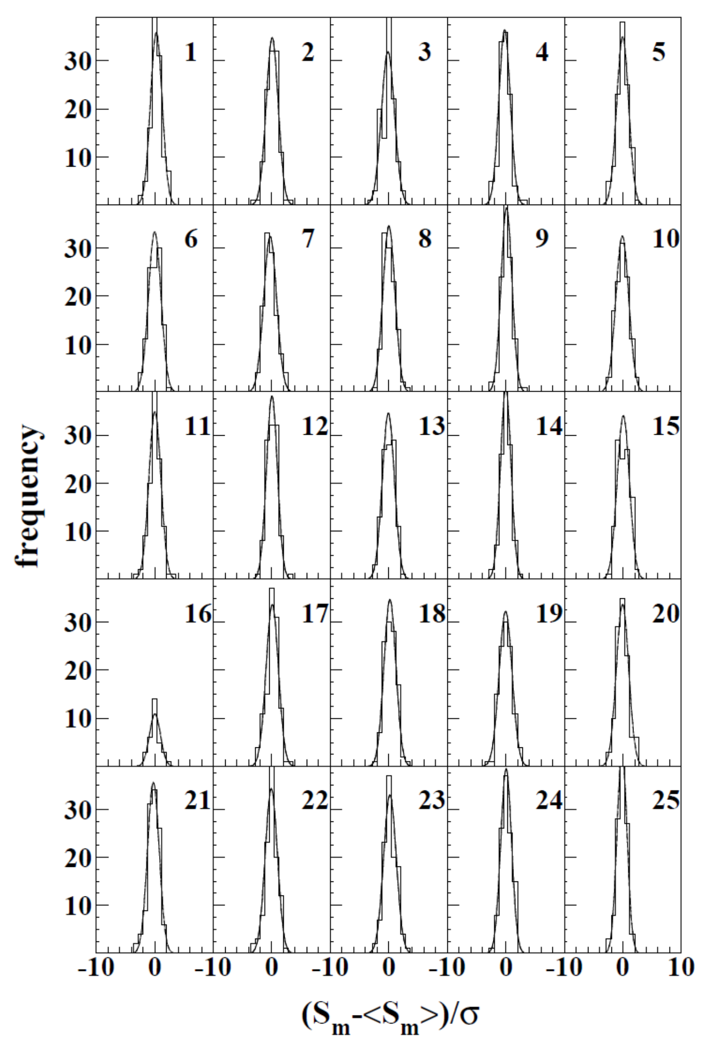
Statistical distributions of the modulation amplitudes (S_m)

a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)
b) $<S_m>$ = mean values over the detectors and the annual cycles for each energy bin; σ = error on S_m

DAMA/LIBRA-phase1 (7 years)

total exposure: 1.04 ton×yr

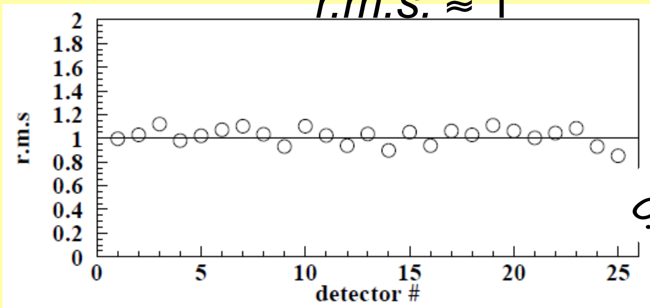
Each panel refers to each detector separately; 112 entries = 16 energy bins in 2-6 keV energy interval × 7 DAMA/LIBRA-phase1 annual cycles (for crys 16, 2 annual cycle, 32 entries)



2-6 keV

Standard deviations of
$(S_m - \langle S_m \rangle)/\sigma$
for each detectors

r.m.s. ≈ 1



0.85 < *r.m.s.* < 1.12

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

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

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, energy bins and annual cycles

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

DAMA/NaI (7 years) + **DAMA/LIBRA-phase1 (7 years)**

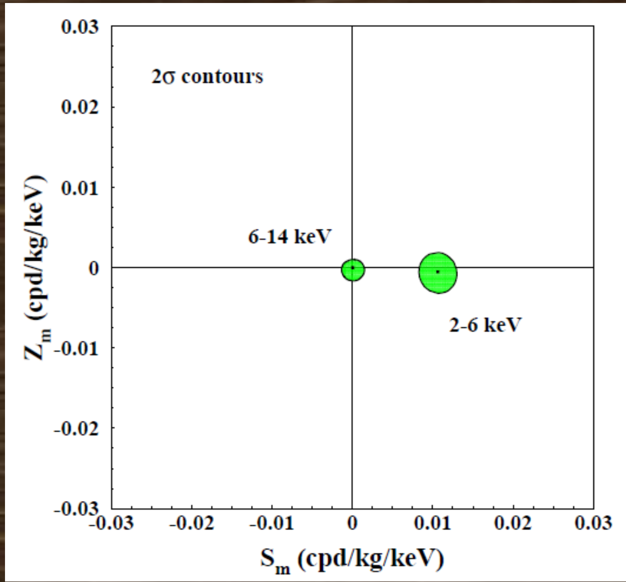
total exposure: 487526 kg×day **= 1.33 ton × yr**

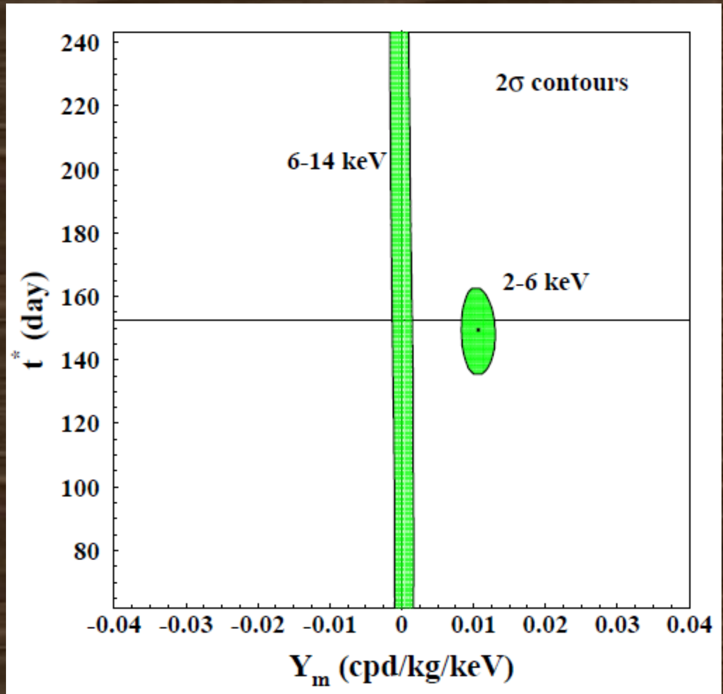
$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right] + Z_m \sin\left[\omega\left(t - t_0\right)\right] = S_0 + Y_m \cos\left[\omega\left(t - t^*\right)\right]$$

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	0.0106 ± 0.0012	-0.0006 ± 0.0012	0.0107 ± 0.0012	149.5 ± 7.0
6-14	0.0001 ± 0.0007	0.0000 ± 0.0005	0.0001 ± 0.0008	--

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

Additional investigations on the stability parameters

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

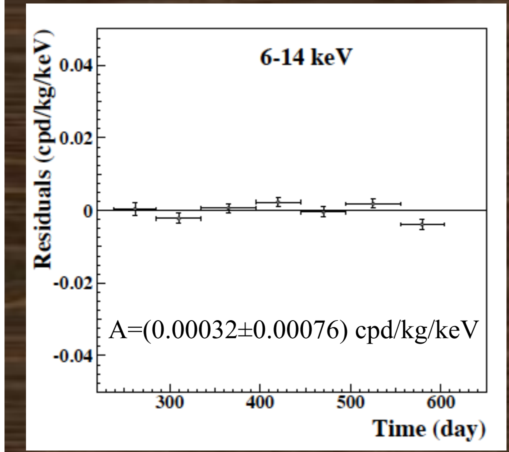
Running conditions stable at a level better than 1% also in the last running period

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4	DAMA/LIBRA-5	DAMA/LIBRA-6	DAMA/LIBRA-7
Temperature (°C)	-(0.0001 ± 0.0061)	(0.0026 ± 0.0086)	(0.001 ± 0.015)	(0.0004 ± 0.0047)	(0.0001 ± 0.0036)	(0.0007 ± 0.0059)	(0.0000 ± 0.0054)
Flux N_2 (l/h)	(0.13 ± 0.22)	(0.10 ± 0.25)	-(0.07 ± 0.18)	-(0.05 ± 0.24)	-(0.01 ± 0.21)	-(0.01 ± 0.15)	-(0.00 ± 0.14)
Pressure (mbar)	(0.015 ± 0.030)	-(0.013 ± 0.025)	(0.022 ± 0.027)	(0.0018 ± 0.0074)	-(0.08 ± 0.12) $\times 10^{-2}$	(0.07 ± 0.13) $\times 10^{-2}$	-(0.26 ± 0.55) $\times 10^{-2}$
Radon (Bq/m^3)	-(0.029 ± 0.029)	-(0.030 ± 0.027)	(0.015 ± 0.029)	-(0.052 ± 0.039)	(0.021 ± 0.037)	-(0.028 ± 0.036)	(0.012 ± 0.047)
Hardware rate above single ph.e. (Hz)	-(0.20 ± 0.18) $\times 10^{-2}$	(0.09 ± 0.17) $\times 10^{-2}$	-(0.03 ± 0.20) $\times 10^{-2}$	(0.15 ± 0.15) $\times 10^{-2}$	(0.03 ± 0.14) $\times 10^{-2}$	(0.08 ± 0.11) $\times 10^{-2}$	(0.06 ± 0.10) $\times 10^{-2}$

All the measured amplitudes well compatible with zero
+ none can account for the observed effect
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

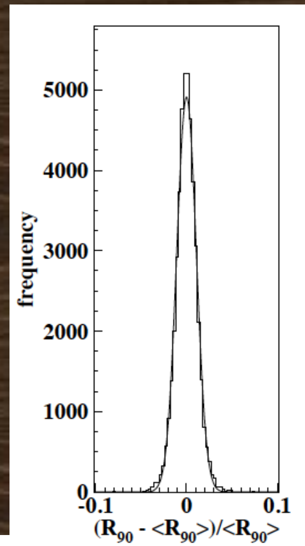
Summarizing on
a hypothetical background modulation in DAMA/LIBRA-phase1

• **No Modulation above 6 keV**



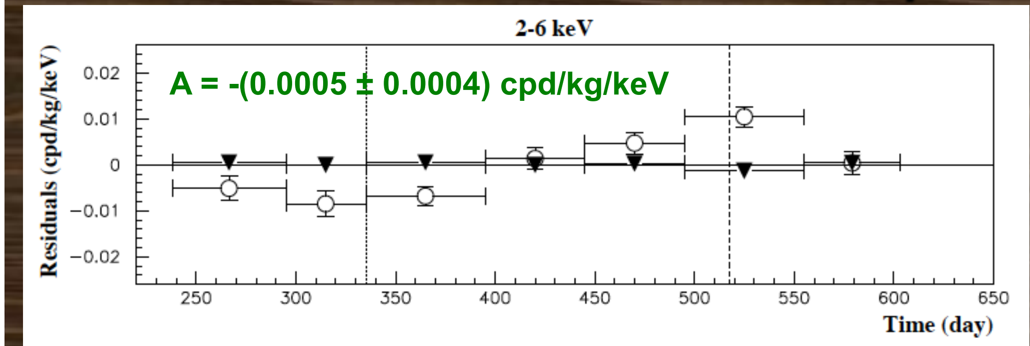
• **No modulation in the whole energy spectrum**

σ ≈ 1%



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

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



multiple-hits residual rate (filled triangles) vs *single-hit* residual rate (open circles)

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

Nevertheless, additional investigations performed . See DAMA literature

No role for μ in DAMA annual modulation result

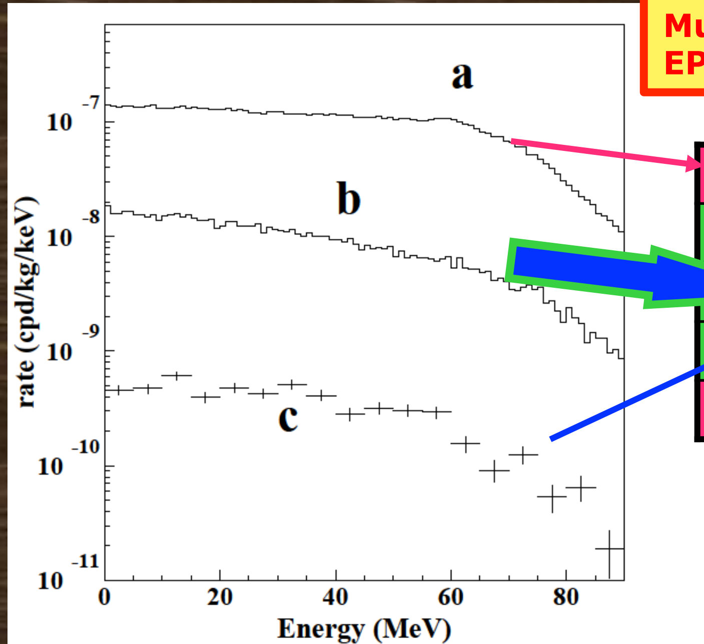
✓ **Direct μ interaction in DAMA/LIBRA set-up:**

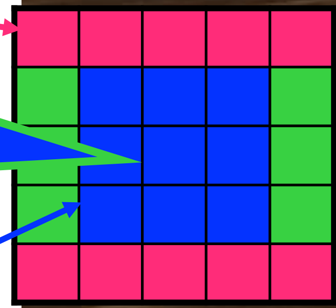
DAMA/LIBRA surface ≈0.13 m^2
μ flux @ DAMA/LIBRA ≈2.5 μ/day

MonteCarlo simulation:
- muon intensity distribution
- Gran Sasso rock overburden map
- Single hit events

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

Much more in EPJC72(2012)2064





Detector's matrix

✓ **Rate, R_n, of fast neutrons produced by μ:**

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

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Measured neutron Yield @ LNGS:

  $Y=1\div 7\ 10^{-4}$ n/μ/(g/cm^2)

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

Annual modulation amplitude at low energy due to μ modulation:

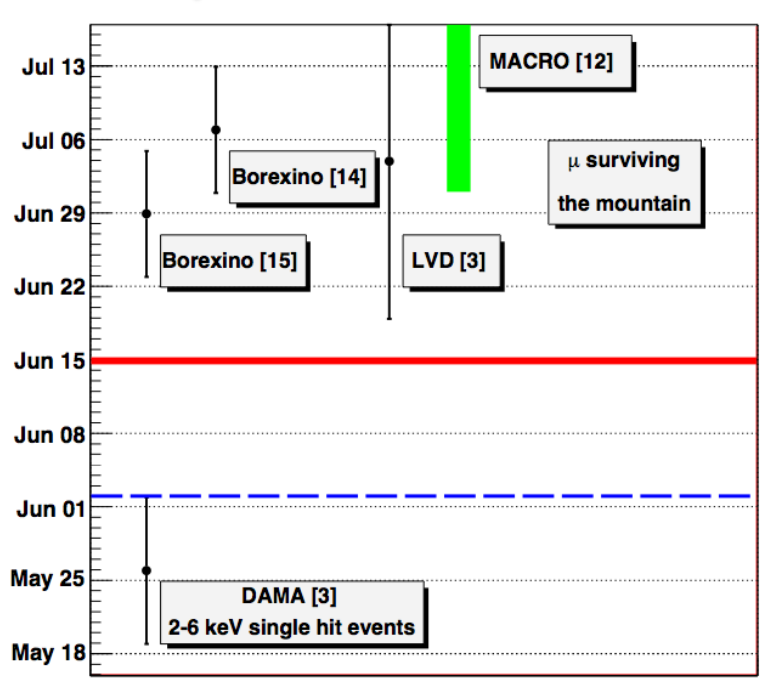
$S_m^{(m)} = R_n\, g\, \varepsilon\, f_{DE}\, f_{single}\ 2\% /(M_{setup}\ \Delta E)$

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

$$S_m^{(m)} < (0.3\text{-}2.4) \times 10^{-5}\ \text{cpd/kg/keV}$$

- Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events
- It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.

Inconsistency of the phase between DAMA signal and μ modulation



μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈$3 \cdot 10^{-4}$ $m^{-2}s^{-1}$; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)

but

- the muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a "mean" of the muon phase of each year
- The DAMA: modulation amplitude 10^{-2} cpd/kg/keV, in 2-6 keV energy range for single hit events; phase: May 26 ± 7 days (stable over 13 years)

considering the seasonal weather al LNGS, quite impossible that the max. temperature of the outer atmosphere (on which μ flux variation is dependent) is observed e.g. in June 15 which is 3 σ from DAMA

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

Similar for the whole DAMA/LIBRA-phase1

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

- only events at low energy,
- only *single-hit* events,
- no sizable effect in the *multiple-hit* counting rate
- pulses with time structure as scintillation light

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

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

Also this cannot mimic the signature: different phase

… and for many others arguments and details EPJC72(2012)2064

Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

(NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022,…)

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

DAMA/LIBRA-phase1

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

Final model independent result
DAMA/NaI+DAMA/LIBRA-phase1

Presence of modulation over 14 annual cycles at 9.3σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 14 independent experiments of 1 year each one

The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.33 ton × yr (14 annual cycles)

In fact, as required by the DM annual modulation signature:

1)
The *single-hit* events show a clear cosine-like modulation, as expected for the DM signal

2)
Measured period is equal to (0.998±0.002) yr, well compatible with the 1 yr period, as expected for the DM signal

3)
Measured phase (144±7) days is well compatible with the roughly about 152.5 days as expected for the DM signal

4)
The modulation is present only in the low energy (2—6) keV energy interval and not in other higher energy regions, consistently with expectation for the DM signal

5)
The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal

6)
The measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2-6) keV energy interval is: (0.0112 ± 0.0012) cpd/kg/keV (9.3σ C.L.).

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

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

well compatible with several candidates and interactions

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

Neutralino as LSP in various SUSY theories

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

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

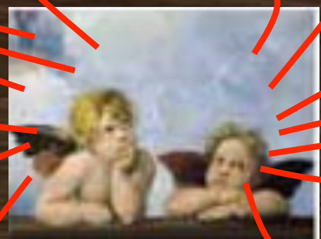
Mirror Dark Matter

Light Dark Matter

Self interacting Dark Matter

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

Sterile neutrino



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

Elementary Black holes such as the Daemons

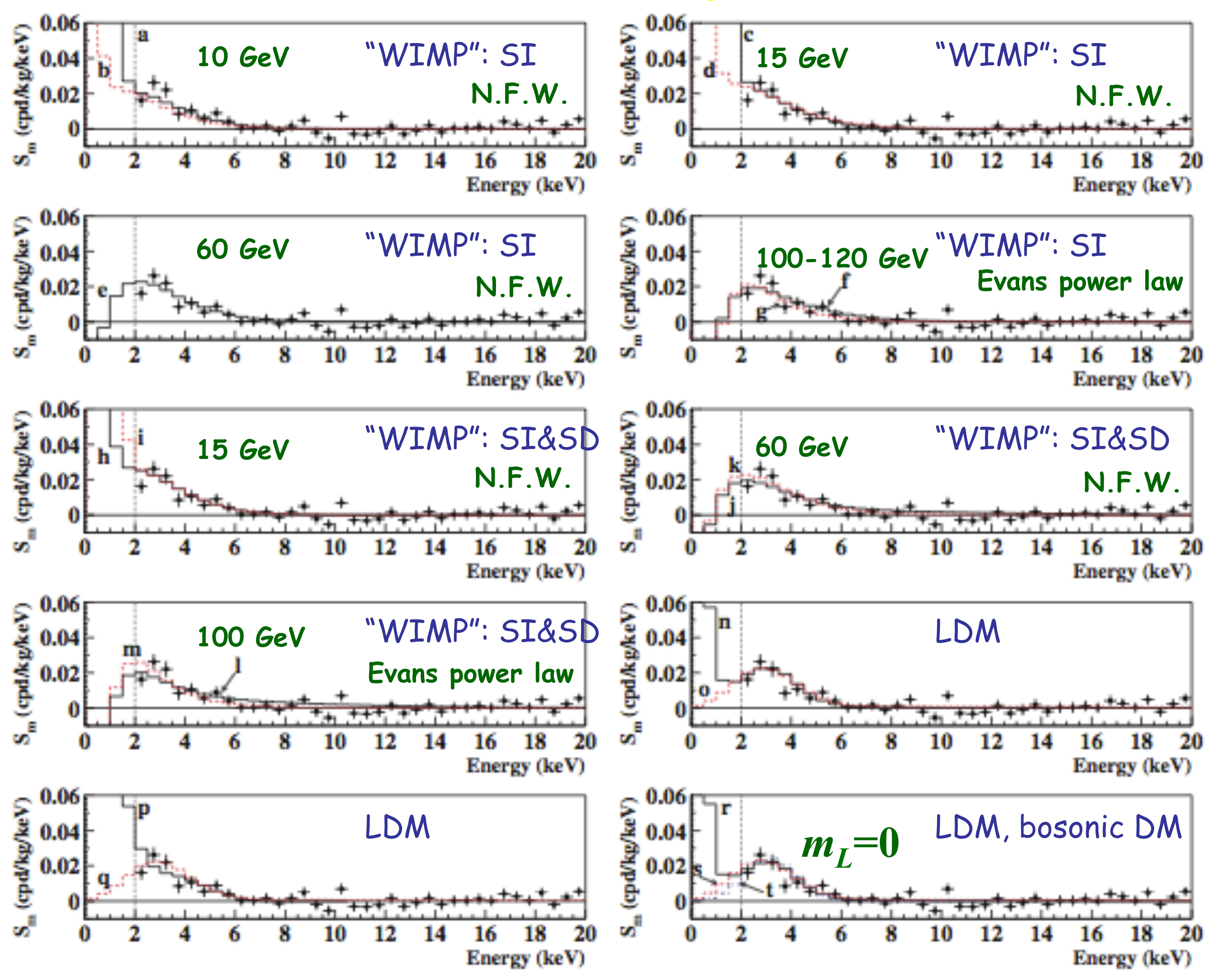
Kaluza Klein particles

… and more

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

Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with possible positive hints In various scenarios

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



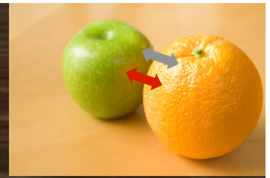
Not best fit
About the same C.L.

$\theta = 2.435$

EPJC56(2008)333, IJMPA28(2013)1330022

Compatibility with several candidates; other ones are open

About model dependent exclusion plots

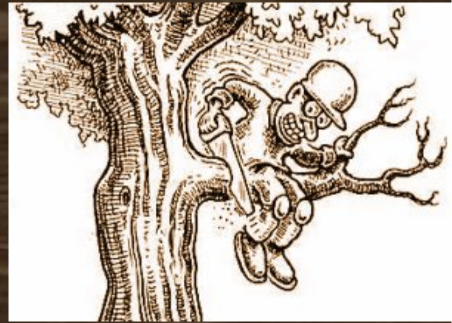


Selecting just one simplified model framework, making lots of assumptions, fixing large numbers of parameters … but…

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

road sign or labyrinth?

and experimental aspects …



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

etc., etc.

+ no uncertainties accounted for

No sensitivity to DM annual modulation signature,

Different target materials

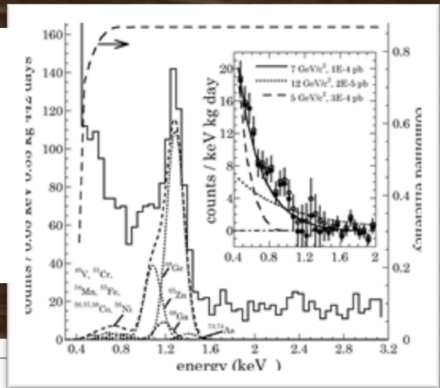
+ generally implications of DAMA model-independent results presented in incorrect/incomplete/non-updated way

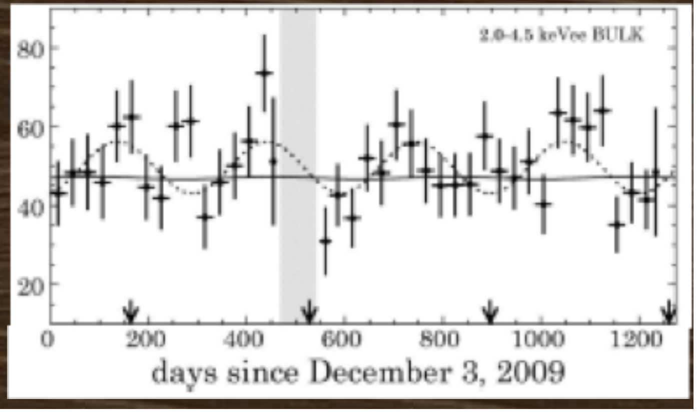
Exclusion plots have no "universal validity" and cannot disproof a model independent result in any given general model framework (they depend not only on the general assumptions largely unknown at present stage of knowledge, but on the details of their cooking) + **generally overestimated** + methodological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

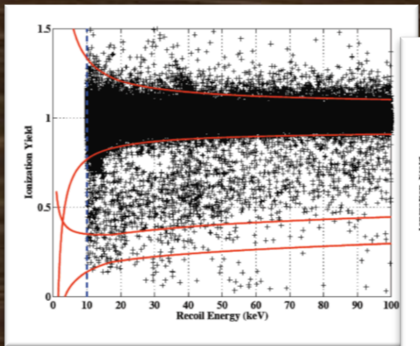
On the other hand, possible positive hints should be interpreted. Large space for compatibility.

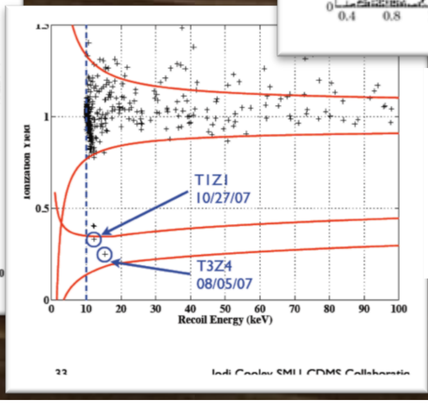
DAMA vs possible positive hints 2010 - 2013

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



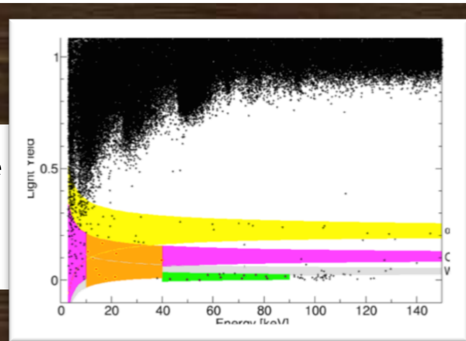


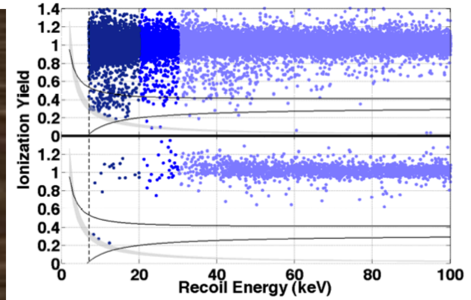




CDMS-Ge:
after many data selections and cuts, 2 Ge candidate recoil-like survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)

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



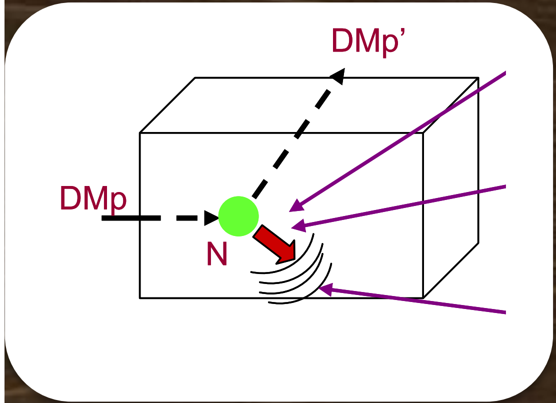


CDMS-Si:
after many data selections and cuts, 3 Si candidate recoil-like survive in an exposure of 140.2 kg x day. estimated as expected residual background 0.41

All those possible recoil-like excesses with respect to an estimated bckg surviving many cuts as well as the CoGeNT hint are compatible with the DAMA 9.3 σ C.L. annual modulation result in various scenarios

... an example ...

DM particles inducing elastic scatterings on target-nuclei, SI case



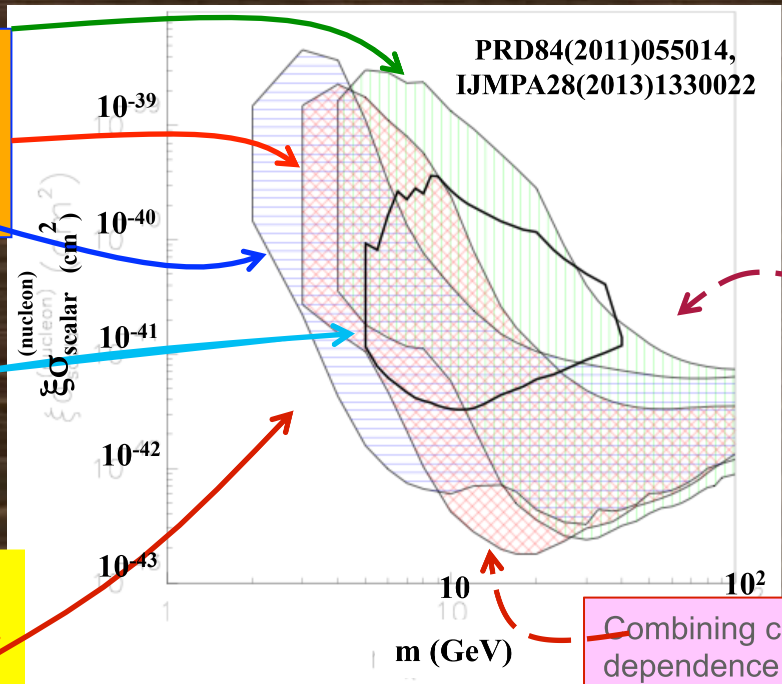
Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

Including the Migdal effect
→Towards lower mass/higher σ

DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent quenching Factors (red)

7.5σ C.L.



Co-rotating halo,
Non thermalized component
→ Enlarge allowed region towards larger mass

CoGeNT

1.64σ C.L.

q.f. at a fixed assumed value

Compatibility also with CRESST and CDMS, if the two CDMS-Ge recoil-like events, the three CDMS-Si and the CRESST ones surviving the many applied cuts in marginal exposures are assumed as nuclear recoils induced by DM interactions

Combining channeling and energy dependence of q.f. (AstrPhys33 (2010) 40)
→Towards lower σ

... examples in some given frameworks

See also a wide literature

DM particle with preferred inelastic interaction

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

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

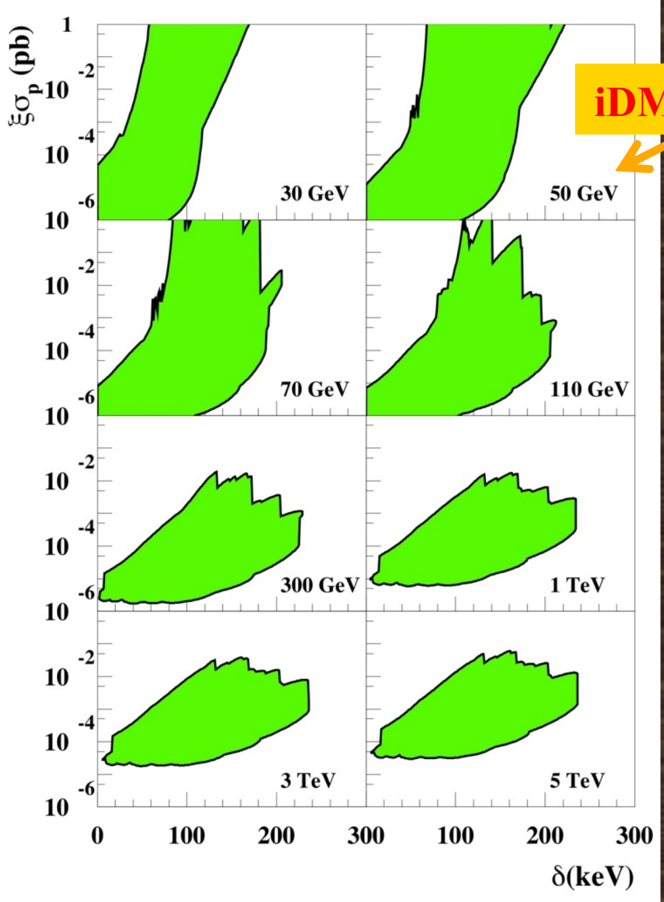
→ DMp has two mass states χ^{+}, χ^{-} with δ mass splitting

→ Kinematical constraint for iDM

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

DAMA/NaI+DAMA/LIBRA

Slices from the 3-dimensional allowed volume



iDM interaction on Iodine nuclei

Fund. Phys. 40(2010)900

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

- For **large splittings**, the dominant scattering in NaI(Tl) can occur off of **Thallium nuclei**, with A~205, which are present as a dopant at the 10^{-3} level in NaI(Tl) crystals.

arXiv:1007.2688

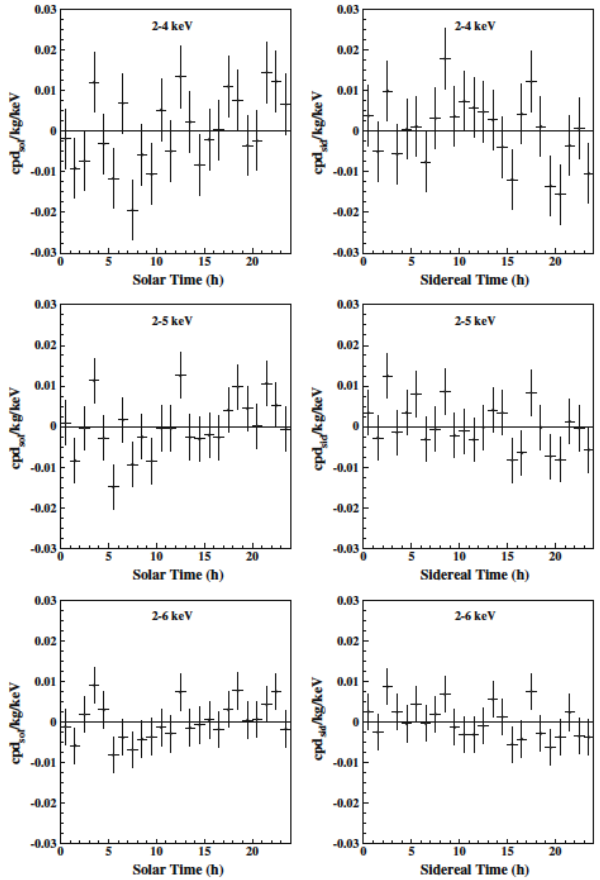
- Inelastic scattering DMp swith **large splittings** do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, …nuclei.

… and much more considering experimental and theoretical uncertainties

Model independent result on possible diurnal effect in DAMA/LIBRA–phase1

Eur. Phys. J. C 74 (2014) 2827

solar sidereal

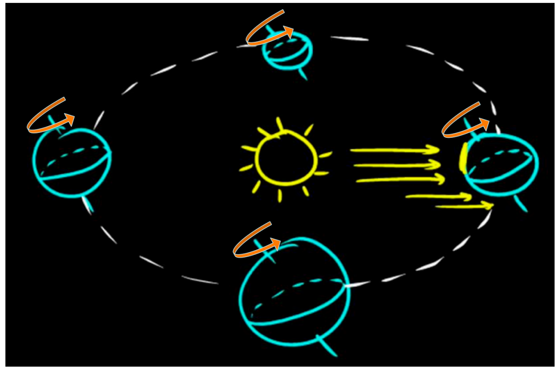


2-4 keV

2-5 keV

2-6 keV

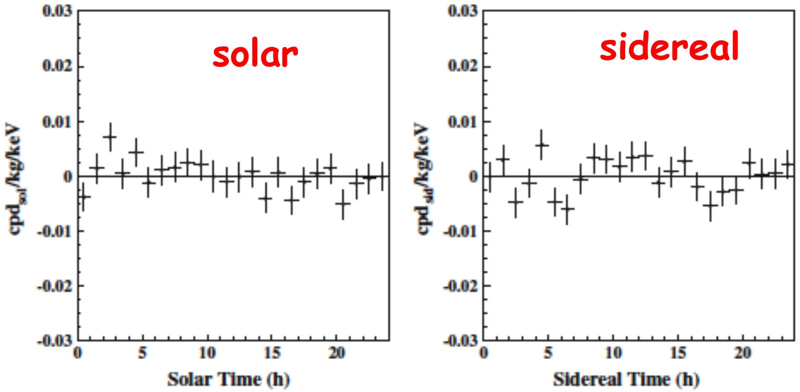
- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.



Energy region where the annual modulation observed.

Energy region just above.

6-14 keV



Energy	Solar Time	Sidereal Time
2–4 keV	χ^2/d.o.f. = 35.2/24 → P = 7%	χ^2/d.o.f. = 28.7/24 → P = 23%
2–5 keV	χ^2/d.o.f. = 35.5/24 → P = 6%	χ^2/d.o.f. = 24.0/24 → P = 46%
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24 → P = 6%

no diurnal variation with significance of 95% C.L.

+ run test to verify the hypothesis that the positive and negative data points are randomly distributed: lower tail probabilities (in the four energy regions): 43, 18, 7, 26% for solar case and 54, 84, 78, 16% for sidereal case

→ presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity

A diurnal effect with the sidereal time is expected for DM because of Earth rotation

Velocity of the detector in the terrestrial laboratory:

Eur. Phys. J. C 74 (2014) 2827

$$\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t),$$

Since:

- $|\vec{v}_s| = |\vec{v}_{LSR} + \vec{v}_{\odot}| \approx 232 \pm 50 \text{ km/s},$
- $|\vec{v}_{rev}(t)| \approx 30 \text{ km/s}$
- $|\vec{v}_{rot}(t)| \approx 0.34 \text{ km/s}$

$$v_{lab}(t) \simeq v_s + \hat{v}_s \cdot \vec{v}_{rev}(t) + \hat{v}_s \cdot \vec{v}_{rot}(t).$$

$\vec{v}_{LSR}$	velocity of the Local Standard of Rest (LSR) due to the rotation of the Galaxy
$\vec{v}_{\odot}$	Sun peculiar velocity with respect to LSR
$\vec{v}_{rev}(t)$	velocity of the revolution of the Earth around the Sun
$\vec{v}_{rot}(t)$	velocity of the rotation of the Earth around its axis at the latitude and longitude of the laboratory.

Annual modulation term:

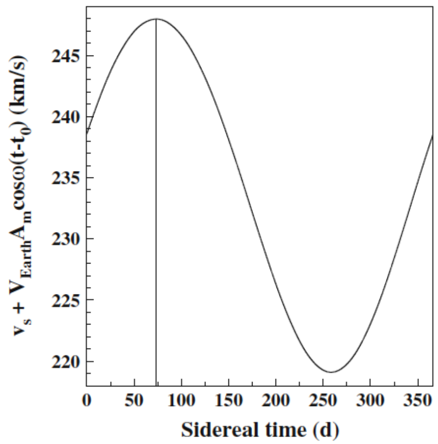
$$\hat{v}_s \cdot \vec{v}_{rev}(t) = V_{Earth} B_m \cos(\omega(t - t_0))$$

- V_{Earth} is the orbital velocity of the Earth ≈ 30 km/s
- $B_m \approx 0.489$
- $t_0 \approx t_{equinox}$ + 73.25 days ≈ June 2

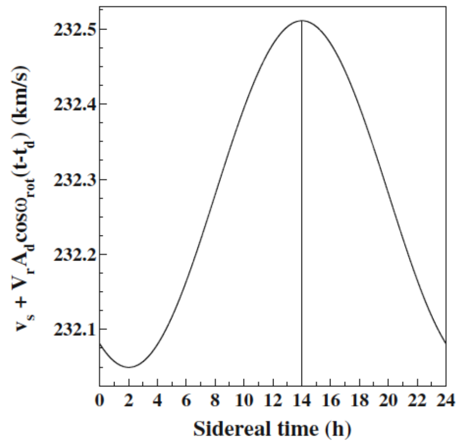
Diurnal modulation term:

$$\hat{v}_s \cdot \vec{v}_{rot}(t) = V_r B_d \cos\left[\omega_{rot}\left(t - t_d\right)\right]$$

- V_r is the rotational velocity of the Earth at the given latitude (for LNGS ≈ 0.3435 km/s)
- $B_d \approx 0.671$
- $t_d \approx 14.02$ h (at LNGS)



Velocity of the Earth in the galactic frame as a function of the sidereal time, with starting point March 21 (around spring equinox). The contribution of diurnal rotation has been dropped off. The maximum of the velocity (vertical line) is about 73 days after the spring equinox.



Sum of the Sun velocity in the galactic frame (v_s) and of the rotation velocity of a detector at LNGS ($v_s \cdot v_{rot}(t)$) as a function of the sidereal time. The maximum of the velocity is about at 14 h (vertical line).

The time dependence of the counting rate

Expected signal counting rate in a given k-th energy bin: Eur. Phys. J. C 74 (2014) 2827

$$S_k\left[v_{lab}(t)\right] \simeq S_k\left[v_s\right] + \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} \left[V_{Earth} B_m \cos\omega(t-t_0) + V_r B_d \cos\omega_{rot}(t-t_d)\right]$$

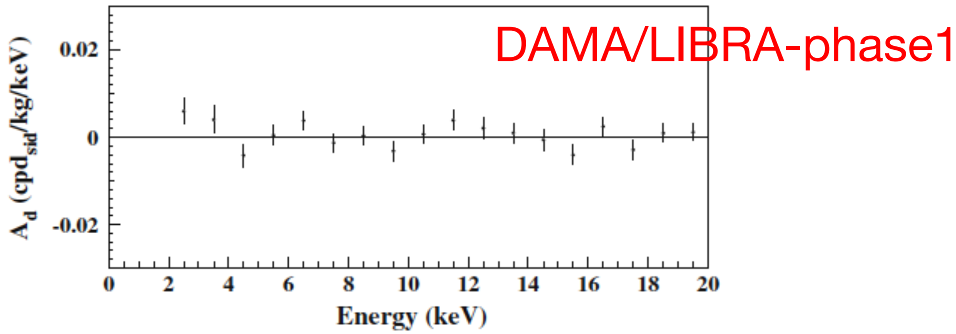
The ratio R_{dy} of the diurnal over annual modulation amplitudes is a model independent constant

- Annual modulation amplitude: $S_m = \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} V_{Earth} B_m$
- Diurnal modulation amplitude $S_d = \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} V_r B_d$

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$ at LNGS latitude

- Observed annual modulation amplitude in DAMA/LIBRA-phase1 in the (2-6) keV energy interval: (0.0097 ± 0.0013) cpd/kg/keV → thus, the expected value of the diurnal modulation amplitude is ≃1.5×10^{-4} cpd/kg/keV.

- When fitting the *single-hit* residuals with a cosine function with amplitude A_d as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.



Energy	A_d^{exp} (cpd/kg/keV)	χ^2/d.o.f.	P
2–4 keV	$(2.0 \pm 2.1) \times 10^{-3}$	27.8/23	22%
2–5 keV	$-(1.4 \pm 1.6) \times 10^{-3}$	23.2/23	45%
2–6 keV	$-(1.0 \pm 1.3) \times 10^{-3}$	20.6/23	61%
6–14 keV	$(5.0 \pm 7.5) \times 10^{-4}$	35.4/23	5%

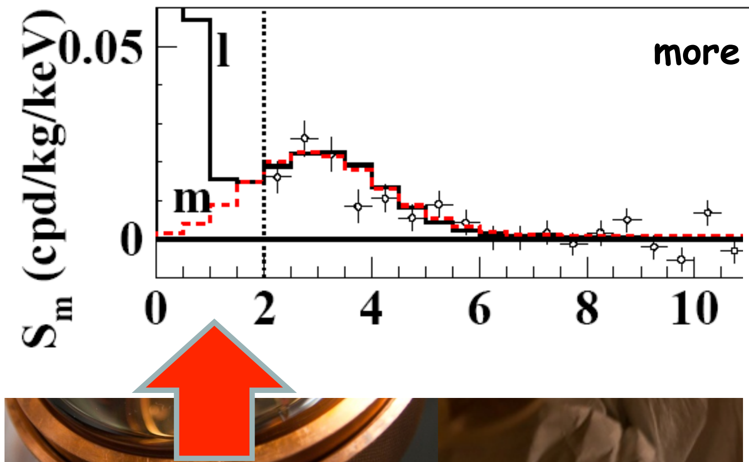
$A_d < 1.2 \times 10^{-3}$ cpd/kg/keV (90%CL)

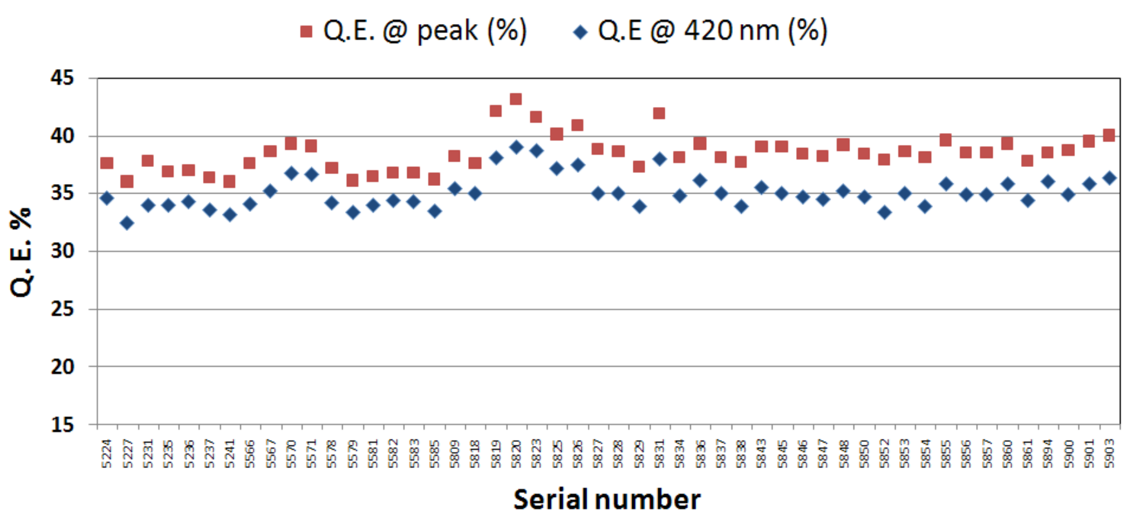
A_d values compatible with zero, having random fluctuations around zero with χ^2/d.o.f. = 19.5/18

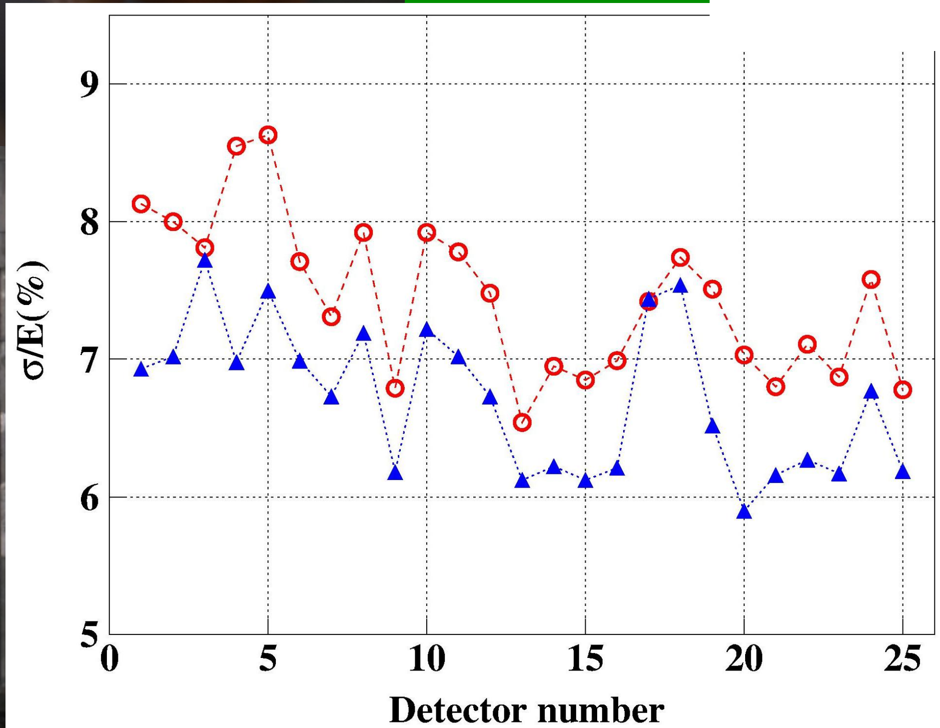
Present experimental sensitivity not yet suitable to explore the expected diurnal modulation amplitude derived from the DAMA/LIBRA-phase1 observed annual modulation effect

adequate sensitivity = larger exposure with DAMA/LIBRA-phase2 which - having a lower software energy threshold - also offers an additional alternative possibility to increase sensitivity to such an effect

DAMA/LIBRA – phase2 JINST 7(2012)03009







ed with new

	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
	47	0.12	83	0.54	-	-
	10	0,02	17	0.16	-	-

typically
DAMA/LIBRA-phase: 5.5-7.5 ph.e./keV
→ DAMA/LIBRA-phase2: 6-10 ph.e./keV

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

DAMA/LIBRA-phase2

The sensitivity of the DM annual modulation signature depends – apart from the counting rate - on the product

$$\varepsilon \times \Delta E \times M \times T \times (\alpha-\beta^2)$$

increased in DAMA/LIBRA-phase2

increased in DAMA/LIBRA-phase2

increased with DAMA/LIBRA-phase2

→ Upgrade at fall 2010 & running time
also equivalent to have enlarged the exposed mass

&: DM annual modulation signature acts itself as a strong bckg reduction strategy as already pointed out in the original paper by Freese et al.

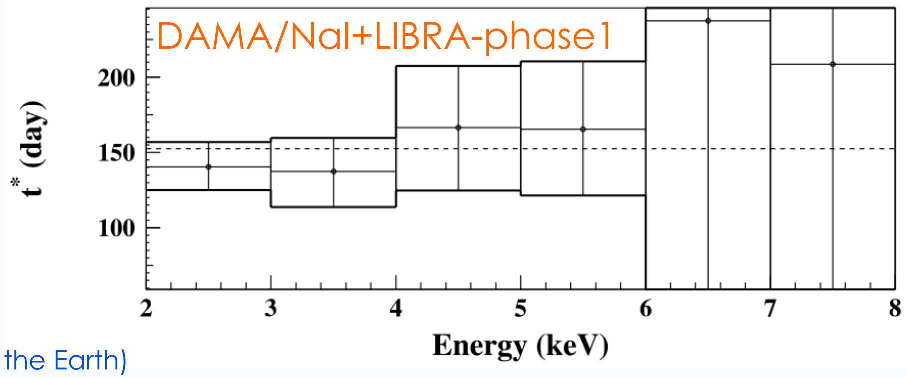
&: No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

The second orders effects to be investigated by DAMA/LIBRA-phase2

The importance of studying second order effects and the annual modulation phase

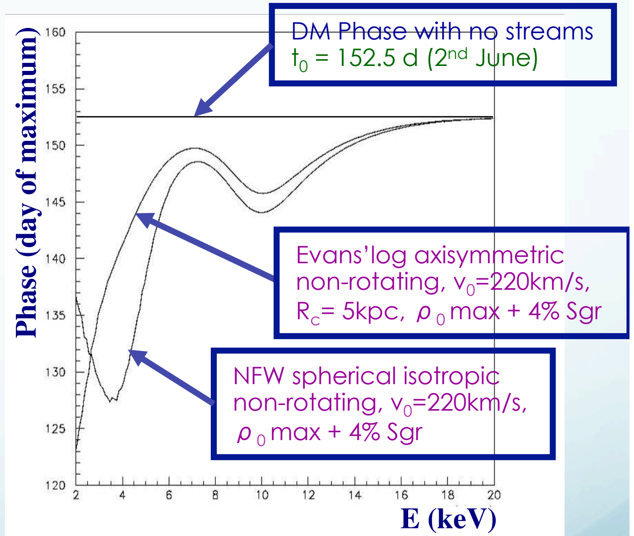
High exposure and lower energy threshold can allow further investigation on:

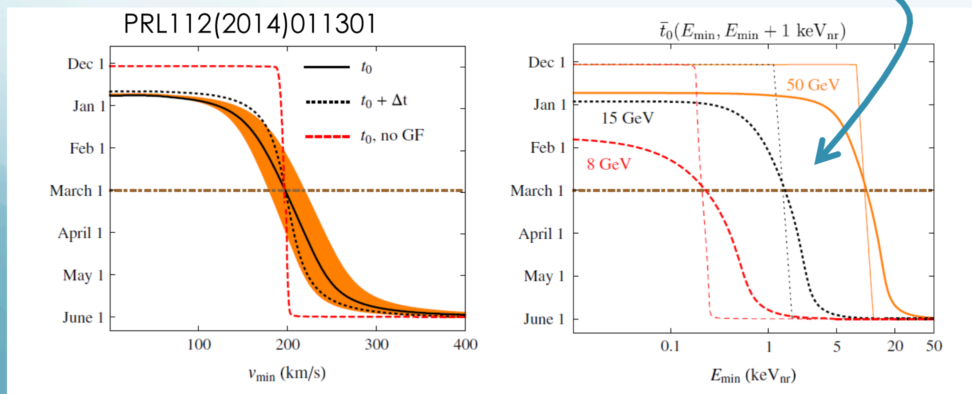
- the nature of the DM candidates
  - ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, form factors, spin-factors …)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DM particles halo?
- possible diurnal effects on the sidereal time
  - ✓ expected in case of high cross section DM candidates (shadow of the Earth)
  - ✓ due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates)
  - ✓ due to the channeling in case of DM candidates inducing nuclear recoils.
- astrophysical models
  - ✓ velocity and position distribution of DM particles in the galactic halo, possibly due to:
    - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";
    - caustics in the halo;
    - gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");
    - possible structures as clumpiness with small scale size
    - Effects of gravitational focusing of the Sun



The annual modulation phase depends on :
- Presence of streams (as SagDEG and Canis Major) in the Galaxy
- Presence of caustics
- Effects of gravitational focusing of the Sun

The effect of the streams on the phase depends on the galactic halo model





A step towards such investigations:

➔**DAMA/LIBRA-phase2**

with lower energy threshold and larger exposure

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo now supported at 9.3σ C.L. (cumulative exposure 1.33 ton $\times$ yr – 14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1)
- The modulation parameters determined with increased precision
- Full sensitivity to many kinds of DM candidates and interactions types (both inducing recoils and/or e.m. radiation), full sensitivity to low and high mass candidates.
- New phase2 in progress to investigate further features of DM signals and second order effects
- Continuing investigations of rare processes other than DM as well as further developments

Thanks for attention