FIRST MODEL INDEPENDENT RESULTS FROM DAMA/LIBRA–PHASE2

21ST BLED WORKSHOP 23.06-01.07.2018

"WHAT COMES BEYOND THE STANDARD MODELS?“

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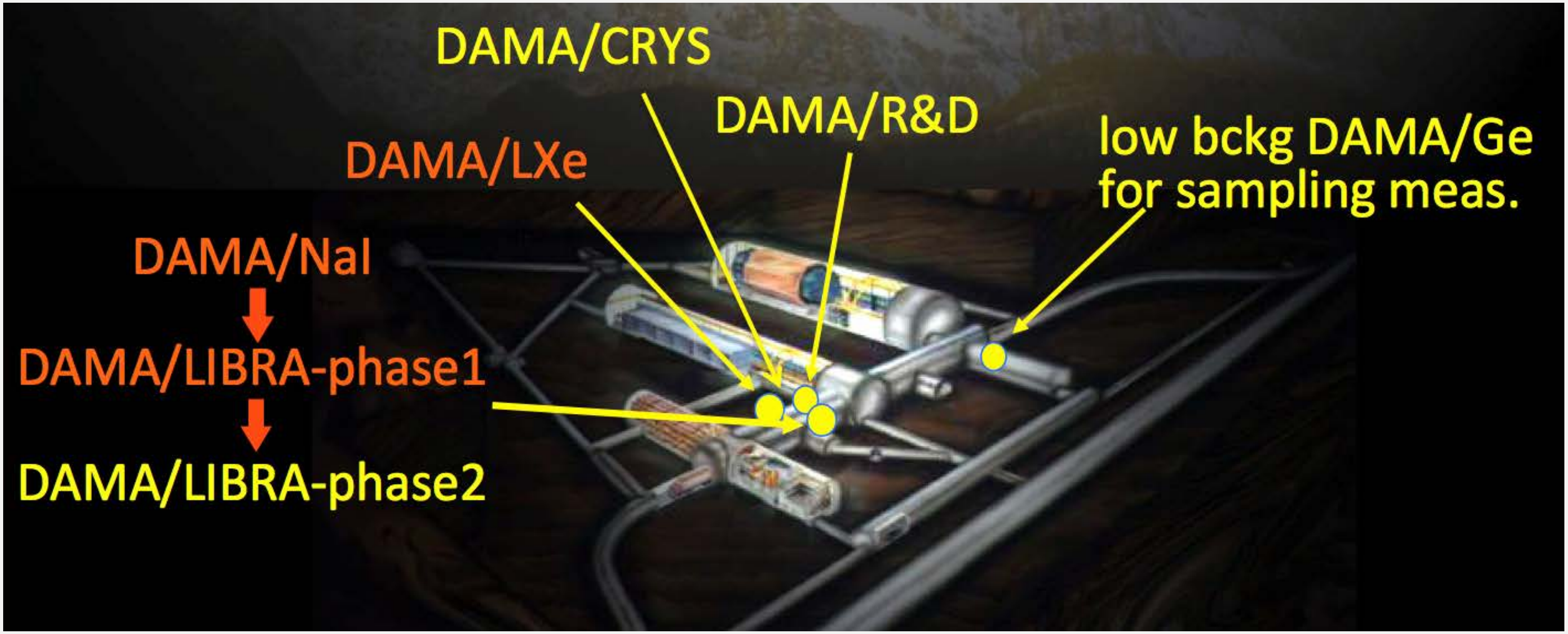
DAMA SET-UPS

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

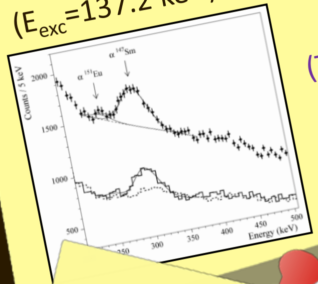
+ in some studies on $\beta\beta$ decays (DST-MAE & Inter-Univ. project): IIT Kharagpur and Ropar, India

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

MAIN RESULTS OBTAINED BY DAMA IN THE SEARCH FOR RARE PROCESSES

- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{156}Dy, ^{158}Dy, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt (observed $2\nu2\beta$ decay in ^{100}Mo, ^{116}Cd)
- The best experimental sensitivities in the field for 2β decays with positron emission (^{106}Cd)

First observation of α decays of ^{151}Eu with a CaF_2(Eu) scintillator and of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os



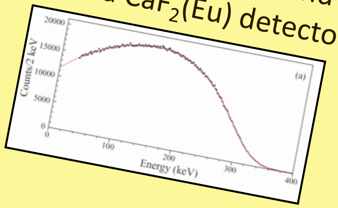
($T_{1/2}=5\times10^{18}$yr)

Observation of correlated e^+e^- pairs emission in α decay of ^{241}Am ($A_{e+e-}/A_\alpha \approx 5\times10^{-9}$)

Search for cluster decays of ^{127}I, ^{138}La and ^{139}La

Search for PEP violating processes in Sodium and in Iodine

Investigations of rare β decays of ^{113}Cd ($T_{1/2}=8\times10^{15}$yr), ^{113m}Cd with $CdWO_4$ scintillator and ^{48}Ca with a CaF_2(Eu) detector



Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

CNC processes, e.g. in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La

Search for ^{7}Li solar axions using resonant absorption in LiF crystal

Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state

Dark Matter investigation

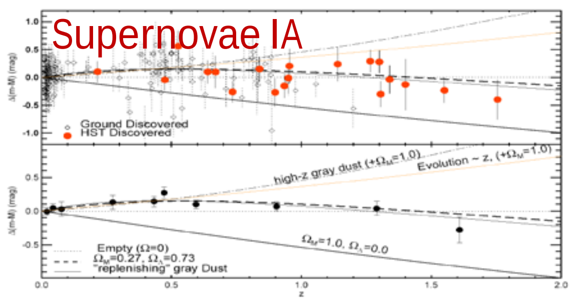
… many others are in progress

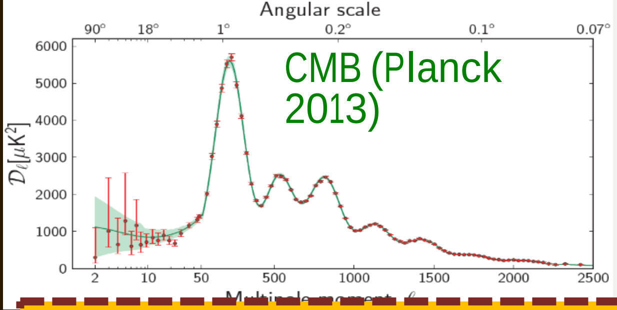
THE DARK SIDE OF THE UNIVERSE: EXPERIMENTAL EVIDENCES …

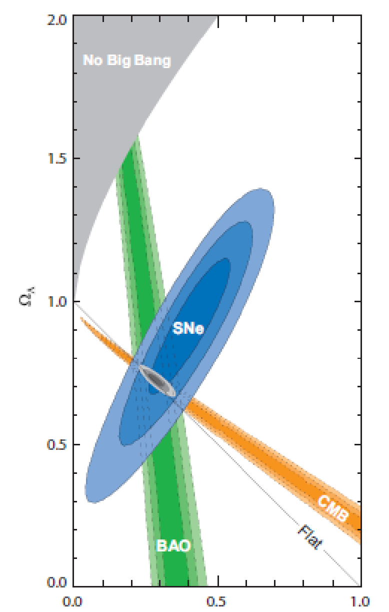
Main evidences

1915-1922: **Milky way models**
1933: **Zwicky claim "*overdensity in Coma Cluster*"**
1936: **Smith: high M/L in Virgo Cluster**
1974: **Study of rotational curves of galaxies**
2006: **Bullet Cluster**

And many others …







Concordance model

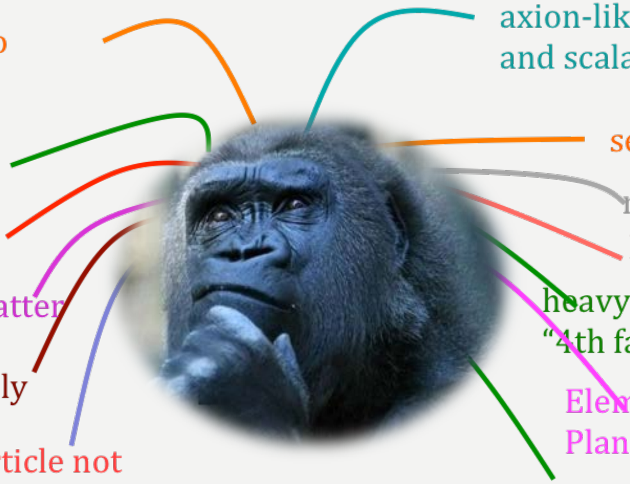
$$\frac{k}{R^2} = (\Omega_m + \Omega_\Lambda) - 1$$

$$\Omega_m = 0.27 \pm 0.03$$
$$\Omega_\Lambda = 0.73 \pm 0.03$$
$$\Omega_\Lambda + \Omega_M = \Omega \approx 1$$

Flat universe

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

RELIC DM PARTICLES FROM PRIMORDIAL UNIVERSE



SUSY
(as neutralino or sneutrino
in various scenarios)

the sneutrino in the Smith
and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not
yet foreseen by theories

etc...

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν’s

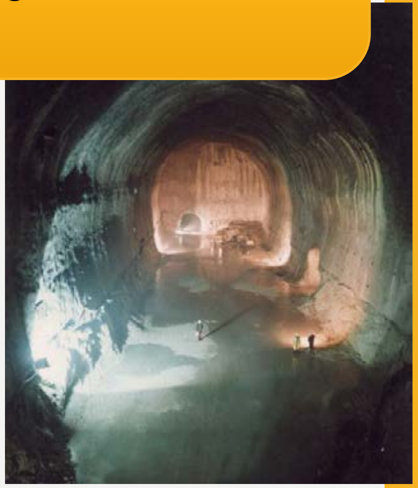
multi-component non-baryonic DM?

What accelerators can do:
to demostrate the existence of some of the possible DM candidates

What accelerators cannot do:
to credit that a certain particle is the Dark Matter solution or the “single” Dark Matter particle solution...

+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

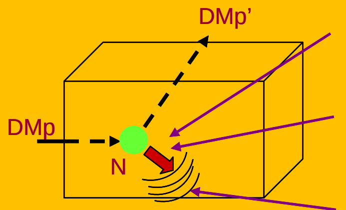
DM direct detection method using a model independent approach and a low-background widely-sensitive target material



SOME DIRECT DETECTION PROCESSES:

- Scatterings on nuclei

  → detection of nuclear recoil energy



Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, …

Scintillation:
NaI(Tl),
LXe,CaF_2(Eu), …

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

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

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

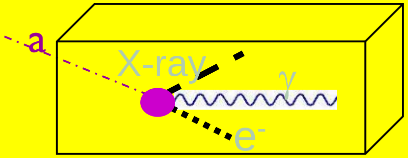
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

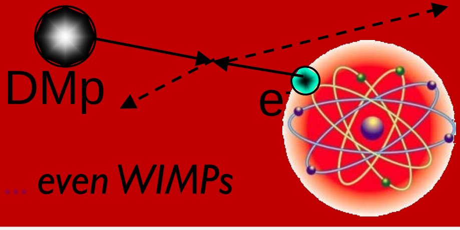
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

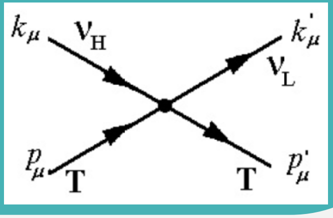


… even WIMPs

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

  → detection of electron/nucleus recoil energy

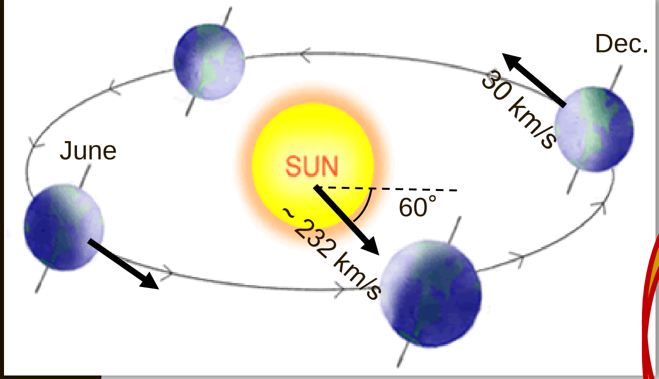
e.g. sterile ν



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



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

In direct detection experiments, the rate induced by DM particles depends on the relative velocity DM-detector, thus R depends on the Earth velocity in the galactic frame: $v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma\cos[\omega(t-t_0)]$

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

Drukier, Freese, Spergel PRD86; Freese et al. PRD88

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

Signal requirements

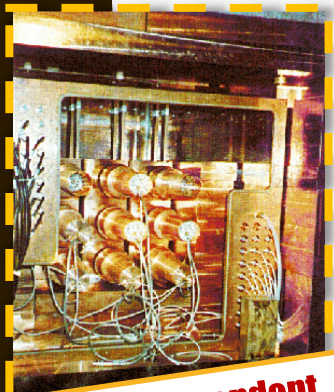
1. Modulated rate according cosine
2. In low energy range
3. With a proper period (1 year)
4. With proper phase (about 2 June)
5. Just for single hit events in a multi-detector set-up
6. With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions,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

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

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.

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

data taking completed on July 2002, last data release 2003 → Total exposure 0,29 ton×yr



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

Results on rare processes: Possible PEP 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, PJC23(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.

The DAMA/LIBRA set-up ~250 kg NaI(Tl)

Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009

Results on rare processes: Possible PEPv: EPJC62(2009)327, arXiv1712.08082; CNC: EPJC72(2012)1920; IPP in ^{241}Am: EPJA49(2013)64

Results on DM particles:

Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.

Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, EPJC75(2015)400, IJMPA31(2016) dedicated issue, EPJC77(2017)83

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

DAMA/LIBRA–phase1 (7 annual cycles, 1.04 ton×yr) confirmed the model-**independent evidence of DM: reaching 9.3σ C.L.**

DAMA/LIBRA–PHASE2

Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

JINST 7(2012)03009

Q.E. of the new PMTs:

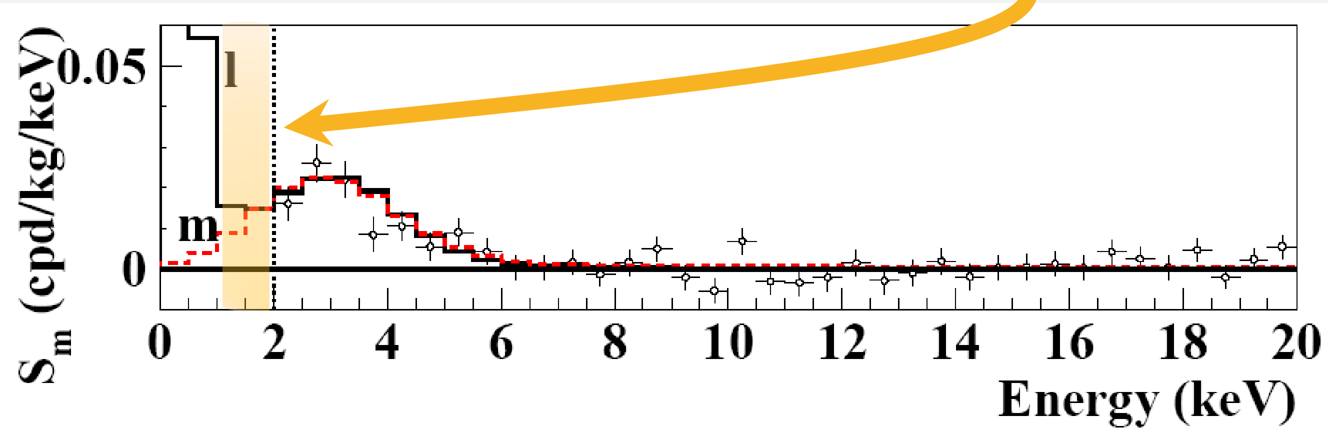
33 – 39% @ 420 nm
36 – 44% @ peak

DAMA/LIBRA–PHASE2

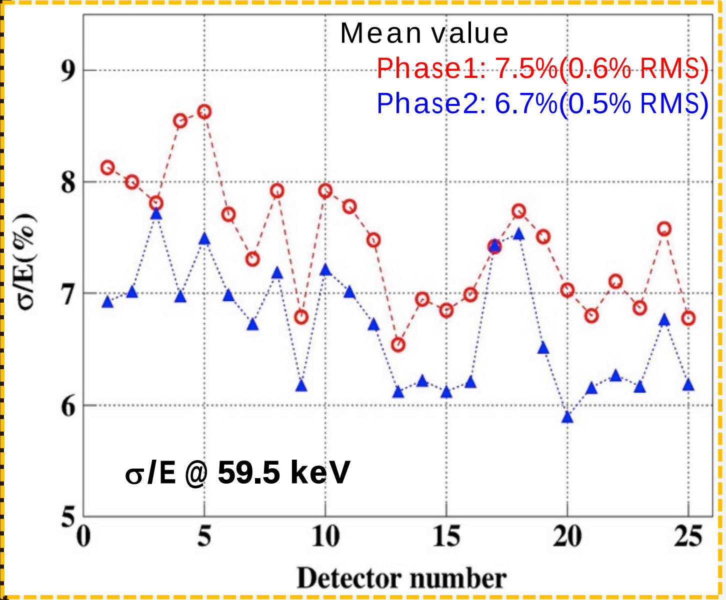
JINST 7(2012)03009

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*



The resolution:



The contaminations:

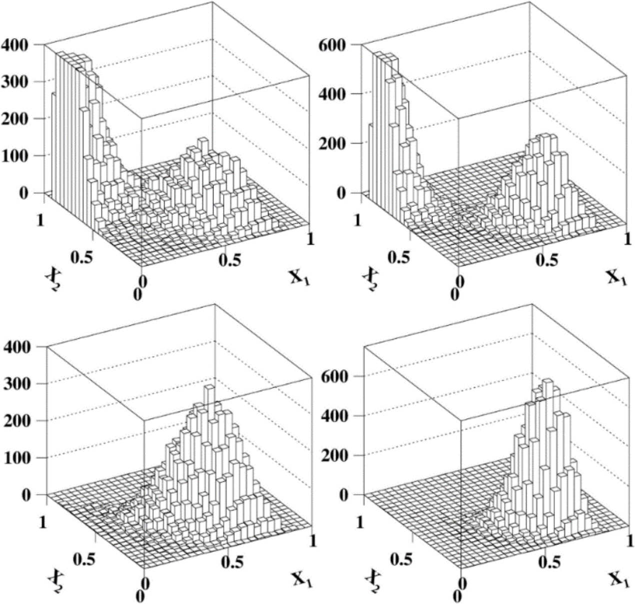
	^{226}Ra (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)
Mean Contamination	0.43	47	0.12	83	0.54
Standard Deviation	0.06	10	0.02	17	0.16

The light responses:

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

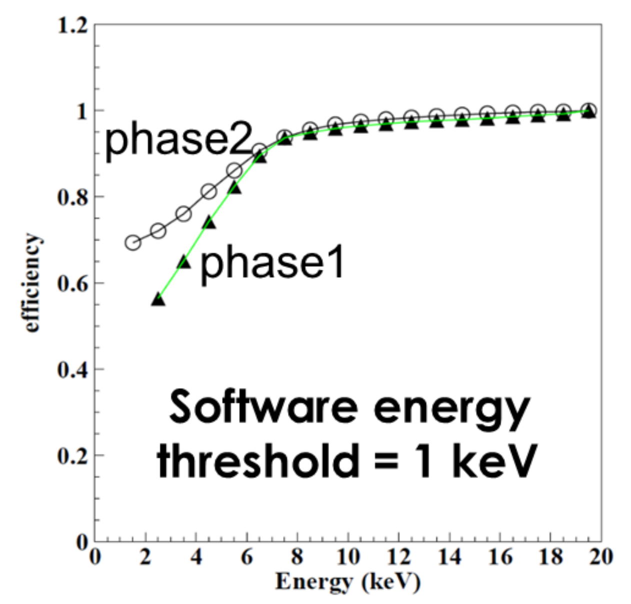
NOISE REJECTION IN PHASE2

JINST 7(2012)03009



- Comparison of the noise and the scintillation pulses distributions in 1-3 keV and 3-6 keV
- production data (top) vs γ source (bottom)
- scintillation events well separated from noise

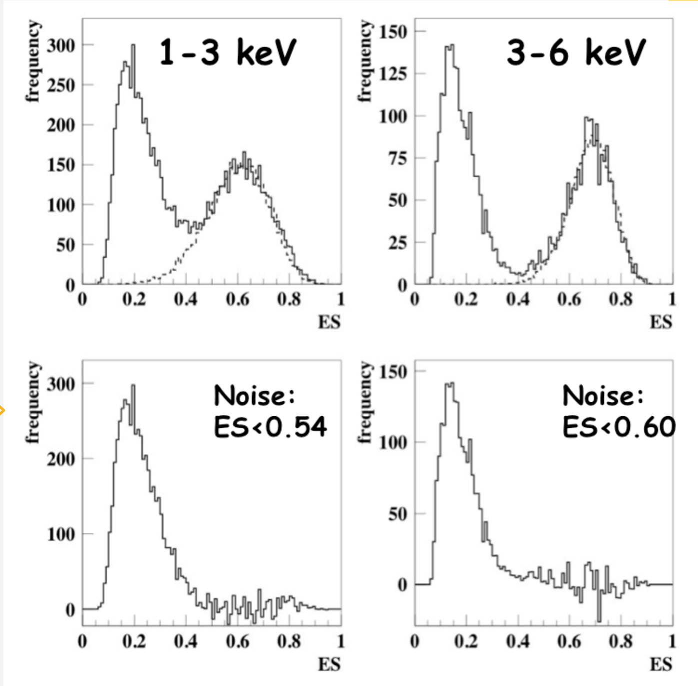
$$X_1 = \frac{Area(from\ 100\ to\ 60\ ns)}{Area(from\ 0\ to\ 60\ ns)} \qquad X_2 = \frac{Area(from\ 0\ to\ 50\ ns)}{Area(from\ 0\ to\ 60\ ns)}$$



Evaluation of residual noise

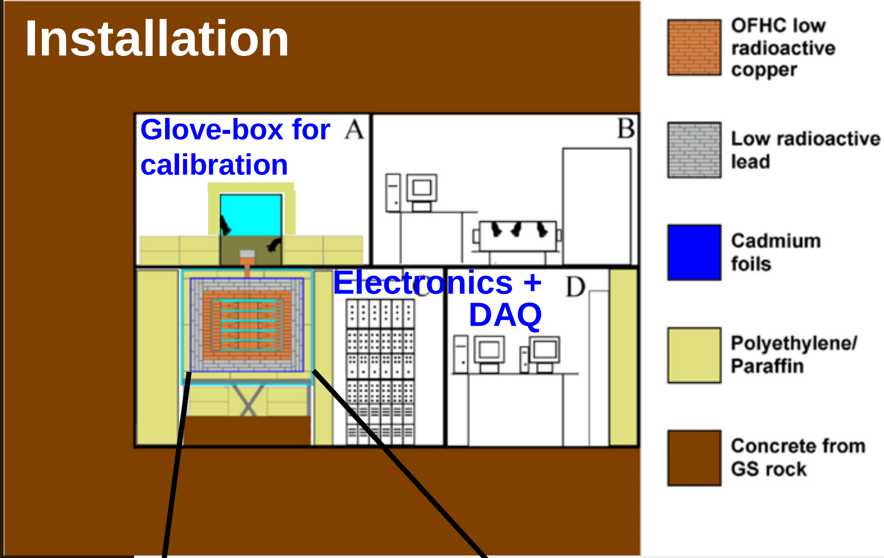
$$ES = \frac{1-(X_2-X_1)}{2}$$

Bottom plot obtained after subtraction from production data (continuous histos) of γ source data (dashed)

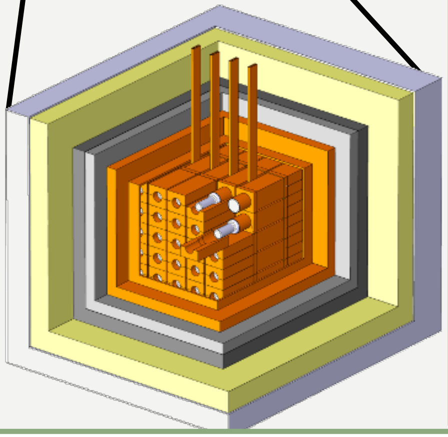


→ possible noise contamination, *f*, in the selected events <3% @ software energy threshold

THE DAMA/LIBRA–PHASE2 SET-UP



- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two new high Q.E. PMTs for each crystal working in coincidence at the single ph. el. threshold
- **6-10 phe/keV; 1 keV software energy threshold**
- Whole setup decoupled from ground
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- Dismounting/Installing protocol in HPN_2
- All the materials selected for low radioactivity
- **Three-level system to exclude Radon from the detectors**



- Multiton-multicomponent passive shield (>10 cm of OFHC Cu, 15 cm of boliden Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Calibrations in the same running conditions as prod runs
- Never neutron source in DAMA installations
- 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 Acqiris DC270 (2chs per detector), 1 *Gs/s,* 8 bit, bandwidth 250 MHz both for single-hit and multiple-hit events
- Data collected from low energy up to MeV region, despite the hardware optimization for low energy
- DAQ with optical readout
- New electronic modules

NIMA592(2008)297, JINST 7(2012)03009, IJMPA31(2017)issue31

DAMA/LIBRA-PHASE2 DATA TAKING

JINST 7(2012)03009, arXiv:1805.10486

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)

Annual Cycles	Period	Mass (kg)	Exposure	$(\alpha-\beta^2)$
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

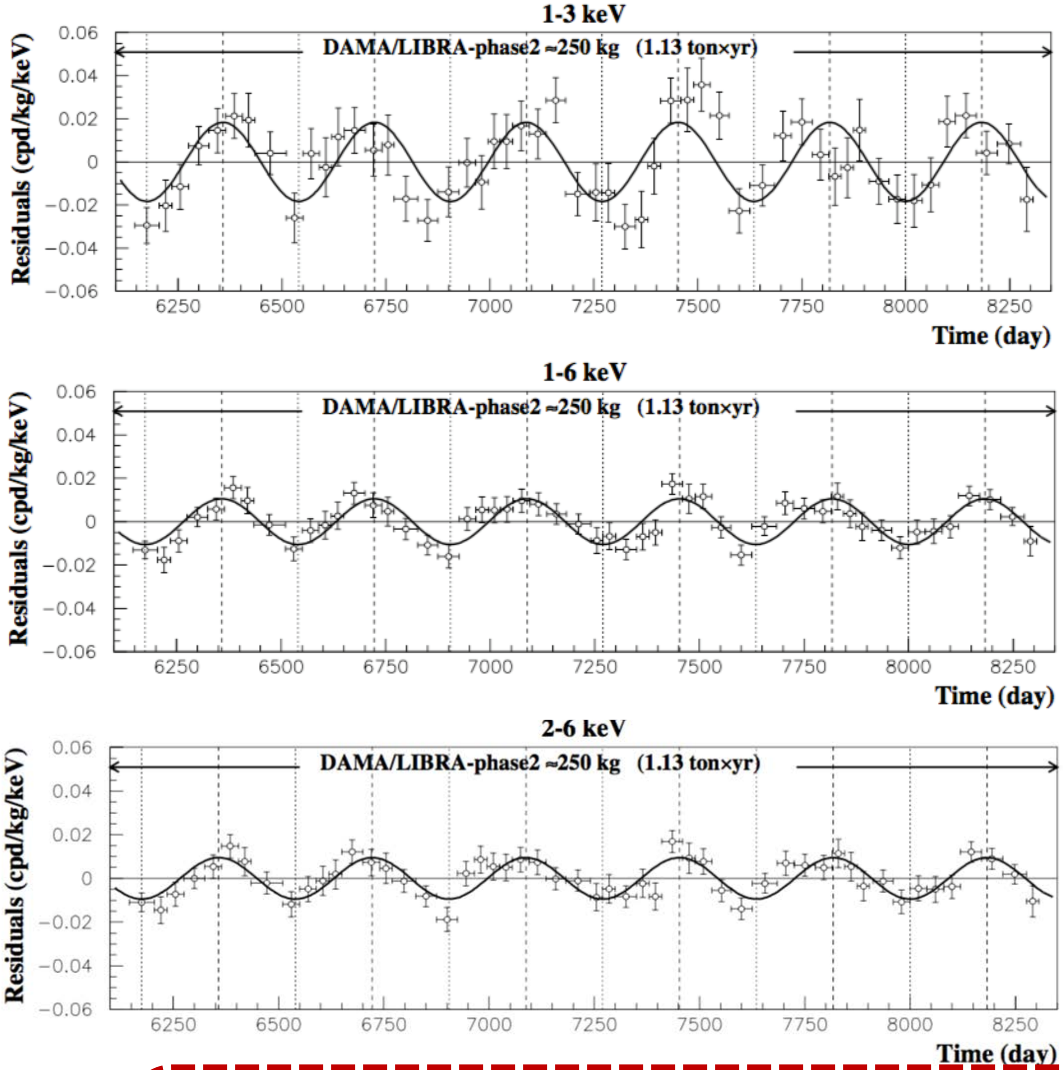
- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 6 a.c.: ≈1.3 x 10^8 events from sources
- ✓ Acceptance window eff. 6 a.c.: ≈3.4 x 10^6 events (≈1.4 x 10^5 events/keV)

Exposure first data release of DAMA/LIBRA-phase2: 1.13 ton x yr
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: 2.46 ton x 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 ⇒ P(A=0) = 3×10^{-8}
- 1-6 keV: χ^2/dof=150/52 ⇒ P(A=0) = 2×10^{-11}
- 2-6 keV: χ^2/dof=116/52 ⇒ 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

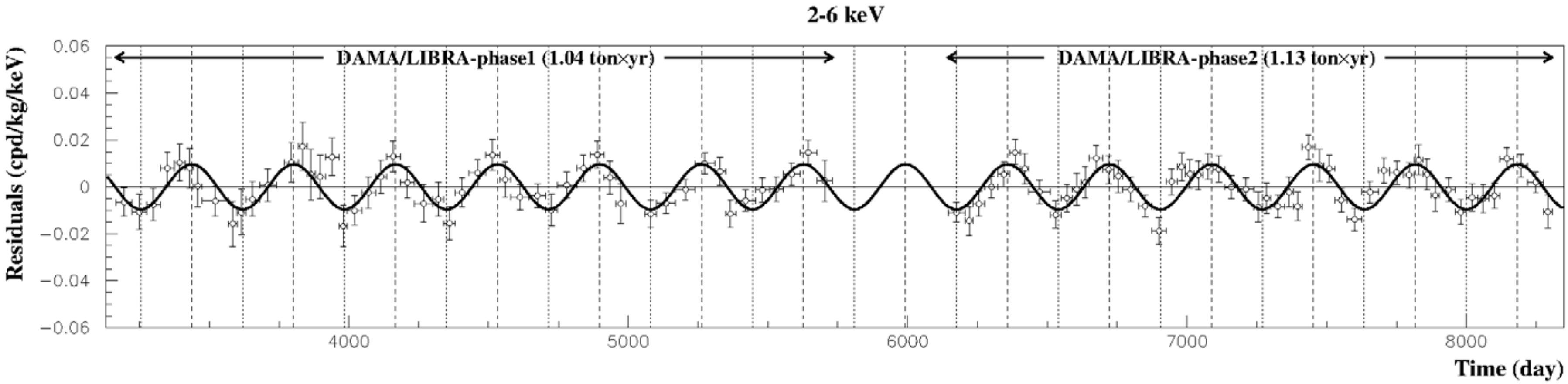
χ^2/dof = 42.5/51 **8.6 σ C.L.**

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 11.9 σ 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=2π/ω (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)

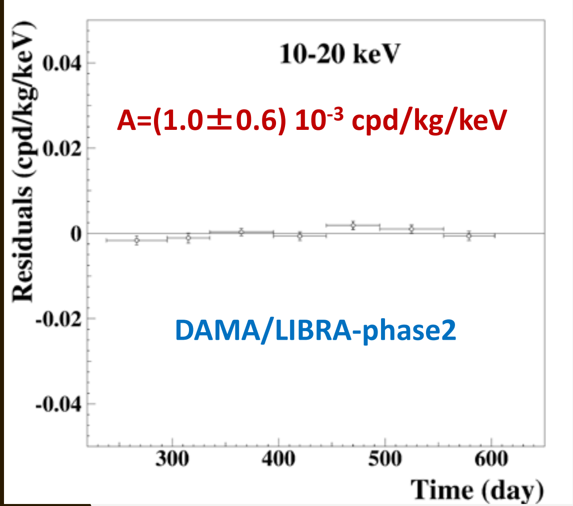
DAMA/LIBRA-ph1 (1.04 ton x yr)

DAMA/LIBRA-ph2 (1.13 ton x yr)

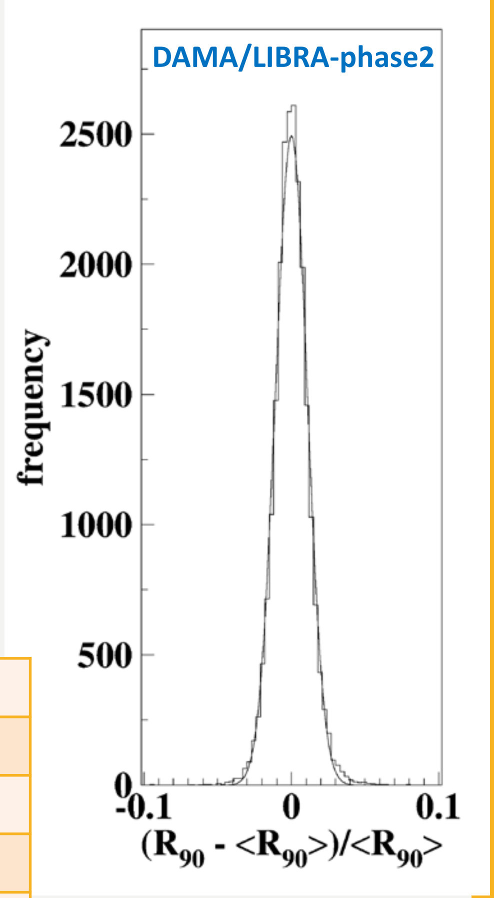
total exposure = 2.46 ton×yr

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



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 in the DAMA/LIBRA running periods
- Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:
  consistent with zero

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

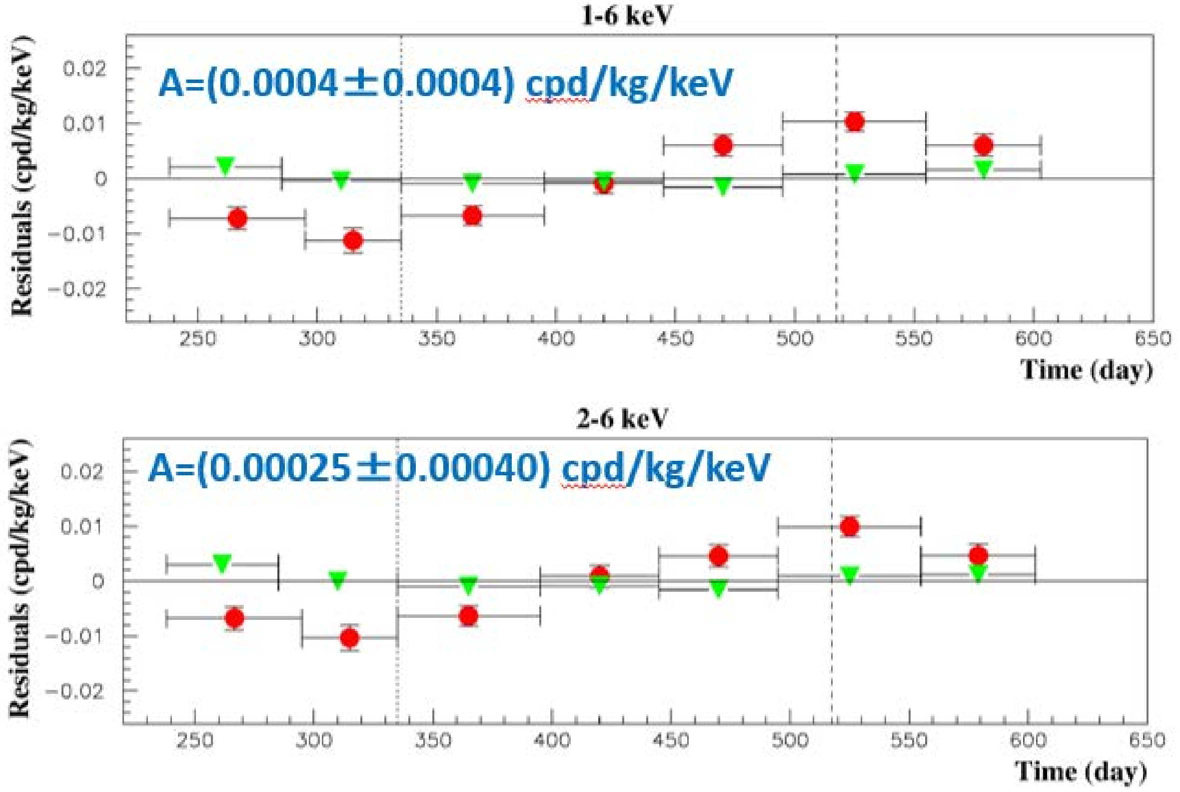
+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

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

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

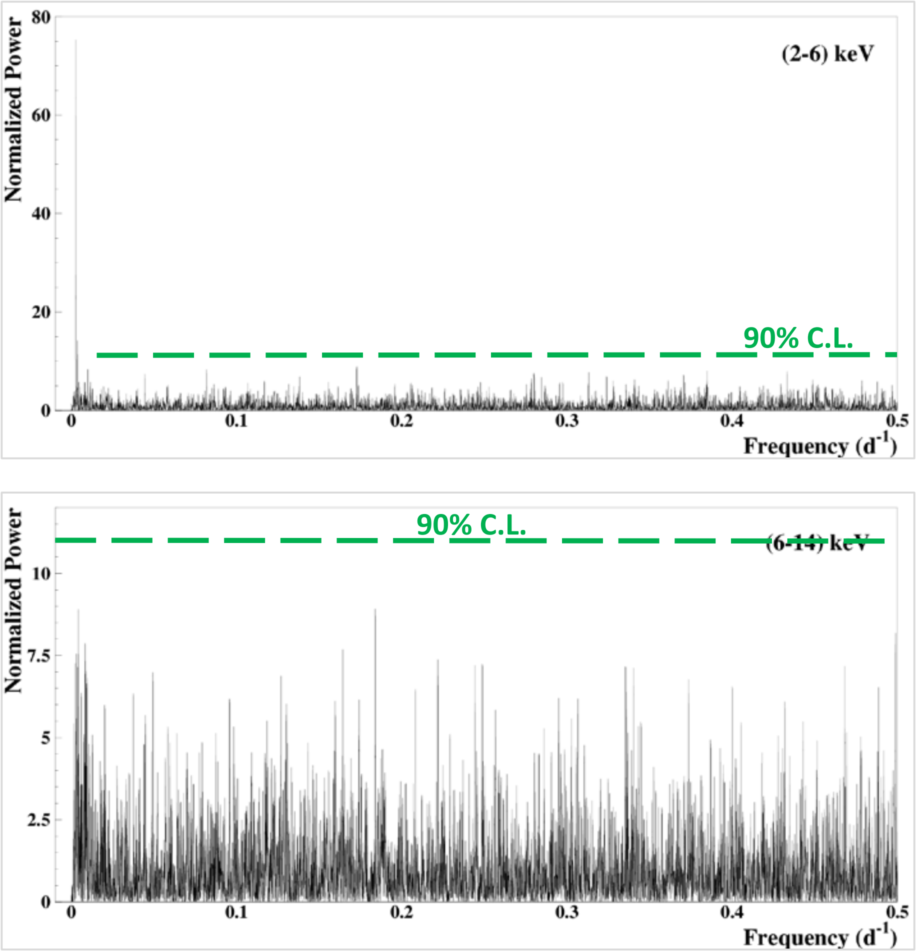
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

THE ANALYSIS IN FREQUENCY

(according to Phys. Rev. D 75 (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

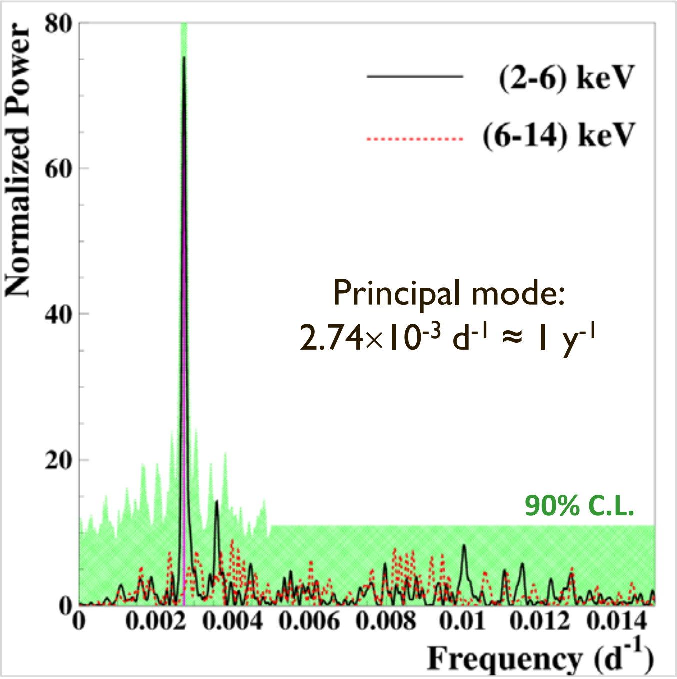
Whole power spectra up to the Nyquist frequency



DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (20 yr)

total exposure: 2.46 ton × yr

Zoom around the 1 y^{-1} peak



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

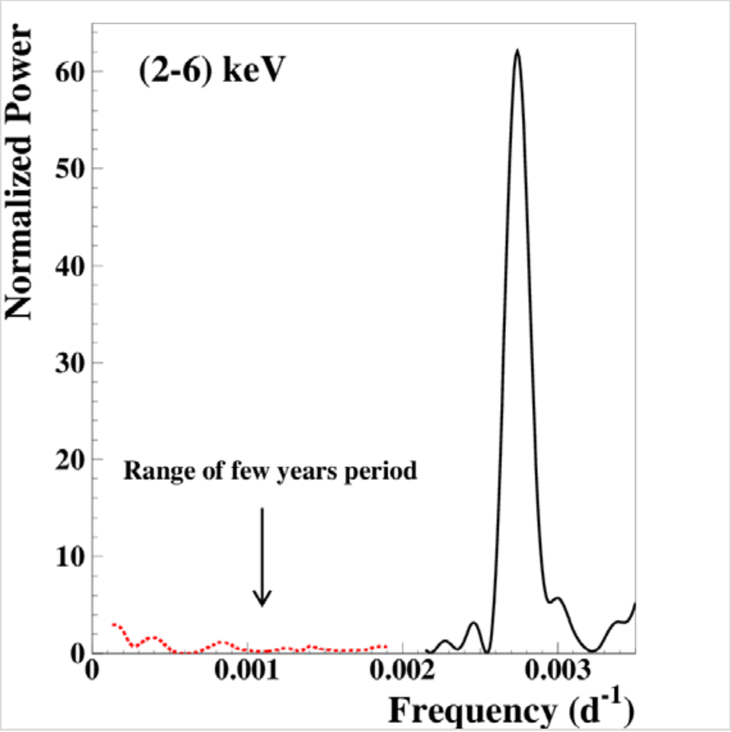
Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region

INVESTIGATING THE POSSIBLE PRESENCE OF LONG TERM MODULATION IN THE COUNTING RATE

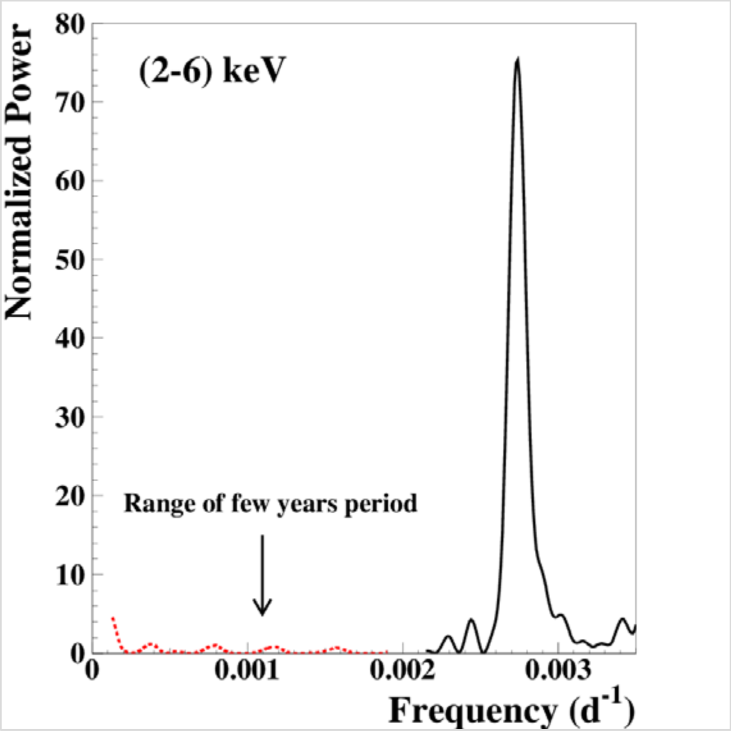
We calculated annual baseline counting rates – that is the averages on all the detectors (j index) of *flat*$_j$ (i.e. the single-hit scintillation rate of the j-th detector averaged over the annual cycle)

For comparison the power spectra for the measured single-hit residuals in (2–6) keV are also shown: Principal modes @ 2.74×10^{-3} d^{-1} ≈ 1 y^{-1}

DAMA/LIBRA-(ph1+ph2)



DAMA/NaI + DAMA/LIBRA-(ph1+ph2)



No statistically significant peak at lower frequency

ENERGY DISTRIBUTION OF THE MODULATION AMPLITUDES

Max-likelihood analysis

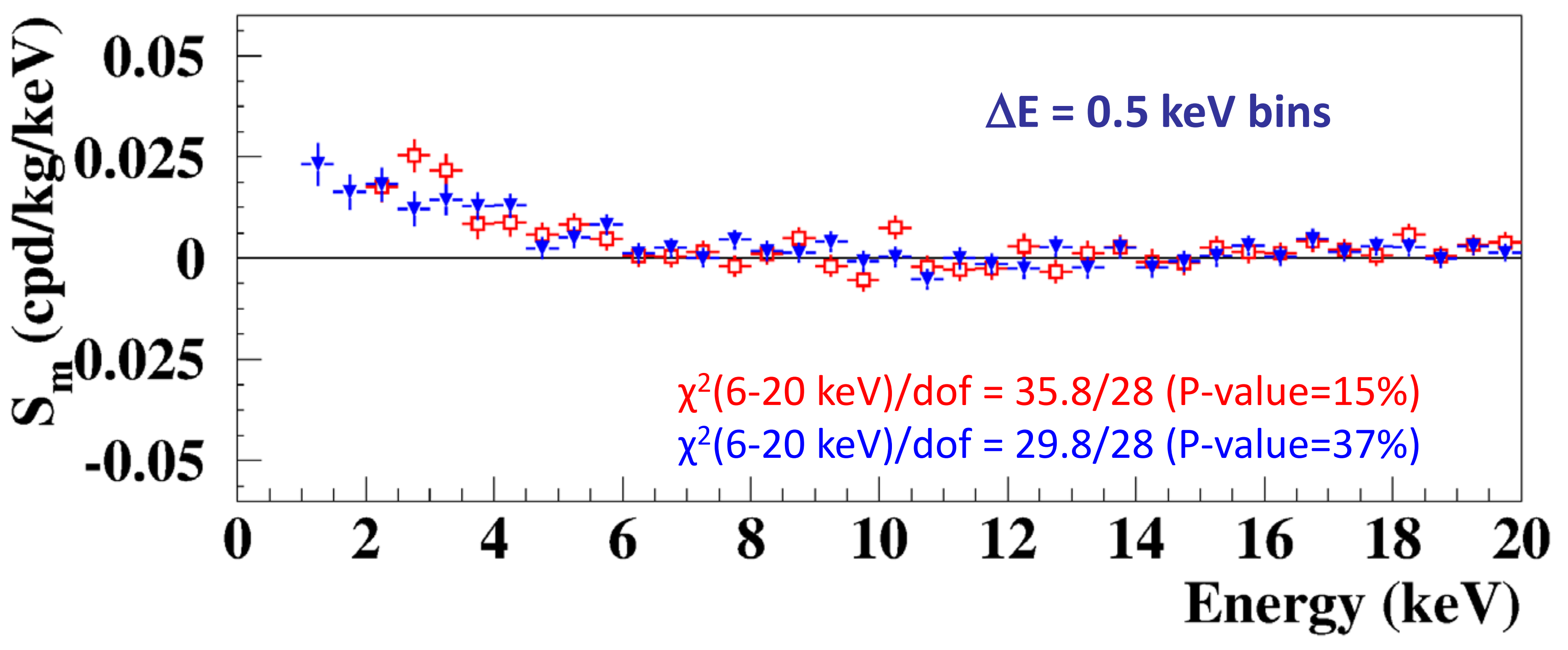
$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right]$$

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

DAMA/NaI + DAMA/LIBRA-phase1

vs

DAMA/LIBRA-phase2



χ^2(6-20 keV)/dof = 35.8/28 (P-value=15%)

χ^2(6-20 keV)/dof = 29.8/28 (P-value=37%)

The two S_m energy distributions obtained by DAMA/NaI+DAMA/LIBRA-ph1 and DAMA/LIBRA-ph2 are consistent in the (2–20) keV energy interval:

$\chi^2 = \Sigma (r_1 - r_2)^2/(\sigma_1^2+\sigma_2^2)$	(2-20) keV	χ^2/d.o.f.=32.7/36	(P=63%)
	(2-6) keV	χ^2/d.o.f.=10.7/8	(P=22%)

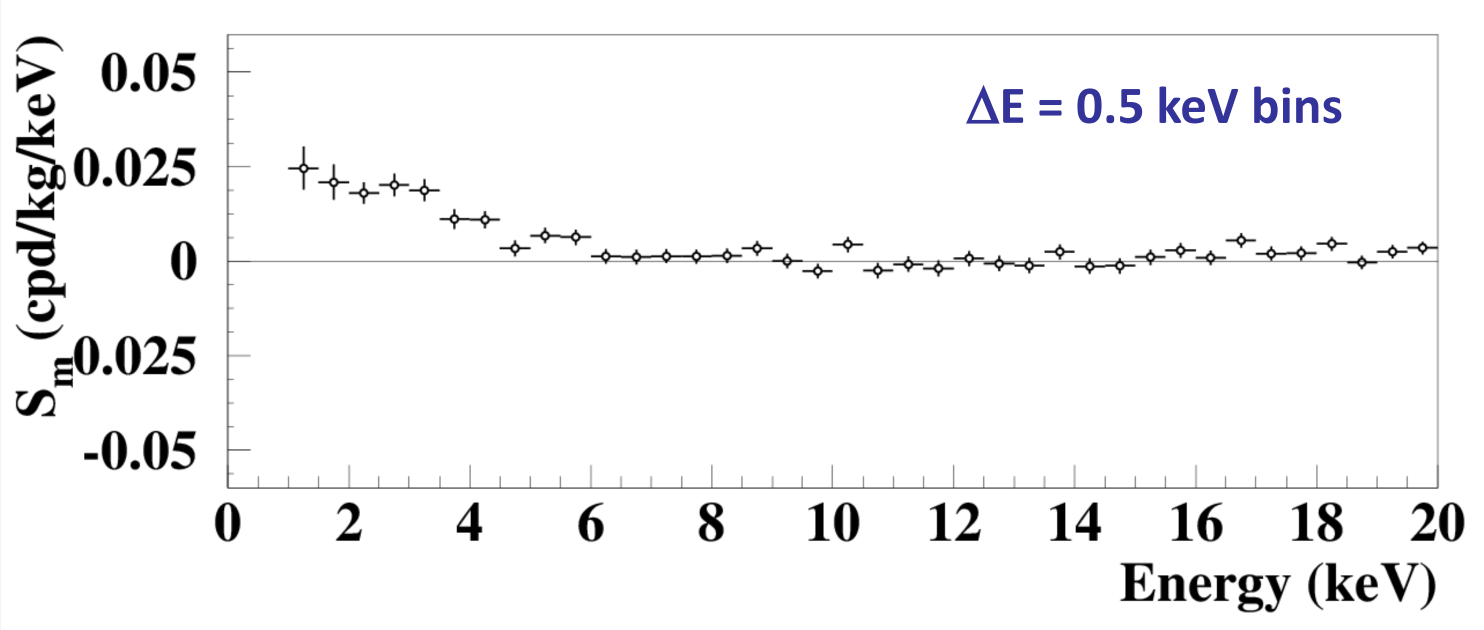
ENERGY DISTRIBUTION OF THE MODULATION AMPLITUDES

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

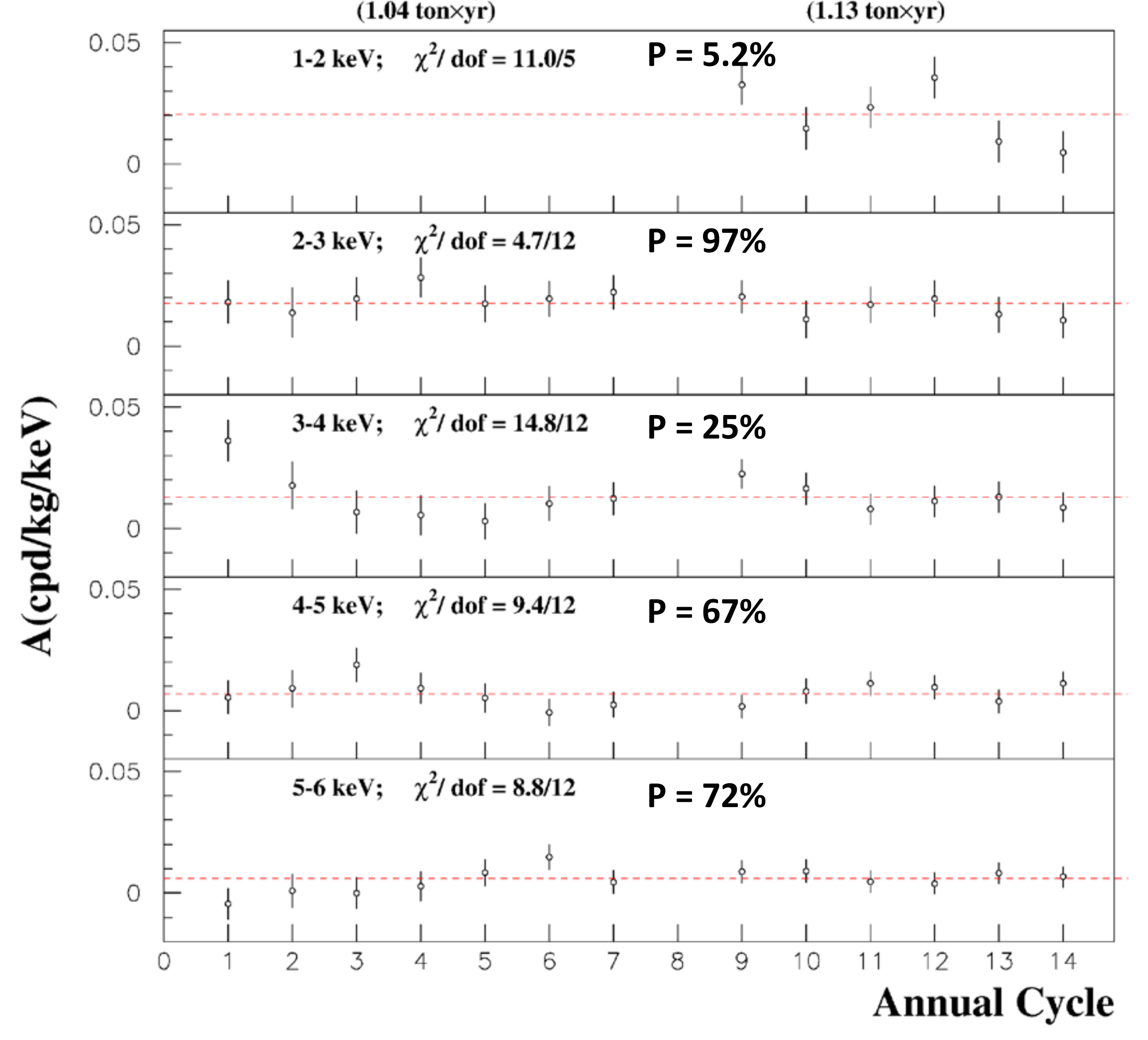
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (2.46 ton × yr)



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 ANNUAL CYCLE



DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: **2.46 ton×yr**

Energy bin (keV)	run test probability	
	Lower	Upper
1-2	70%	70%
2-3	50%	73%
3-4	85%	35%
4-5	88%	30%
5-6	88%	30%

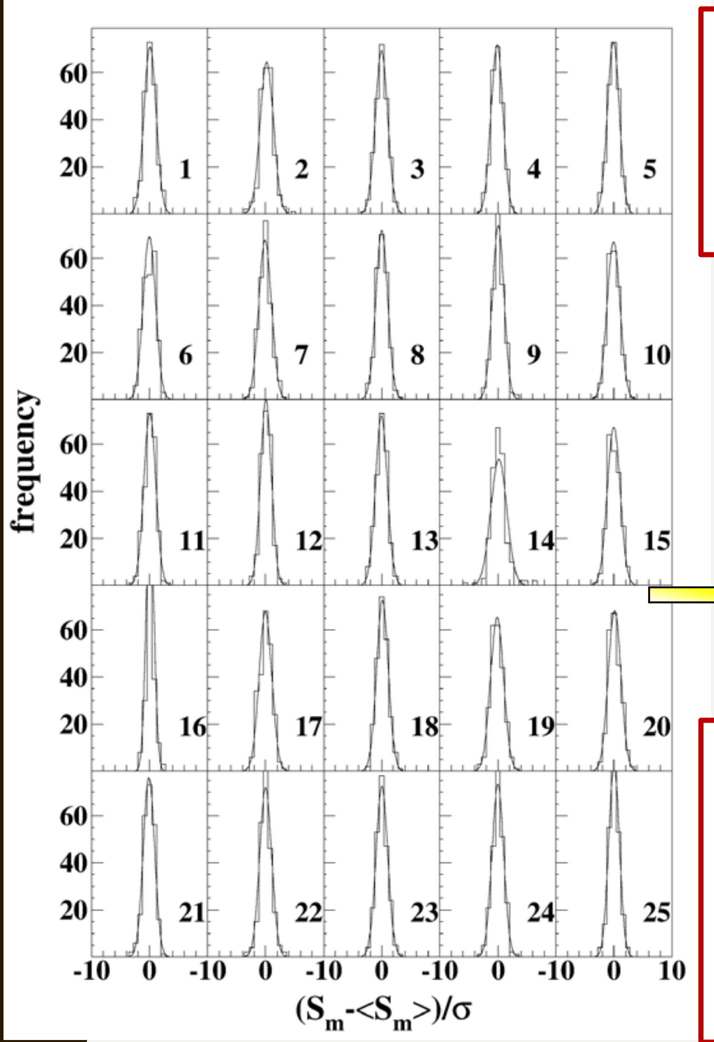
The signal is well distributed over all the annual cycles in each energy bin

STATISTICAL DISTRIBUTIONS OF THE MODULATION AMPLITUDES (S_M)

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

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



Each panel refers to each detector separately; 232 entries (the 16 energy bins in the (2–6) keV energy interval of the 7 DAMA/LIBRA–phase1 annual cycles and the 20 energy bins in the (1–6) keV energy interval of the 6 DAMA/LIBRA–phase2 annual cycles)**, but 152 for the 16th detector** (only 2 annual cycles of DAMA/LIBRA-phase1)

2–6 keV phase1 + 1-6 keV phase2

$$x=(S_m-<S_m>)/\sigma \qquad \chi^2=\Sigma x^2$$

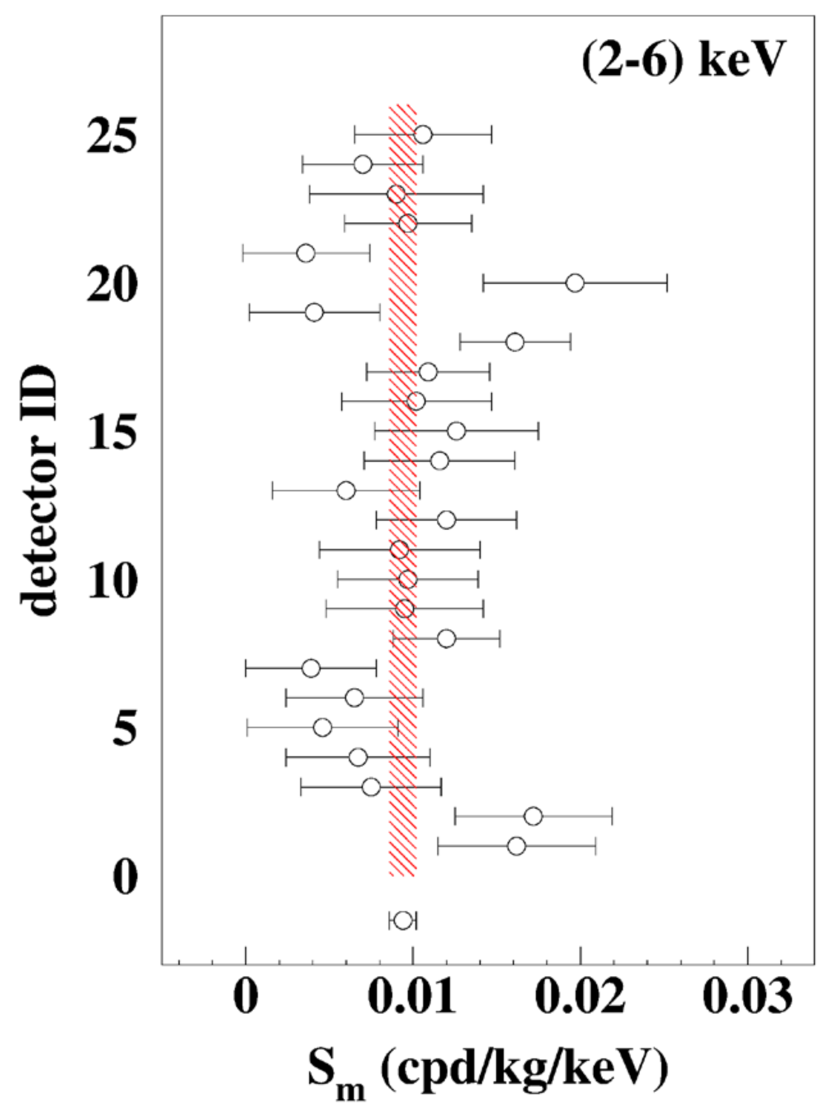
Individual S_m values follow a normal distribution since ***x*** is distributed as a Gaussian with a unitary standard deviation

S_m statistically well distributed in all the detectors, energy bin and annual cycles

The $\chi^2/d.o.f.$ values range from 0.69 to 1.95 for all the 25 detectors

- The mean value of the 25 χ^2 is 1.07, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of ≤ 2.1×10^{-4} cpd/kg/keV, if quadratically combined, or ≤ 3×10^{-5} cpd/kg/keV, if linearly combined, to the modulation amplitude below 6 keV.
- This possible additional error (≤2% or ≤0.3%, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible syst. effects

S_M FOR EACH DETECTOR



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

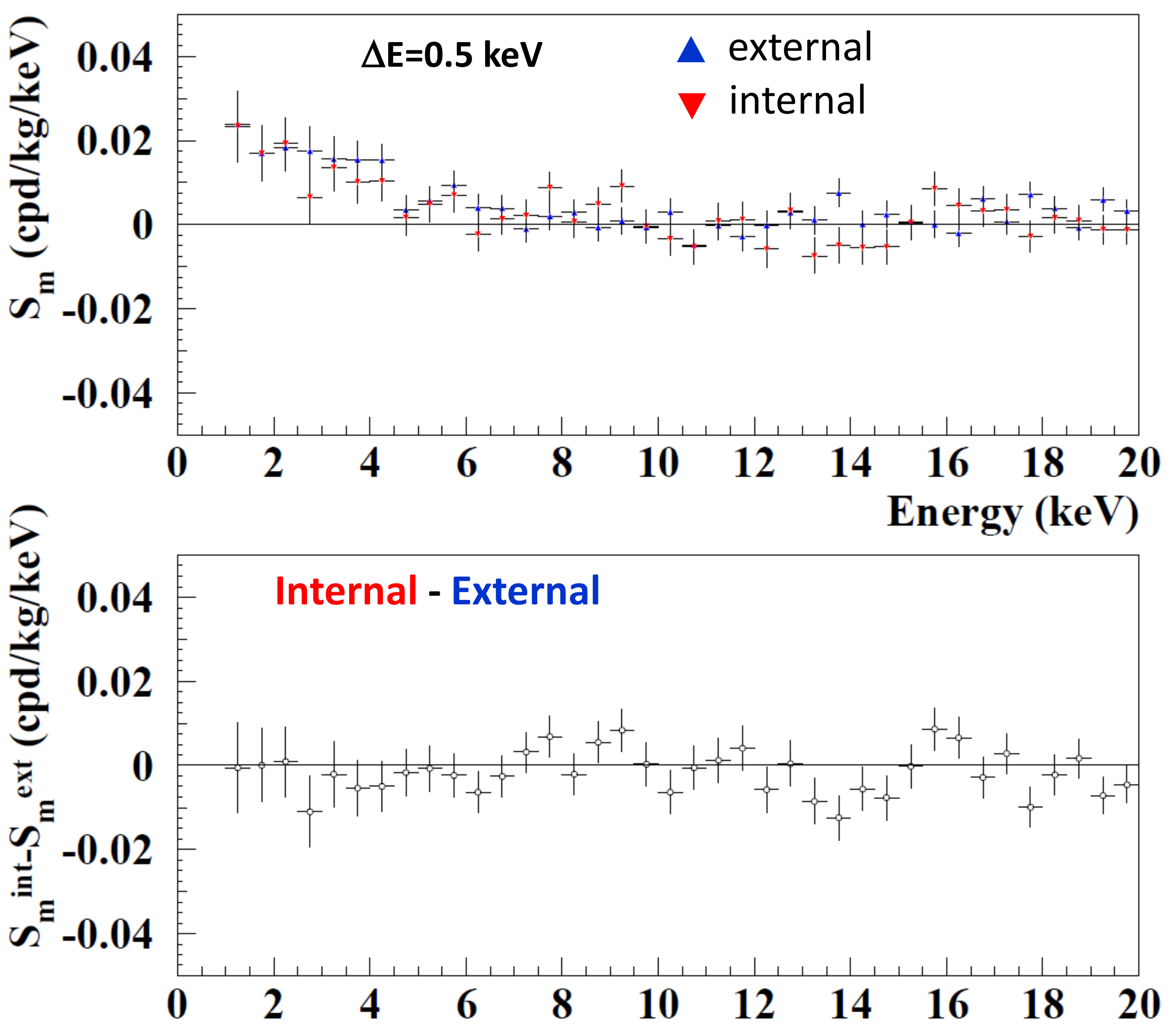
S_m integrated in the range (2 - 6) keV for each of the 25 detectors (1σ error)

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

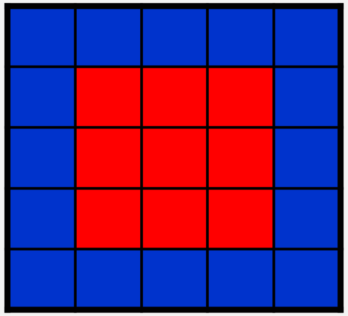
χ^2/dof = 23.9/24 d.o.f.

The signal is well distributed over all the 25 detectors.

EXTERNAL VS INTERNAL DETECTORS:



DAMA/LIBRA-phase2
1.13 ton × yr



1-4 keV	**χ^2/dof =2.5/6**
1-10 keV	**χ^2/dof =12.1/8**
1-20 keV	**χ^2/dof =40.8/38**

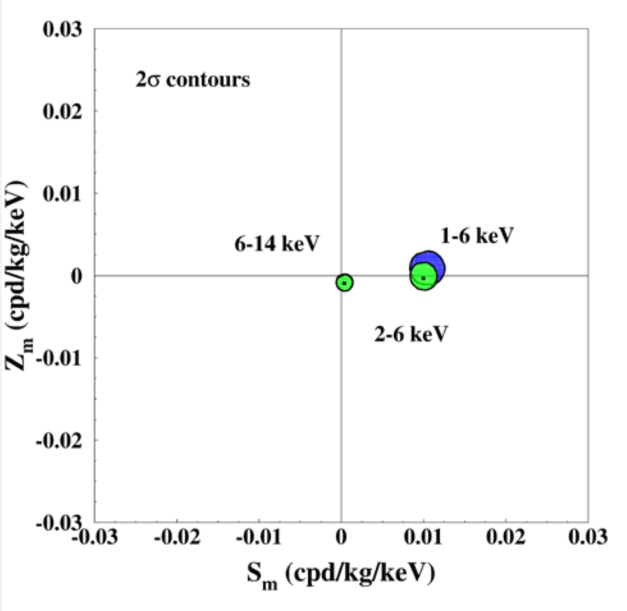
IS THERE A SINUSOIDAL CONTRIBUTION IN THE SIGNAL? PHASE ≠ 152.5 DAY?

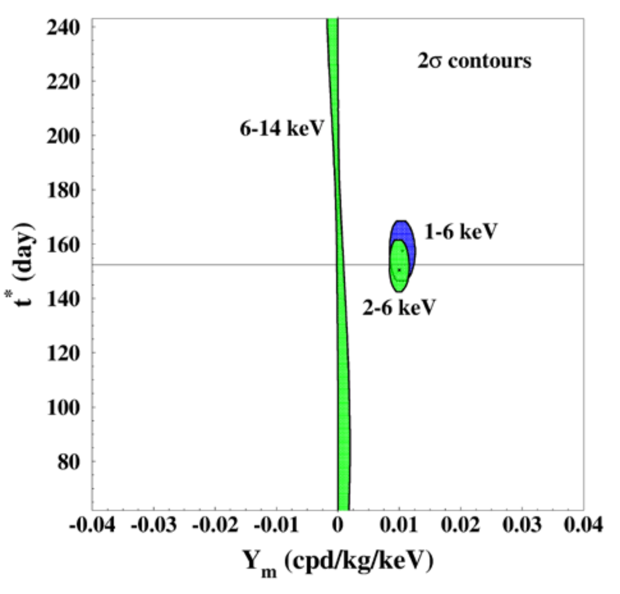
$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right] + Z_m \sin\left[\omega\left(t - t_0\right)\right] = S_0 + Y_m \cos\left[\omega\left(t - t^*\right)\right]$$

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

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



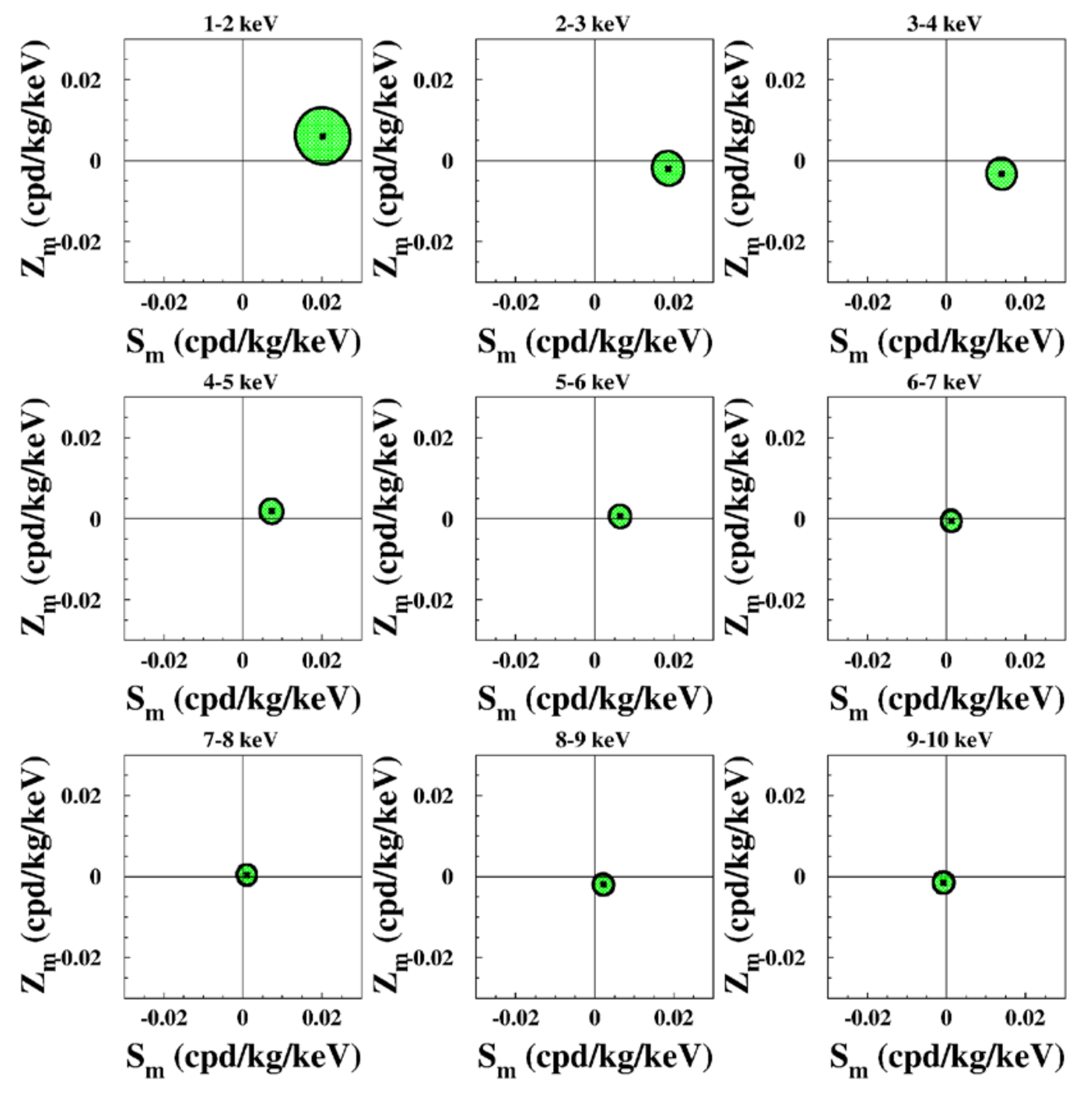


E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0100 ± 0.0008	- 0.0003 ± 0.0008	0.0100 ± 0.0008	150.5 ± 5.0
6-14	0.0003 ± 0.0005	-0.0009 ± 0.0006	0.0010 ± 0.0013	undefined
DAMA/LIBRA-ph2				
1-6	0.0105 ± 0.0011	0.0009 ± 0.0010	0.0105 ± 0.0011	157.5 ± 5.0

Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)

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

2σ contours



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

For Dark Matter induced signals:

$|Z_m| \ll |Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

$\omega = 2\pi/T$

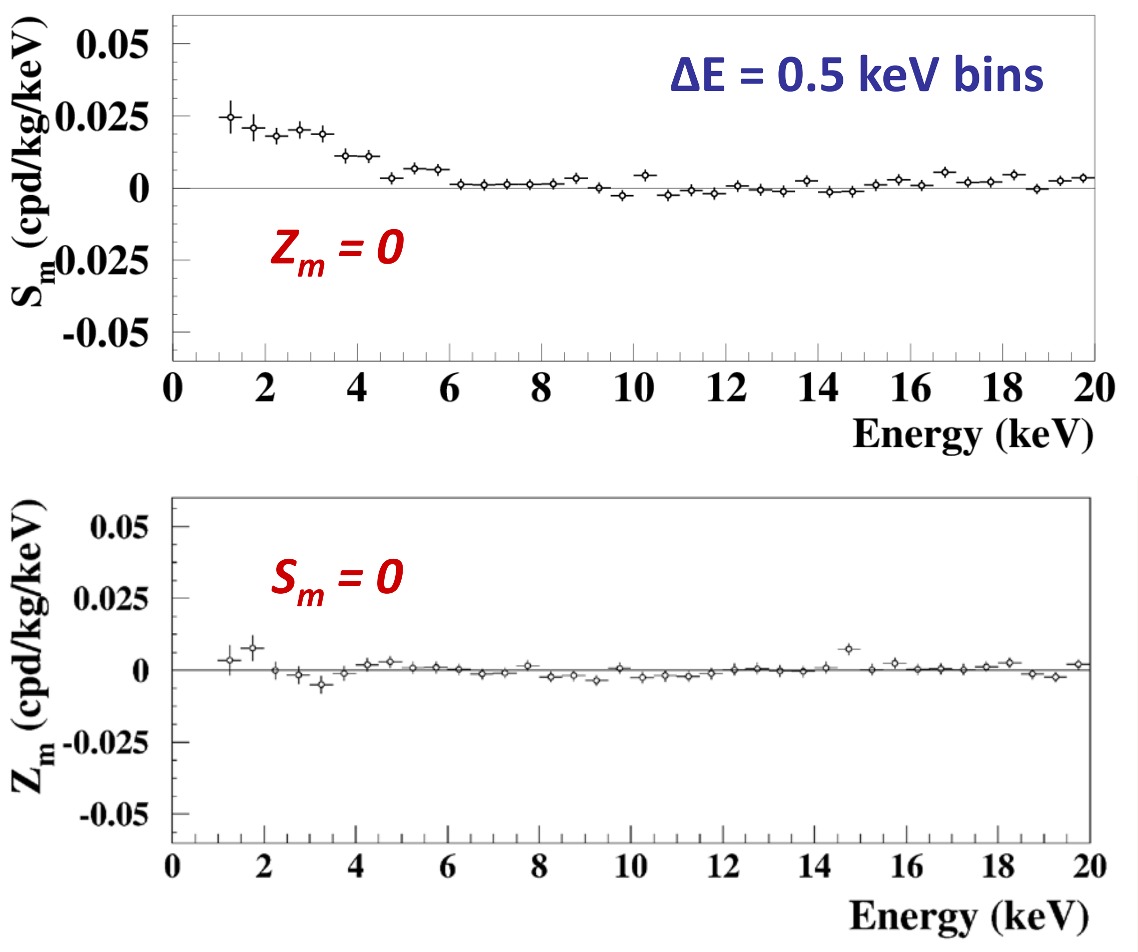
$T = 1$ year

Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as the SagDEG stream)

ENERGY DISTRIBUTIONS OF COSINE (S_M) AND SINE (Z_M) MODULATION AMPLITUDES

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

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



t_0 = 152.5 day **(2nd June)**
***maximum at* 2nd June**
as for DM particles

***maximum at* 1st September**
***T/4* days after 2° June**

The χ^2 test in (1-20) keV energy region (χ^2/dof = 44.5/38 probability of 22%) supports the hypothesis that the $Z_{m,k}$ values are simply fluctuating around zero

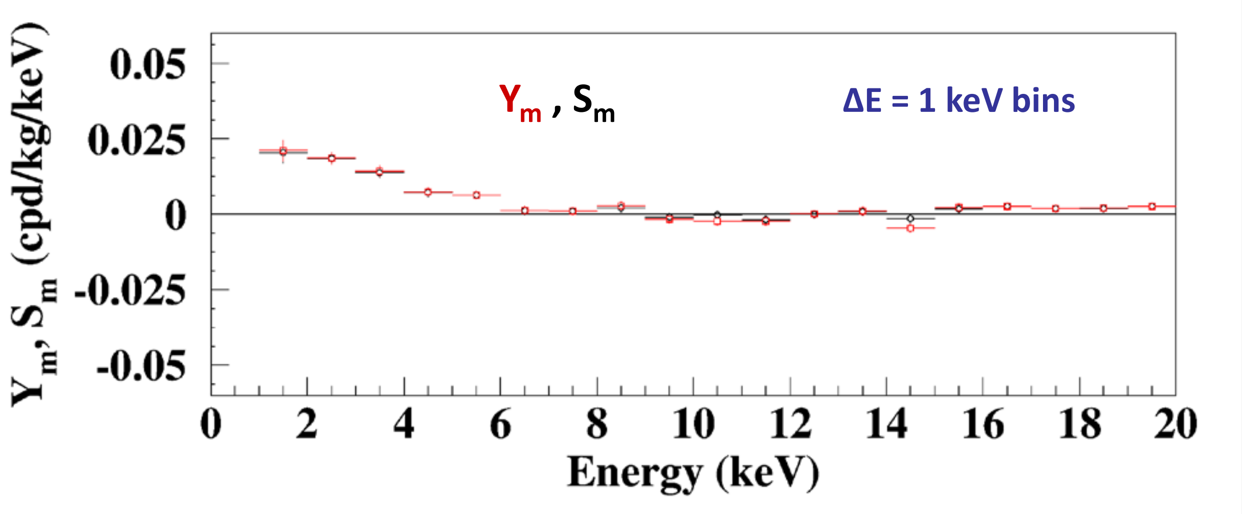
PHASE VS ENERGY

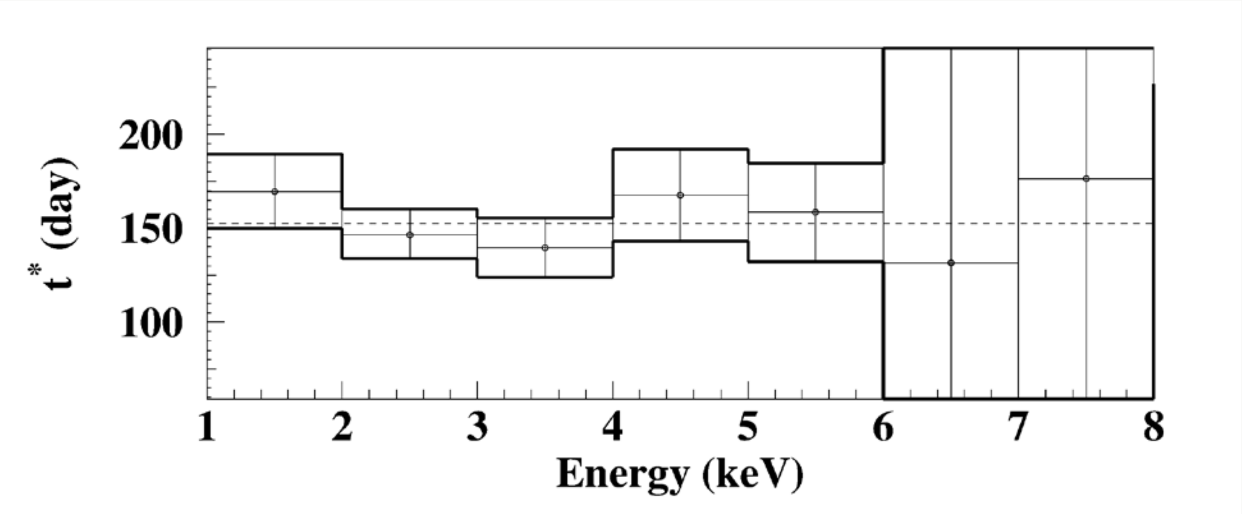
$$R(t) = S_0 + Y_m \cos\left[\omega\left(t - t^*\right)\right]$$

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

For Dark Matter signals:

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





Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)

STABILITY PARAMETERS OF DAMA/LIBRA–PHASE2

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 new running periods

	DAMA/LIBRA-phase2_2	DAMA/LIBRA-phase2_3	DAMA/LIBRA-phase2_4	DAMA/LIBRA-phase2_5	DAMA/LIBRA-phase2_6	DAMA/LIBRA-phase2_7
Temperature (°C)	(0.0012 ± 0.0051)	-(0.0002 ± 0.0049)	-(0.0003 ± 0.0031)	(0.0009 ± 0.0050)	(0.0018 ± 0.0036)	-(0.0006 ± 0.0035)
Flux N_2 (l/h)	-(0.15 ± 0.18)	-(0.02 ± 0.22)	-(0.02 ± 0.12)	-(0.02 ± 0.14)	-(0.01 ± 0.10)	-(0.01 ± 0.16)
Pressure (mbar)	$(1.1 \pm 0.9)\times10^{-3}$	$(0.2 \pm 1.1)\ )\times10^{-3}$	$(2.4 \pm 5.4)\times10^{-3}$	$(0.6 \pm 6.2)\times10^{-3}$	$(1.5 \pm 6.3)\times10^{-3}$	$(7.2 \pm 8.6)\times10^{-3}$
Radon (Bq/m^3)	(0.015 ± 0.034)	-(0.002 ± 0.050)	-(0.009 ± 0.028)	-(0.044 ± 0.050)	(0.082 ± 0.086)	(0.06 ± 0.11)
Hardware rate above single ph.e. (Hz)	$-(0.12 \pm 0.16)\times10^{-2}$	$(0.00 \pm 0.12)\times10^{-2}$	$-(0.14 \pm 0.22)\times10^{-2}$	$-(0.05 \pm 0.22)\times10^{-2}$	$-(0.06 \pm 0.16)\times10^{-2}$	$-(0.08 \pm 0.17)\times10^{-2}$

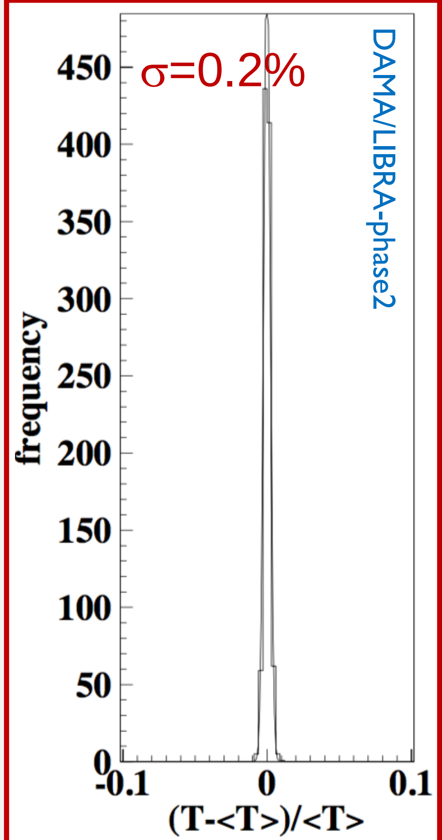
All the measured amplitudes well compatible with zero

+ 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)

TEMPERATURE

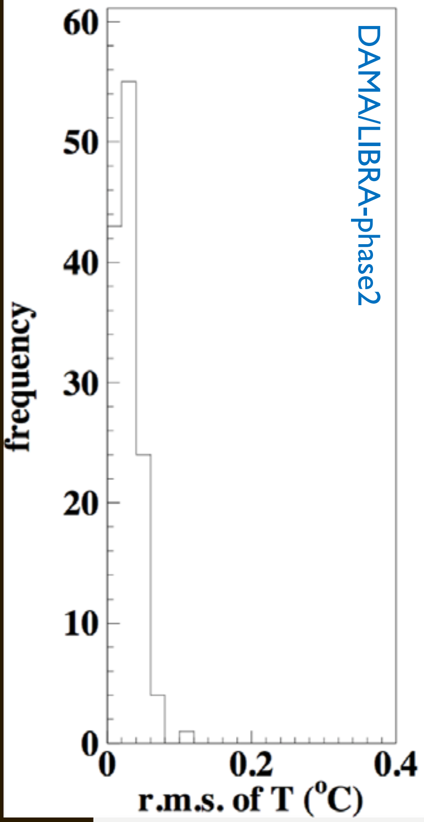
- Detectors in Cu housings directly in contact with multi-ton shield → huge heat capacity ($\approx 10^6$ cal/°C)
- Experimental installation continuosly air conditioned (2 independent systems for redundancy)
- Operating T of the detectors continuously controlled



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**

	T (°C)
DAMA/LIBRA-ph2_2	(0.0012 ± 0.0051)
DAMA/LIBRA-ph2_3	-(0.0002 ± 0.0049)
DAMA/LIBRA-ph2_4	-(0.0003 ± 0.0031)
DAMA/LIBRA-ph2_5	(0.0009 ± 0.0050)
DAMA/LIBRA-ph2_6	(0.0018 ± 0.0036)
DAMA/LIBRA-ph2_7	-(0.0006 ± 0.0035)



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

mean value ≈ 0.03°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

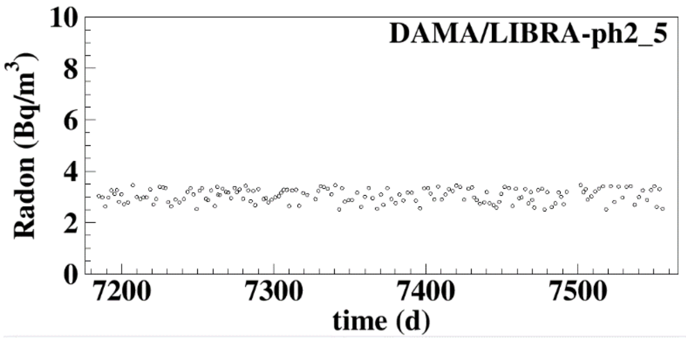
+ Any possible modulation due to temperature would always fail some of the peculiarities of the signature

RADON

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

Amplitudes for annual modulation of Radon external to the shield:

	Radon (Bq/m^3)
DAMA/LIBRA-ph2_2	(0.015 ± 0.034)
DAMA/LIBRA-ph2_3	-(0.002 ± 0.050)
DAMA/LIBRA-ph2_4	-(0.009 ± 0.028)
DAMA/LIBRA-ph2_5	-(0.044 ± 0.050)
DAMA/LIBRA-ph2_6	(0.082 ± 0.086)
DAMA/LIBRA-ph2_7	(0.06 ± 0.11)

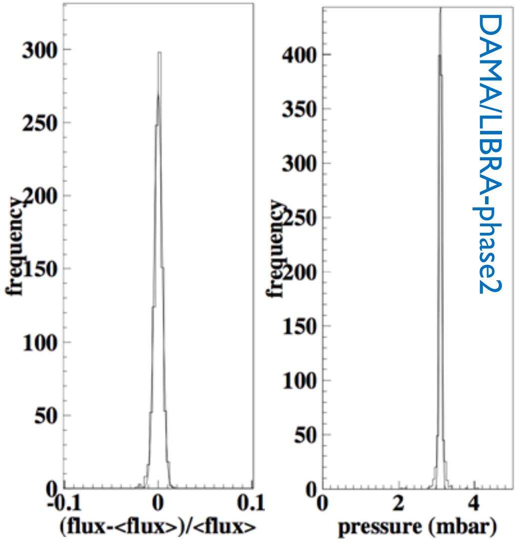


Time behaviours of the environmental radon in the installation (i.e. after the Supronyl), from which in addition the detectors are excluded by other two levels of sealing!

measured values at level of sensitivity of the used radonmeter

<flux> ≈ 320 l/h

Over pressure ≈ 3.1 mbar



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

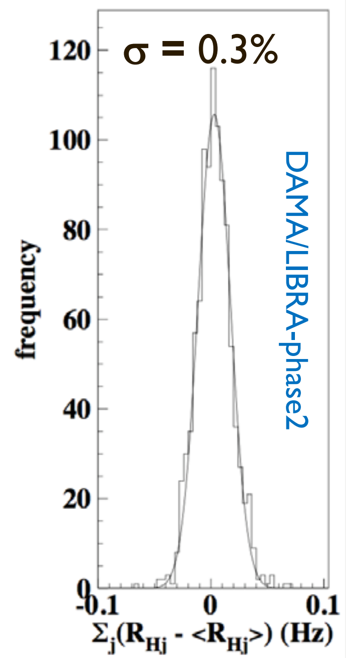
Investigation in the HP Nitrogen atmosphere of the Cu-box

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

$<2.5\times10^{-6}$ cpd/kg/keV (<0.01% $S_m^{observed}$)

An effect from Radon can be excluded

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



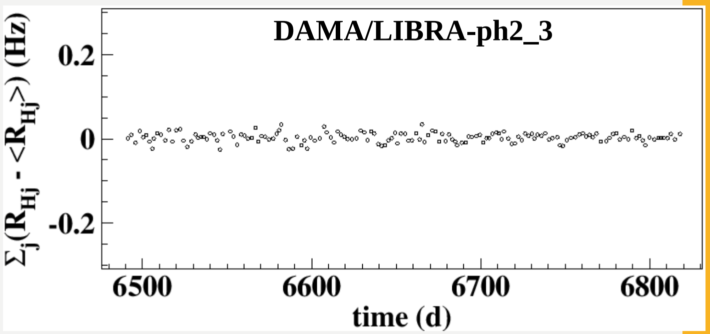
NOISE

Distribution of variations of total hardware rates of the crystals above the single ph.el. threshold (that is from noise to "infinity") during DAMA/LIBRA running periods

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

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

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



Amplitudes for annual modulation well compatible with zero:

	Hardware rate (Hz)
DAMA/LIBRA-ph2_2	$-(0.12 \pm 0.16) \times 10^{-2}$
DAMA/LIBRA-ph2_3	$(0.00 \pm 0.12) \times 10^{-2}$
DAMA/LIBRA-ph2_4	$-(0.14 \pm 0.22) \times 10^{-2}$
DAMA/LIBRA-ph2_5	$-(0.05 \pm 0.22) \times 10^{-2}$
DAMA/LIBRA-ph2_6	$-(0.06 \pm 0.16) \times 10^{-2}$
DAMA/LIBRA-ph2_7	$-(0.08 \pm 0.17) \times 10^{-2}$

CAN A NOISE TAIL ACCOUNT FOR THE OBSERVED MODULATION EFFECT?

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

The modulation amplitude of the "Hardware Rate" (period and phase as for DM particles) is compatible with zero (DAMA/LIBRA-ph2_2-6): **$-(0.061 \pm 0.067) \times 10^{-2}$ Hz** → **$< 0.6 \times 10^{-3}$ Hz (90% CL)**

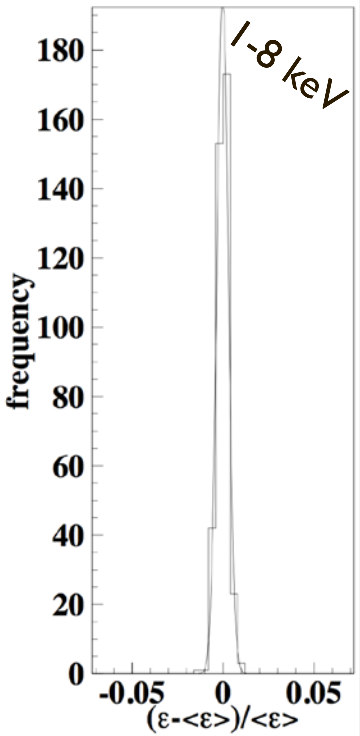
Hardware Rate = noise + bckg [up to ≈MeV] + signal [up to ≈6keV]

noise/crystal ≈ 0.10 Hz

relative modulation amplitude from noise $< 0.6\ 10^{-3}$ Hz/2.5 Hz ≈ 2.4×10^{-4} (90%CL)

even in the *worst* *hypothetical* case of 10% residual tail of noise in the data → relative modulation amplitude from noise at low energy $< 2.4 \times 10^{-5}$ → **$<10^{-4}$ cpd/kg/keV** NO

THE EFFICIENCIES



σ = 0.3 %

Distribution of variations of the efficiency values with respect to their mean values during DAMA/LIBRA-phase2 running periods

Time behaviour: modulation amplitudes obtained by fitting the time behaviours of the efficiencies including a DM-like cosine modulation for DAMA/LIBRA-phase2 running periods

	Amplitudes ($\times 10^{-3}$)					
Energy (keV)	DAMA/LIBRA-ph2_2	DAMA/LIBRA-ph2_3	DAMA/LIBRA-ph2_4	DAMA/LIBRA-ph2_5	DAMA/LIBRA-ph2_6	DAMA/LIBRA-ph2_7
1-4	-(0.8±0.7)	(0.7±0.8)	(0.9±0.8)	-(1.3±0.8)	-(0.1±0.8)	(0.2±0.8)
4-6	(0.9±1.0)	(0.9±1.0)	-(1.3±1.0)	(0.5±1.0)	-(1.0±1.1)	-(0.2±1.0)
6-8	(0.8±0.8)	-(0.7±0.7)	(0.6±0.8)	-(0.1±0.8)	-(1.1±0.8)	(0.5±0.8)
8-10	-(0.3±0.6)	-(0.5±0.5)	-(0.5±0.5)	-(0.3±0.5)	(0.4±0.6)	(0.3±0.6)

Energy	**Modulation amplitudes (DAMA/LIBRA-phase2)**
1-4 keV	**$-(0.10 \pm 0.32) \times 10^{-3}$**
4-6 keV	**$(0.00 \pm 0.41) \times 10^{-3}$**

Amplitudes well compatible with zero
+ cannot mimic the signature

THE CALIBRATION FACTORS

- Distribution of the percentage variations (ε_{tdcal}) of each energy scale factor ($tdcal_k$) with respect to the value measured in the previous calibration ($tdcal_{k-1}$).
- Distribution of the percentage variations (ε_{HE}) of the high energy scale factor with respect to the mean values.

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

$$\sigma = \sqrt{\sigma_{res}^2 + \sigma_{cal}^2} \approx \sigma_{res} \cdot \left[1 + \frac{1}{2}\left(\frac{\sigma_{cal}}{\sigma_{res}}\right)^2\right];$$

$$\frac{1}{2}\left(\frac{\sigma_{cal}/E}{\sigma_{res}/E}\right)^2 \leq 7.5 \cdot 10^{-4} \frac{E}{20keV}$$

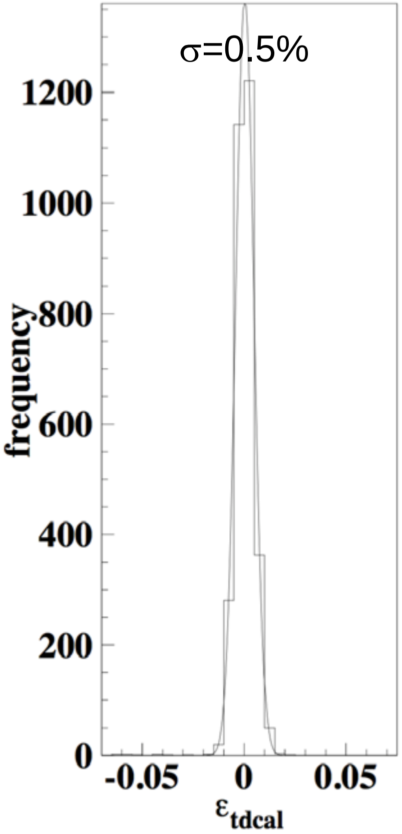
Negligible effect considering routine calibrations and energy resolution at low energy

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

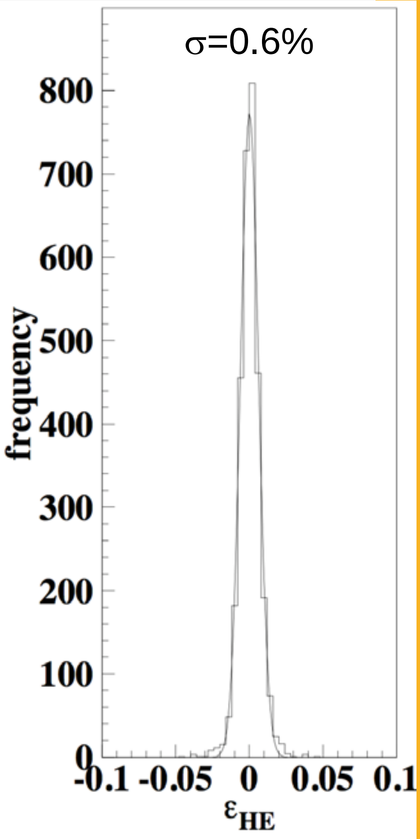
No modulation in the energy scale
+ cannot mimic the signature

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

gaussian behaviours



Low-Energy calibration factors (ε_{tdcal})



High-Energy calibration factors (ε_{HE})

- 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]	–	$< 8 \times 10^{-6}$	[2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3 \times 10^{-3}$	[2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to$ n from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi_0^{(\mu)} \simeq 20\ \mu$ 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	$\Phi_0^{(\nu)} \simeq 6 \times 10^{10}\ \nu$ 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

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 + intrinsic 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**

+ 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+PHASE2

Presence of modulation over 20 annual cycles at 12.9 σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 20 independent experiments of 1 year each one

The total exposure by former DAMA/NaI, DAMA/LIBRA-phase1 and phase2 is 2.46 ton × yr

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 (0.999±0.001)* yr, well compatible with the 1 yr period, as expected for the DM signal

3 Measured phase (145±5)* 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 is: (0.0103 ± 0.0008)* cpd/kg/keV (12.9 σ C.L.).

* Here 2-6 keV energy interval

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

… and well compatible with several candidates
(in many possible astrophysical, nuclear and particle physics scenarios)

MODEL-INDEPENDENT EVIDENCE BY DAMA/NAI AND DAMA/LIBRA-PH1, -PH2

well compatible with several candidates
in many 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 n of the 4-th family

WIMP with preferred inelastic scattering

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

Mirror Dark Matter

Light Dark Matter

Self interacting Dark Matter

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

Sterile neutrino

Elementary Black holes such as the Daemons

heavy exotic canditates, as "4th family atoms", ...

… and more

Kaluza Klein particles

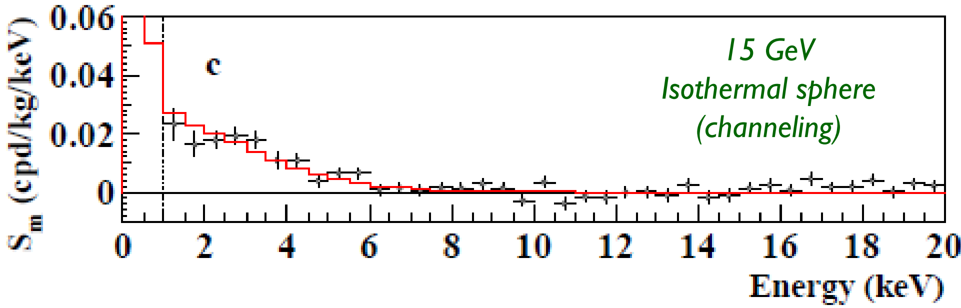
PRELIMINARY

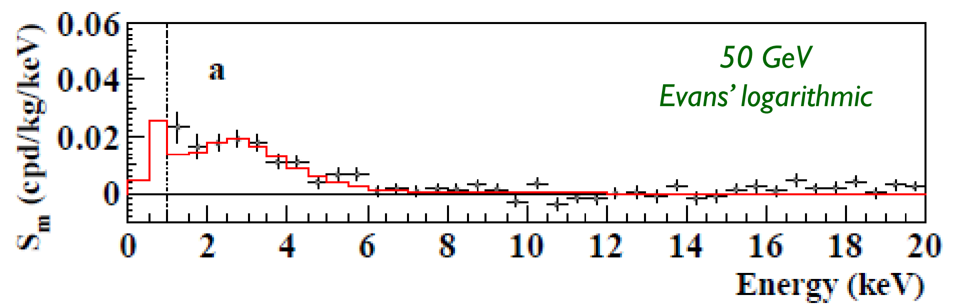
MODEL-INDEPENDENT EVIDENCE BY DAMA/NAI AND DAMA/LIBRA

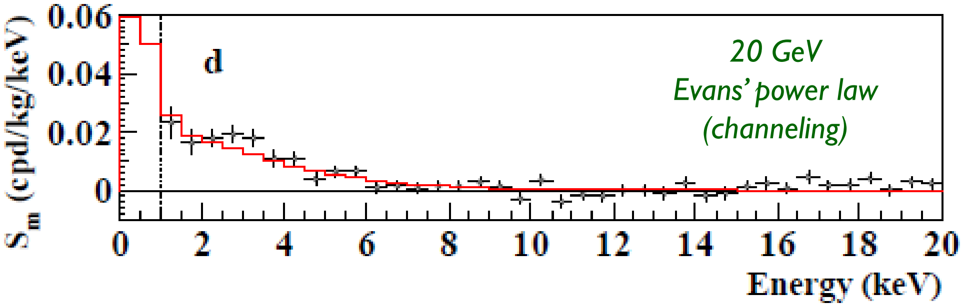
well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

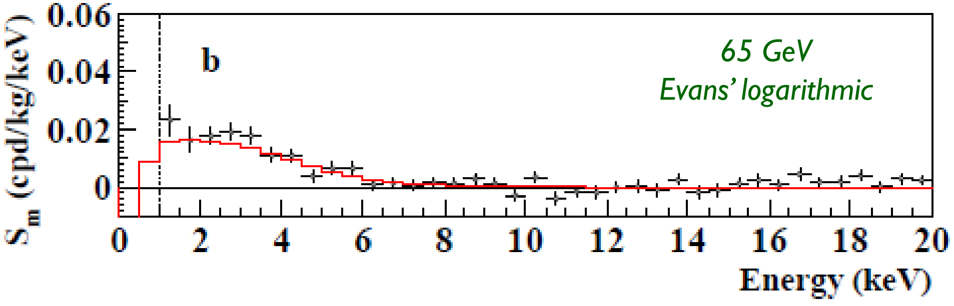
Just few <u>examples</u> of interpretation of the annual modulation in terms of candidate particles in <u>some scenarios</u>

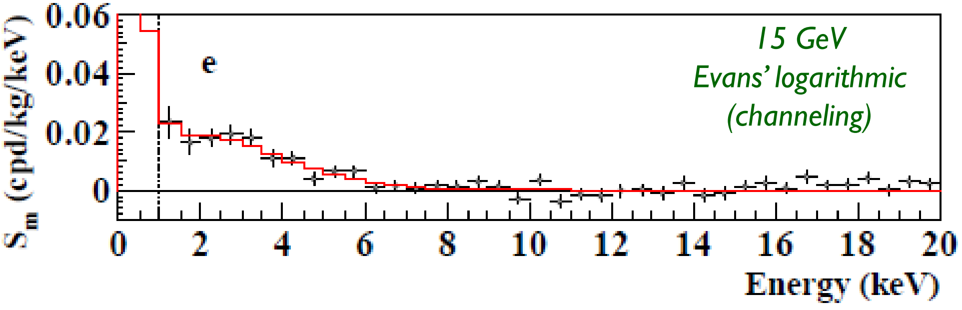
WIMP SI











PRELIMINARY

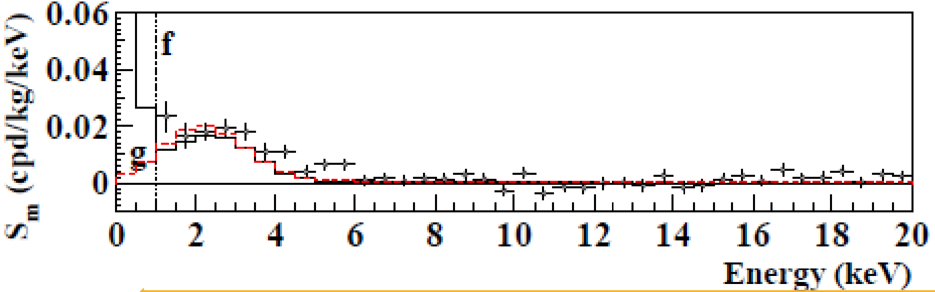
MODEL-INDEPENDENT EVIDENCE BY DAMA/NAI AND DAMA/LIBRA

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

LDM candidates

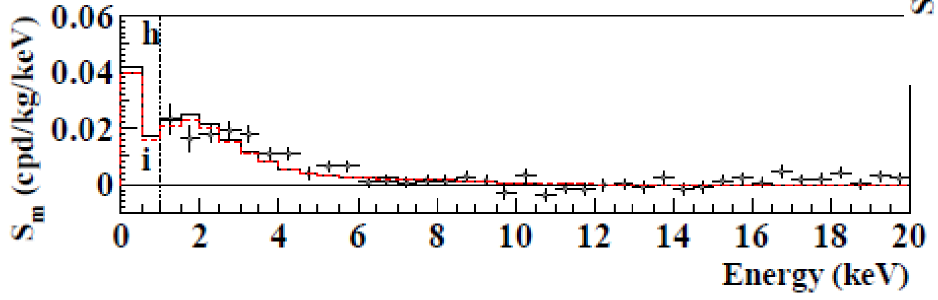
Halo model: NFW (v_0=170 km/s, ρ=0.17 GeV/cm^3)



LDM with coherent scattering on nuclei

f - m_H=30 MeV, δ=13 MeV σ=1.0x10^{-6} pb

g - m_H=100 MeV, δ=36 MeV σ=2.2x10^{-6} pb



LDM with incoherent scattering on nuclei

h - m_H=30 MeV, δ=6 MeV σ=0,008 pb

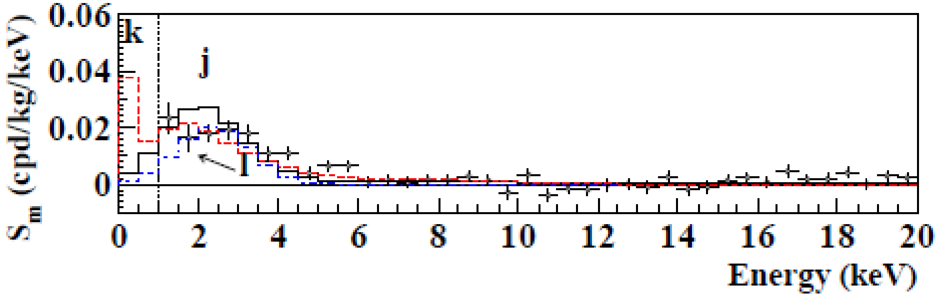
i - m_H=100 MeV, δ=2 MeV σ=0,026 pb

LDM with m_L=0 MeV (δ=m_H)

j - coherent on nucl. m_H=75 MeV, σ=1.7x10^{-6} pb

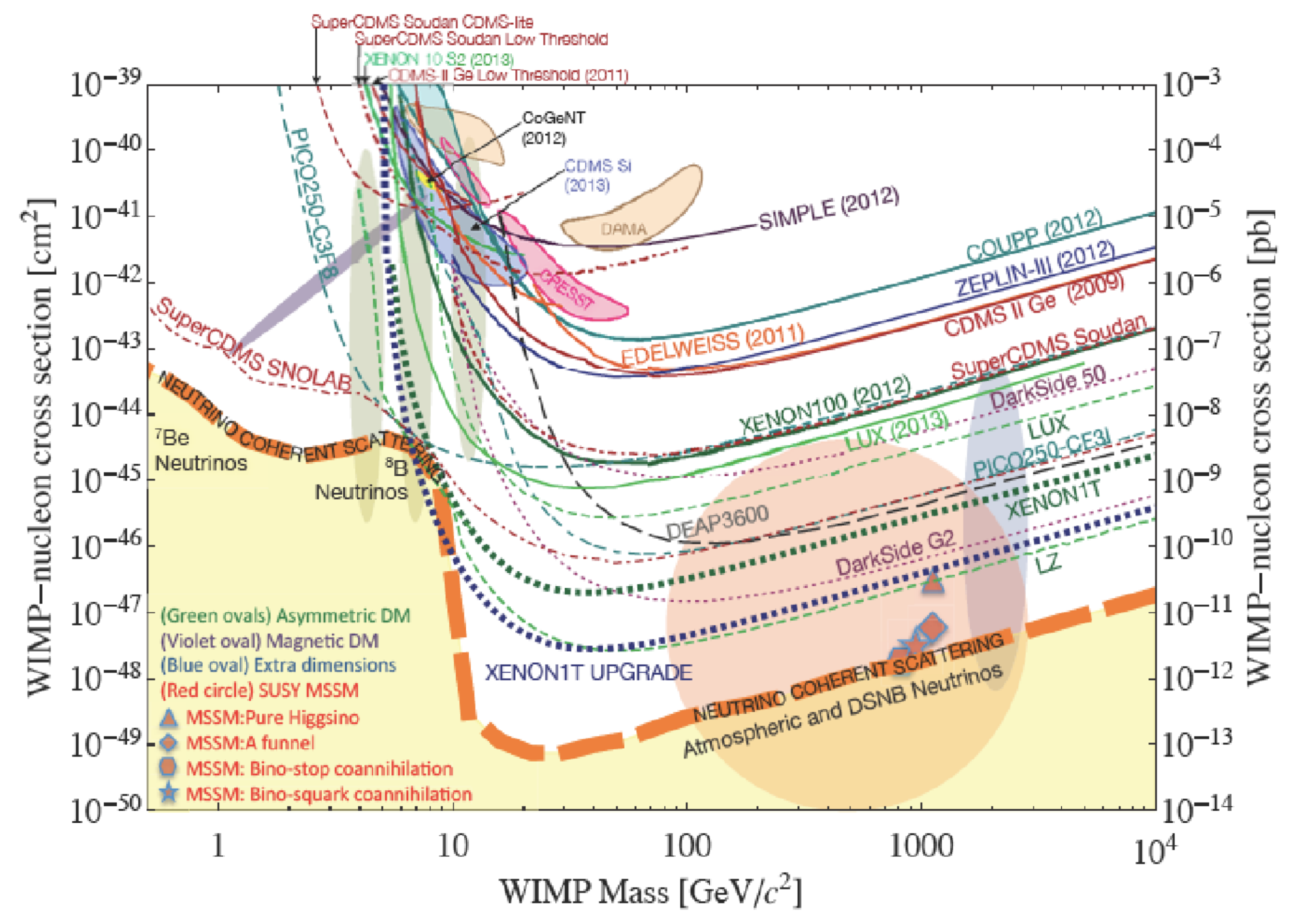
k - incoherent on nucl. m_H=19 MeV, σ=0,005 pb

L - on electrons m_H=52 keV, σ=0.2x10^{-6} pb



Compatibility with several candidates; other ones are open

IS IT AN "UNIVERSAL" AND "CORRECT" WAY TO APPROACH THE PROBLEM OF DM AND COMPARISONS?



No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

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…

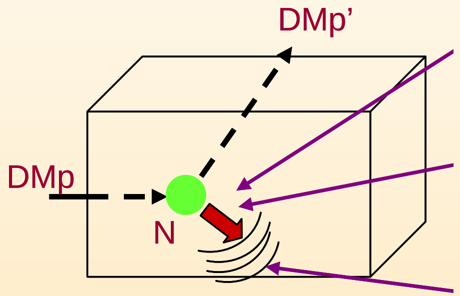
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- 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

example…

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



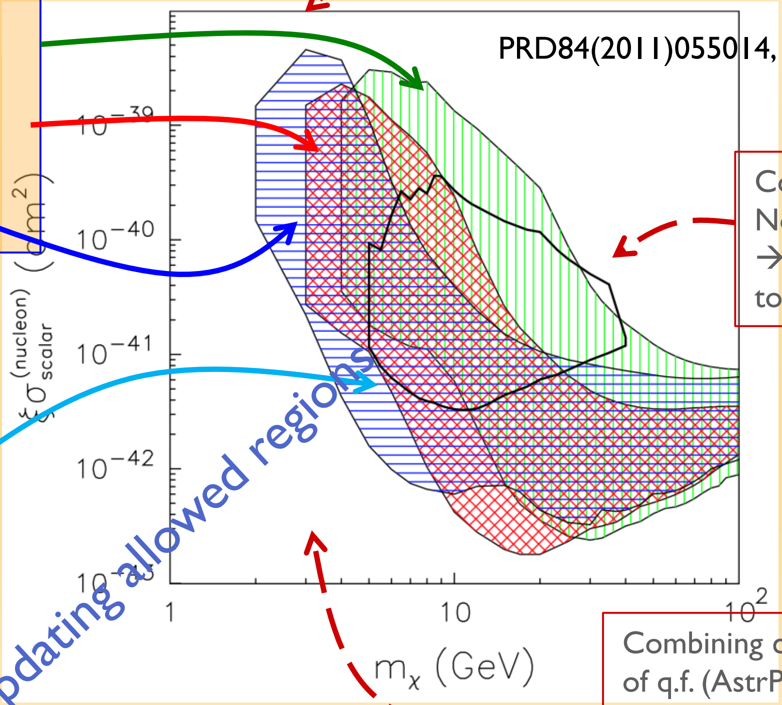
Regions in the nucleon cross section vs DM particle mass plane

- 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);

7.5 σ C.L.



PRD84(2011)055014, IJMPA28(2013)1330022

Updating allowed regions

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

CoGeNT; qf at fixed assumed value

1.64 σ C.L.

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

Scratching Below the Surface of the Most General Parameter Space

(S. Scopel arXiv:1505.01926)

Most general approach: consider ALL possible NR couplings, including those depending on velocity and momentum

- A much wider parameter space opens up
- First explorations show that indeed large rooms for compatibility can be achieved

$$\mathcal{O}_1 = 1_\chi 1_N,$$
$$\mathcal{O}_2 = (v^\perp)^2,$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N,$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp,$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N},$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}.$$

… and much more considering experimental and theoretical uncertainties

Other examples

DMp with preferred inelastic interaction:

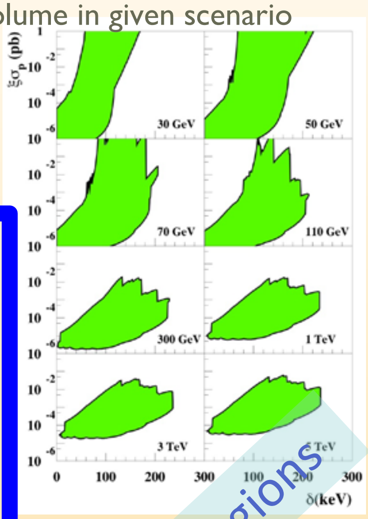
$\chi^- + N \rightarrow \chi^+ + N$

- iDM mass states χ^+, χ^- with δ mass splitting
- Kinematic 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 3d allowed volume in given scenario



Fund. Phys. 40(2010)900

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

PRL106(2011)011301

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

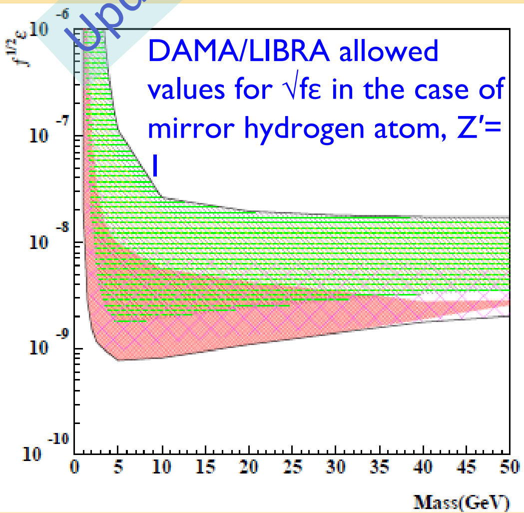
Mirror Dark Matter

Asymmetric mirror matter: mirror parity spontaneously broken ⇒ mirror sector becomes a heavier and deformed copy of ordinary sector

(See EPJC75(2015)400)

- Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$
- mirror atom scattering of the ordinary target nuclei in the NaI(Tl) detectors of DAMA/LIBRA set-up with the Rutherford-like cross sections.

$\sqrt{f} \cdot \epsilon$ coupling const. and fraction of mirror atom



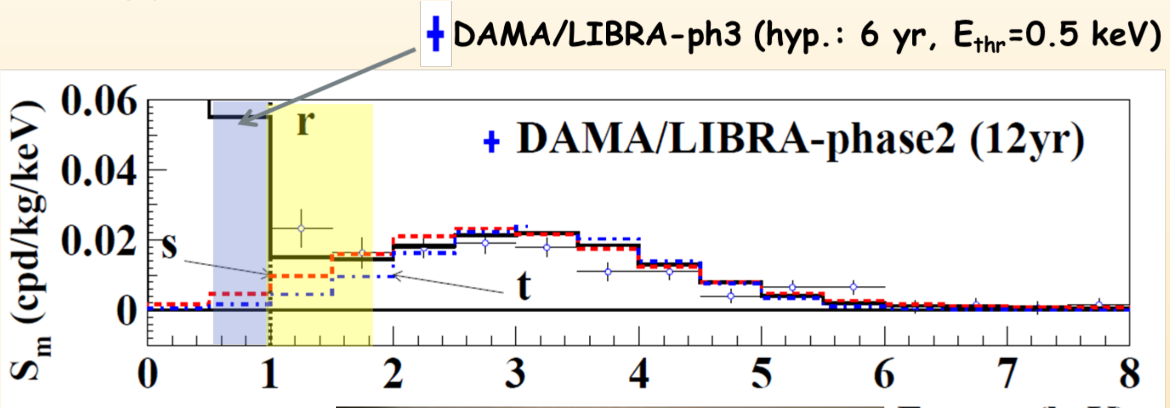
DAMA/LIBRA allowed values for √fε in the case of mirror hydrogen atom, Z′=1

Updating allowed regions

Running phase2 and towards future 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



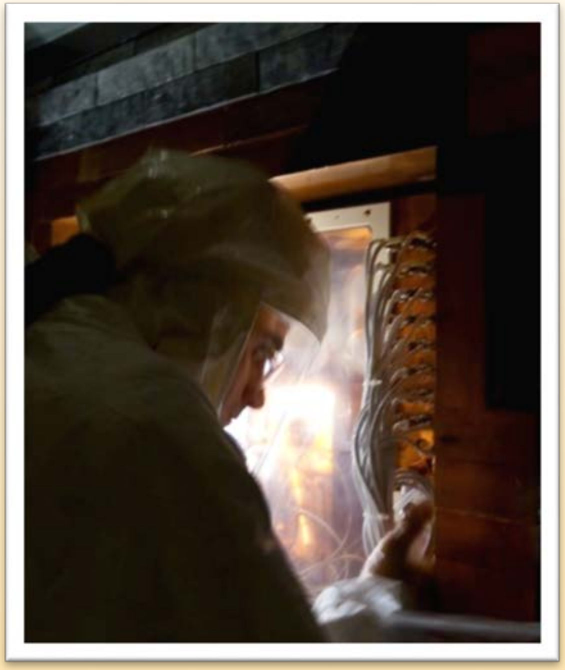
- R&D towards possible DAMA/LIBRA-phase3 continuing:
  - ① new development of high Q.E. PMTs with increased radio-purity to directly couple them to the crystals.
  - ② new protocols for possible modifications of the detectors;
  - ③ alternative strategies under investigation.
  - ④ **Other possible option**: new ULB crystal scintillators (e.g. $ZnWO_4$) placed in between the DAMA/LIBRA detectors to add also a high sensitivity directionality measurement.

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).

4 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 × 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

Thanks for your attention