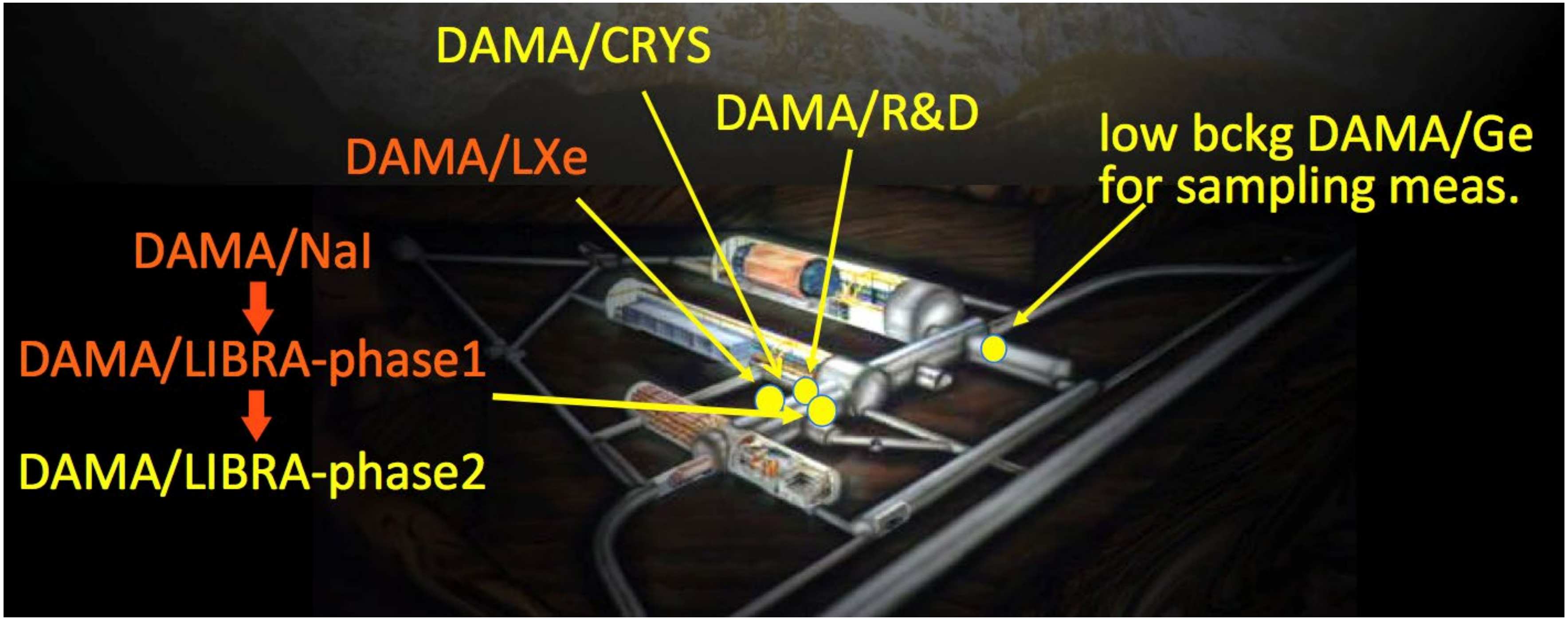
First Model Independent Results from DAMA/LIBRA–phase2

WIN19
International Workshop on Weak Interactions and Neutrinos
Bari - June 7th, 2019

V. Caracciolo (INFN – LNGS)
on behalf of the DAMA collaboration

DAMA set-ups

an observatory for rare processes @ LNGS



Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev + other institutions

+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

+ in some studies on ββ decays (DST-MAE and Inter-Universities project):

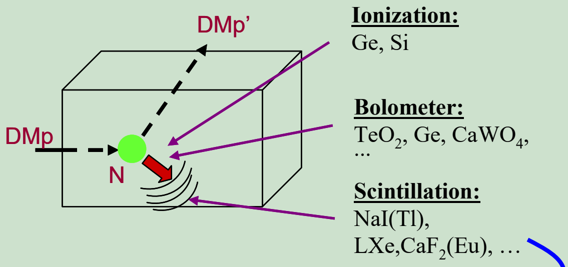
IIT Kharagpur and Ropar, India

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

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



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

  → W has 2 mass states χ+ , χ- with δ mass splitting

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

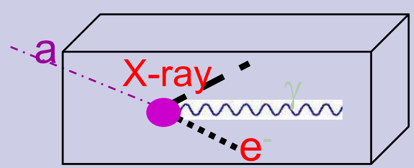
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

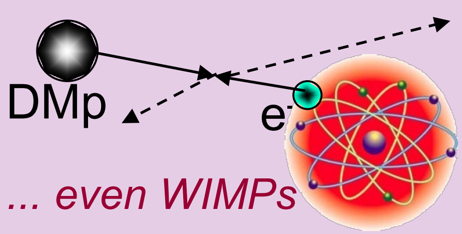
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e$^-$



- Interaction only on atomic electrons

  → detection of e.m. radiation

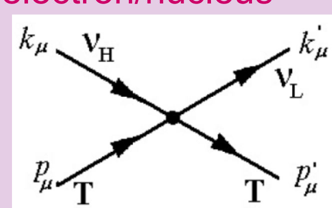


... *even WIMPs*

- 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 …

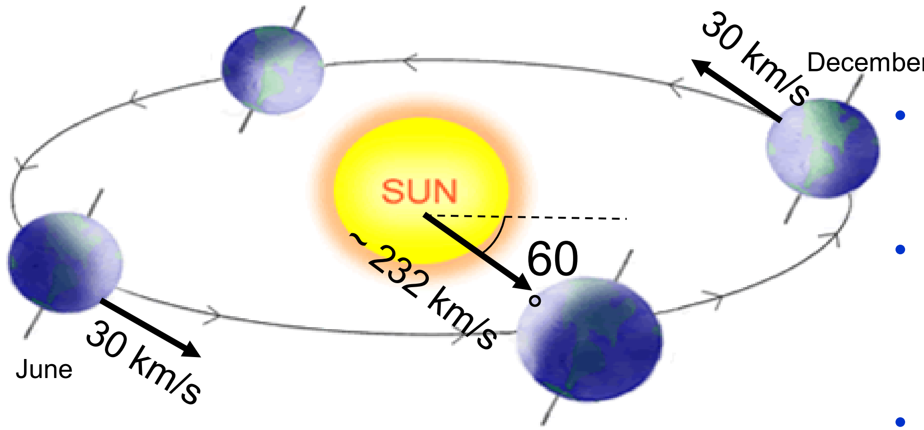
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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

Requirements:

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



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

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

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

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

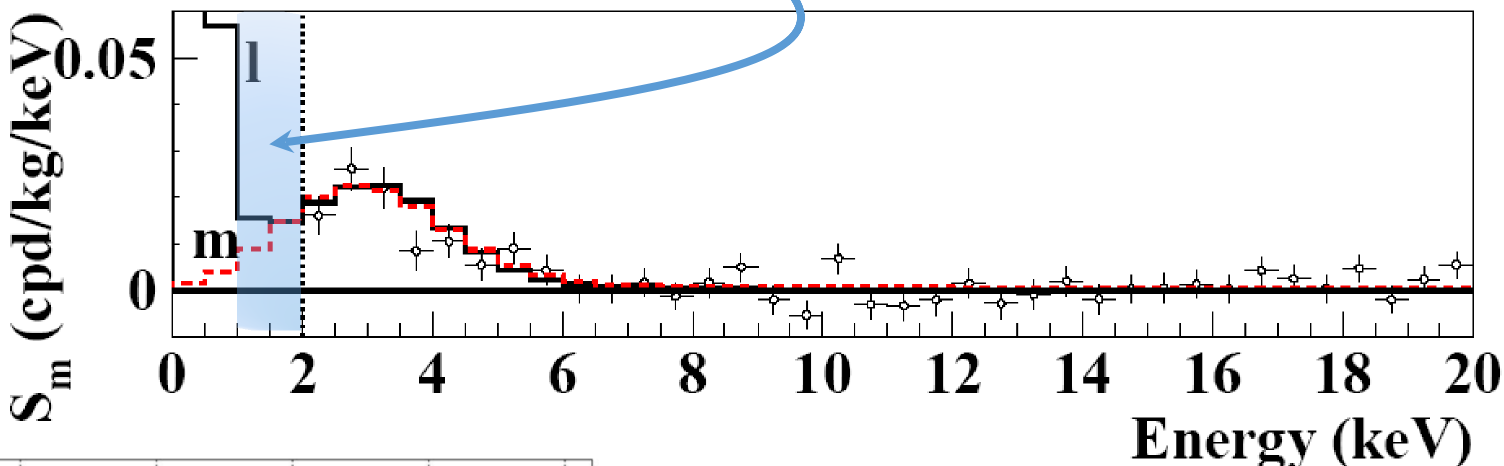
To mimic this signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

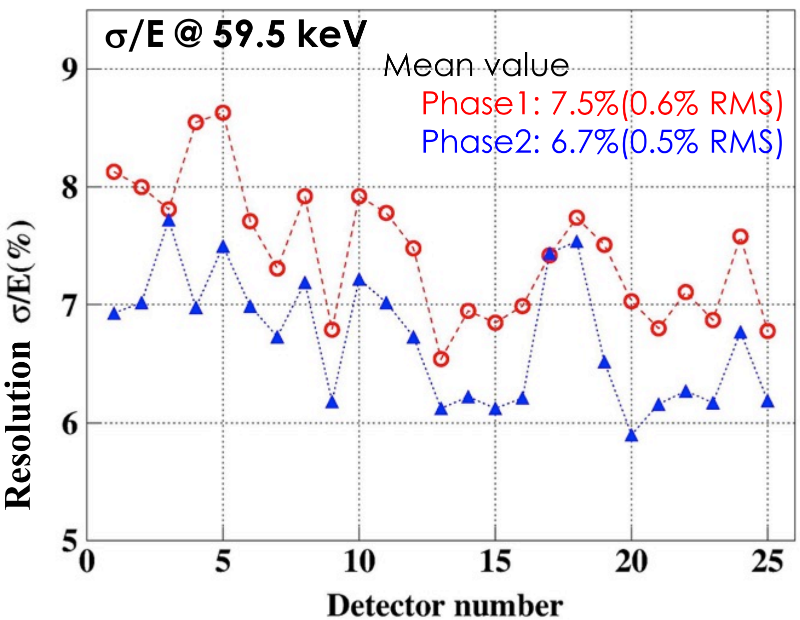
DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
Bled Workshop in Physics 19, 2 (2018) 27

Lowering software energy threshold below 2 keV:

- to study the nature of the particles and features of astrophysical, nuclear and particle physics aspects, and to investigate 2nd order effects
- special data taking for *other rare processes*





PMTs' contaminations:

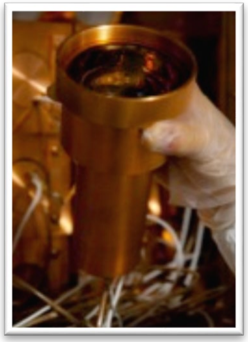
	^{226}Ra (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)
Mean Contamination	0.43	47	0.12	83	0.54
Standard Deviation	0.06	10	0.02	17	0.16

The light responses:

DAMA/LIBRA-phase1: 5.5 – 7.5 ph.e./keV
DAMA/LIBRA-phase2: 6-10 ph.e./keV

DAMA/LIBRA-phase2 data taking

Second upgrade at end of 2010: all PMTs replaced with new ones of higher Q.E.



Energy resolution @ 60 keV mean value: prev. PMTs 7.5% (0.6% RMS) new HQE PMTs 6.7% (0.5% RMS)

- ✓ Fall 2012: new preamplifiers installed + special trigger modules
- ✓ Calibrations 6 a. c.: $\approx 1.3 \times 10^8$ events from sources
- ✓ Acceptance window eff. 6 a. c.: $\approx 3.4 \times 10^6$ events ($\approx 1.4 \times 10^5$ events/keV)

Annual Cycles	Period	Mass (kg)	Exposure (kg×day)	$(\alpha-\beta^2)$
I	Dec 23, 2010 - Sept. 9, 2011	commissioning		
II	Nov. 2, 2011 - Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 - Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 - Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 - Sept. 9, 2015	242.5	71180	0.486
VI	Sept. 10, 2015 - Aug. 24, 2016	242.5	67527	0.522
VII	Sept. 7, 2016 - Sept. 25, 2017	242.5	75135	0.480

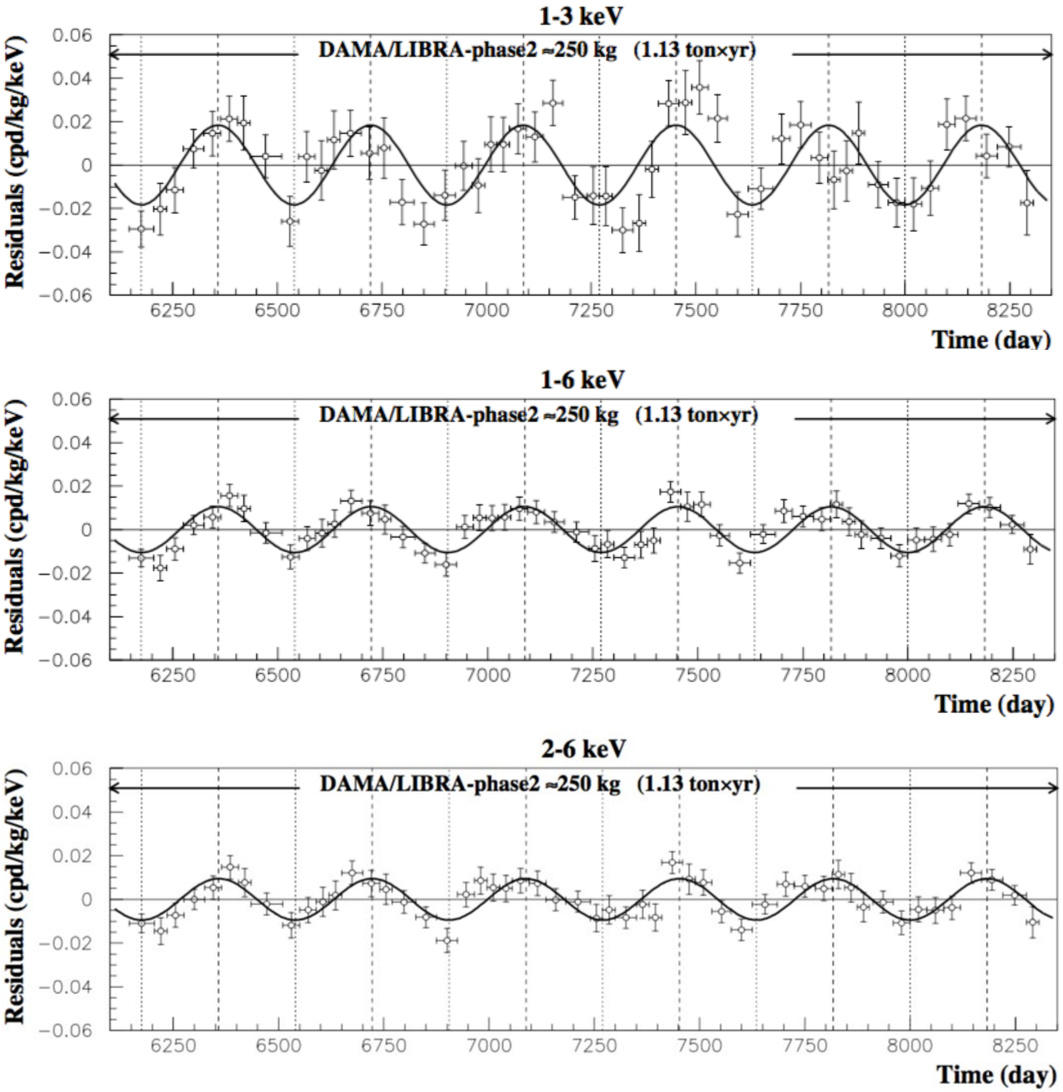
Exposure first data release of DAMA/LIBRA-phase2: **1.13 ton × yr**

Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.46 ton × yr**

DM model-independent Annual Modulation Result

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

DAMA/LIBRA-phase2 (1.13 ton × yr)



Absence of modulation? No

- 1-3 keV: χ^2/dof=127/52 $\Rightarrow$ P(A=0) = 3×10^{-8}
- 1-6 keV: χ^2/dof=150/52 $\Rightarrow$ P(A=0) = 2×10^{-11}
- 2-6 keV: χ^2/dof=116/52 $\Rightarrow$ P(A=0) = 8×10^{-7}

Fit on DAMA/LIBRA-phase2

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

1-3 keV

A=(0.0184±0.0023) cpd/kg/keV

χ^2/dof = 61.3/51 **8.0 σ C.L.**

1-6 keV

A=(0.0105±0.0011) cpd/kg/keV

χ^2/dof = 50.0/51 **9.5 σ C.L.**

2-6 keV

A=(0.0095±0.0011) cpd/kg/keV

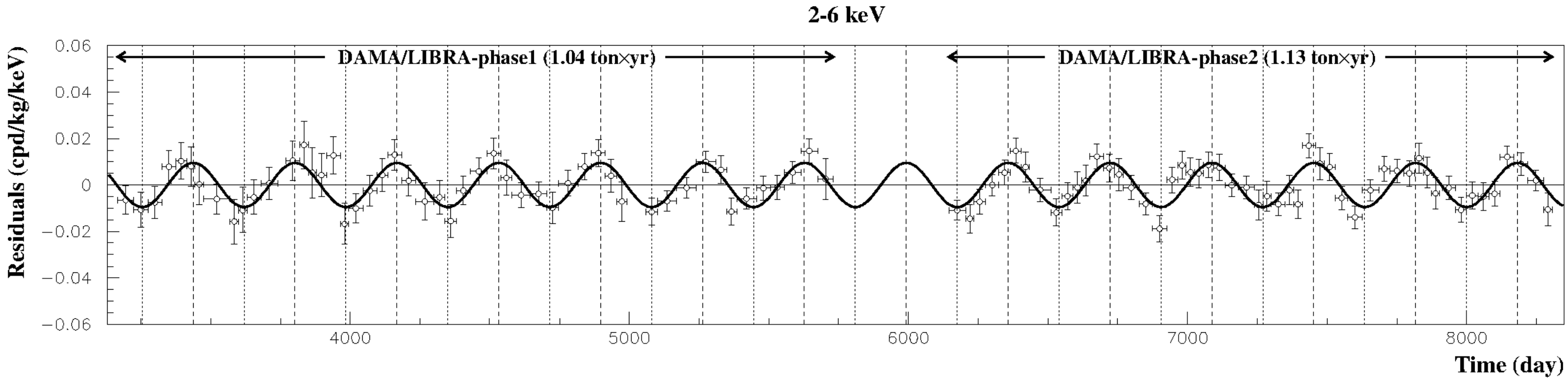
χ^2/dof = 42.5/51 **8.6 σ C.L.**

The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 9.5σ C.L.

DM model-independent Annual Modulation Result

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

DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.17 ton × yr)



Absence of modulation? No

- 2-6 keV: χ^2/dof=199.3/102 ⇒ P(A=0) =2.9×10^{-8}

Fit on DAMA/LIBRA-phase1+ DAMA/LIBRA-phase2

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

2-6 keV

A=(0.0095±0.0008) cpd/kg/keV

χ^2/dof = 71.8/101 **11.9σ C.L.**

The data of DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.9 σ C.L.

Releasing period (T) and phase (t_0) in the fit

	ΔE	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0184 ± 0.0023	1.0000 ± 0.0010	153 ± 7	8.0σ
	(1-6) keV	0.0106 ± 0.0011	0.9993 ± 0.0008	148 ± 6	9.6σ
	(2-6) keV	0.0096 ± 0.0011	0.9989 ± 0.0010	145 ± 7	8.7σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0096 ± 0.0008	0.9987 ± 0.0008	145 ± 5	12.0σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0103 ± 0.0008	0.9987 ± 0.0008	145 ± 5	12.9σ

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

DAMA/NaI (0.29 ton x yr)

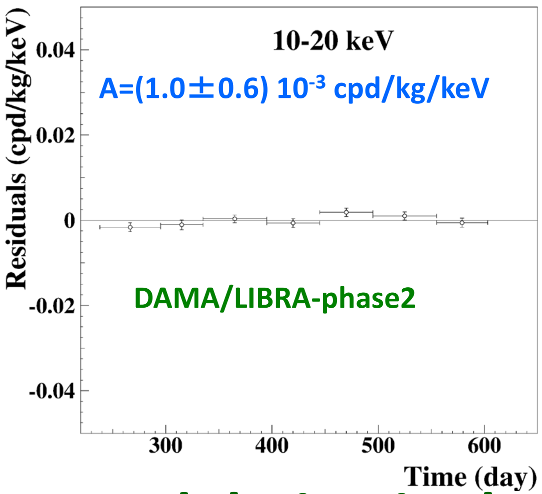
DAMA/LIBRA-ph1 (1.04 ton x yr)

DAMA/LIBRA-ph2 (1.13 ton x yr)

total exposure = 2.46 ton×yr

Rate behaviour above 6 keV

• No Modulation above 6 keV

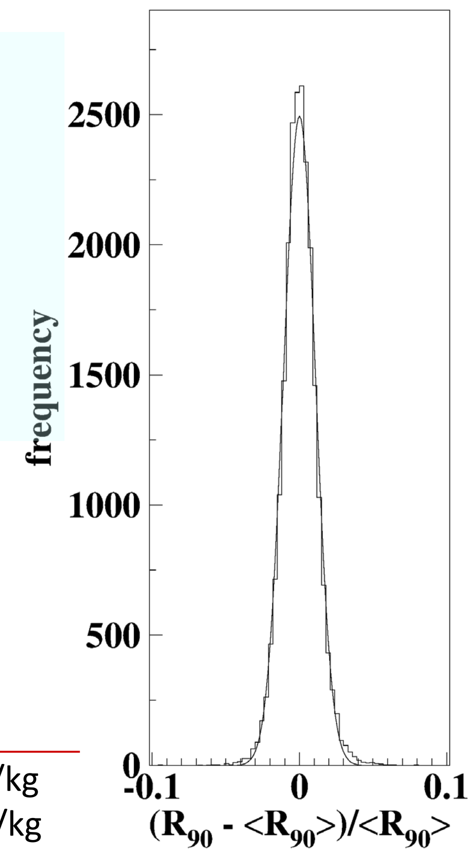


Mod. Ampl. (6-14 keV): cpd/kg/keV

(0.0032 ± 0.0017) DAMA/LIBRA-ph2_2
(0.0016 ± 0.0017) DAMA/LIBRA-ph2_3
(0.0024 ± 0.0015) DAMA/LIBRA-ph2_4
-(0.0004 ± 0.0015) DAMA/LIBRA-ph2_5
(0.0001 ± 0.0015) DAMA/LIBRA-ph2_6
(0.0015 ± 0.0014) DAMA/LIBRA-ph2_7

→ statistically consistent with zero

DAMA/LIBRA-phase2



σ ≈ 1%, fully accounted by statistical considerations

• No modulation in the whole energy spectrum:

studying integral rate at higher energy, R_{90}

- R_{90} percentage variations with respect to their mean values for single crystal
- Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles: **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

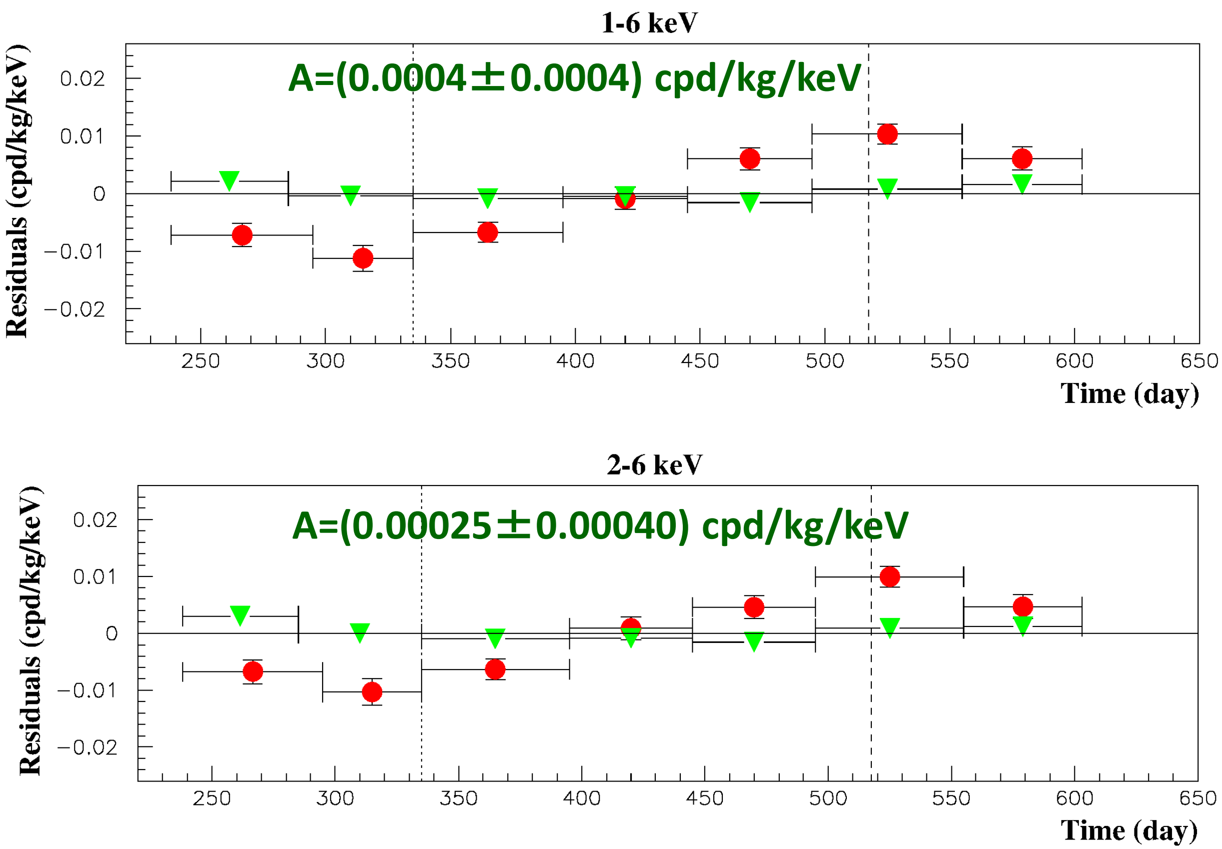
Period	Mod. Ampl.
DAMA/LIBRA-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg

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

DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.13 ton × yr)

Multiple hits events = Dark Matter particle "switched off"



Single hit residual rate (red)

vs

Multiple hit residual rate (green)

- Clear modulation in the single hit events;
- No modulation in the residual rate of the multiple hit events

This result furthermore rules out any side effect either from hardware or from software procedures or from background

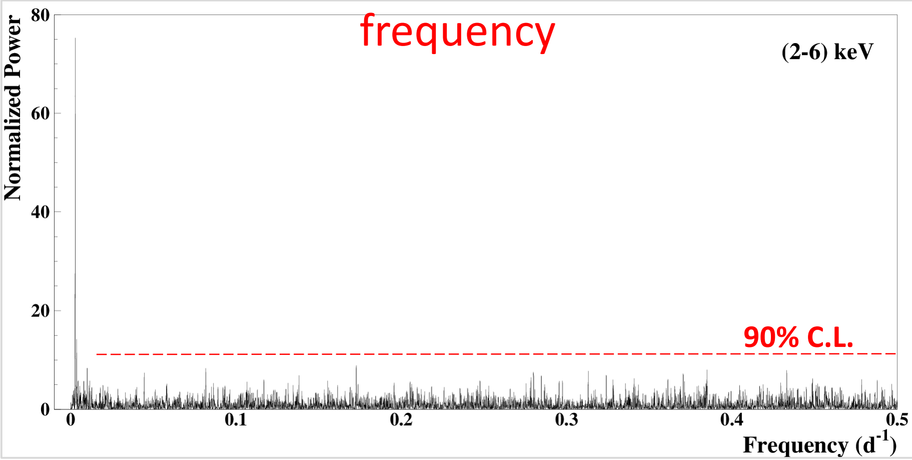
The analysis in frequency

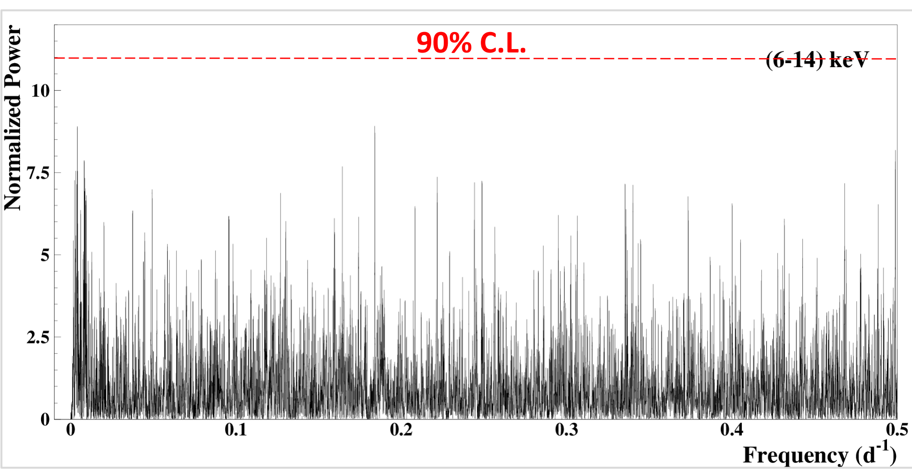
(according to PRD75 (2007) 013010)

To perform the Fourier analysis of the data in a wide region of frequency, the single-hit scintillation events have been grouped in 1 day bins

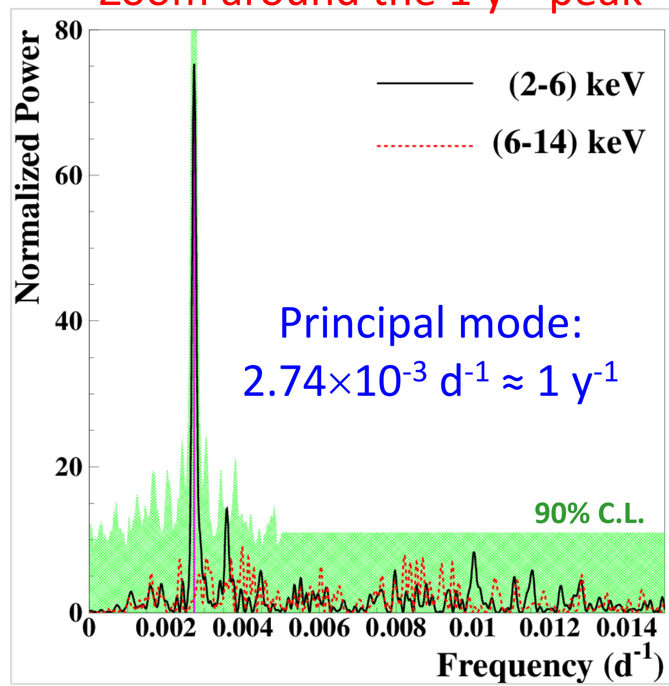
DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (20 yr)
total exposure: 2.46 ton×yr

The whole power spectra up to the Nyquist frequency





Zoom around the 1 y^{-1} peak



Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region

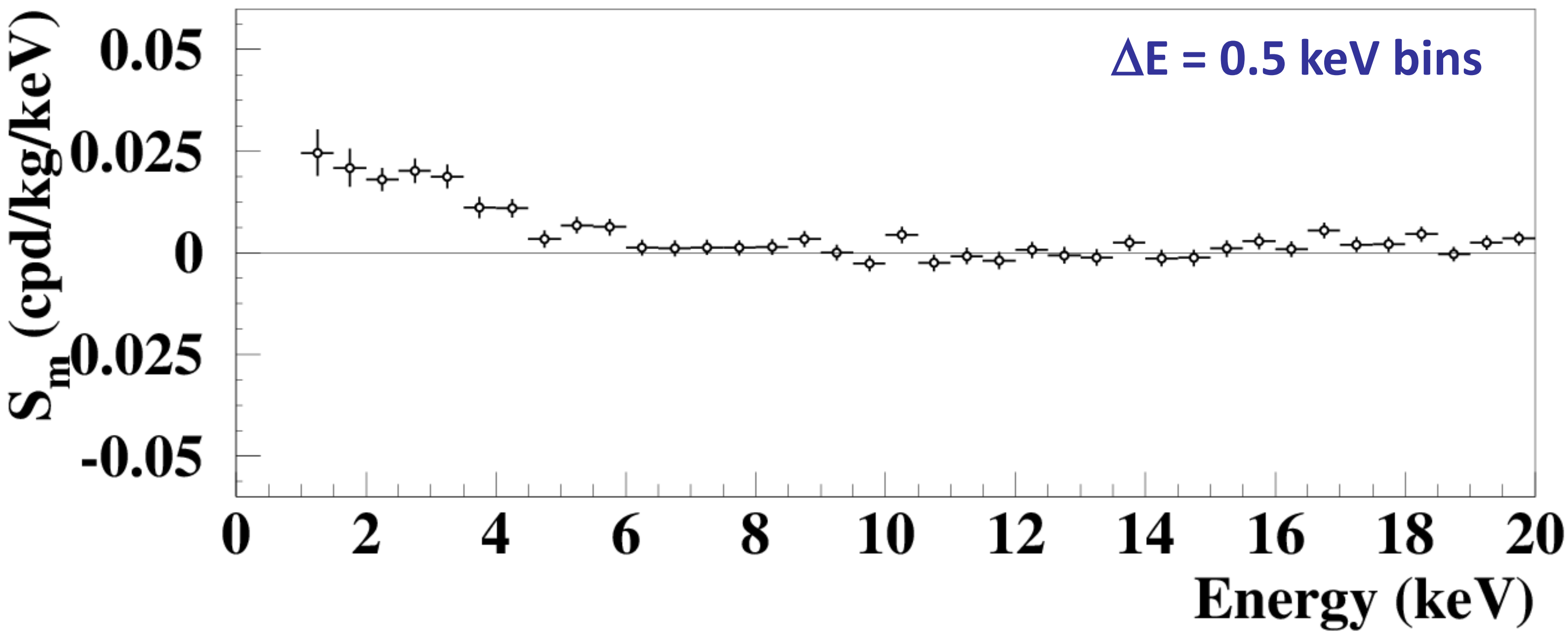
Energy distribution of the modulation amplitudes

Max-likelihood analysis

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

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

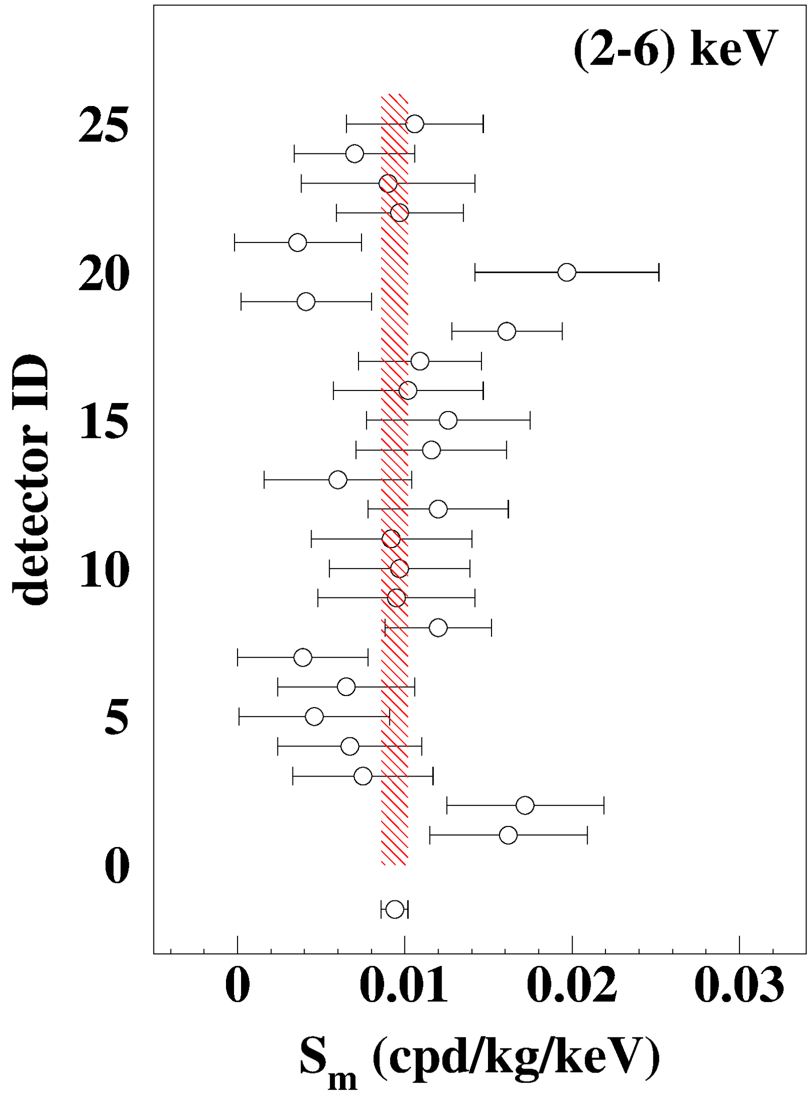
DAMA/NaI + DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2 (2.46 ton×yr)



A clear modulation is present in the (1-6) keV energy interval, while S_m values compatible with zero are present just above

- The S_m values in the (6–14) keV energy interval have random fluctuations around zero with χ^2 equal to 19.0 for 16 degrees of freedom (upper tail probability 27%).
- In (6–20) keV χ^2/dof = 42.6/28 (upper tail probability 4%). The obtained χ^2 value is rather large due mainly to two data points, whose centroids are at 16.75 and 18.25 keV, far away from the (1–6) keV energy interval. The P-values obtained by excluding only the first and either the points are 11% and 25%.

S_m for each detector



DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: **2.17 ton×yr**

S_m integrated in the range (2 - 6) keV for each of the 25 detectors (1σ error)

Shaded band = weighted averaged $S_m \pm 1\sigma$

χ^2/dof = 23.9/24 d.o.f.

The signal is well distributed over all the 25 detectors

•Contributions to the total neutron flux at LNGS;
•Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by:

- neutrons,
- muons,
- solar neutrinos.

$$\Phi_k = \Phi_{0,k}\left(1+\eta_k cos\omega\left(t-t_k\right)\right)$$
$$R_k = R_{0,k}\left(1+\eta_k cos\omega\left(t-t_k\right)\right)$$

EPJC 74 (2014) 3196 (also EPJC 56 (2008) 333, EPJC 72 (2012) 2064,IJMPA 28 (2013) 1330022)

Modulation amplitudes

	Source	$\Phi^{(n)}_{0,k}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)		$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2}-10^{-1}$ eV)	1.08×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8\times10^{-6}$	[2, 7, 8]	$\ll 8\times10^{-7}$	$\ll 7\times10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3\times10^{-3}$	[2, 7, 8]	$\ll 3\times10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha,n)\to$ n (1-10 MeV)	$\simeq 0.9\times10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6\times10^{-4}$	[2, 7, 8]	$\ll 6\times10^{-5}$	$\ll 5\times10^{-3}$
	$\mu\to$ n from rock ($>$ 10 MeV)	$\simeq 3\times10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7\times10^{-4}$	(see text and [2, 7, 8])	$\ll 9\times10^{-6}$	$\ll 8\times10^{-4}$
	$\mu\to$ n from Pb shield ($>$ 10 MeV)	$\simeq 6\times10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4\times10^{-3}$	(see text and footnote 3)	$\ll 2\times10^{-5}$	$\ll 1.6\times10^{-3}$
	$\nu\to$ n (few MeV)	$\simeq 3\times10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7\times10^{-5}$	(see text)	$\ll 2\times10^{-6}$	$\ll 2\times10^{-4}$
	direct μ	$\Phi^{(\mu)}_0\simeq 20$ μ $m^{-2}d^{-1}$ [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0\simeq 6\times10^{10}$ ν $cm^{-2}s^{-1}$ [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

All are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude.

+ In no case neutrons (of whatever origin) can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail, such as the neutrons would induce e.g. variations in all the energy spectrum, variation in the multiple hit events,… which were not observed.

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

NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, 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, EPJC74(2014)3196, IJMPA31(2017)issue31, Universe4(2018)03009, Beld19,2(2018)27

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<10^{-4} cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**<10^{-4} cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**<1-2 ×10^{-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	**<3×10^{-5} cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

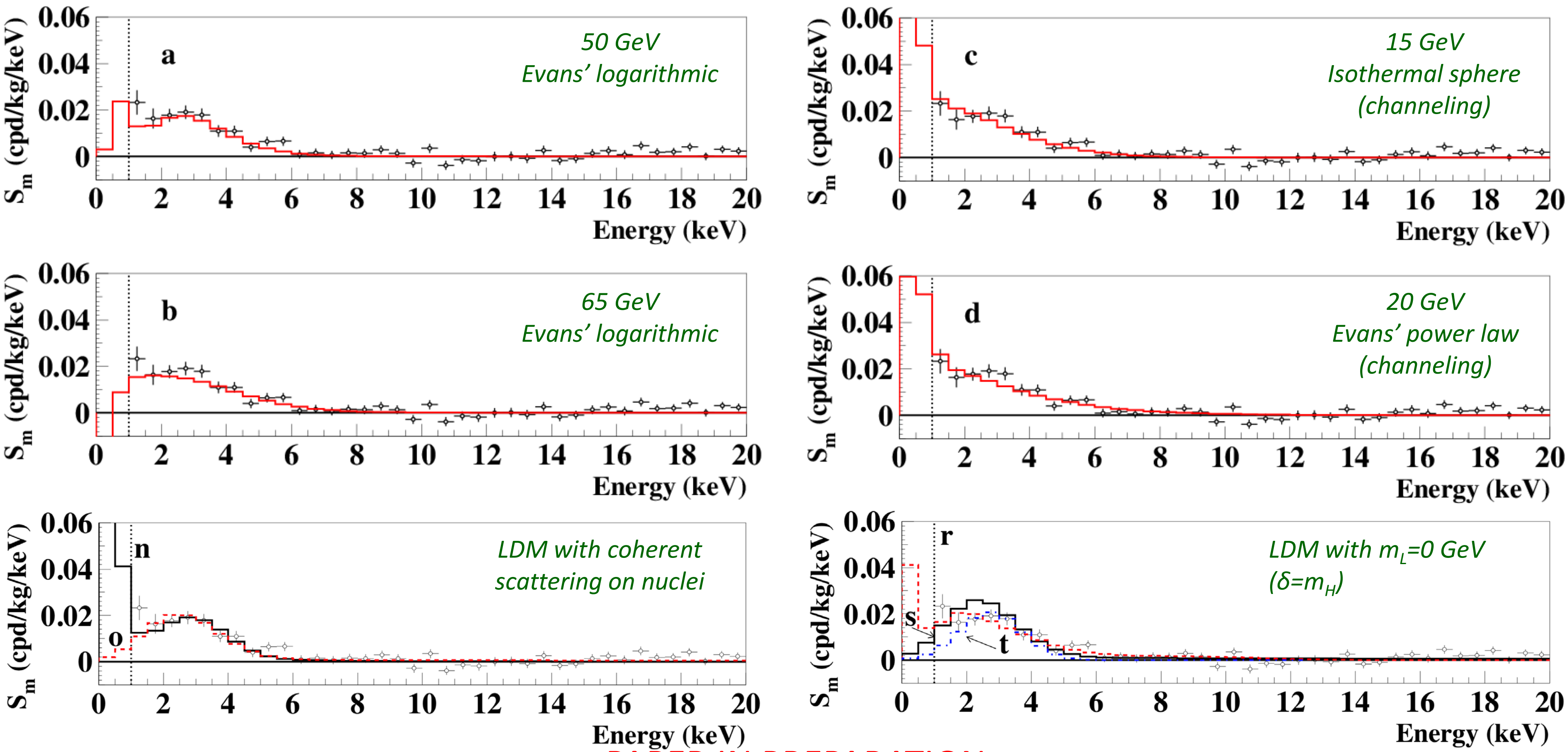
→

Thus, they cannot mimic the observed annual modulation effect

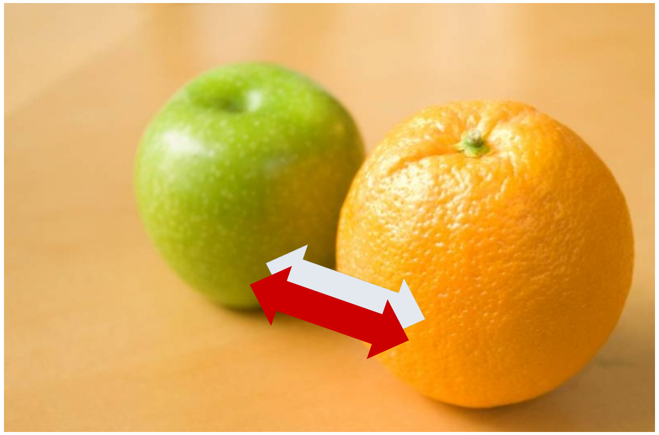
Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

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



… PAPER IN PREPARATION…



About interpretations and comparisons

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(2013)1330022

…models…

- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

…and experimental aspects…

- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling, …
- …

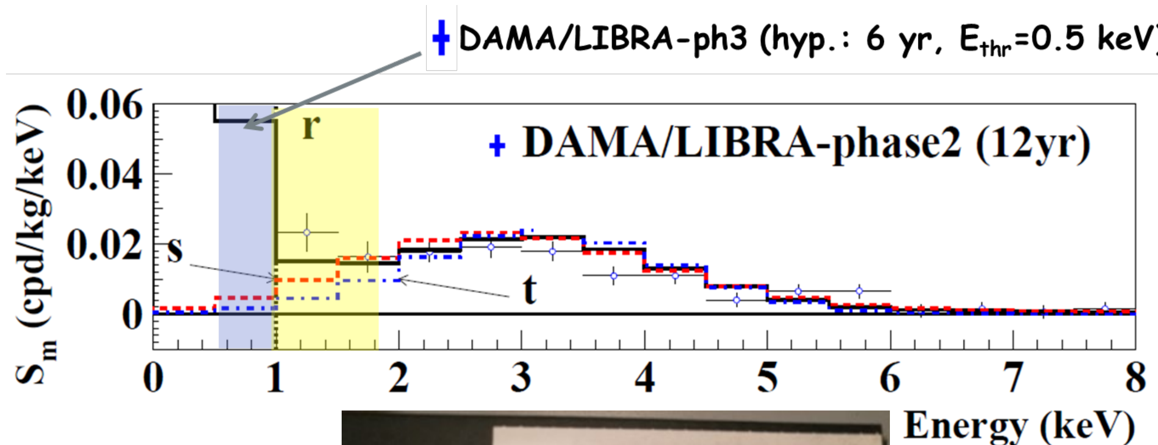
Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA

Running phase2 and towards DAMA/LIBRA–phase3 with software energy threshold below 1 keV

Enhancing sensitivities for DM corollary aspects, other DM features, second order effects and other rare processes:

- The light collection of the detectors can further be improved
- Light yields and the energy thresholds will improve accordingly
- The electronics can be improved too



- Chosen strategy:
  ① new development of high Q.E. PMTs with increased radio-purity.
  ② new miniaturized low background pre-amps directly mounted on the low background voltage dividers.
  ③ S/N increase by decreasing noise.

The presently-reached metallic PMTs features:

- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- Radio-purity at level of 5 mBq/PMT (^{40}K), 3-4 mBq/PMT (^{232}Th), 3-4 mBq/PMT (^{238}U), 1 mBq/PMT (^{226}Ra), 2 mBq/PMT (^{60}Co).

several prototypes from a dedicated R&D with HAMAMATSU at hand

Conclusions

- Model-independent positive evidence for the presence of DM particles in the galactic halo at **12.9σ** C.L. (20 independent annual cycles with 3 different set-ups: 2.46 ton $\times$ yr)
- Modulation parameters determined with increasing precision
- New investigations on different peculiarities of the DM signal exploited in progress
- 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**

- DAMA/LIBRA–phase2 **continuing data taking**
- DAMA/LIBRA–phase3 **R&D in progress**
- R&D for a possible DAMA/1ton - full sensitive mass - set-up, proposed to INFN by DAMA since 1996, **continuing at some extent** as well as **some other R&Ds**
- New corollary analyses **in progress**
- Continuing investigations of **rare processes** other than DM