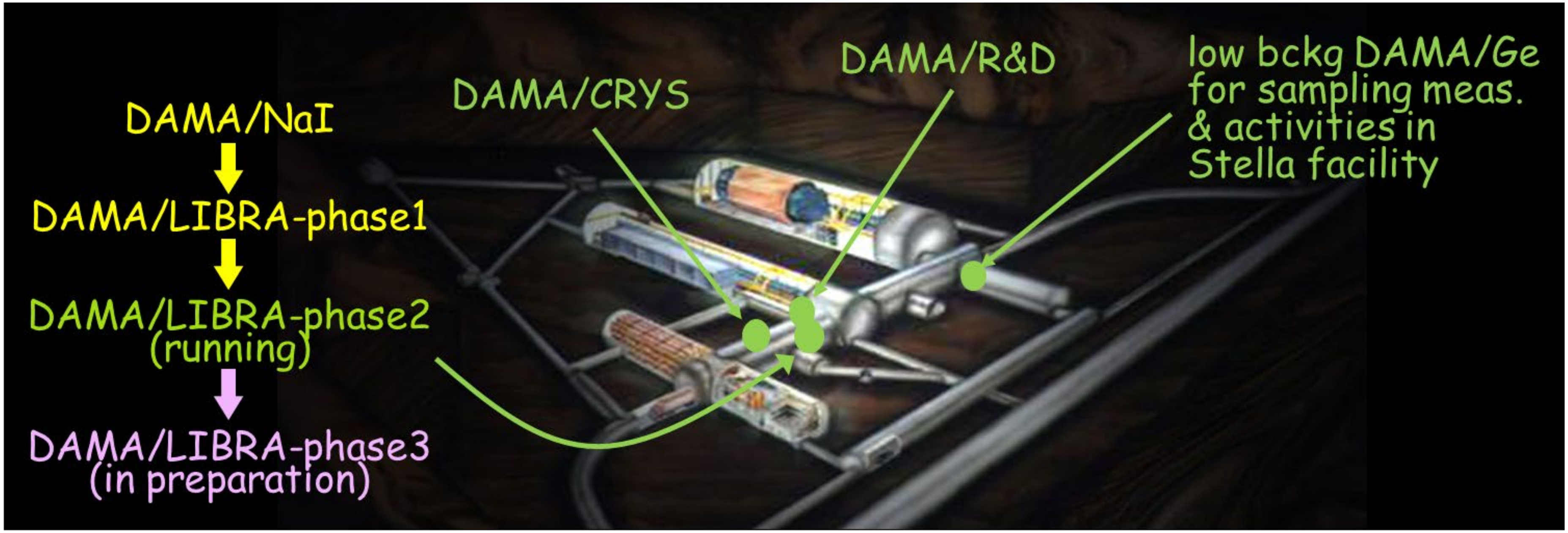
The DAMA project: achievements, implications and perspectives

23rd Bled Workshop
"What comes beyond the standard models?"
Bled, Slovenia
July 4-12, 2020

Vincenzo Caracciolo
on behalf of DAMA collaboration
University of Roma "Tor Vergata" and INFN

DAMA set-ups

an observatory for rare processes @ LNGS



Collaboration:

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

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

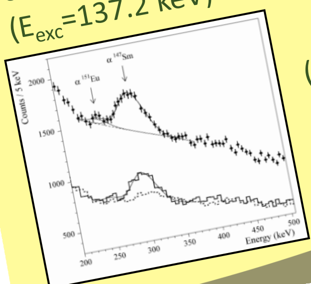
+ in some studies on ββ decays (DST-MAE and Inter-Universities project):

IIT Kharagpur and Ropar, India

Main results obtained by DAMA in the search for rare processes

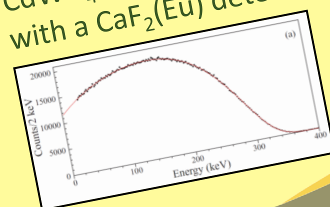
- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40,46,48}Ca, ^{64,70}Zn, ^{100}Mo, ^{96,104}Ru, ^{106,108,114,116}Cd, ^{112,124}Sn, ^{134,136}Xe, ^{130}Ba, ^{136,138,142}Ce, ^{150}Nd, ^{156,158}Dy, ^{162,170}Er, ^{180,186}W, ^{184,192}Os, ^{190,198}Pt (observed 2ν2β decay in ^{100}Mo, ^{116}Cd , ^{150}Nd)
- 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)

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



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

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

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

Search for PEP violating processes in Sodium and in Iodine

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

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

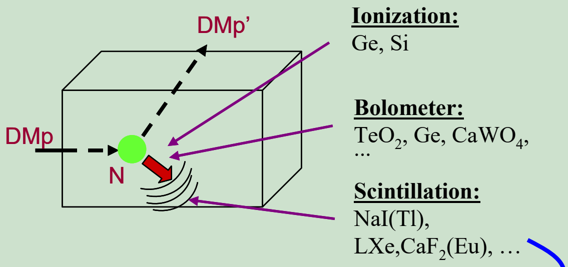
Dark Matter investigation

... many others are in progress

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

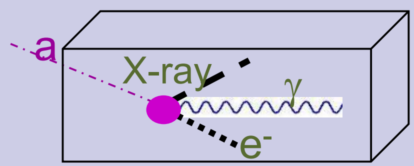
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

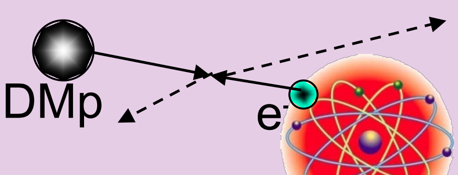
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

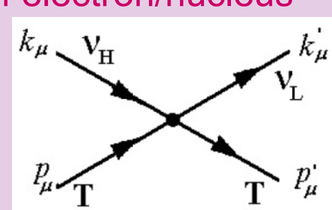


... even WIMPs

- 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



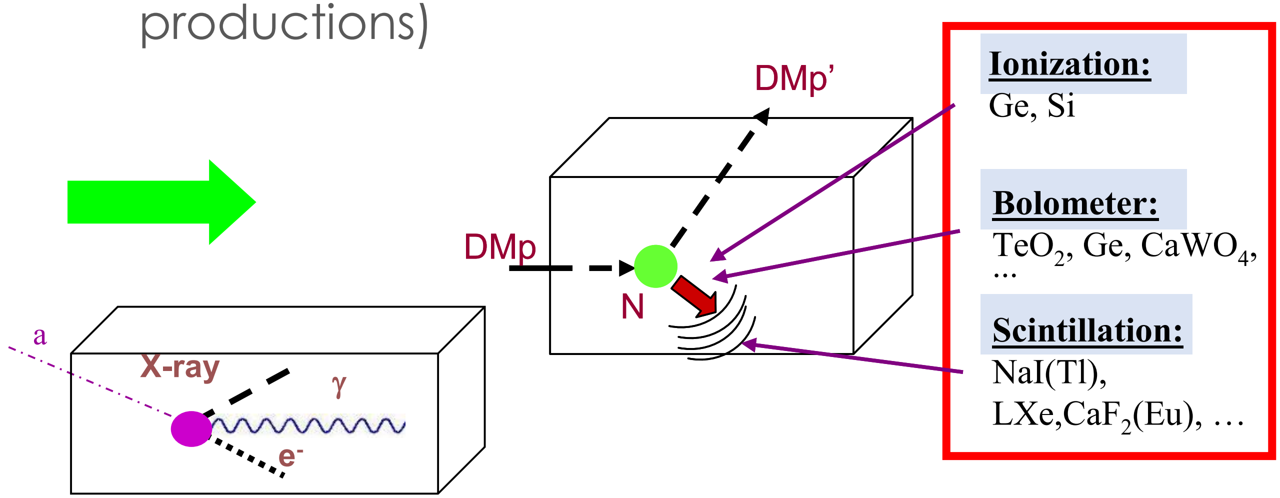
e.g. signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

Direct detection experiments

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

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

2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)



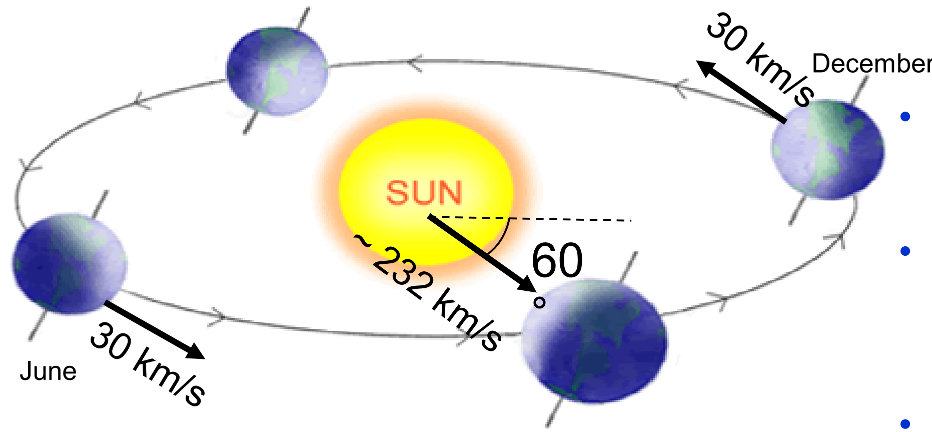
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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 = 2nd June (when $v_\oplus$ is maximum)

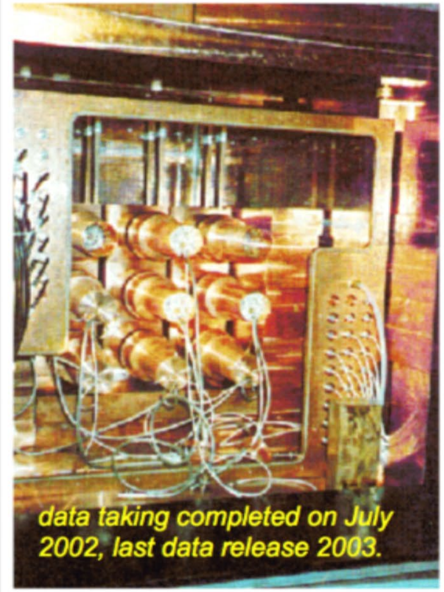
$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma\cos[\omega(t-t_0)]$$

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

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

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



Performances:

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

Results on rare processes:

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

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- **Annual Modulation Signature** — PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

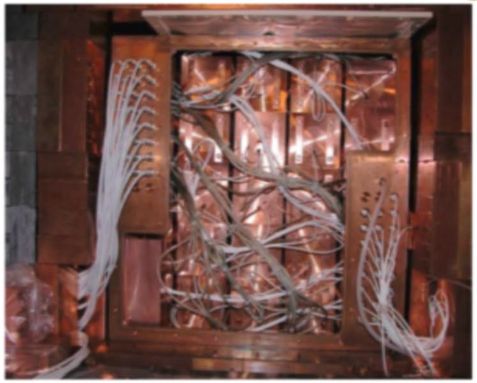
Model independent evidence of a particle DM component in the galactic halo at 6.3 σ C.L.

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 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques
(all operations involving - 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



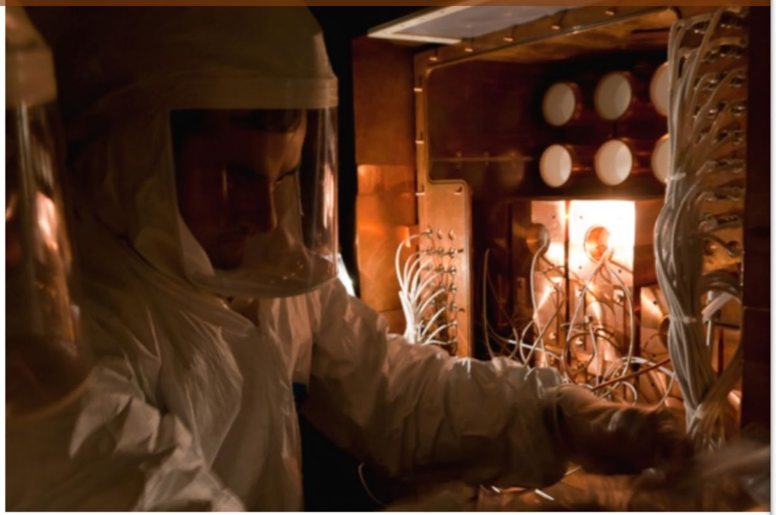
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles,
  - Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  - Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, EPJC75(2015)400, IJMPA31(2016) dedicated issue, EPJC77(2017)83
- Results on rare processes:
  - PEPv: EPJC62(2009)327, arXiv1712.08082;
  - CNC: EPJC72(2012)1920;
  - IPP in ^{241}Am: EPJA49(2013)64

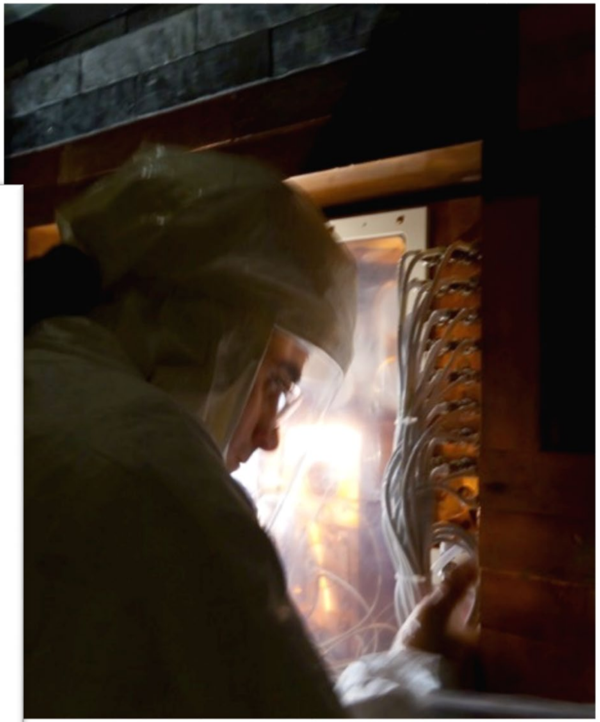
DAMA/LIBRA–phase1 (7 annual cycles, 1.04 ton×yr) confirmed the model-independent evidence of DM: reaching 9.3σ C.L.

DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled W. in Phys.19 (2018) 27

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





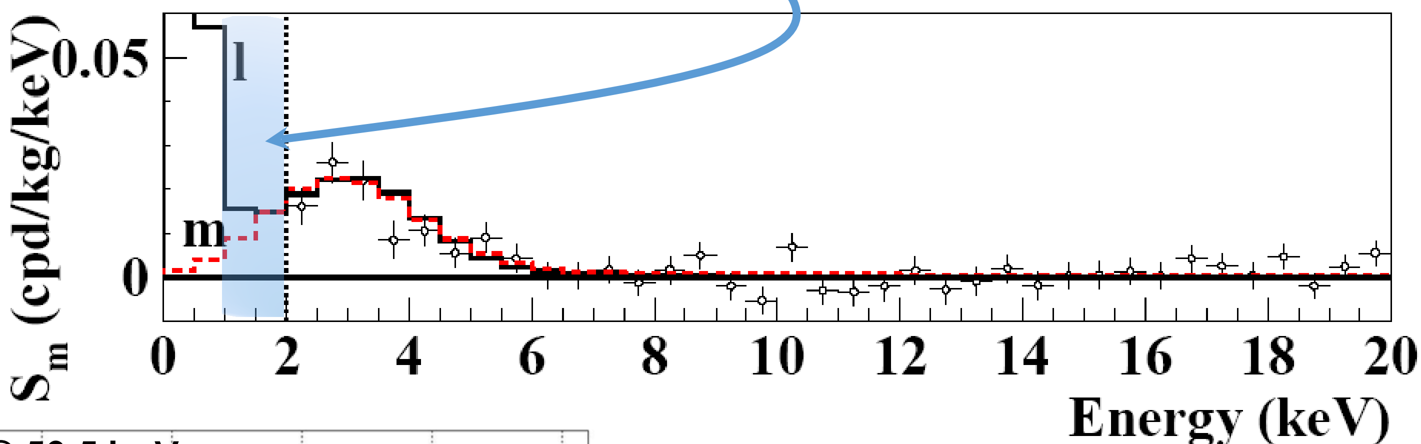
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak

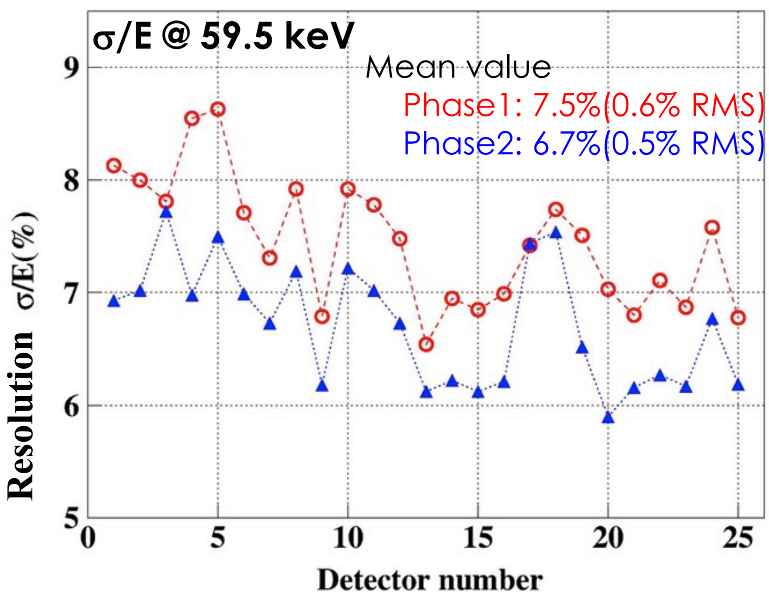
DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 207
Bled W. in Phys.19 (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

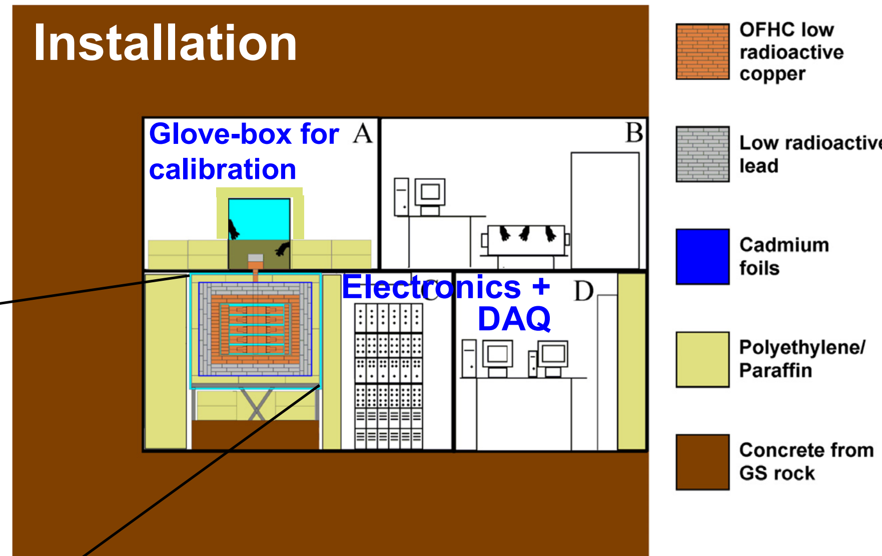
The light responses:

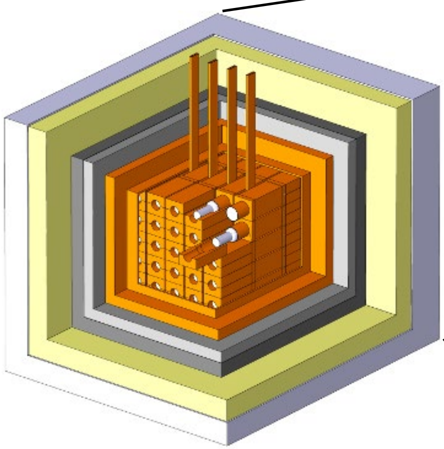
DAMA/LIBRA-phase1: 5.5 – 7.5 ph.e./keV
DAMA/LIBRA-phase2: 6-10 ph.e./keV

The DAMA/LIBRA–phase2 set-up

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

- 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 HP N_2
- All the materials selected for low radioactivity
- 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

- Multiton-multicomponent passive shield (>10 cm OFHC Cu, 15 cm boliden Pb + Cd foils, 10/40 cm polyethylene/paraffin, ~1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- 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

DAMA/LIBRA-phase2 data taking

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

JINST 7(2012)03009

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.: ≈ 1.3×10^8 events from sources
- ✓ Acceptance window eff. 6 a.c.: ≈ 3.4×10^6 events (≈1.4×10^5 events/keV)

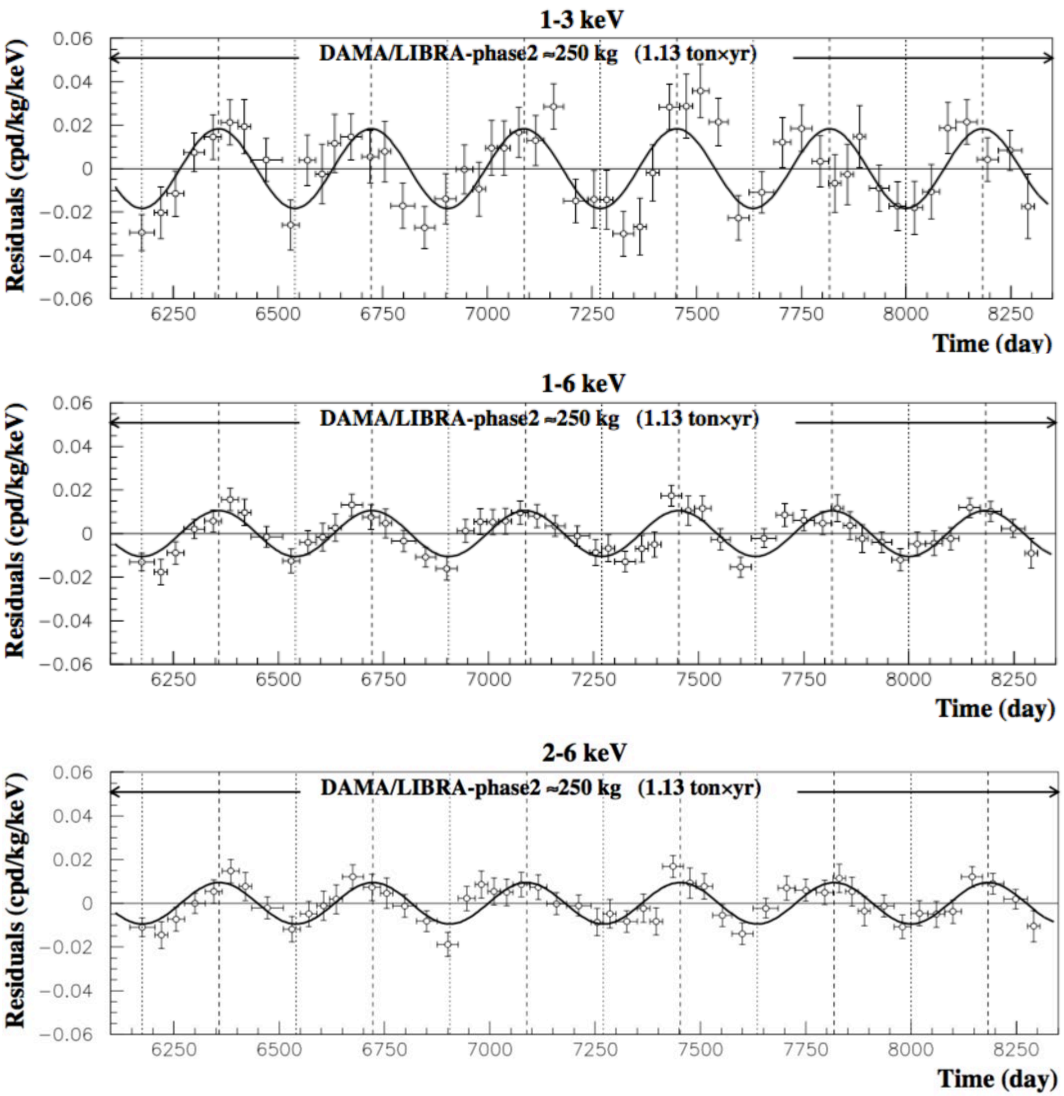
Annual Cycles	Period	Mass (kg)	Exposure (kg×day)	$(\alpha-\beta^2)$
I	Dec 23, 2010 – Sept. 9, 2011	commissioning		
II	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 – Sept. 9, 2015	242.5	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

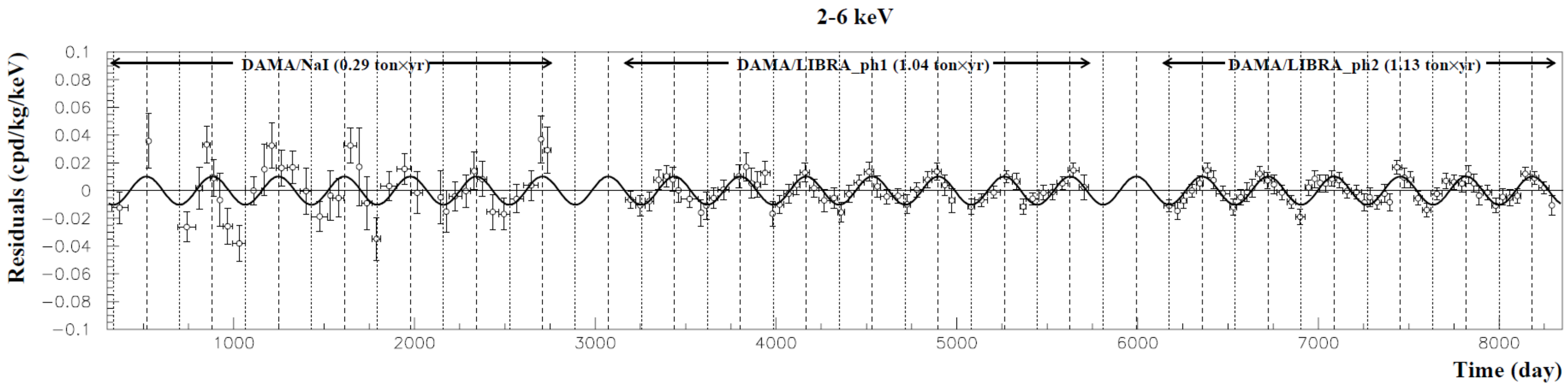
χ^2/dof = 42.5/51 **8.6 σ C.L.**

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/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.46 ton $\times$ yr)



Absence of modulation? No

- 2-6 keV: χ^2/dof=272.3/142 $\Rightarrow$ P(A=0) =3.0×10^{-10}

Fit on DAMA/NaI+ DAMA/LIBRA-ph1+ DAMA/LIBRA-ph2

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

2-6 keV

A=(0.0102$\pm$0.0008) cpd/kg/keV

χ^2/dof = 113.8/138 **12.8 σ C.L.**

The data of DAMA/NaI + DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 12.8 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

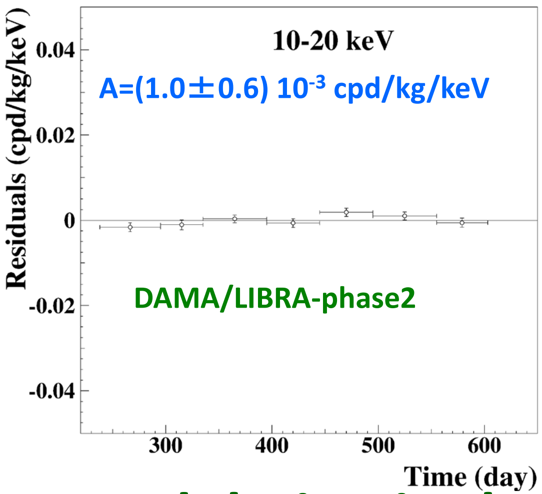
$A\cos[\omega(t-t_0)]$

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

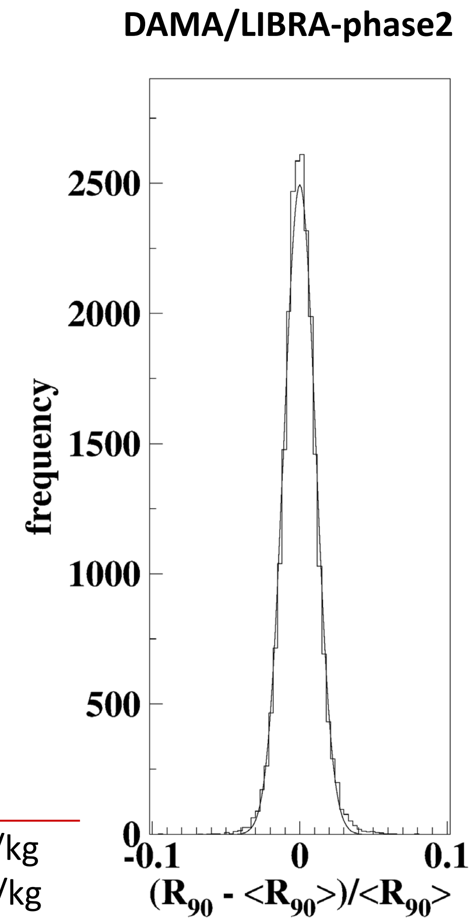
• No Modulation above 6 keV



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
- $-(0.0004 \pm 0.0015)$ DAMA/LIBRA-ph2_5
- (0.0001 ± 0.0015) DAMA/LIBRA-ph2_6
- (0.0015 ± 0.0014) DAMA/LIBRA-ph2_7

→ statistically consistent with zero



$\sigma \approx 1\%$, 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**

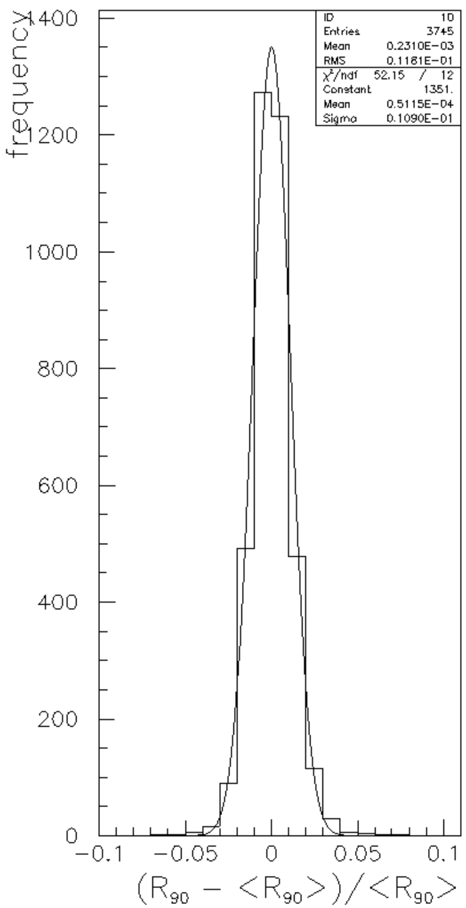
Period	Mod. Ampl.
DAMA/LIBRA-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg

+ 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 background and is consistent with the studies on the various components

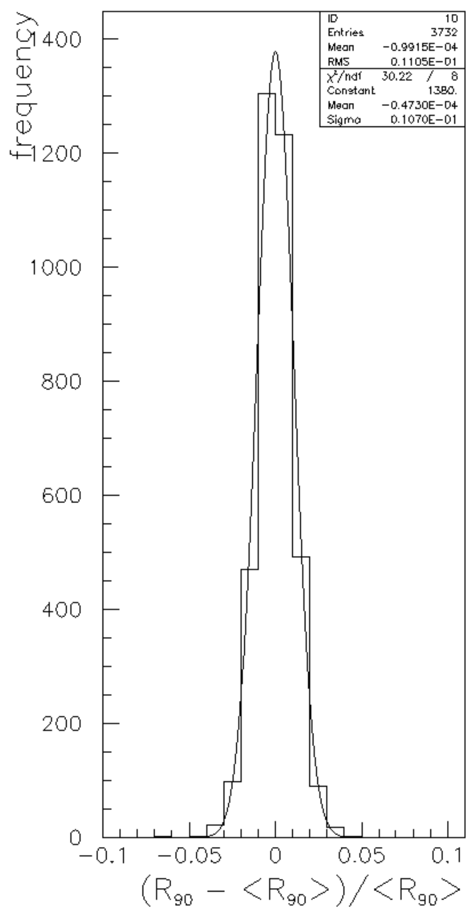
Totale rate above 90 keV (R90)



DAMA/LIBRA-ph2_5

σ=1.1%

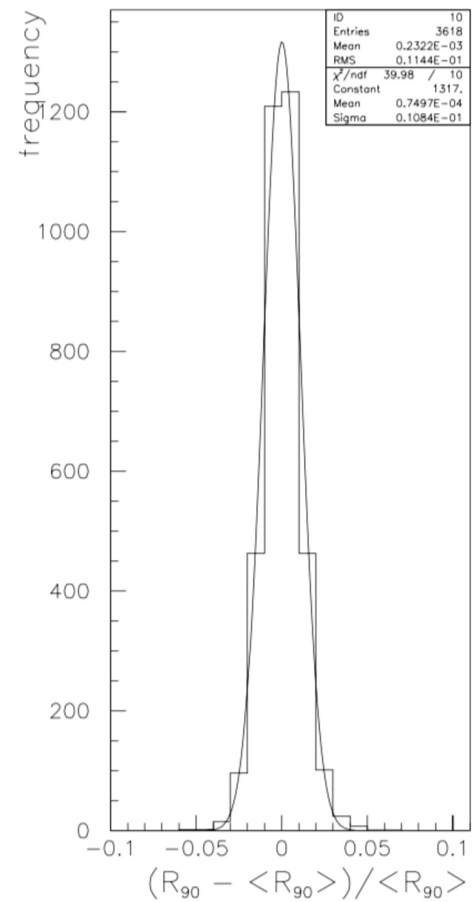
A_{mod}= -(0.05±0.14) cpd/kg



DAMA/LIBRA-ph2_6

σ=1.1%

A_{mod}= (0.03±0.13) cpd/kg



DAMA/LIBRA-ph2_7

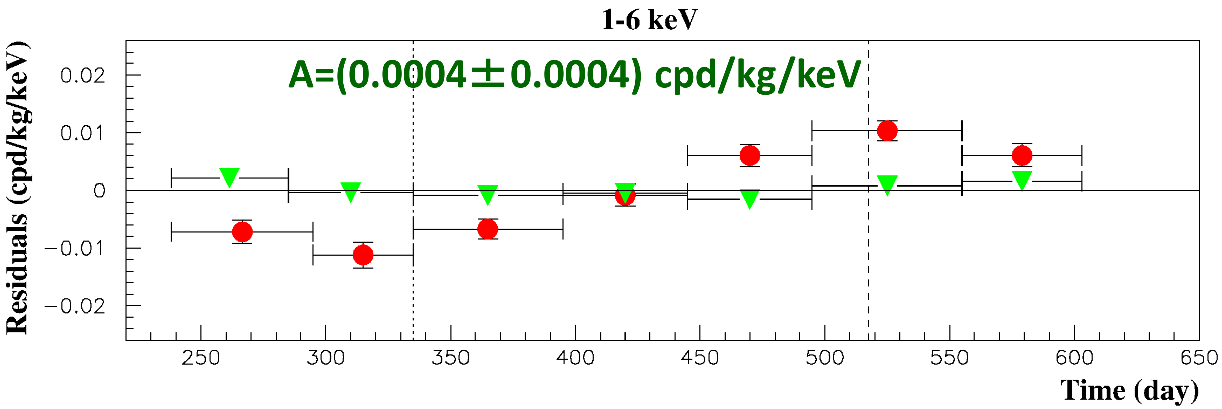
σ=1.1%

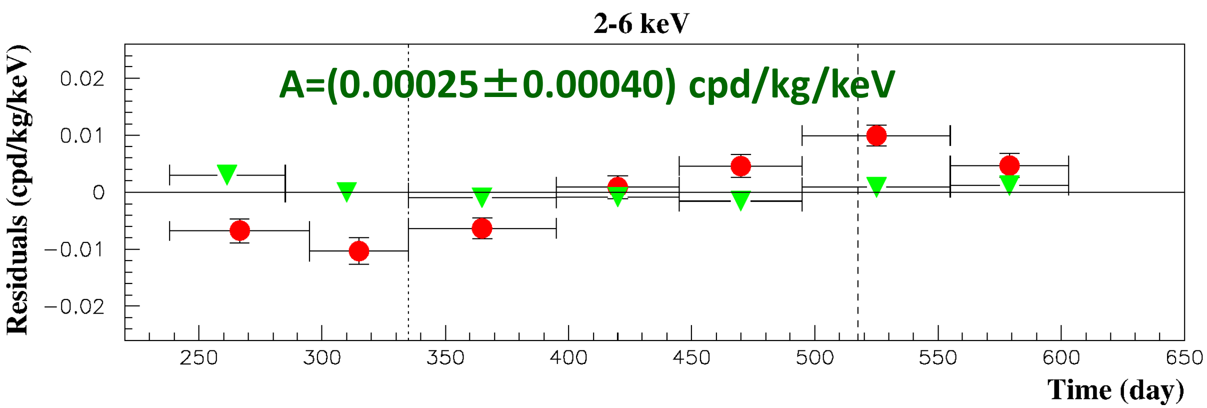
A_{mod}= -(0.09±0.14) cpd/kg

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

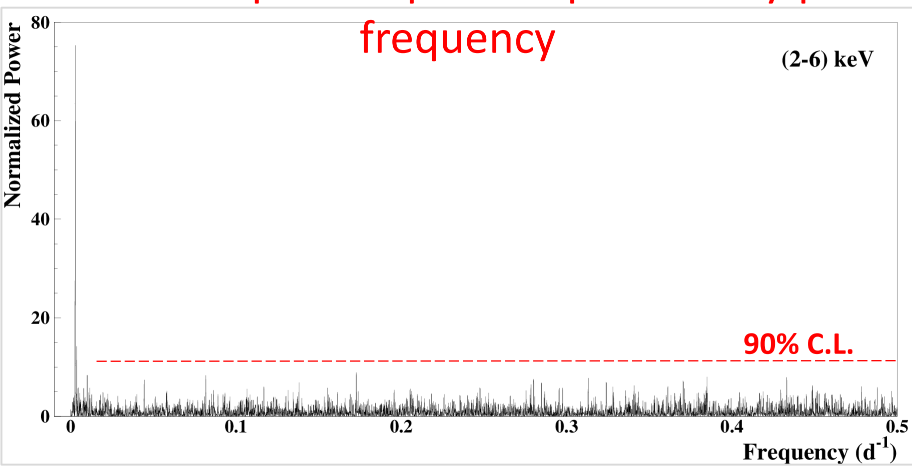
This result furthermore rules out any side effect either from hardware or from software procedures or from background

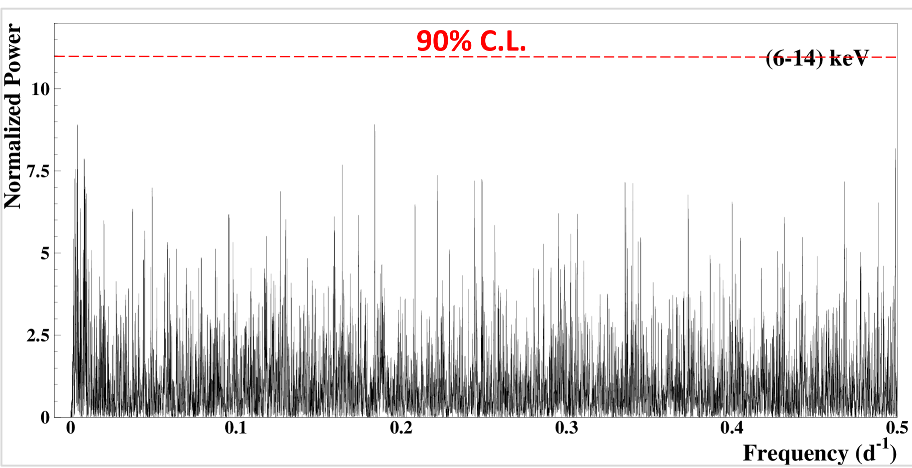
The analysis in frequency

(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

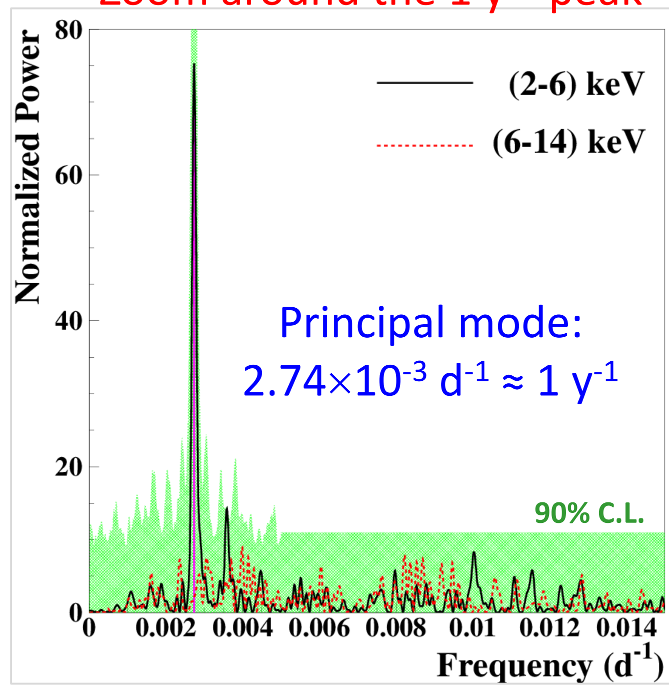
The whole power spectra up to the Nyquist frequency





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

Zoom around the 1 y^{-1} peak



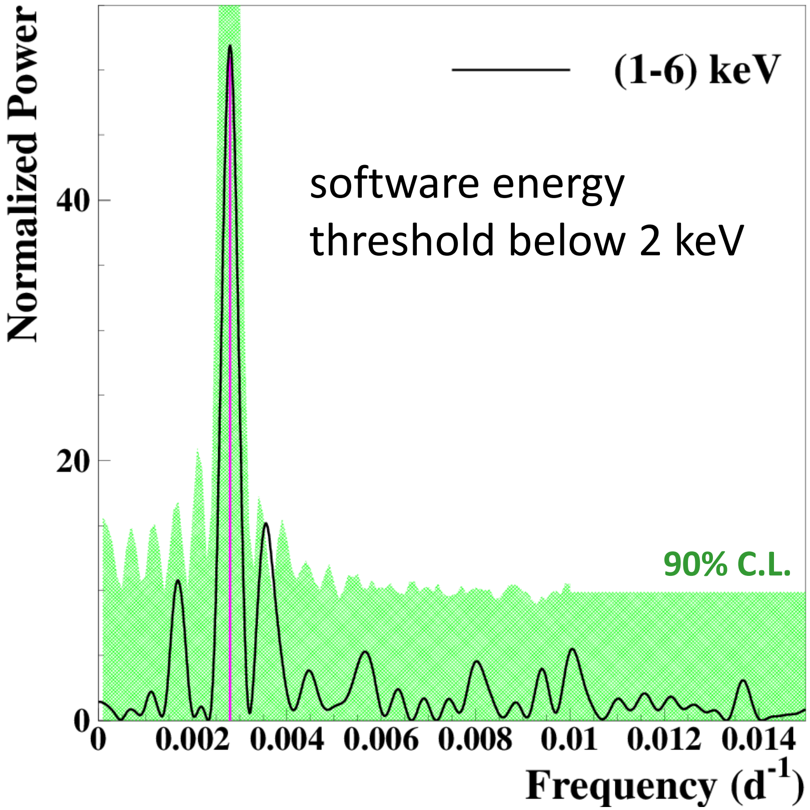
Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

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

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/LIBRA-phase2 (6 yr)
total exposure: 1.13 ton×yr

Principal mode: 2.79×10^{-3} d^{-1} ≈ 1 y^{-1}

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

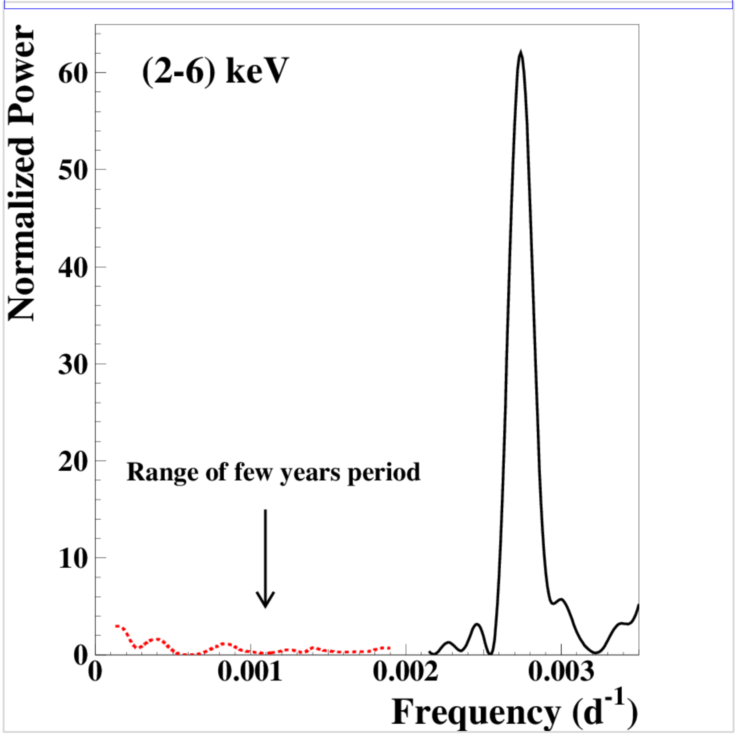
Clear annual modulation in (1-6) keV single-hit scintillation events

Investigating the possible presence of long term modulation in the counting rate

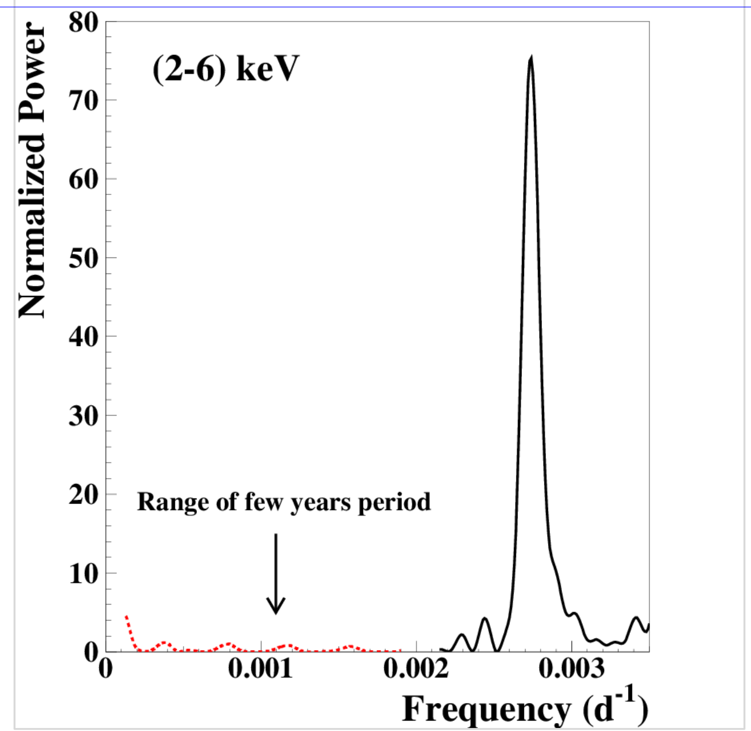
We calculated annual baseline counting rates – that is the averages on all the detectors (j index) of $flat_j$ (i.e. the single-hit scintillation rate of the j-th detector averaged over the annual cycle)

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

DAMA/LIBRA-(ph1+ph2)



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



No statistically significant peak at lower frequency

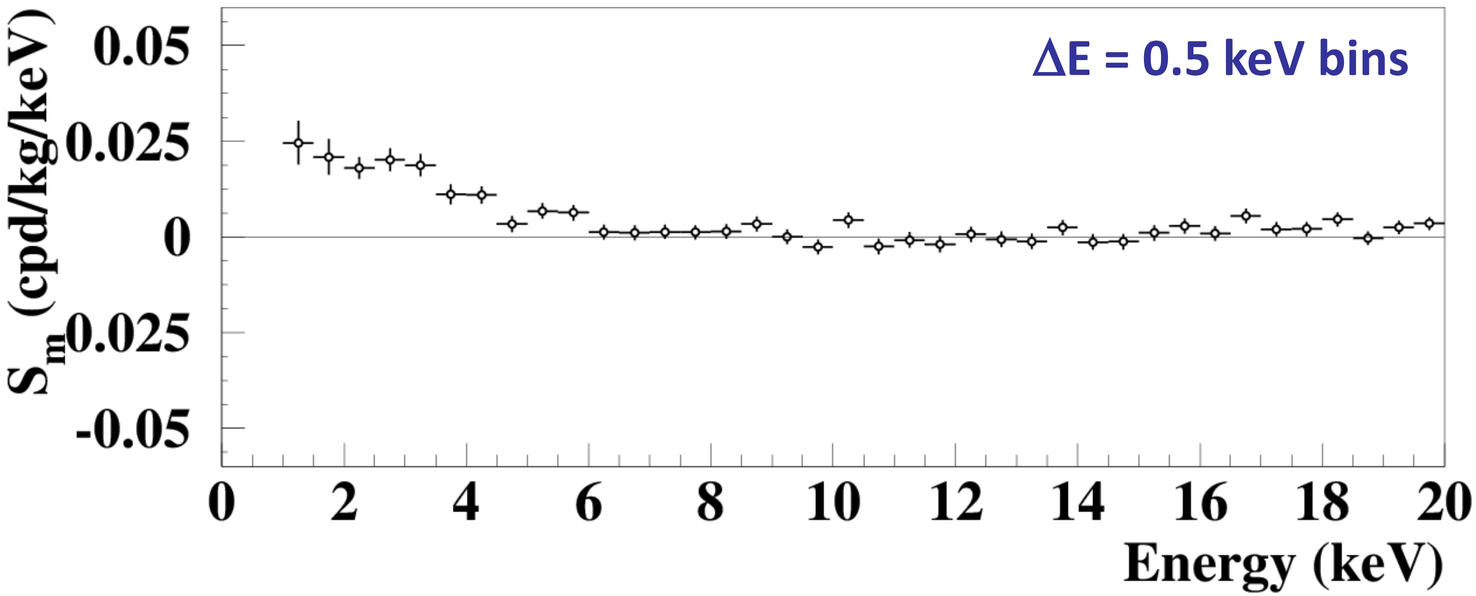
Energy distribution of the modulation amplitudes

Max-likelihood analysis

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

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

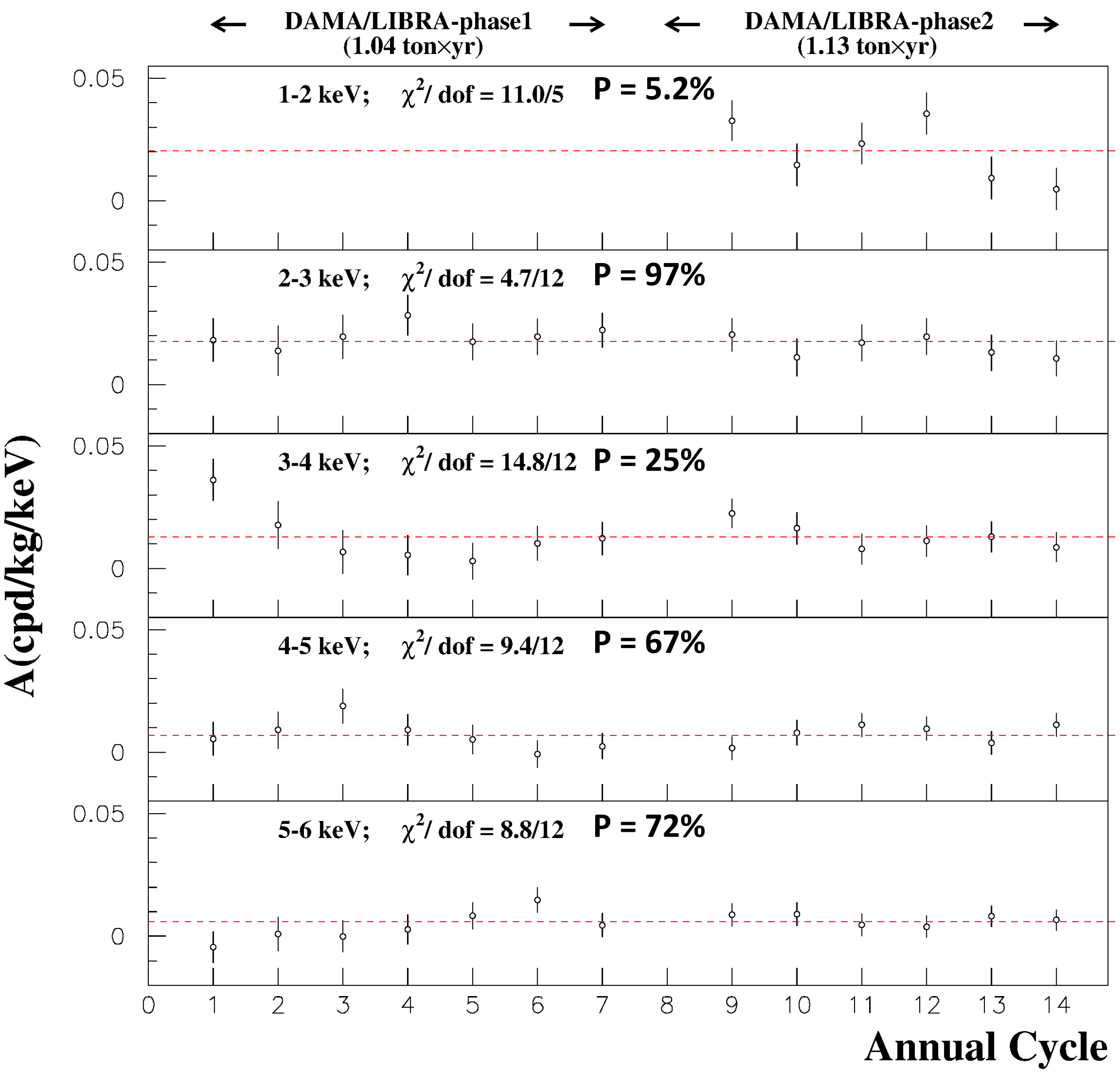
DAMA/NaI + DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2 (2.46 ton×yr)



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%

*it verifies the hypothesis that the positive (above the mean value) and negative (under the mean value) data points are randomly distributed

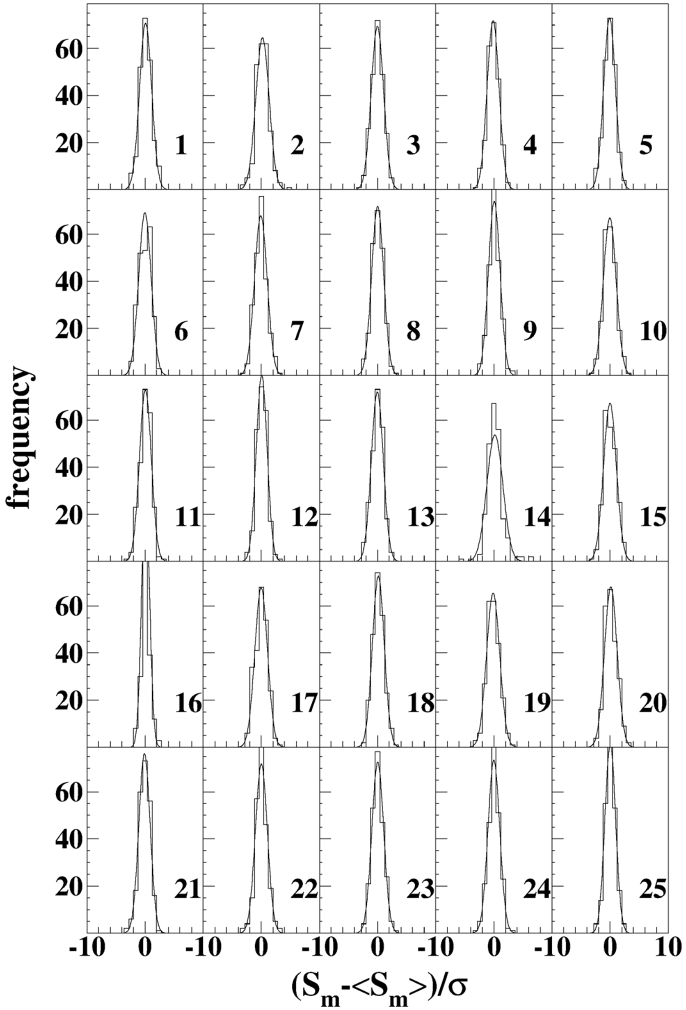
The signal is well distributed over all the annual cycles in each energy bin

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) $\langle S_m \rangle$ = mean values over the detectors and the annual cycles for each energy bin; σ = error on S_m

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



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

$$x=(S_m-\langle S_m\rangle)/\sigma, \qquad \chi^2=\Sigma x^2$$

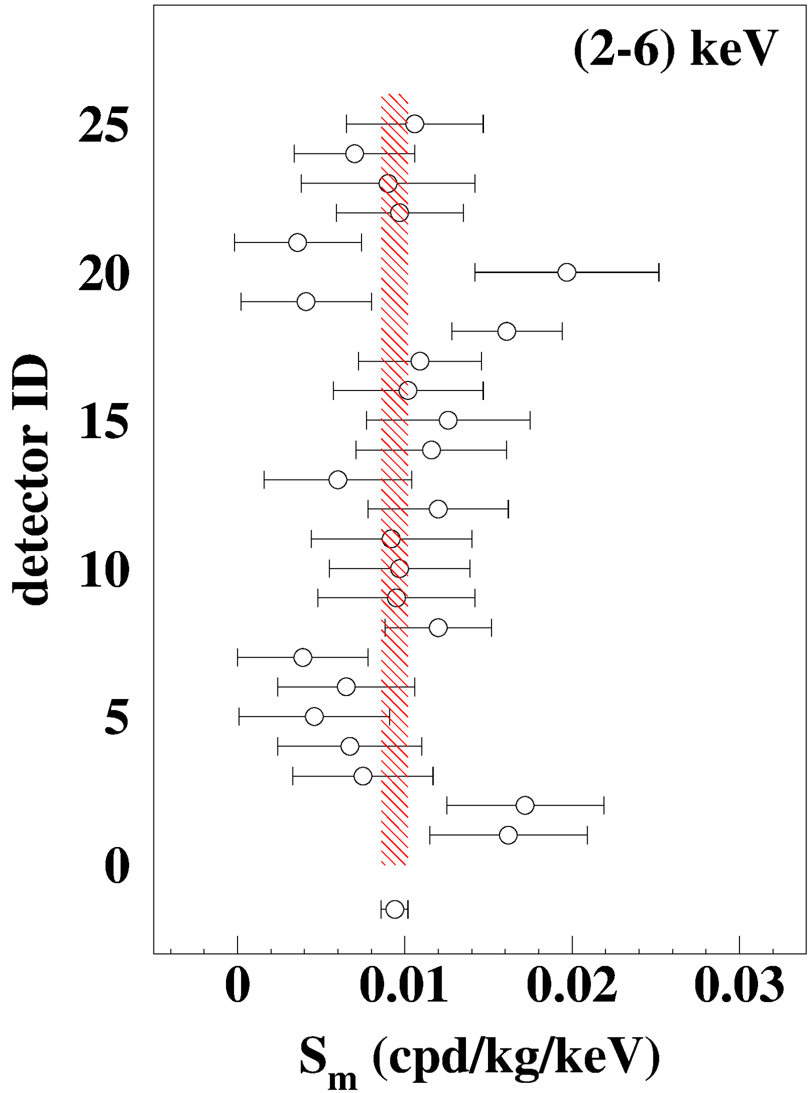
Individual S_m values follow a normal distribution since ***x*** is distributed as a Gaussian with a unitary standard deviation

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 $\leq 2.1 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 3 \times 10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude below 6 keV.
- This possible additional error ($\leq$2% or $\leq$0.3%, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic 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 $S_m \pm 1\sigma$

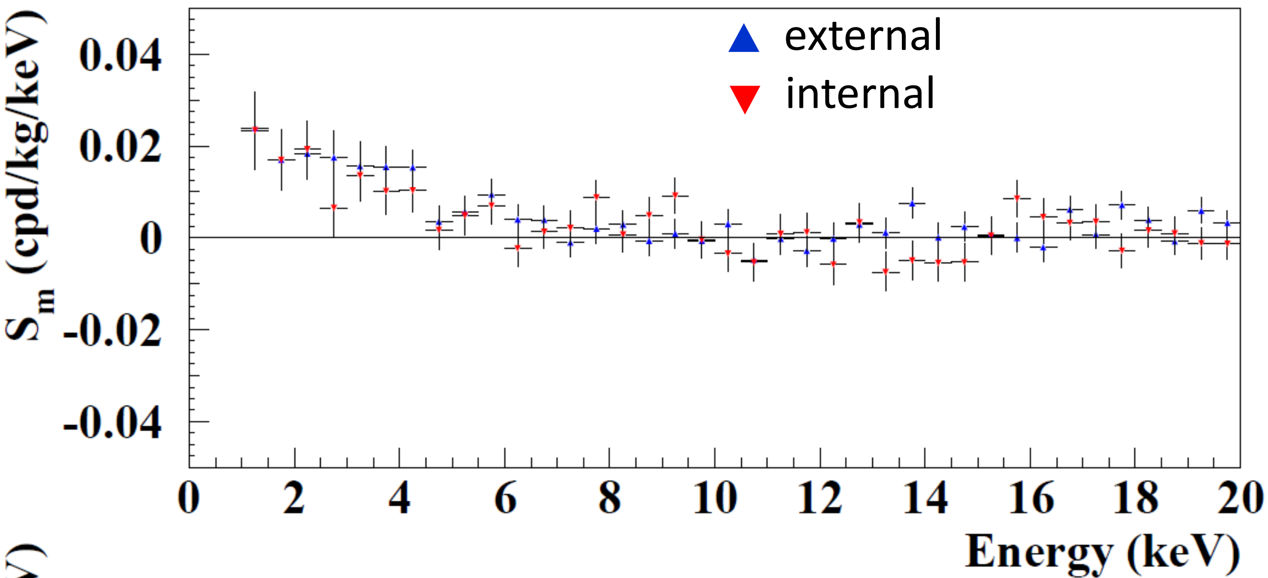
χ^2/dof = 23.9/24 d.o.f.

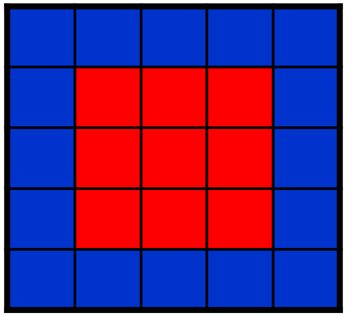
The signal is well distributed over all the 25 detectors

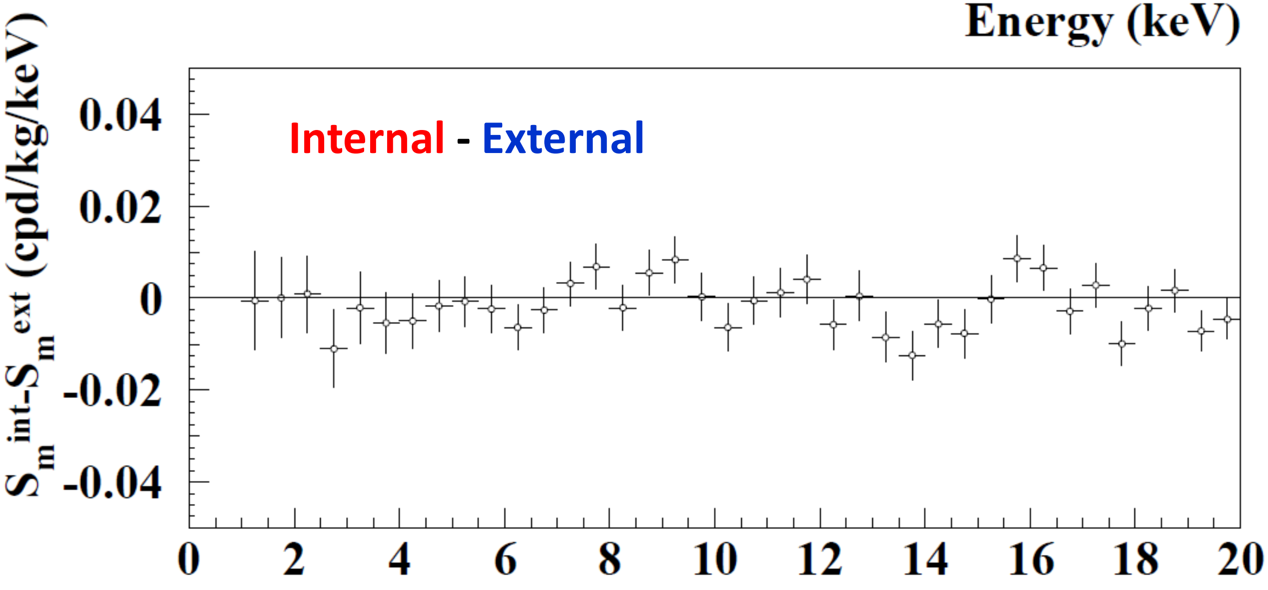
External vs internal detectors

DAMA/LIBRA-phase2

ΔE=0.5 keV







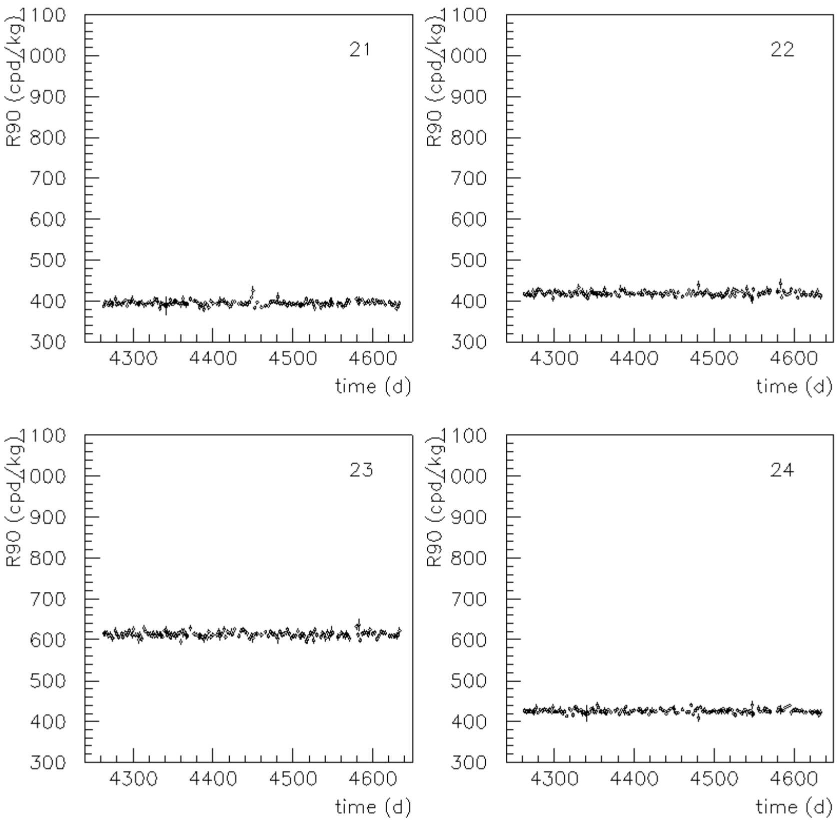
1-4 keV χ^2/dof =2.5/6

1-10 keV χ^2/dof =12.1/8

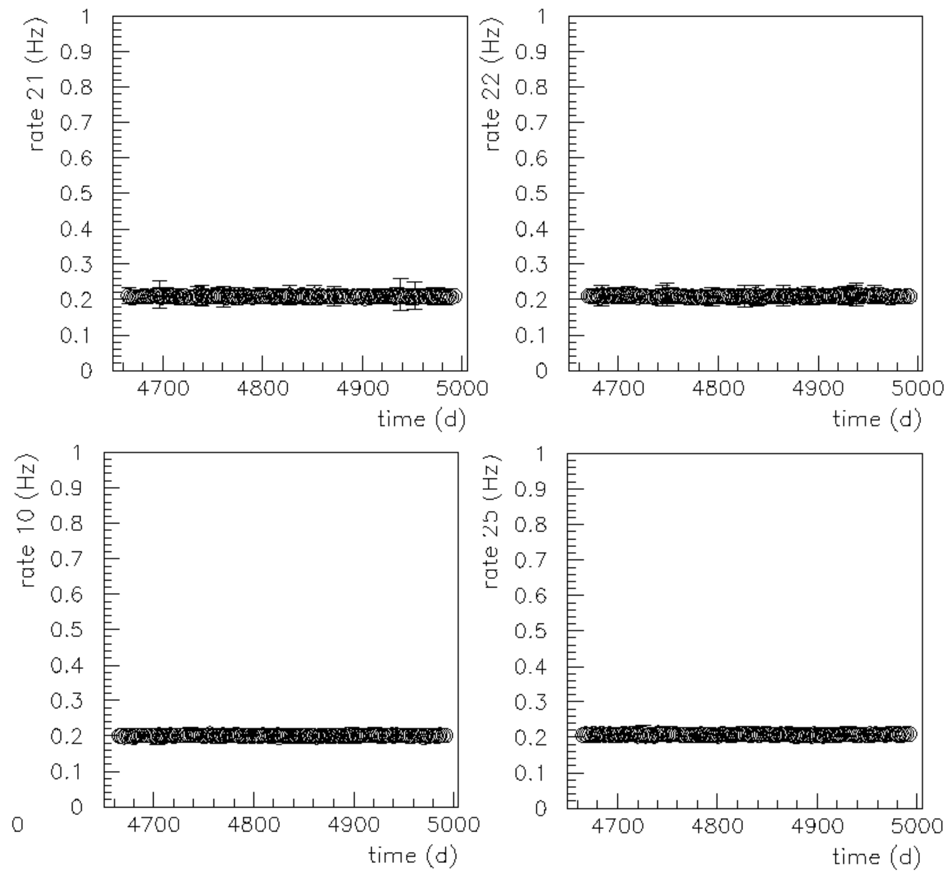
1-20 keV χ^2/dof =40.8/38

Stability parameters of DAMA/LIBRA–phase2

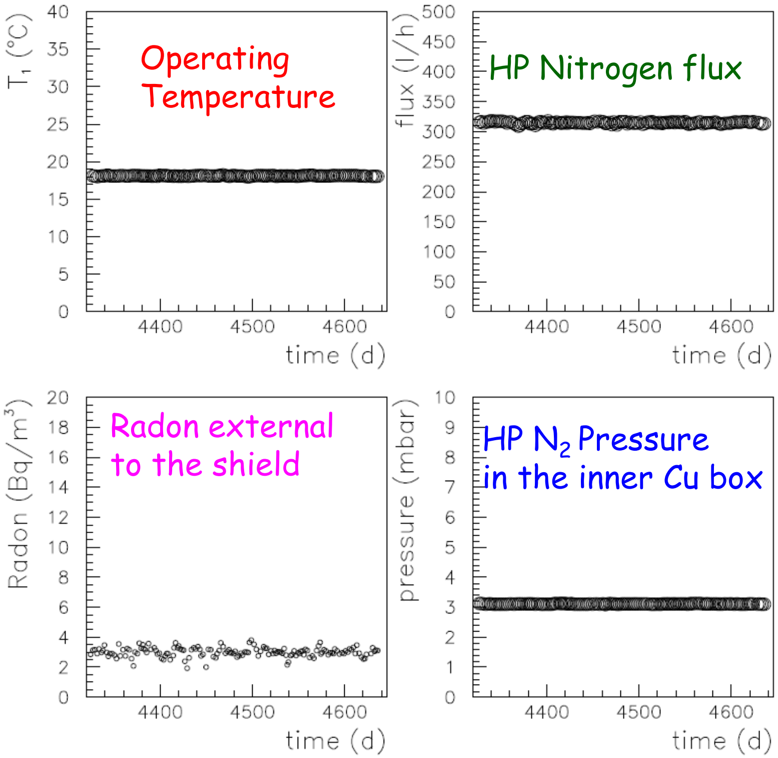
Examples of R90 vs time:
some crystals in DAMA/LIBRA-ph2_5

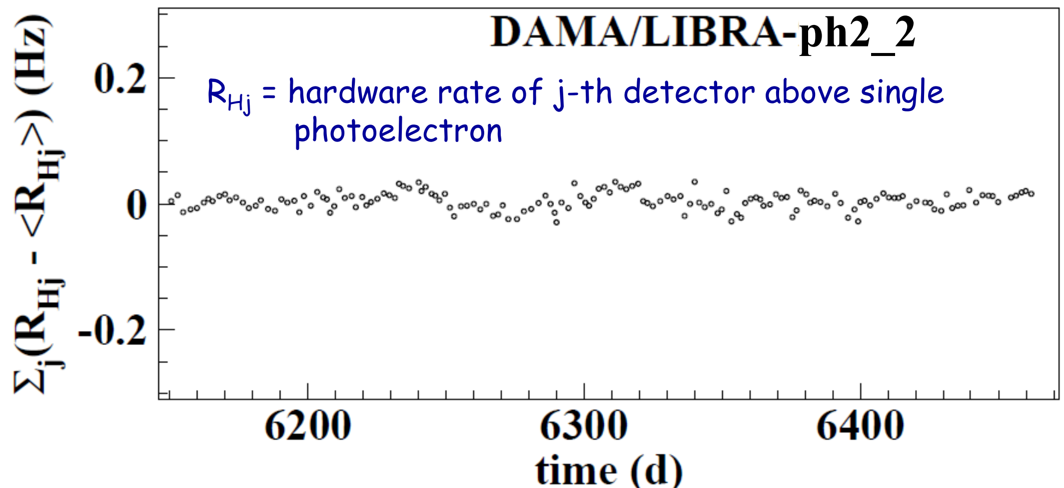


Examples of hardware rates vs time:
some crystals in DAMA/LIBRA-ph2_3



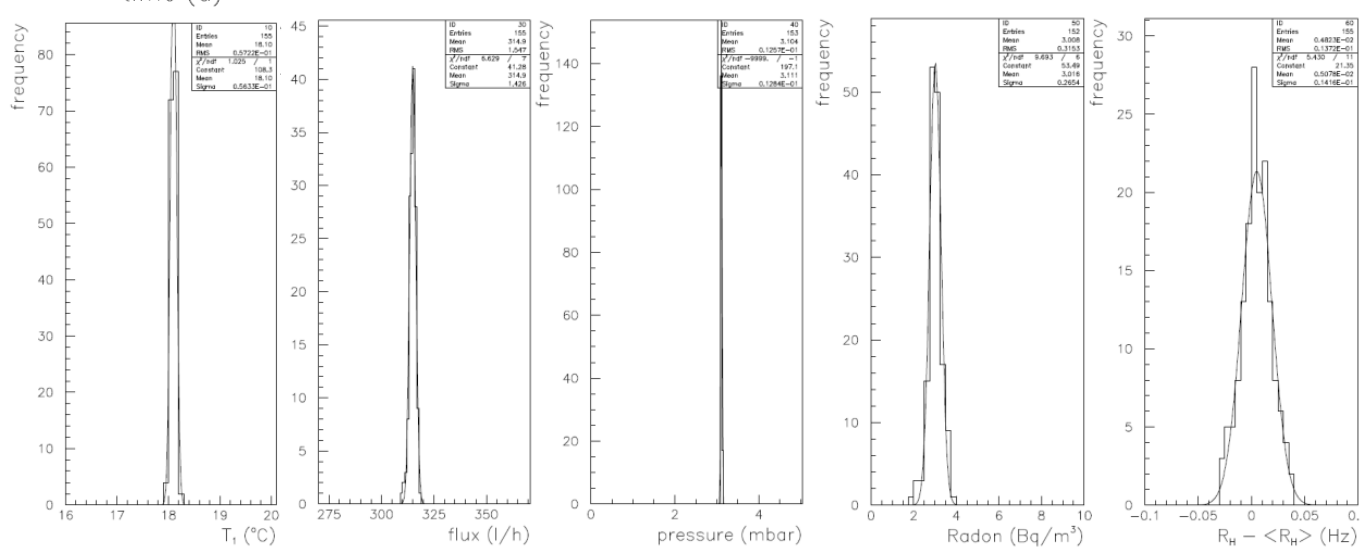
Example of Stability Parameters: DAMA/LIBRA-ph2_2





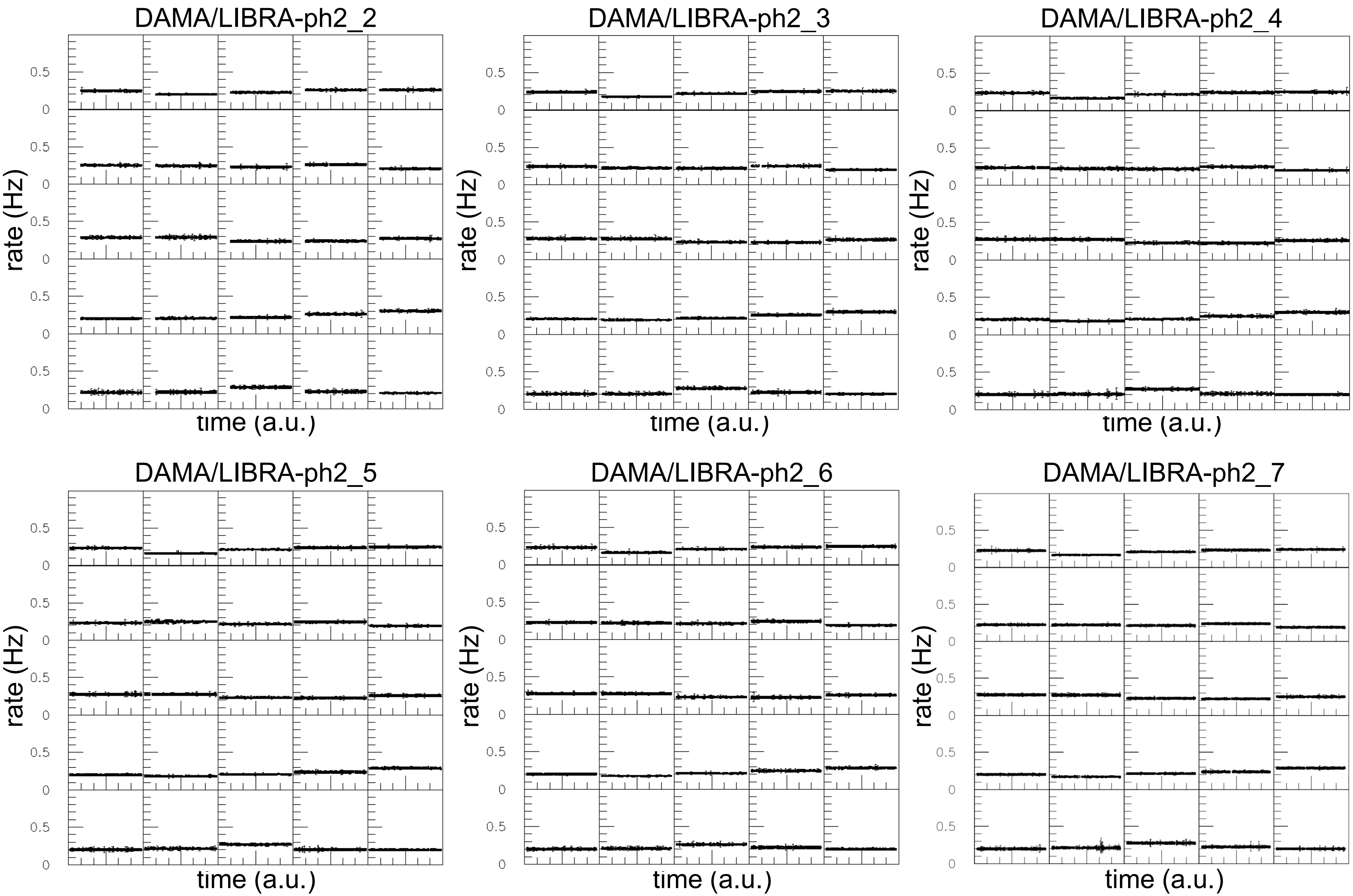
Running conditions stable at level < 1%

Parameters distributions



All amplitudes well compatible with zero
+ no effect can mimic the annual modulation

Time behaviour of hardware rate for each crystal



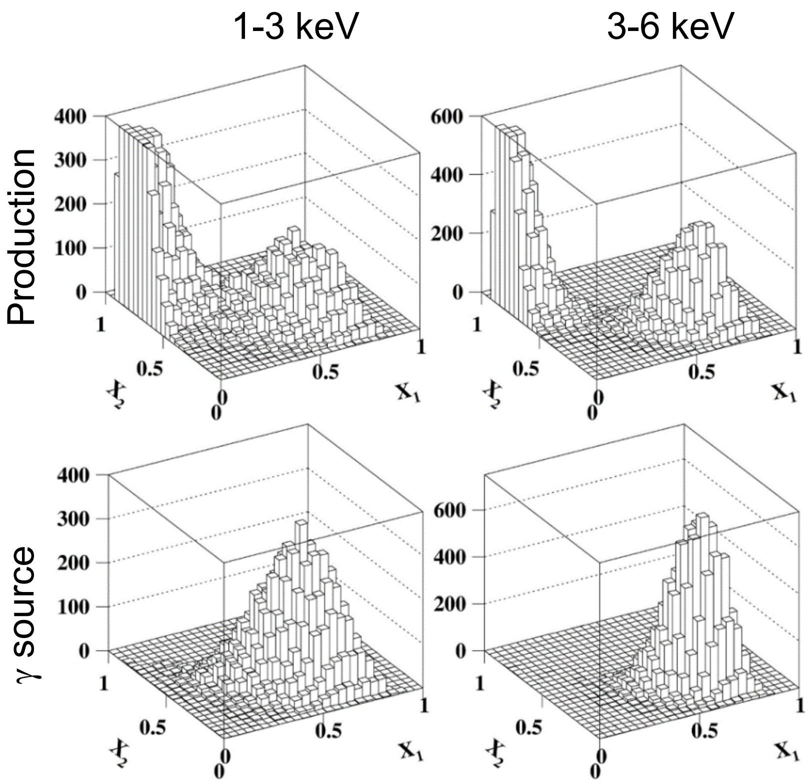
No modulation effect found + can not mimic the annual modulation

Noise rejection in phase2

JINST 7(2012)03009

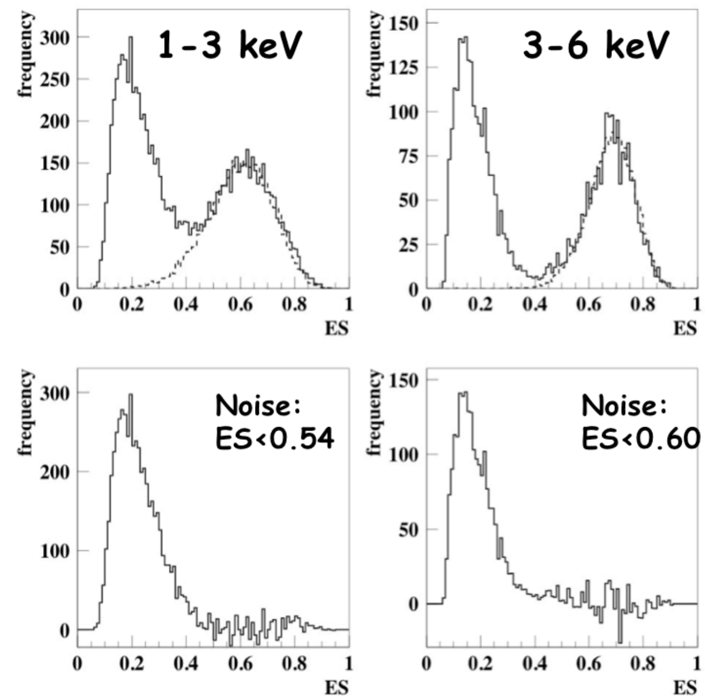
- Comparison of the noise and the scintillation pulses distributions in 1-3 keV and 3-6 keV
- production data vs γ source
- scintillation events well separated from noise

X_1=Area from 100 to 600 ns / Area from 0 to 600 ns
X_2=Area from 0 to 50 ns / Area from 0 to 600 ns

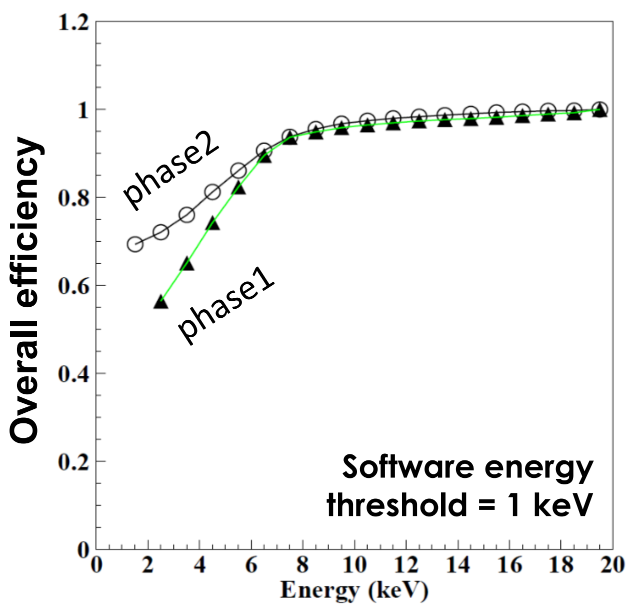


Evaluation of residual noise

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



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



After cut the residual noise is compatible with 0
⇒ noise contamination < 3% at software energy threshold

Possible residual noise contribution?

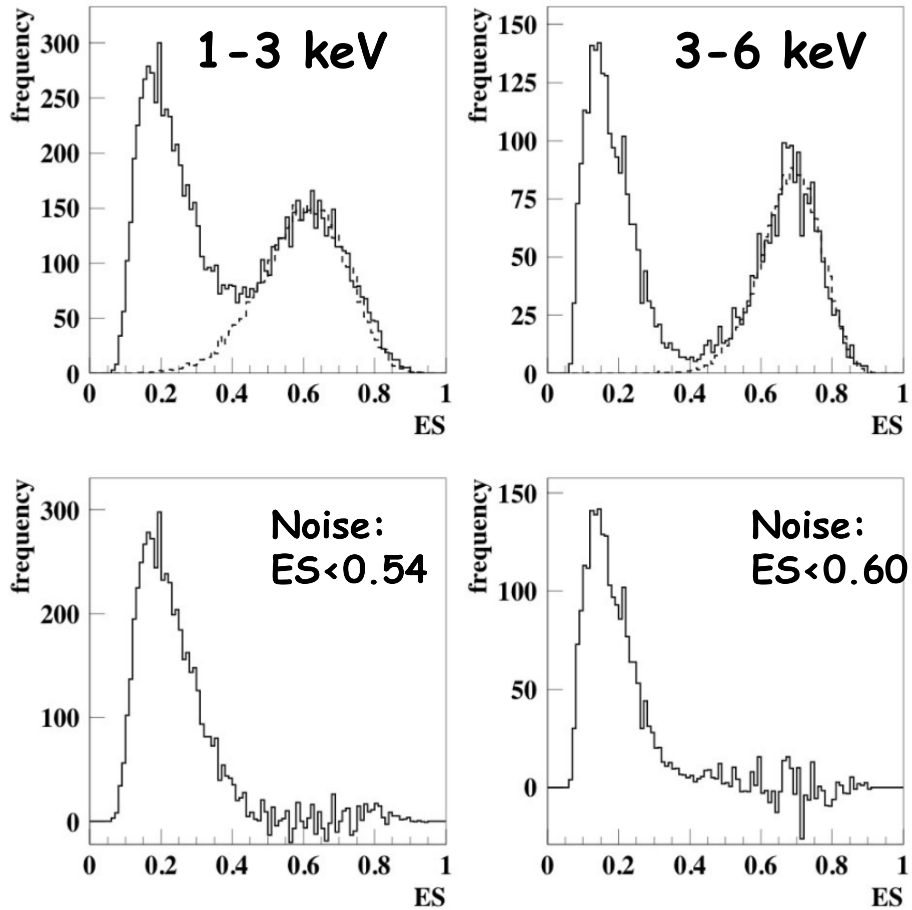
JINST 7(2012)03009

Measure of the upper limit on residual noise contribution in the population of scintillation events selected by applying the acceptance window on *lego plot*

Analysis for a sample of events in production data

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

This variable allows us to take into account contemporaneously the info of both the X1 and X2 variables of each event in a single plot



Bottom plots obtained after subtracting from the distributions of the production data the distributions obtained with γ sources

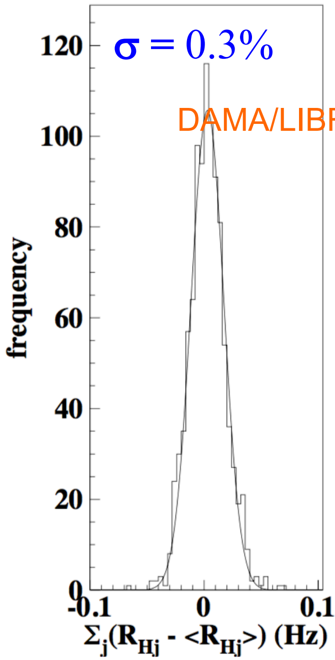
They represent the distributions for noise events

Production data = continuous histogram
γ source data = dashed histogram

Residual noise events: (15±62) in 1-3 keV
-(18±41) in 3-6 keV

Corresponding to noise events: <120 (1-3 keV) & <51 (3-6 keV) at 90% C.L.

Noise

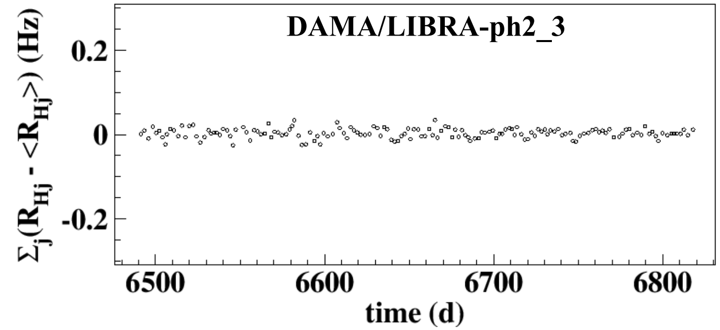


Distribution of variations of total hardware rates of the crystals above the single ph.e. threshold (that is from noise to "infinity") during DAMA/LIBRA running periods

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 < 2.4×10^{-5} → $< 10^{-4}$ cpd/kg/keV

NO

The calibration factors

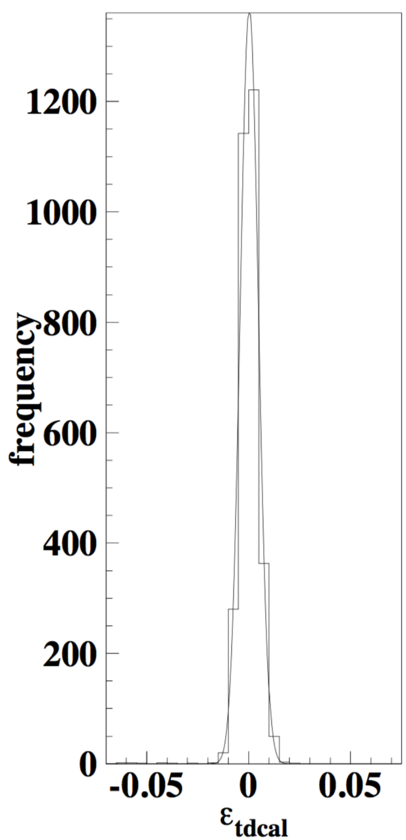
DAMA/LIBRA-phase2

- 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.

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

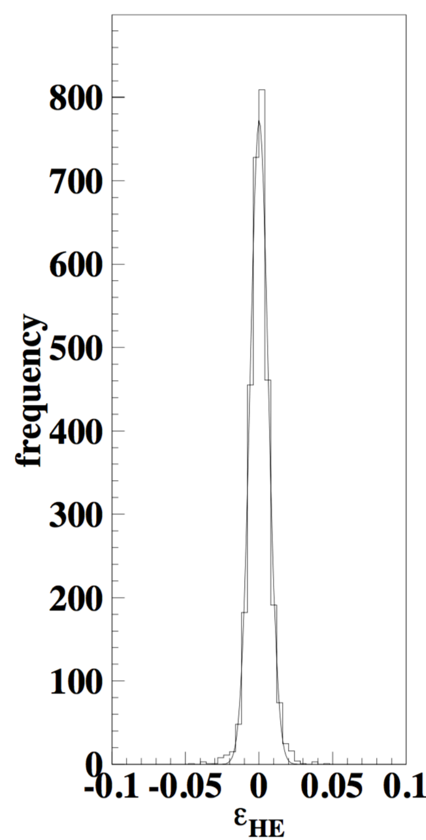
gaussian behaviours

σ=0.5%



Low-Energy calibr. factors (ε_{tdcal})

σ=0.6%



High-Energy calibr. factors (ε_{HE})

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

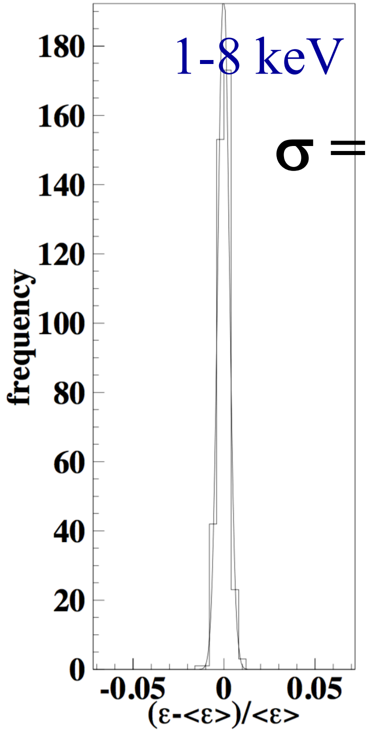
$$\sigma = \sqrt{\sigma_{res}^2 + \sigma_{cal}^2} \approx \sigma_{res} \cdot \left[1 + \frac{1}{2}\left(\frac{\sigma_{cal}}{\sigma_{res}}\right)^2\right]; \frac{1}{2}\left(\frac{\sigma_{cal}/E}{\sigma_{res}/E}\right)^2 \le 7.5 \cdot 10^{-4} \frac{E}{20keV}$$

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

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	$-(0.10\pm0.32) \times 10^{-3}$
4-6 keV	$(0.00\pm0.41) \times 10^{-3}$

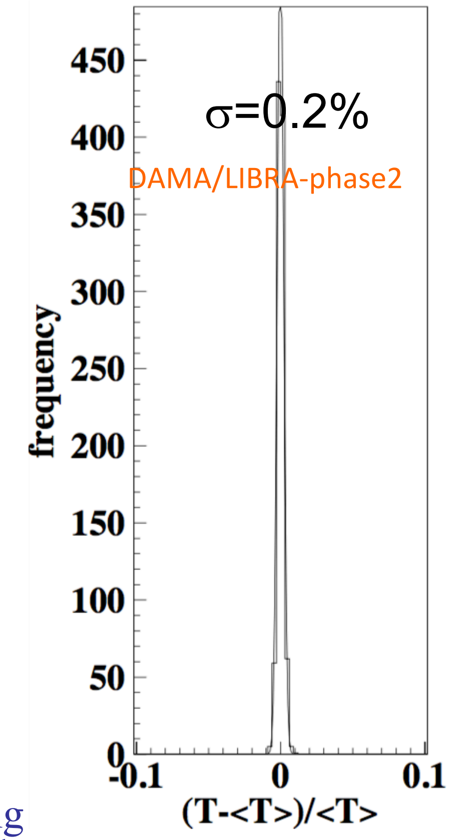
Amplitudes well compatible with zero + cannot mimic the signature

Temperature

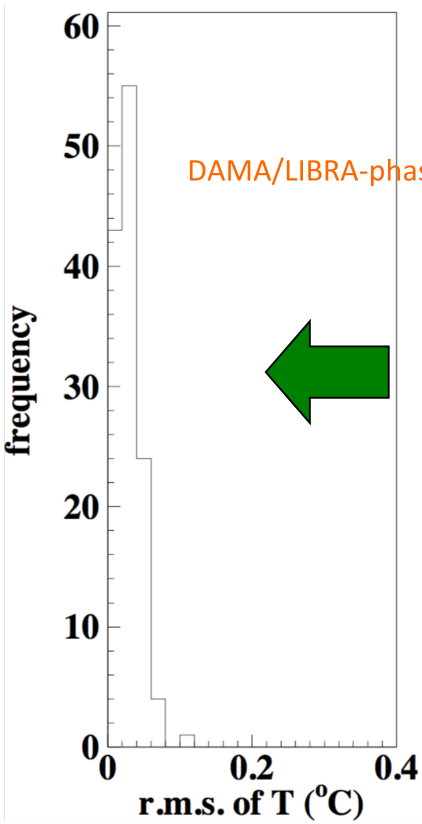
- Detectors in Cu housings directly in contact with multi-ton shield $\rightarrow$huge heat capacity ($\approx 10^6$ cal/^{0}C)
- Experimental installation continuosly air conditioned (2 independent systems for redundancy)
- Operating T of the detectors continuously controlled

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 relative variations of the operating T of the detectors



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} :

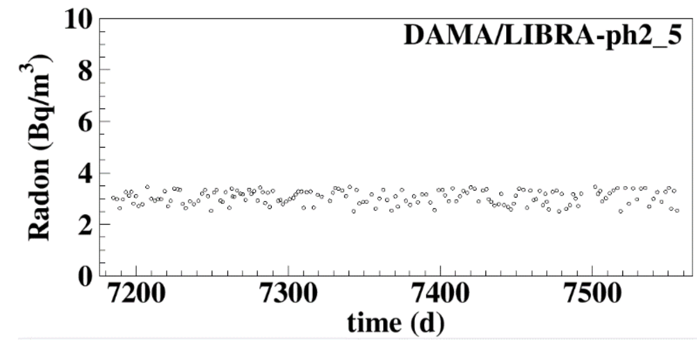
<10^{-4} cpd/kg/keV (< 0.5% $S_m^{observed}$)

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



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!

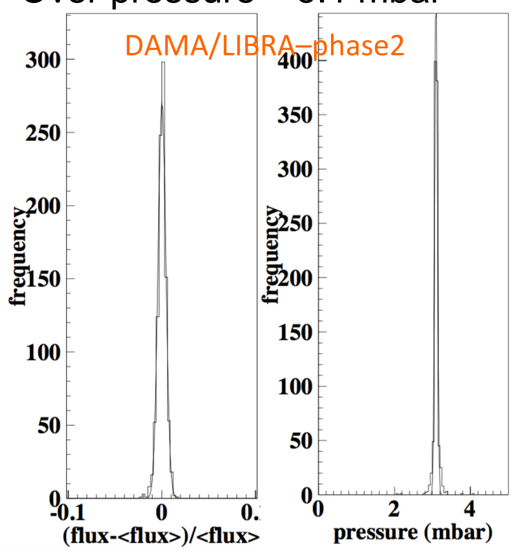
measured values at level of sensitivity of the used radonmeter

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

Amplitudes for annual modulation of Radon external to the shield:

<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:**

$<2.5 \times 10^{-6}$ 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

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

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

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

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Annual modulation amplitude at low energy due to μ **modulation**:

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

Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events

✓ **Inconsistency of the phase between DAMA signal and μ modulation**

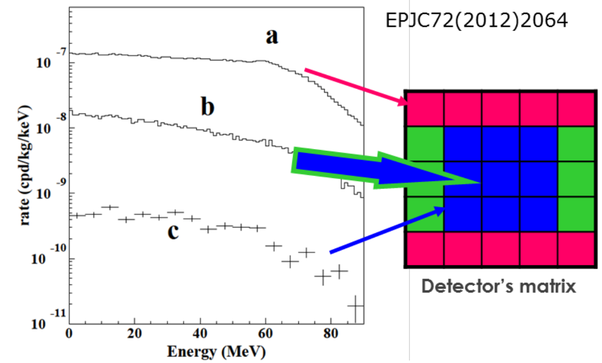
μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈$3 \cdot 10^{-4}$ $m^{-2}s^{-1}$; modulation amplitude 1.5%; **phase**: July 7 ± 6 d, June 29 ± 6 d (Borexino)

The DAMA phase: May 26 ± 7 days (stable over 13 years)

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

… many others arguments EPJC72(2012)2064, EPJC74(2014)3196

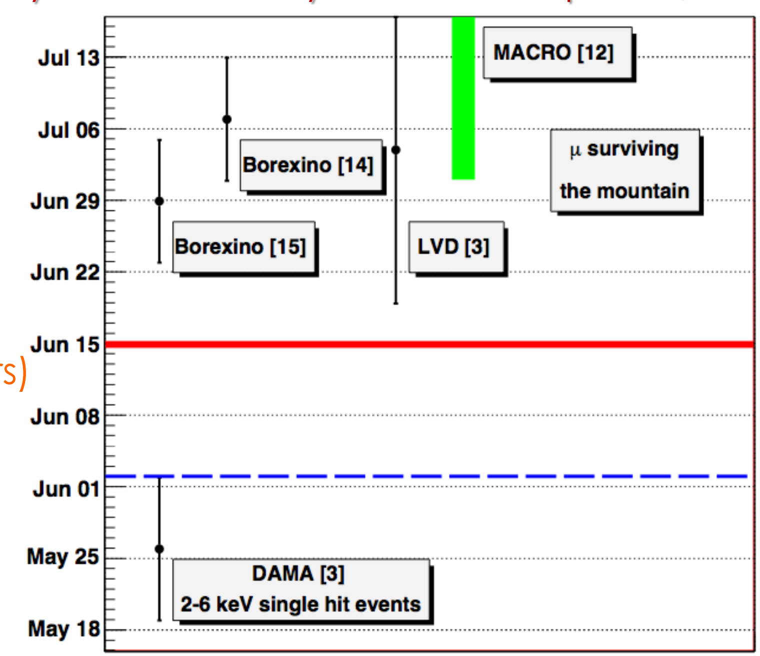
EPJC72(2012)2064



MonteCarlo simulation

$S_m^{(\mu)}$ < (0.3-2.4) × 10^{-5} cpd/kg/keV

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



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)	$-(0.0002 \pm 0.0049)$	$-(0.0003 \pm 0.0031)$	(0.0009 ± 0.0050)	(0.0018 ± 0.0036)	$-(0.0006 \pm 0.0035)$
Flux N_2 (l/h)	$-(0.15 \pm 0.18)$	$-(0.02 \pm 0.22)$	$-(0.02 \pm 0.12)$	$-(0.02 \pm 0.14)$	$-(0.01 \pm 0.10)$	$-(0.01 \pm 0.16)$
Pressure (mbar)	$(1.1 \pm 0.9) \times 10^{-3}$	$(0.2 \pm 1.1)\,) \times 10^{-3}$	$(2.4 \pm 5.4) \times 10^{-3}$	$(0.6 \pm 6.2) \times 10^{-3}$	$(1.5 \pm 6.3) \times 10^{-3}$	$(7.2 \pm 8.6) \times 10^{-3}$
Radon (Bq/m^3)	(0.015 ± 0.034)	$-(0.002 \pm 0.050)$	$-(0.009 \pm 0.028)$	$-(0.044 \pm 0.050)$	(0.082 ± 0.086)	(0.06 ± 0.11)
Hardware rate above single ph.e. (Hz)	$-(0.12 \pm 0.16) \times 10^{-2}$	$(0.00 \pm 0.12) \times 10^{-2}$	$-(0.14 \pm 0.22) \times 10^{-2}$	$-(0.05 \pm 0.22) \times 10^{-2}$	$-(0.06 \pm 0.16) \times 10^{-2}$	$-(0.08 \pm 0.17) \times 10^{-2}$

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)

- 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	$\Phi^{(\mu)}_0 \simeq 20\ \mu$ 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	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}\ \nu$ 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, 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$\rightarrow$ 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 $\times10^{-4}$ 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	**<3×10^{-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**

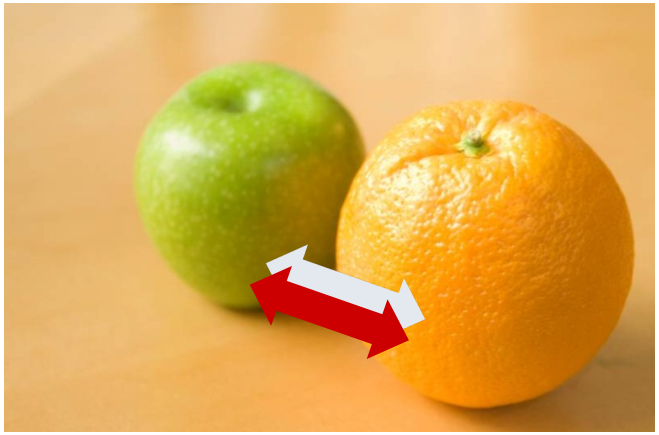
5) **The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal**

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)



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?
- ...

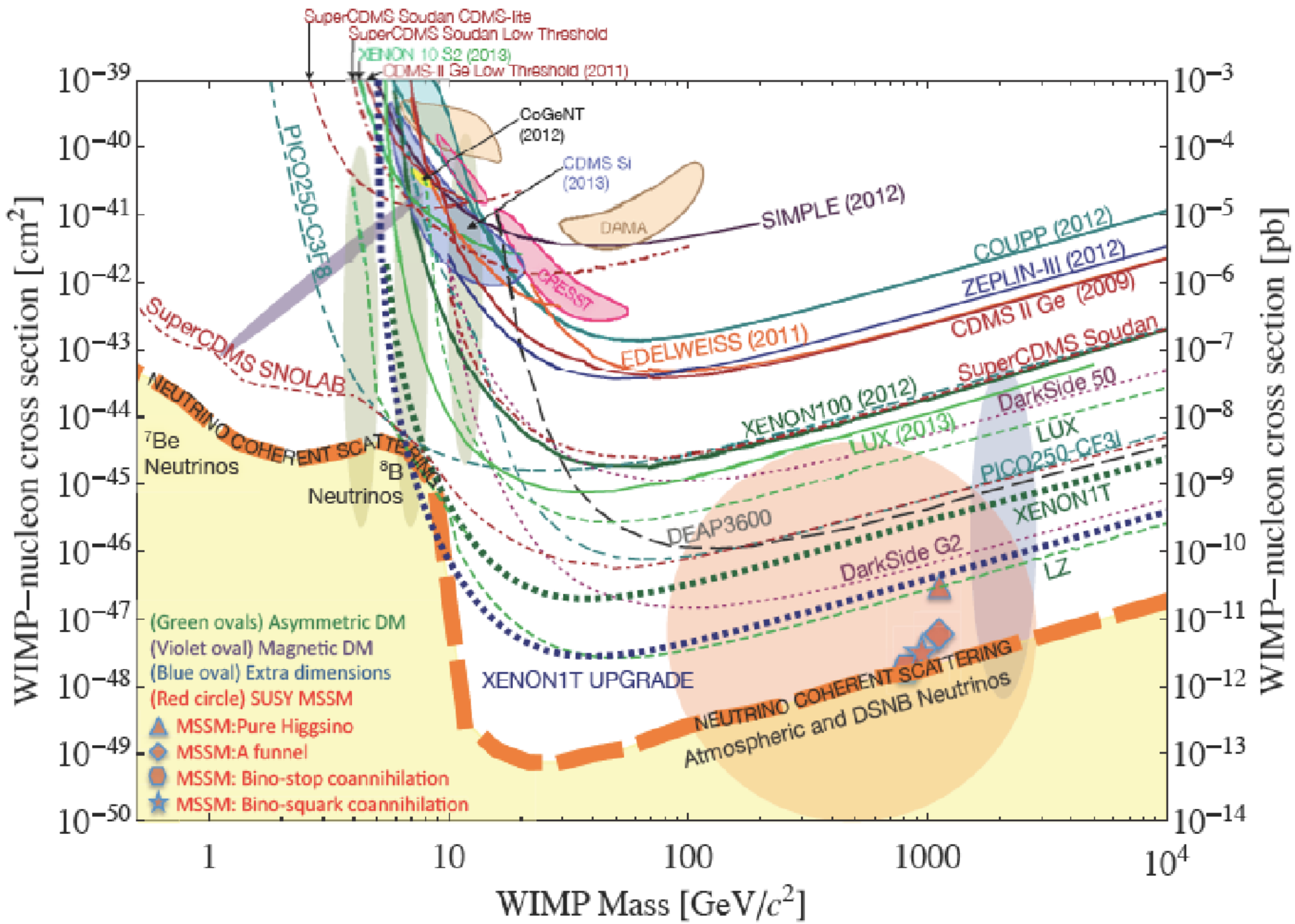
...and experimental aspects...

- 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

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

Examples of uncertainties in models and scenarios

see for some details e.g.:
Riv.N.Cim.26 n.1 (2003) 1, IJMPD13(2004)2127, EPJC47 (2006)263, IJMPA21 (2006)1445

Nature of the candidate and couplings

- WIMP class particles (neutrino, sneutrino, etc.): SI, SD, mixed SI&SD, preferred inelastic
  + e.m. contribution in the detection
- Light bosonic particles
- Kaluza-Klein particles
- Mirror dark matter
- Heavy Exotic candidate
- …etc. etc.

Halo models & Astrophysical scenario

- Isothermal sphere ⇒ very simple but unphysical halo model
- Many consistent halo models with different density and velocity distribution profiles can be considered with their own specific parameters (see e.g. PRD61(2000)023512)
- Caustic halo model
- Presence of non-thermalized DM particle components
- Streams due e.g. to satellite galaxies of the Milky Way (such as the Sagittarius Dwarf)
- Multi-component DM halo
- Clumpiness at small or large scale
- Solar Wakes
- …etc. …

Instrumental quantities

- Energy resolution
- Efficiencies
- Quenching factors
- Channeling effects
- Their dependence on energy
- …

Scaling laws
of cross sections for the case of recoiling nuclei

- Different scaling laws for different DM particle:

$\sigma_A \propto \mu^2 A^2 (1+\varepsilon_A)$

$\varepsilon_A = 0$ *generally assumed*

$\varepsilon_A \approx \pm 1$ *in some nuclei? even* for neutralino candidate in MSSM (see Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301)

Form Factors
for the case of recoiling nuclei

- Many different profiles available in literature for each isotope
- Parameters to fix for the considered profiles
- Dependence on particle-nucleus interaction
- In SD form factors: no decoupling between nuclear and Dark Matter particles degrees of freedom + dependence on nuclear potential

Spin Factors
for the case of recoiling nuclei

- Calculations in different models give very different values also for the same isotope
- Depend on the nuclear potential models
- Large differences in the measured counting rate can be expected using:

  either SD not-sensitive isotopes

  or SD sensitive isotopes depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the ^{23}Na and ^{127}I cases).

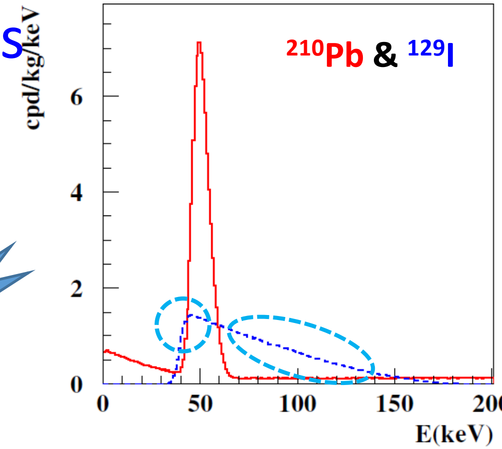
Quenching Factor

- differences are present in different experimental determinations of *q* for the same nuclei in the same kind of detector depending on its specific features (e.g. *q* depends on dopant and on the impurities; in liquid noble gas e.g.on trace impurities, on presence of degassing/releasing materials, on thermodynamical conditions, on possibly applied electric field, etc); assumed 1 in bolometers
- channeling effects possible increase at low energy in scintillators (dL/dx)
- possible larger values of *q* (AstropPhys33 (2010) 40)

  → energy dependence

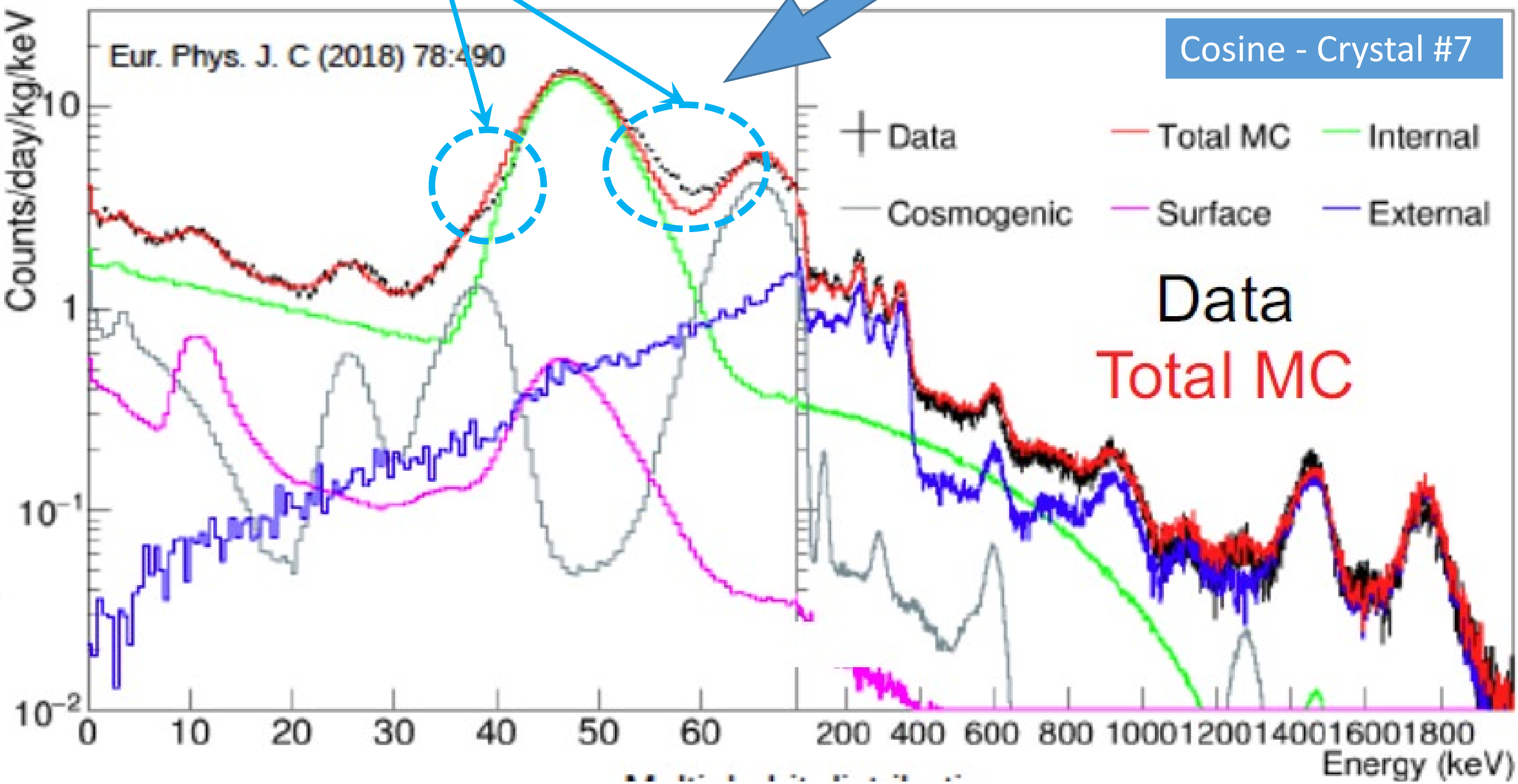
… and more …

^{129}I completely forgotten in Cosine-100 data analysis



Very important discrepancies (note the log scale) in the reconstruction of the structure at ≈ 45 keV, due to:

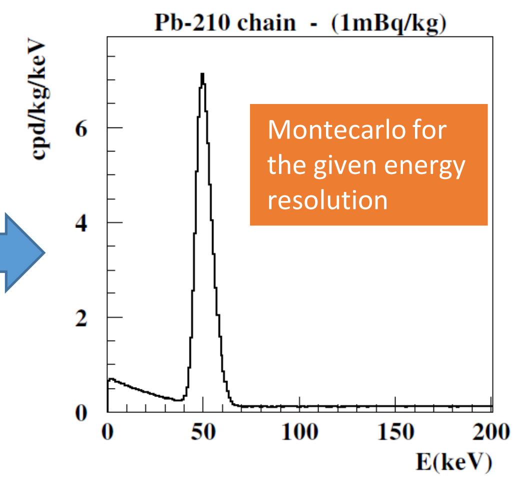
1. **Missing contribute of ^{129}I**
2. **Overestimate contribute of ^{210}Pb**

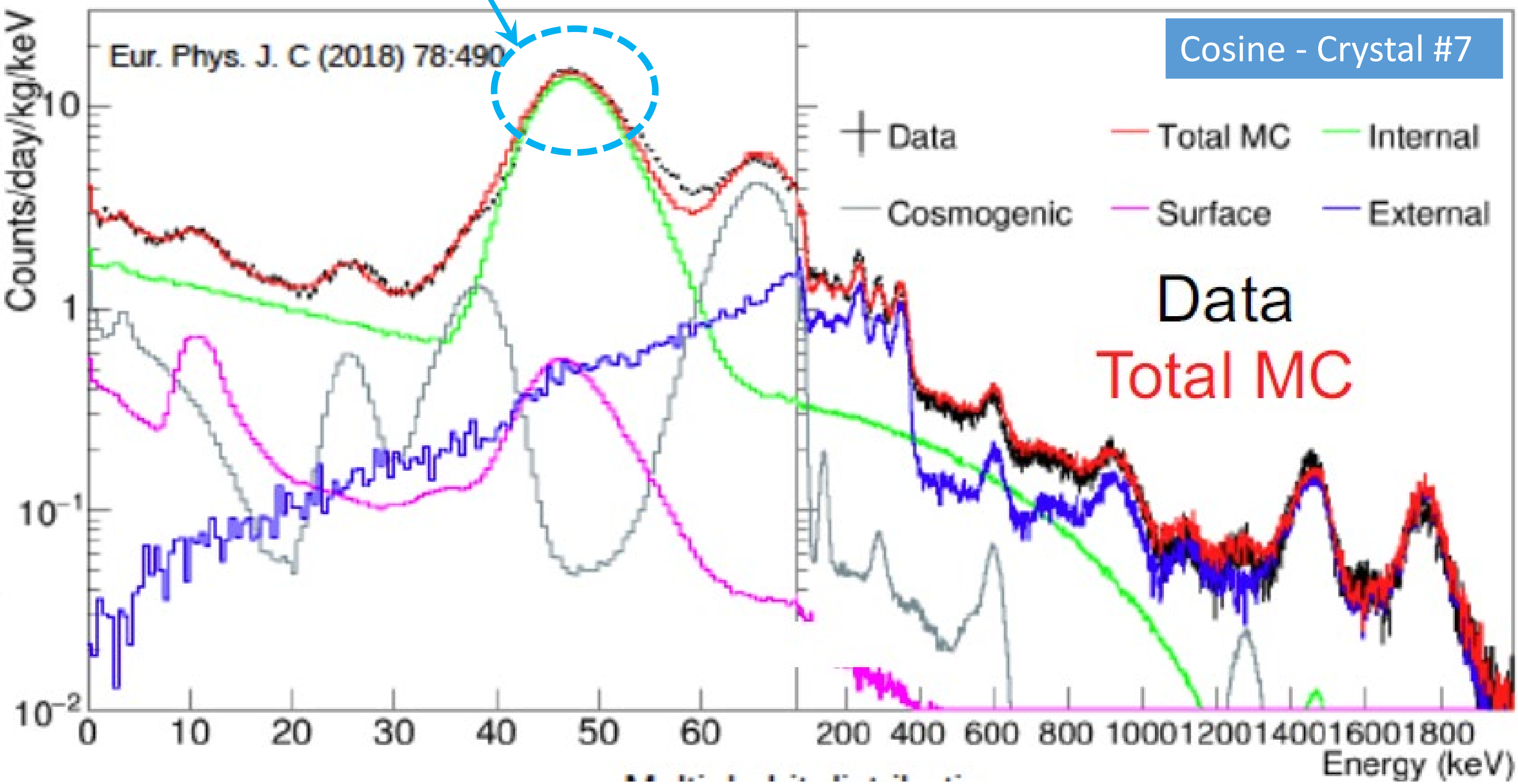


… and ^{210}Pb significantly overestimated

In green spectrum, the ^{210}Pb peak height is ≈ 14cpd/kg/keV, that is ≈ 2mBq/kg

But the measured α rate in crystal 7 is (1.54±0.4) mBq/kg and this should be an upper limit for ^{210}Pb activity!





In conclusion:

the Cosine-100 low energy analysis is wrong and the exclusion plot meaningless

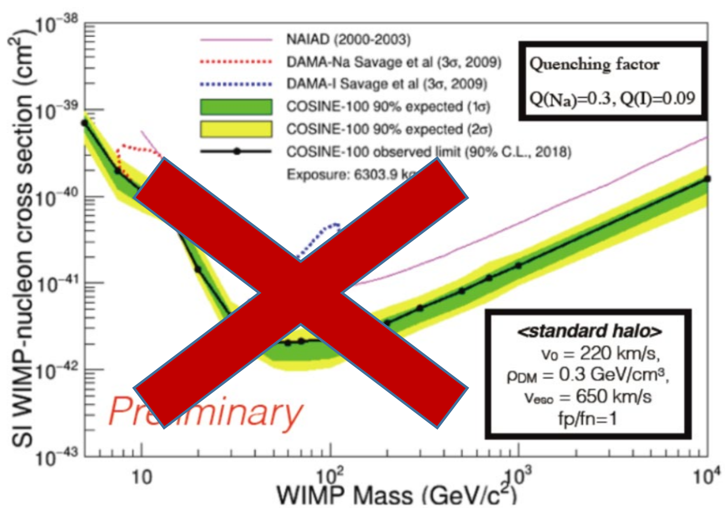
Cosine - Crystal #7

Components	Background 2-6 keV (dru)
Internal ^{210}Pb	1.50 +/- 0.07
Internal ^{40}K	0.05 +/- 0.01
Surface ^{210}Pb	0.38 +/- 0.21
^{3}H (Cosmogenic)	0.58 +/- 0.54
^{109}Cd (Cosmogenic)	0.09 +/- 0.09
Other cosmogenic	0.05 +/-0.03
External	0.03 +/- 0.02
Total expected	**2.70 +/- 0.59**
Data	**2.64 +/- 0.05**

Internal ^{210}Pb seems to give the main (≈60%) contribution in 2-6 keV region, but , as shown, the assumed value is wrong: < 1.2 dru

To be revised

Wrong: expected << observed
Large space for DM signal



An example: how not to do to get a result (exclusion limits)
The case of COSINE-100

- The methodology of the background subtraction, used for example by Cosine-100, is strongly discouraged and deprecated because of the impossibility to have a precise knowledge of the background contribution in particular at low energy, leading to large systematic uncertainties.

Very important discrepancies in the reconstruction of the structure at ≈ 45 keV, due to:

1. Missing contribute of ^{129}I (emended in a later paper, but not in the exclusion limits))
2. Overestimate contribute of ^{210}Pb

Components	Background 2-6 keV (dru)
Internal ^{210}Pb	1.50 +/- 0.07
Internal ^{40}K	0.05 +/- 0.01
Surface ^{210}Pb	0.38 +/- 0.21
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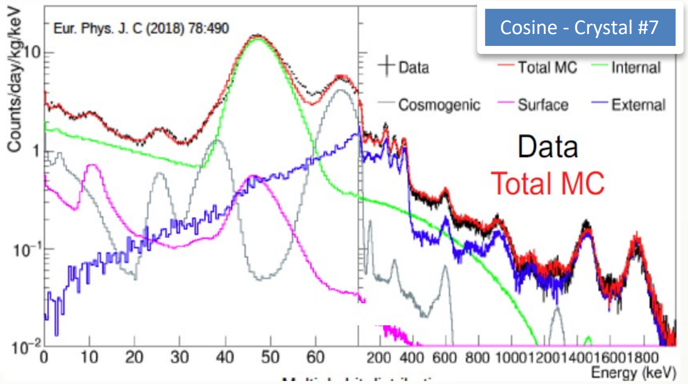


✓ Even considering the background model as correct, the analysis has fault.

✓ They get null residuals in each crystal (even always negative) starting from a wrong bckg hypothesis!

Data−model = −0.105±0.276 cpd/kg/keV
→ S_0<0.36 cpd/kg/keV 90%CL in the (2-6) keV energy region
Still large space for DM

Since time, by simple and direct determination in DAMA: S_0<0.18 cpd/kg/keV in (2-4) keV (DAMA/LIBRA-phase2).

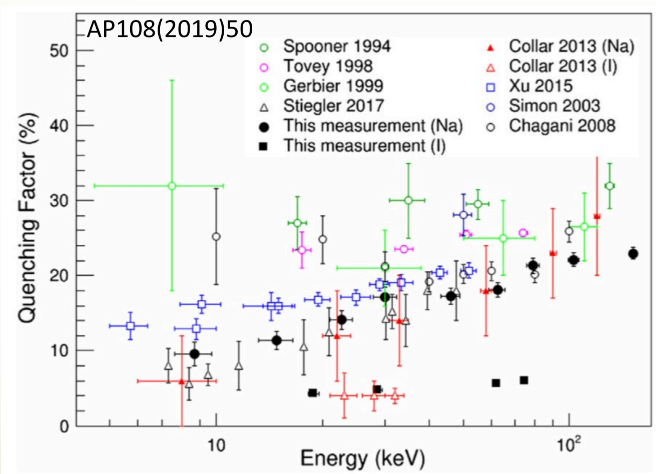
Cosine-100 low energy analysis is wrong and the exclusion limits are meaningless (published on Nature!!)

In conclusion: the methodology of the background subtraction is a **dangerous** way to claim sensitivities by the fact not supported by large counting rate

The case of the NaI(Tl) quenching factors (QF)

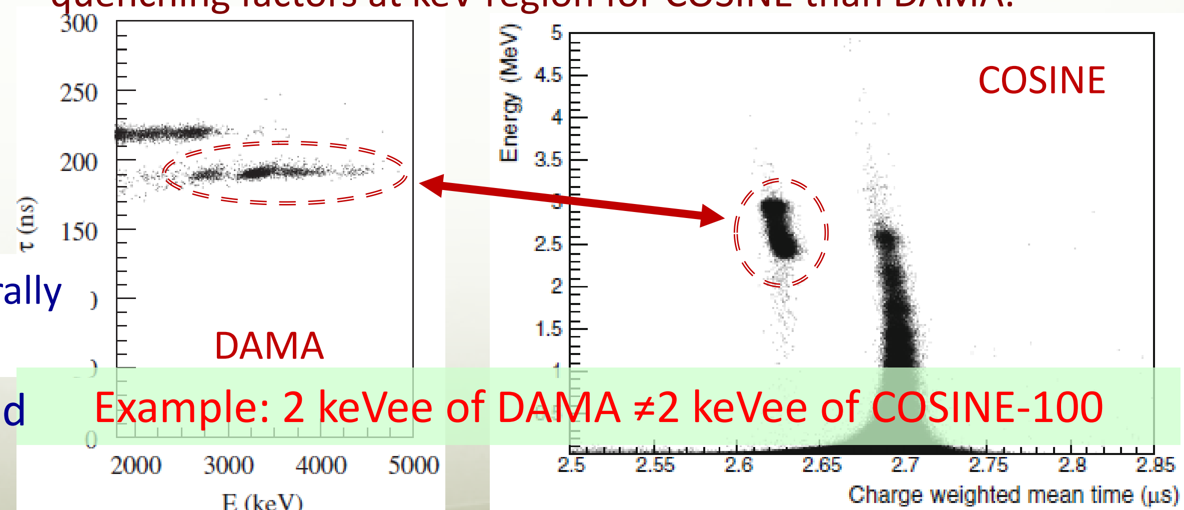
- ✓ The QFs are a property of the specific detector and not general property, particularly in the very low energy range.
- ✓ For example in NaI(Tl), QFs depend on the adopted growing procedures, on Tl concentration and uniformity in the detector, on the specific materials added in the growth, on the mono-crystalline or poly-crystalline nature of the detector, etc.
- ✓ Their measurements are difficult and always affected by significant experimental uncertainties.
- ✓ All these aspects are always relevant sources of uncertainties when comparing whatever results in terms of DM candidates inducing nuclear recoils.

+ QF depending on energy + channeling effects
+ Migdal effect



- A wide spread existing in literature for NaI(Tl)
- This is also confirmed by the different α/β light ratio measured with DAMA and COSINE crystals. This implies much lower quenching factors at keV region for COSINE than DAMA.

CURIOSITY: Recent productions (generally by Bridgman growth) yields low QF…



Example: 2 keVee of DAMA ≠2 keVee of COSINE-100

The model dependent analyses and comparisons must be performed using the QF **measured** for each detector.

Alphas from ^{238}U and ^{232}Th chains span from 2.6 to 4.5 MeVee in DAMA, while from 2.3 to 3.0 MeVee in COSINE

Examples of model-dependent analyses

DM particles elastically interacting with target nuclei – SI interaction

DAMA/NaI, DAMA/LIBRA-ph1 and ph2

arXiv:1907.06405

- A large (but not exhaustive) class of halo models is considered;
- Local velocity v_0 in the range [170,270] km/s;
- Halo density ρ depending on the halo model;
- v_{esc} = 550 km/s (no sizable differences if v_{esc} in the range [550, 650]km/s);
- For DM candidates inducing nuclear recoils: three different sets of values for the nuclear form factor and quenching factor parameters.

σ_{SI} SI point-like DM-nucleon cross section

ξ fractional amount of local density in terms of the considered DM candidate

The point-like SI cross section of DM particles scattering off (A,Z) nucleus:

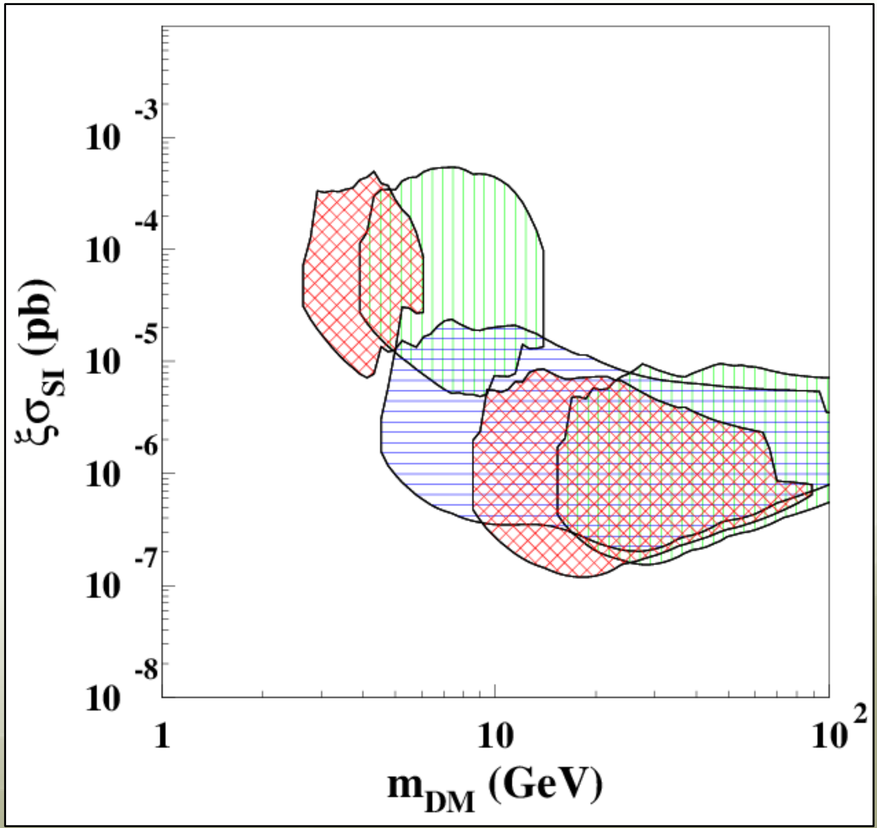
$$\sigma_{SI}(A,Z) \propto m_{red}^2(A,DM)\left[f_p Z + f_n (A-Z)\right]^2$$

where f_p, f_n are the effective DM particle couplings to protons and neutrons.

If $f_p=f_n$: $$\sigma_{SI}(A,Z) = \frac{m_{red}^2(A,DM)}{m_{red}^2(1,DM)} A^2 \sigma_{SI}$$

$\xi\sigma_{SI}$ vs m_{DM}

1. Constants q.f.
2. Varying q.f.(E_R)
3. With channeling effect



Allowed DAMA regions:
Domains where the likelihood-function values differ more than 10σ from absence of signal

Model-dependent analyses

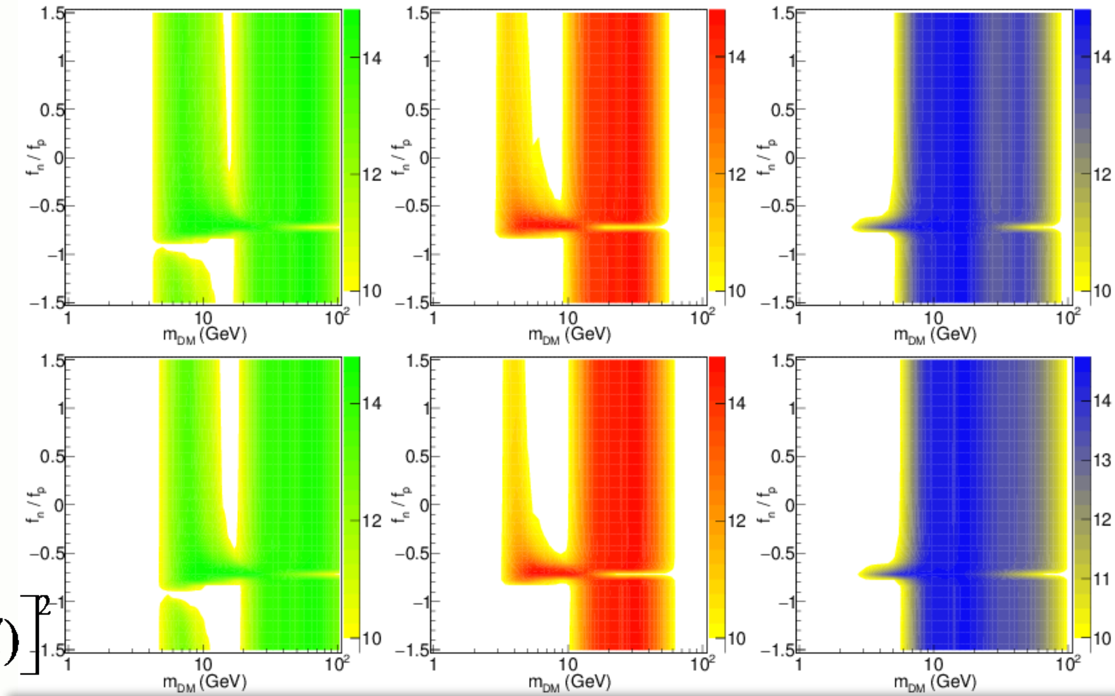
DM particles elastically interacting with target nuclei SI-IV interaction

DAMA/NaI, DAMA/LIBRA-ph1 and ph2

Case of isospin violating SI coupling:

$$f_p \neq f_n$$

$$\sigma_{SI}(A,Z) \propto m^2_{red}(A,DM)\left[f_p Z + f_n (A-Z) \right]^2$$



f_n/f_p vs m_{DM}
marginalizing on $\xi\sigma_{SI}$

1. **Constants q.f.**
2. **Varying q.f.(E_R)**
3. **With channeling effect**

Allowed DAMA regions for A0 (isothermal sphere), B1, C1, D3 halo models (top to bottom)

- Two bands at low mass and at higher mass;
- Good fit for low mass DM candidates at $f_n/f_p \approx -53/74$ = = -0.72 (signal mostly due to ^{23}Na recoils).
- Contrary to what was stated in Ref. [PLB789,262(2019), JCAP07,016(2018), JCAP05,074(2018)] where the low mass DM candidates were disfavored for $f_n/f_p = 1$ by DAMA data, the inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support low mass DM candidates either including or not the channeling effect.
- The case of isospin-conserving f_n/f_p=1 is well supported at different extent both at lower and larger mass.

Model-dependent analyses: other examples

arXiv:1907.06405

DM particles elastically interacting with target nuclei – purely SD interaction

Only possible for target nuclei with spin≠0 $\tan\vartheta = \frac{a_n}{a_p}, \quad \vartheta \text{ in } [0,\pi]$

a_p and a_n are the effective DM-nucleon coupling strengths for SD int.

$\theta = 0 \quad \Rightarrow a_n=0,\ a_p\neq 0$ or $|a_p|>>|a_n|$;

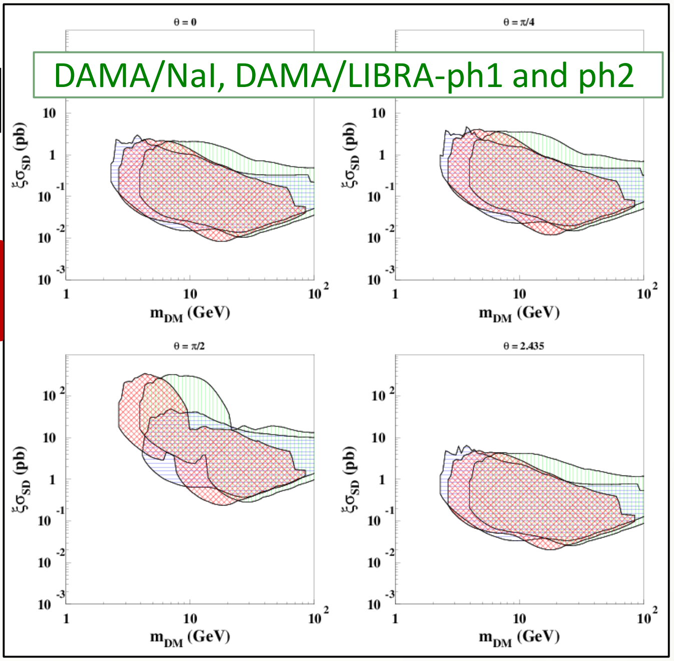
$\theta = \pi/4 \quad \Rightarrow a_n=a_p$;

$\theta = \pi/2 \quad \Rightarrow a_p=0,\ a_n\neq 0$ or $|a_n|>>|a_p|$;

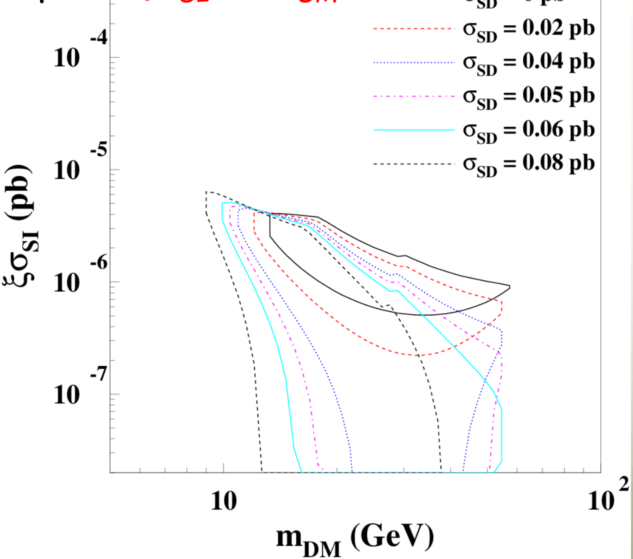
$\theta = 2.435\text{rad} \quad \Rightarrow a_n/a_p=-0.85$, pure Z_0 coupling

$\xi\sigma_{SD}$ vs m_{DM}

1. **Constants q.f.**
2. **Varying q.f.(E_R)**
3. **With channeling effect**



Effect induced by the inclusion of a SD component on allowed regions in the plane $\xi\sigma_{SI}$ vs m_{DM}



- Even a relatively small SD (SI) contribution can drastically change the allowed region in the (m_{DM}, $\xi\sigma_{SI(SD)}$) plane;
- The model-dependent comparison plots between exclusion limits at a given C.L. and regions of allowed parameter space do not hold e.g. for mixed scenarios when comparing experiments with and without sensitivity to the SD component of the interaction.
- The same happens when comparing regions allowed by experiments whose target-nuclei have unpaired proton with exclusion plots quoted by experiments using target-nuclei with unpaired neutron when the SD component of the interaction would correspond either to $\theta\approx 0$ or $\theta\approx\pi$

Model-dependent analyses: other examples

Inelastic DM in the scenario of Smith and Weiner [Phys. Rev. D 64, 043502 (2001)]

W + N → W* + N

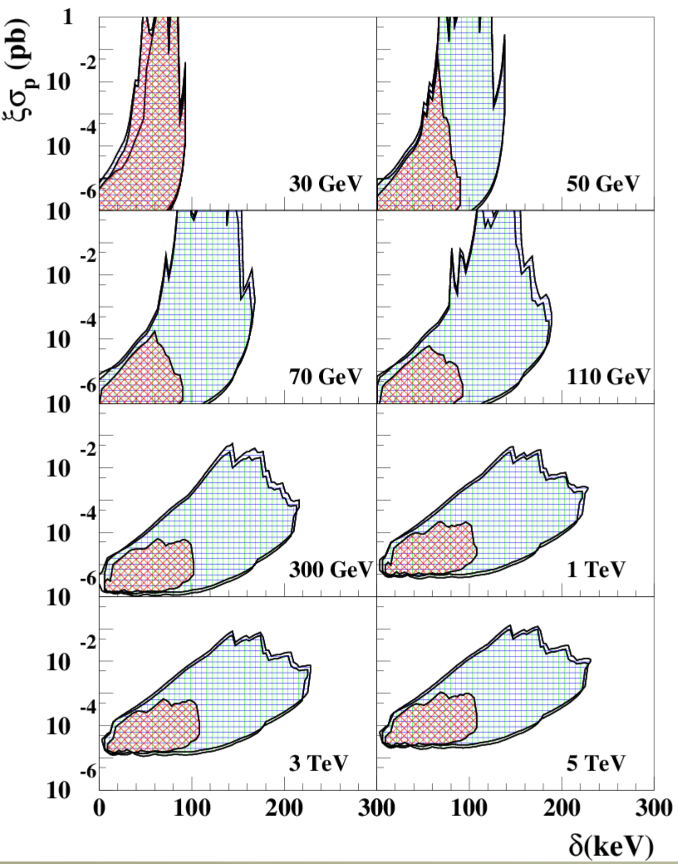
DAMA/NaI, DAMA/LIBRA-ph1 and ph2

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

→ Kinematical constraint for the inelastic scattering of χ- on a nucleus (μ: χ-nucleus reduced mass)

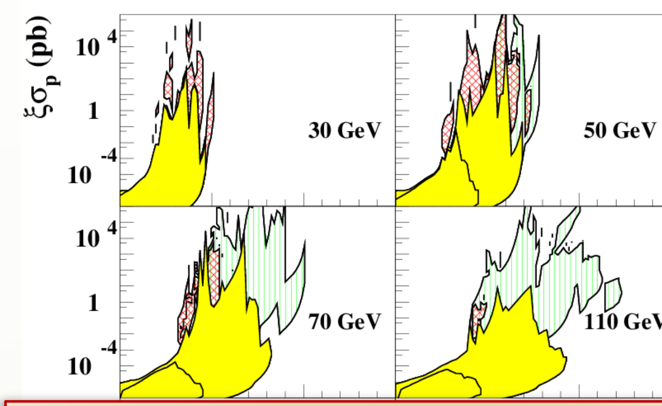
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Higher mass target-nuclei are favourites
- Enhanced S_m with respect to S_0



Slices of the 3-dim allowed volume
($\xi\sigma_p$, m_{DM}, δ)

1. Constants q.f.
2. Varying q.f.(E_R)
3. With channeling effect



Including Thallium: new allowed regions

- New regions with $\xi\sigma_p$ > 1 pb and δ > 100 keV are allowed by DAMA after the inclusion of the inelastic scattering off Thallium nuclei.
- Such regions are not fully accessible to detectors with target nuclei having mass lower than Thallium.

DAMA/LIBRA towards the lowering of the software energy threshold

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>

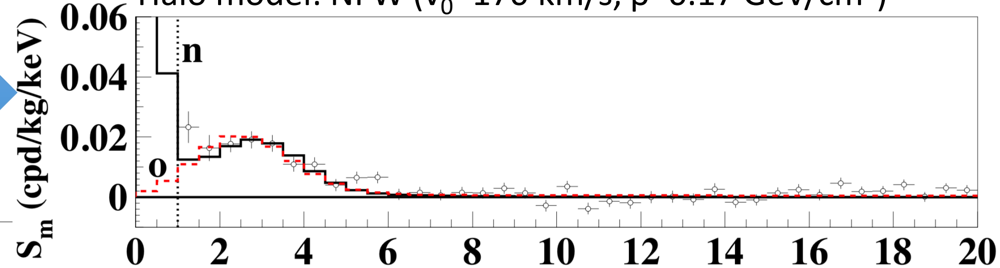
LDM candidates

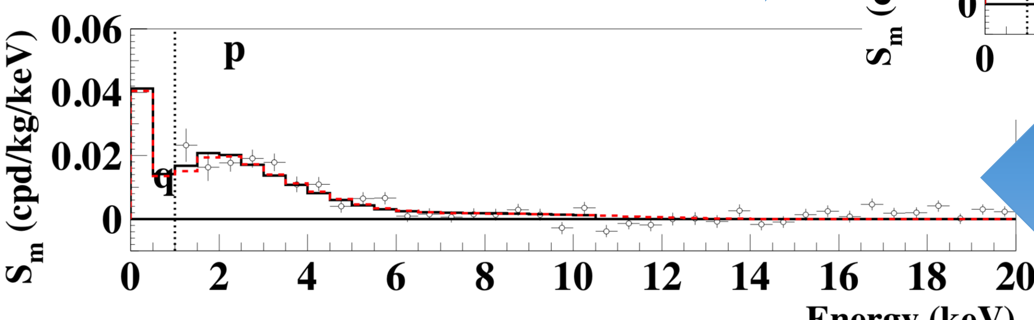
Halo model: NFW (v_0=170 km/s, ρ=0.17 GeV/cm^3)

LDM with coherent scattering on nuclei

n - m_H=30 MeV, δ=16 MeV σ=1.4x10^{-6} pb

o - m_H=100 MeV, δ=45 MeV σ=2.4x10^{-6} pb





LDM with incoherent scattering on nuclei

p - m_H=30 MeV, δ=8 MeV σ=0.008 pb

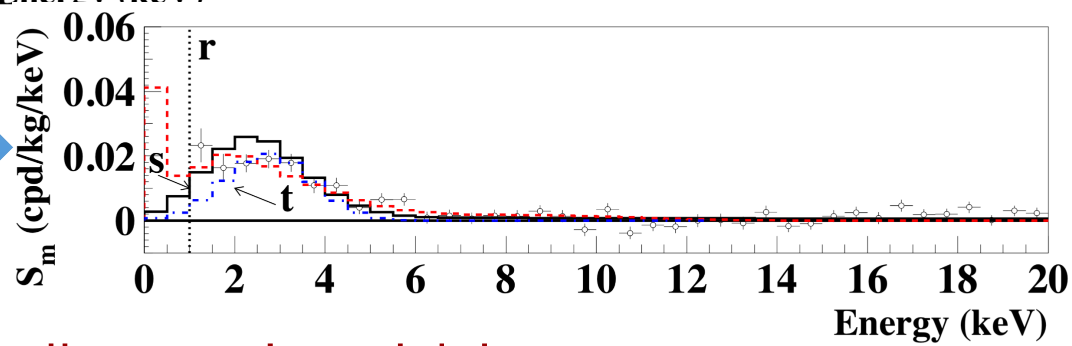
q - m_H=100 MeV, δ=2 MeV σ=0.027 pb

LDM with m_L=0 GeV (δ=m_H)

r - coherent on nucl. m_H=28 MeV, σ=1.3x10^{-6} pb

s - incoherent on nucl. m_H=20 MeV, σ=0.006 pb

t – on electrons m_H=56 keV, σ=2.3x10^{-7} pb

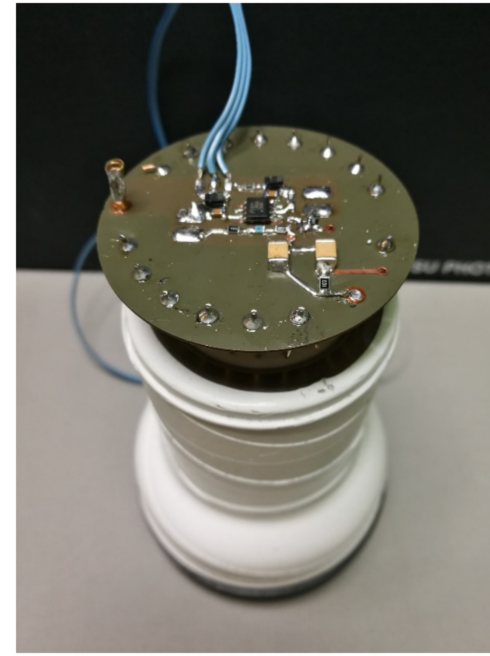


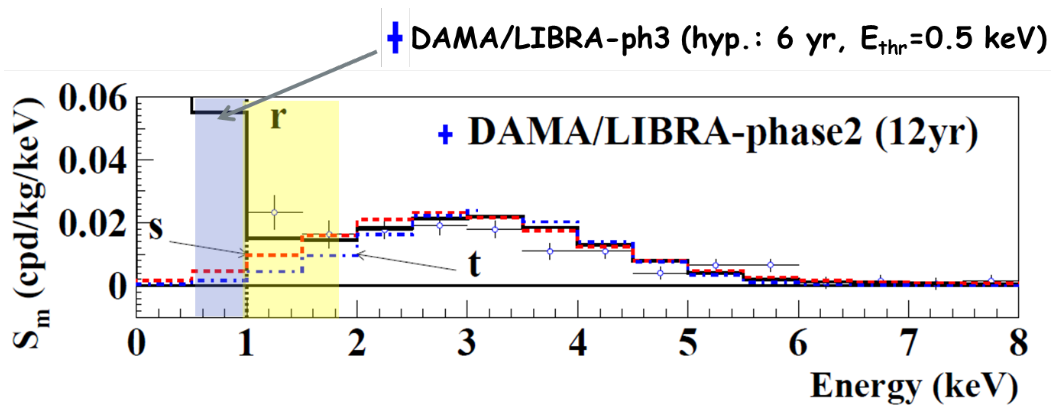
Compatibility with several candidates;
other ones are open

DAMA/LIBRA towards the lowering of the software energy threshold

updating hardware to lower software energy threshold below 1 keV

new miniaturized low background **pre-amps** directly installed on the low-background supports of the **voltage dividers** of the new lower background high Q.E. **PMTs**





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

Features of the DM signal investigated by DAMA at various levels; improvements foreseen towards the lowering of the software energy threshold

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

High exposure and low energy threshold can allow 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**

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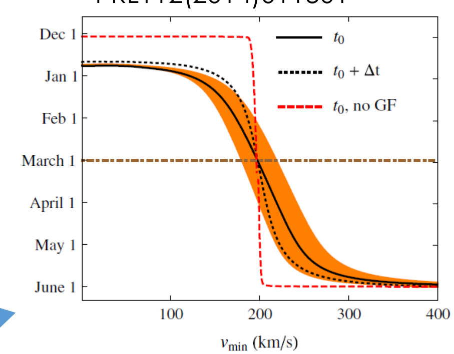
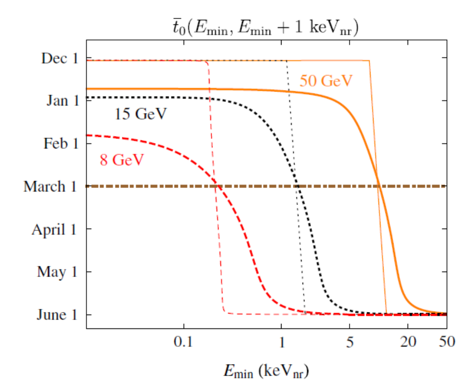
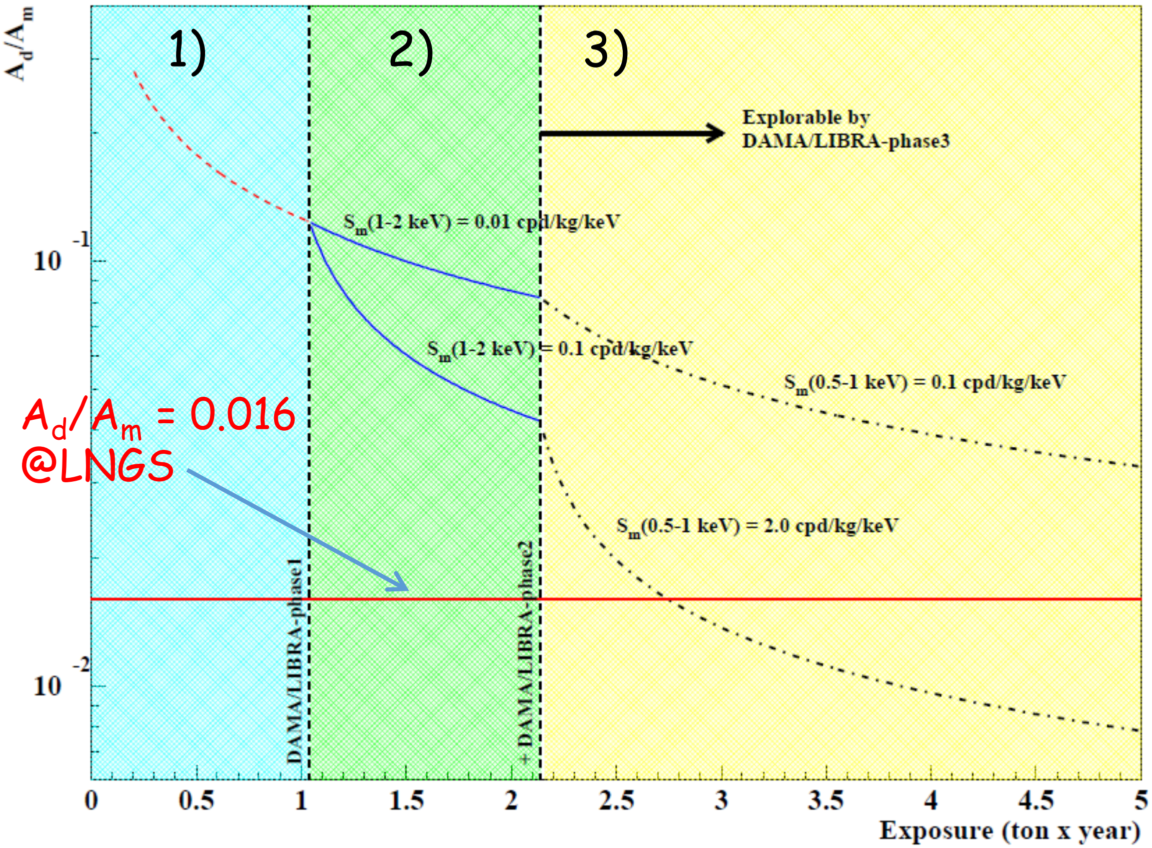




DAMA/LIBRA towards the lowering of the software energy threshold: Sensitivity for the DM Annual Modulation phase



1σ sensitivity for the diurnal/annual modulation amplitudes ratio (A_d/A_m) vs exposure; comparison among:

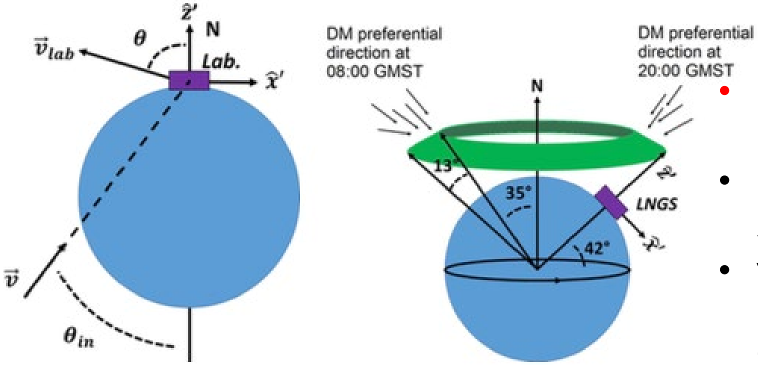
1) DAMA/LIBRA-phase1
   S_m(2-6 keV)=0.01 cpd/kg/keV

2) + DAMA/LIBRA-phase2
   (hyp: S_m(1-2 keV)=0.01 cpd/kg/keV
   or
   S_m(1-2 keV)=0.1 cpd/kg/keV)

3) + DAMA/LIBRA-phase3 (hyp: Eth=0.5 keV and
   S_m(0.5-1 keV)=0.1 cpd/kg/keV
   or
   S_m(0.5-1 keV)=2.0 cpd/kg/keV)

Sensitivity to the diurnal modulation reachable with 1 more ton x year (6 a.c. of phase3 at 0.5 keV thr.) in case of a very large signal below 1 keV

Earth shadowing effect



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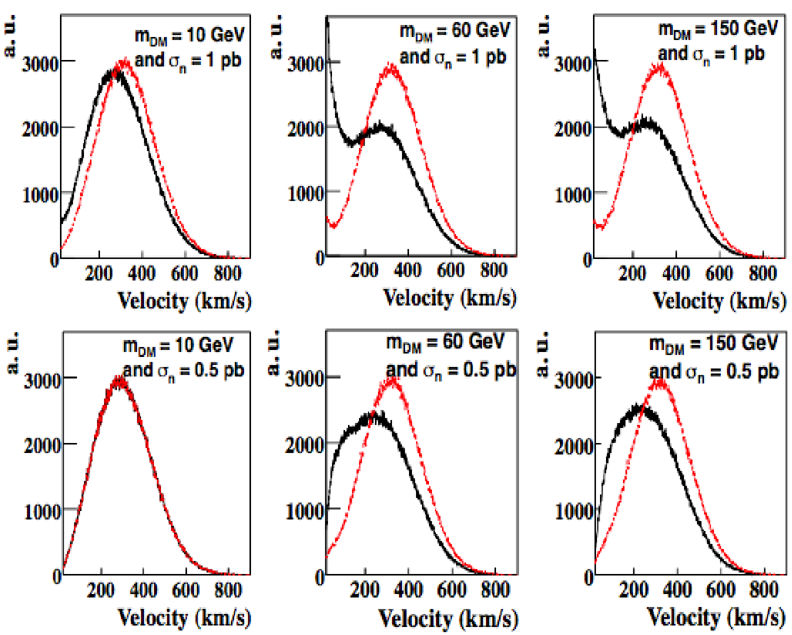
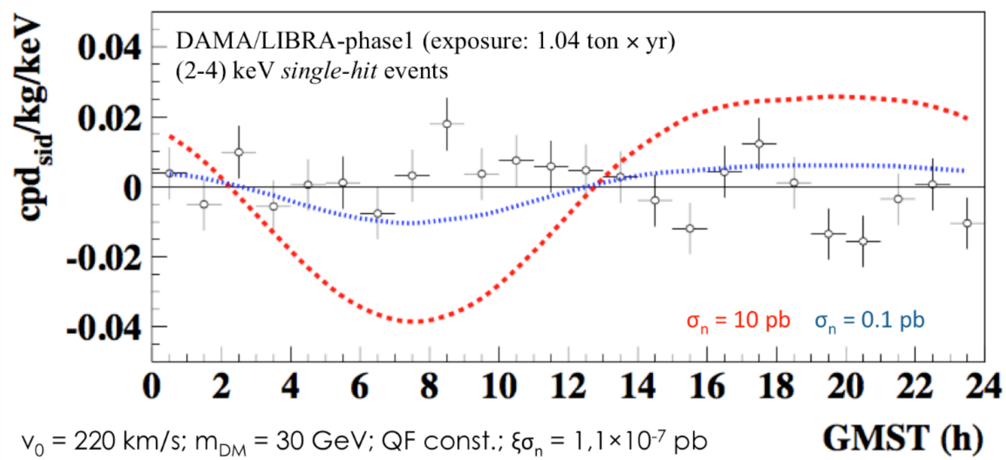
- **Earth Shadow Effect** could be expected for DM candidate particles inducing nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM particle in order to reach the experimental set-up
- DM particles crossing Earth lose their energy

- DM velocity distribution observed in the laboratory frame is modified as function of time (**GMST 8:00 black**; **GMST 20:00 red**)

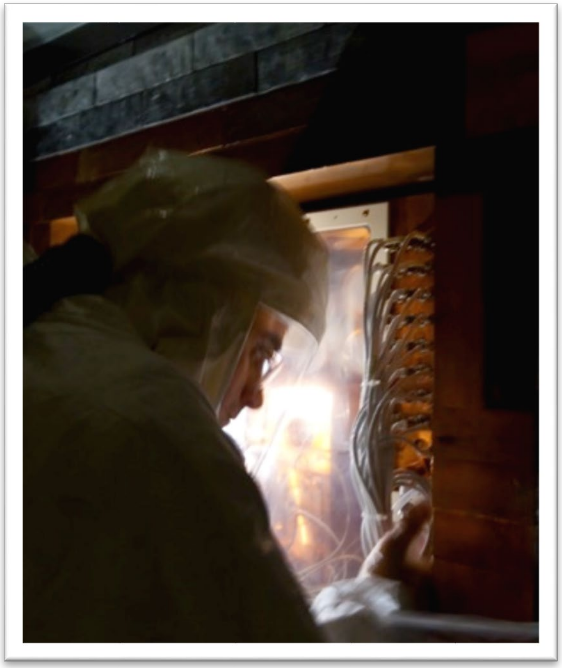


A practical example: the case of DAMA/LIBRA–phase1

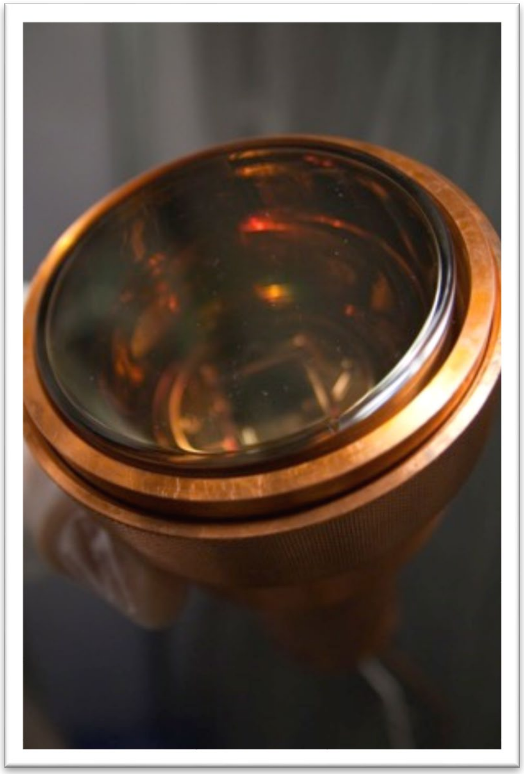


Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the ξ vs σ_n plane for each m_{DM}.

Conclusions



- Model-independent evidence for a signal that satisfies all the requirement of the DM annual modulation signature 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**
- Model dependent analyses on new data allowed significantly improving the C.L. and restricting the allowed parameters' space for the various scenarios with respect to previous DAMA analysis
- DAMA/LIBRA–phase2 **continuing data taking**
- DAMA/LIBRA towards the lowering of the software energy threshold: **some R&D completed other are in progress**
- Continuing investigations of **rare processes** other than DM