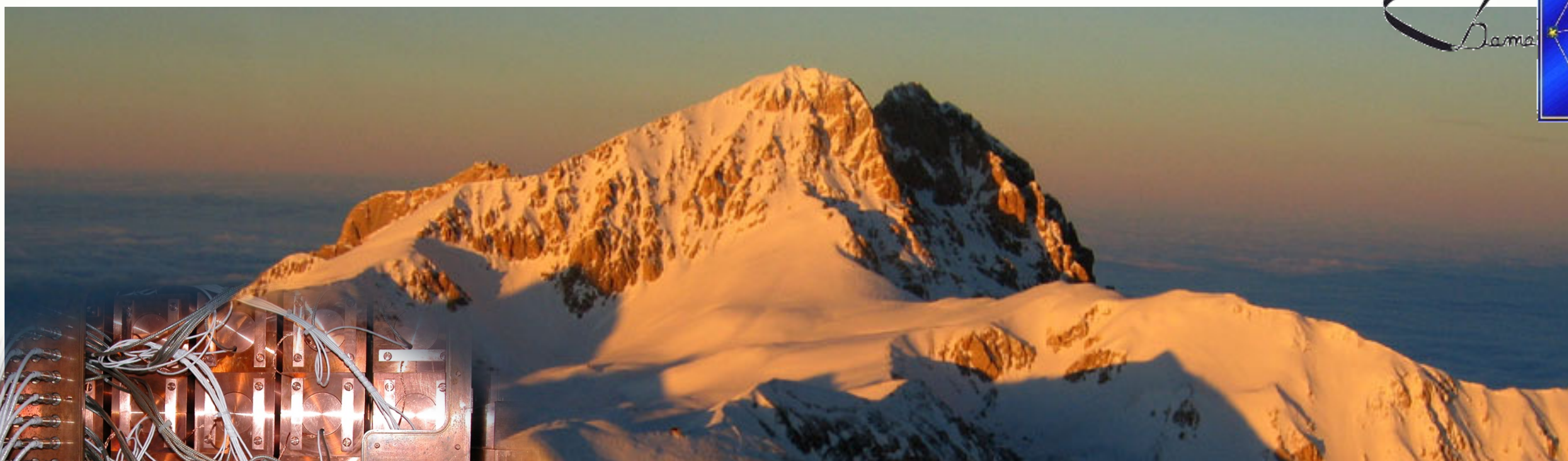
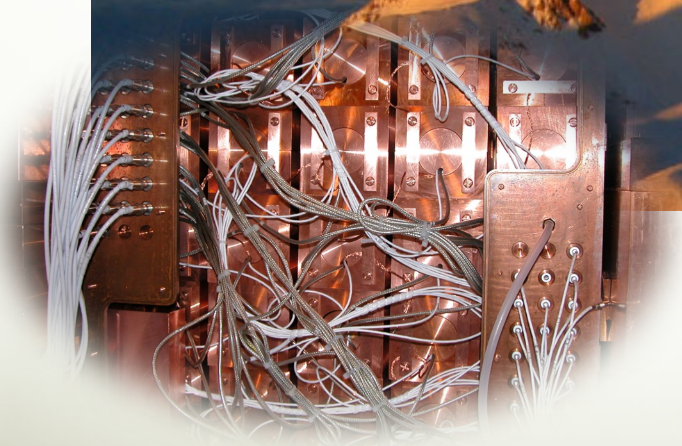
DAMA/LIBRA-phase2 results and perspectives





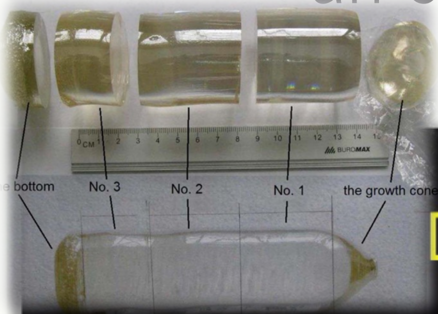
P. Belli
INFN – Roma Tor Vergata

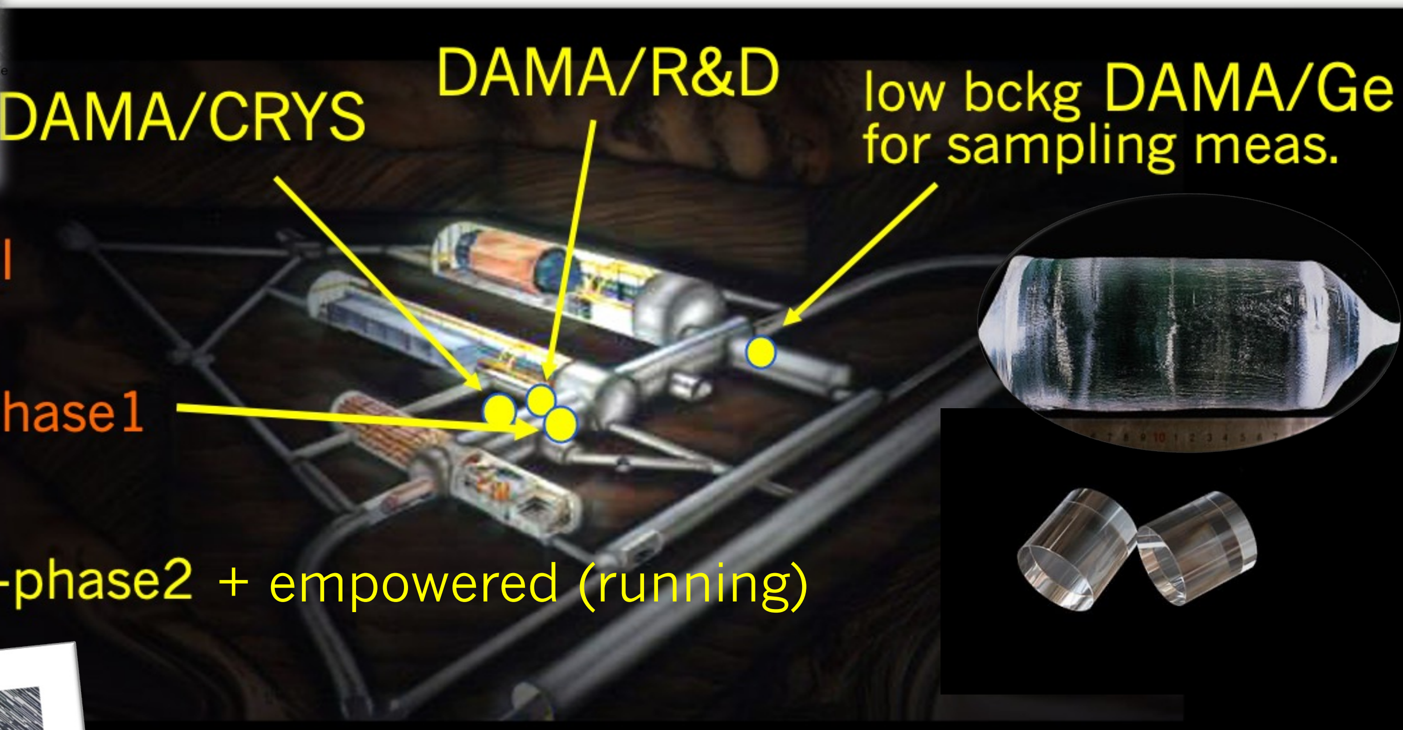
ICNFP 2023, Kolymbari, Crete, Greece, July 10-22, 2023

DAMA set-ups

an observatory for rare processes @ LNGS

web site: https://dama.web.roma2.infn.it/





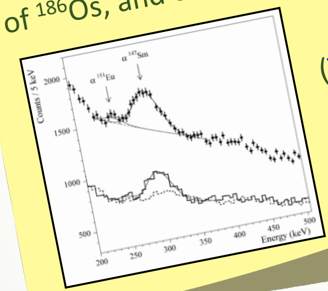
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

- \+ 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

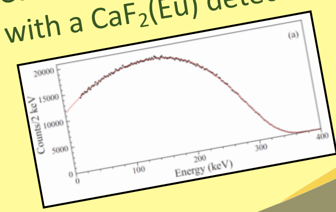
- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{144}Sm, ^{154}Sm, ^{150}Nd, ^{156}Dy, ^{158}Dy, ^{162}Er, ^{168}Yb, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{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, of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os, and of ^{174}Hf with CHC crystal



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

Investigations of rare β decays of ^{113}Cd ($T_{1/2}=8\times10^{15}$yr), ^{113m}Cd with $CdWO_4$ scintillators 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 ^{7}Li solar axions using resonant absorption in LiF crystal

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

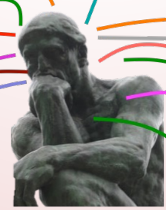
Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state

Search for long-lived super-heavy eka-tungsten with $ZnWO_4$ and $CdWO_4$

Dark Matter investigation

… many others are in progress

Relic DM particles from primordial Universe



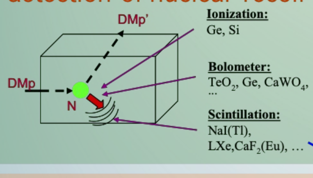
SUSY (as neutralino or sneutrino in various scenarios)
the sneutrino in the Smith and Weiner scenario
sterile ν
electron interacting dark matter
a heavy ν of the 4-th family
even a suitable particle not yet foreseen by theories
etc...
axion-like (light pseudoscalar and scalar candidate)
self-interacting 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?

Accelerators:
- can demonstrate the existence of some possible DM candidates
- cannot credit that a certain particle is the Dark Matter solution or the "single" Dark Matter particle solution...

+ DM candidates and scenarios exist on which accelerators cannot give any information

- Scatterings on nuclei
  → detection of nuclear recoil energy

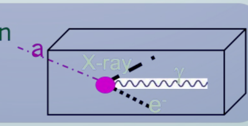


- Inelastic Dark Matter: **W + N → W* + N**
  → W has 2 mass states χ+ , χ- with δ mass splitting
  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

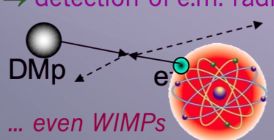
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- 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⁻



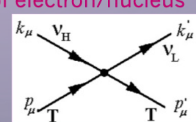
- Interaction only on atomic electrons
  → detection of e.m. radiation



... 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



... also other ideas ...

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

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

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

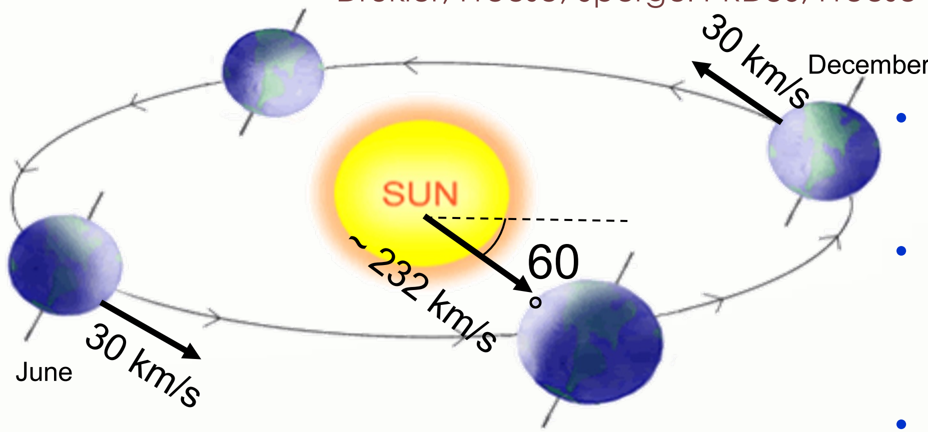
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

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

Requirements:

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



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

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

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

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

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

Annual modulation in DAMA

- 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

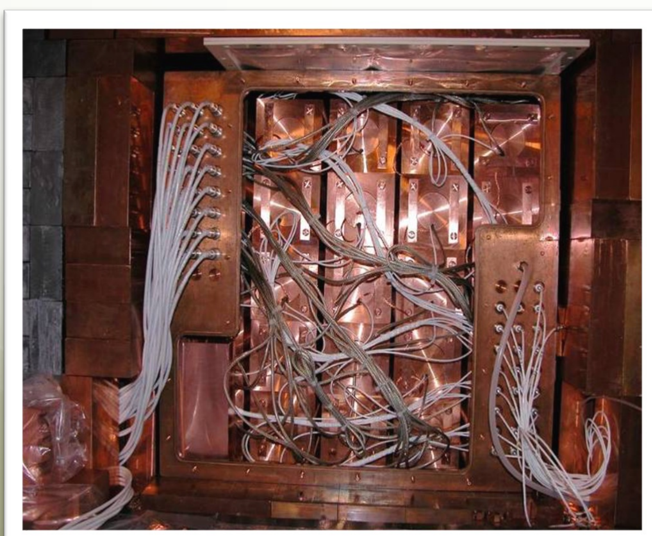
Results on rare processes: PLB408(1997)439, PRC60(1999)065501, PLB460(1999)235, PLB515(2001)6, EPJdirect C14(2002)1, EPJA23(2005)7, EPJA24(2005)51

Results on DM particles: PLB389(1996)757, N.Cim.A112(1999)1541, PRL83(1999)4918

Results on Annual Modulation: 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

Data taking completed on July 2002

- The DAMA/LIBRA ≈ 250 kg NaI(Tl) (**L**arge sodium **I**odide **B**ulk for **RA**re processes)



- As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radio-purification 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

  - Performances: NIMA592(2008)297, JINST7(2012)03009

DAMA/LIBRA–phase1:

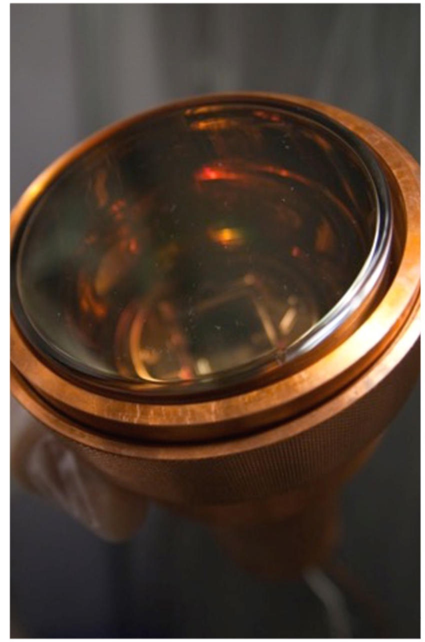
- Results on rare processes: EPJC62(2009)327, EPJC72(2012)1920, EPJA49(2013)64
- Results on DM particles: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28 (2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75 (2015) 239, EPJC75(2015)400, IJMPA31(2016), EPJC77(2017)83
- Results on Annual Modulation: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648

Data taking completed on July 2010

DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4) (2019) 317
PPNP114(2020)103810
NPAE 22(2021) 329
arXiv:2209.00882

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



Goal: software energy threshold at 1 keV – accomplished

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

DAMA/LIBRA–phase2

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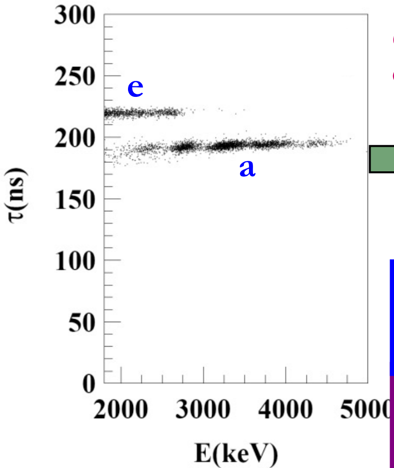
PPNP114(2020)103810
NPAE 22(2021) 329
arXiv:2209.00882

A new stage of the experiment:
Empowered DAMA/LIBRA-phase2 with 0.5 keV energy threshold is running since Dec 1, 2021, see later

Goal: software energy threshold at 1 keV – accomplished

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

Residual contaminants in the ULB NaI(Tl) detectors



α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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

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

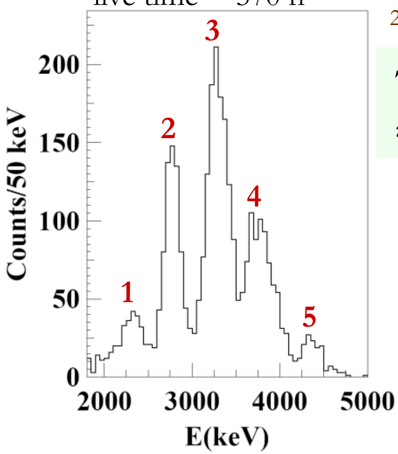
^{232}Th residual contamination

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

^{238}U residual contamination

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

live time = 570 h



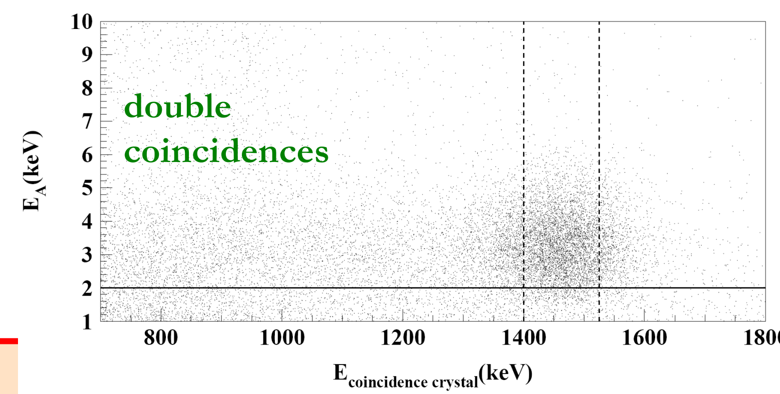
^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

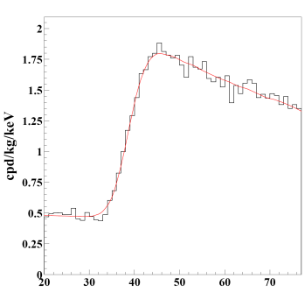
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

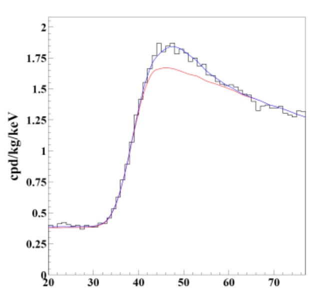
and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{nat}K residual contamination

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







^{129}I and ^{210}Pb

$^{129}I/^{nat}I \approx 1.7\times10^{-13}$ for all the detectors

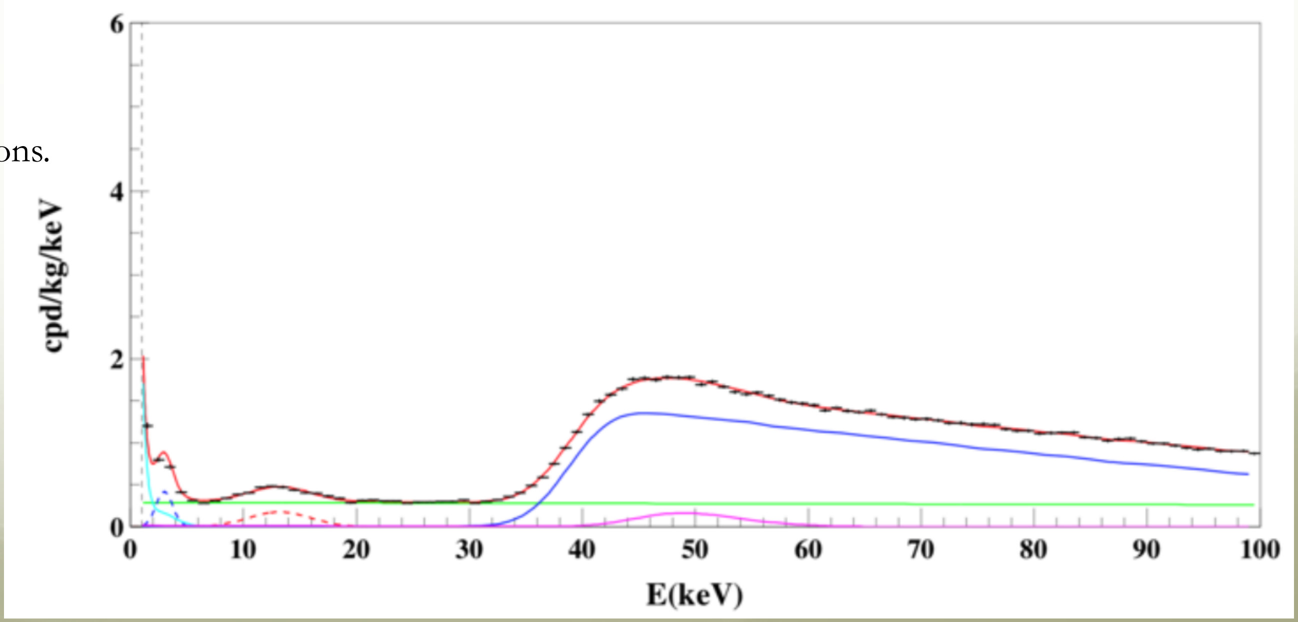
^{210}Pb in the new detectors: (5 − 30) μBq/kg.

No sizable surface pollution by Radon daugthers, thanks to the new handling protocols

... more on NIMA592(2008)297

DAMA/LIBRA energy spectrum

- Example of the energy spectrum of the *single-hit* scintillation events collected by one DAMA/LIBRA–phase2 detector in one annual cycle.
- The software energy threshold of the experiment is 1 keV.
- There are also represented the measured contributions of:
  - the internal cosmogenic ^{129}I: (947 ± 20) μBq/kg (full blue curve)
  - the internal ^{210}Pb: (26 ± 3) μBq/kg, which is in a rather-good equilibrium with ^{226}Ra in the ^{238}U chain (solid pink curve)
  - the broaden structure around 12–15 keV can be ascribed to ^{210}Pb either on the PTFE, wrapping the bare crystal, and/or on the Cu housing, at the level of 1.20 cpd/kg (dashed pink curve)
  - the electron capture of ^{40}K (producing the 3.2 keV peak, binding energy of K shell in ^{40}Ar): 14.2 ppb of ^{nat}K, corresponding to 450 μBq/kg of ^{40}K in this detector (dashed blue curve)
  - the continuum due to high energy γ/β contributions (light green line)
  - below 5 keV a sharp decreasing (cyan) curve represents the derived upper limit on S_0, the un-modulated term of the DM signal.
- The red line is the sum of the previously mentioned contributions.



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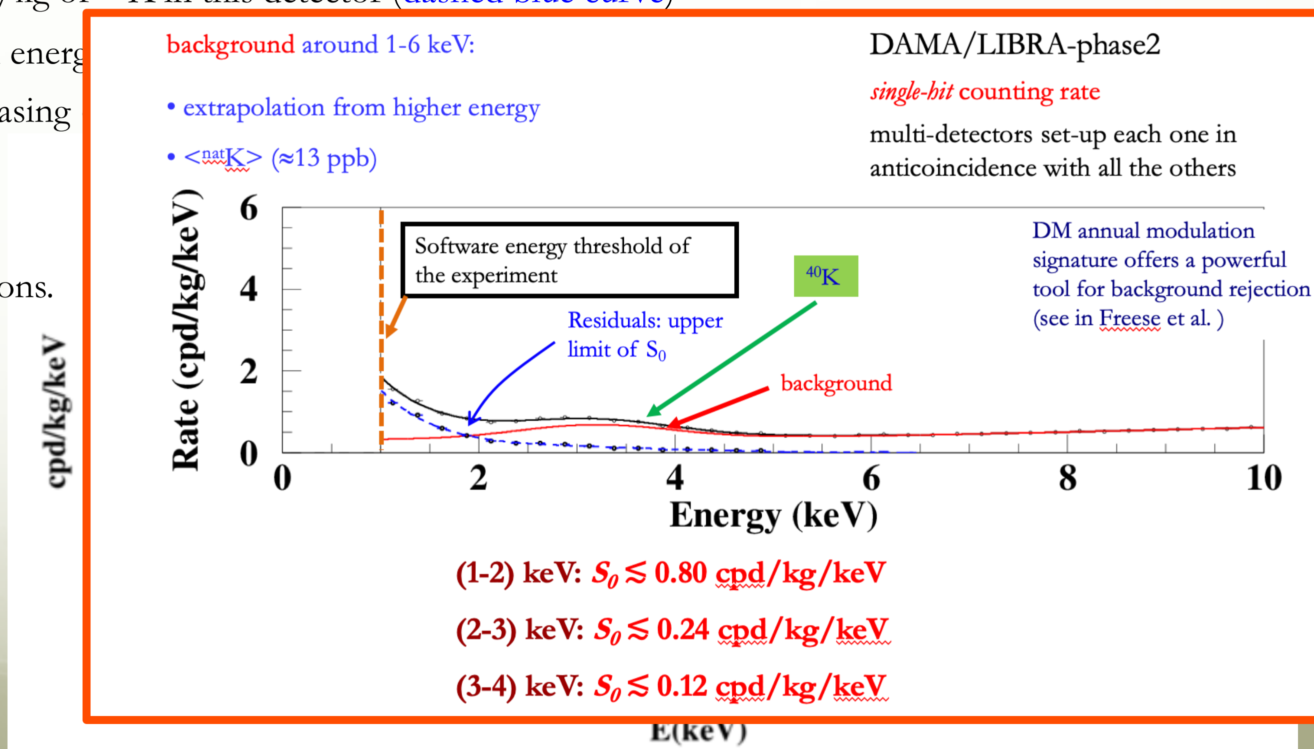
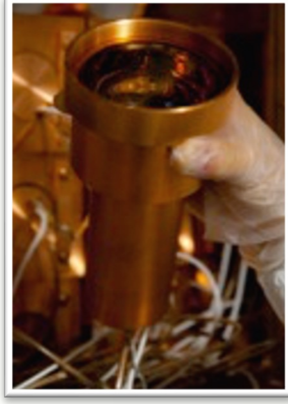


DAMA/LIBRA-phase2 data taking

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)

+ also analyzed with 0.75 keV energy threshold, see later

- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 8 a.c.: $\approx 1.6 \times 10^8$ events from sources
- ✓ Acceptance window eff. 8 a.c.: $\approx 4.2 \times 10^6$ events ($\approx 1.7 \times 10^5$ events/keV)

Annual Cycles	Period	Mass (kg)	Exposure (kg×d)	$(\alpha - \beta^2)$
	Dec 23, 2010 – Sept. 9, 2011	commissioning		
1	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
2	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
3	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
4	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
5	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527	0.522
6	Sept. 7, 2016 – Sept. 25, 2017	242.5	75135	0.480
7	Sept. 25, 2017 – Aug. 20, 2018	242.5	68759	0.557
8	Aug. 24, 2018 – Oct. 3, 2019	242.5	77213	0.446

$(\alpha - \beta^2) = 0.501$

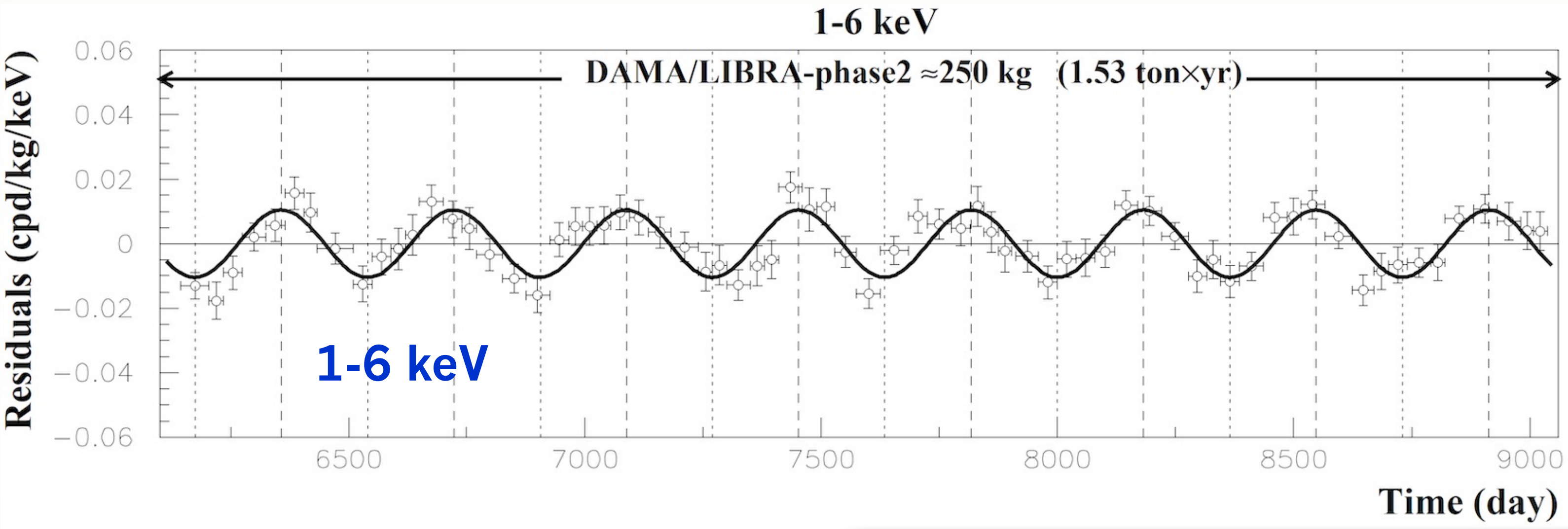
Exposure of DAMA/LIBRA-phase2 with the annual cycles released so far: **1.53 ton × yr**

Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.86 ton × yr**

DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.53 ton × yr)

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



Absence of modulation? No

χ^2/dof = 202/69 (1-6 keV)

Fit on DAMA/LIBRA-phase2

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

1-6 keV

A=(0.01048±0.00090) cpd/kg/keV

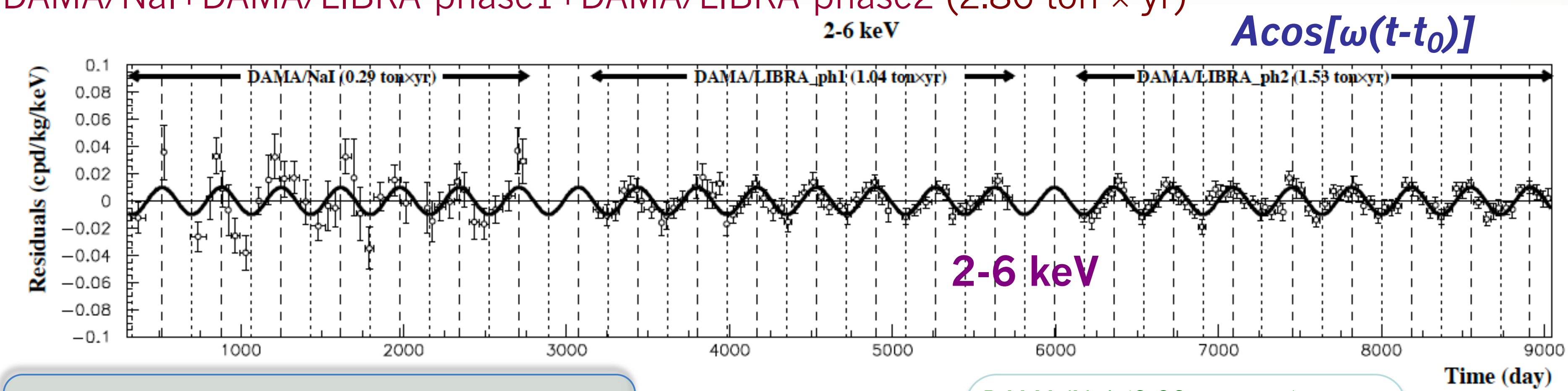
χ^2/dof = 66.2/68 **11.6 σ C.L.**

The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6σ 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 (2.86 ton × yr)



Absence of modulation? No

χ^2/dof=311/156 $\Rightarrow$ P(A=0) =2.3×10^{-12}

DAMA/NaI (0.29 ton x yr)

DAMA/LIBRA-ph1 (1.04 ton x yr)

DAMA/LIBRA-ph2 (1.53 ton x yr)

total exposure = 2.86 ton×yr

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

A=(0.00996±0.00074) cpd/kg/keV

χ^2/dof = 130/155 **13.4 σ C.L.**

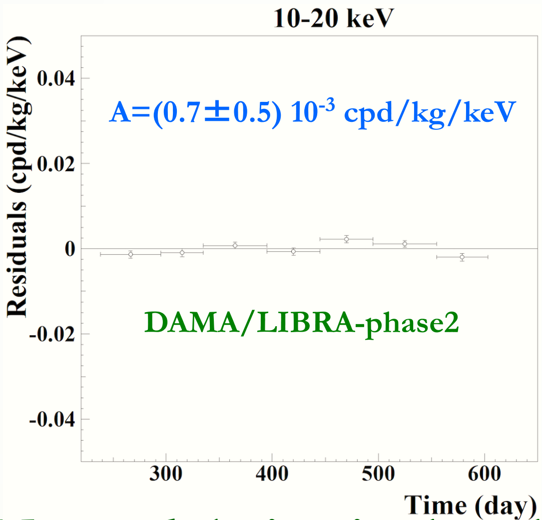
Releasing period (*T*) and phase (t_0) in the fit

	ΔE	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0191±0.0020	0.99952±0.00080	149.6±5.9	9.6σ
	(1-6) keV	0.01058±0.00090	0.99882±0.00065	144.5±5.1	11.8σ
	(2-6) keV	0.00954±0.00076	0.99836±0.00075	141.1±5.9	12.6σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.00959±0.00076	0.99835±0.00069	142.0±4.5	12.6σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.01014±0.00074	0.99834±0.00067	142.4±4.2	13.7σ

The data of DAMA/NaI + DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favour the presence of a modulated behaviour with proper features at 13.7 σ C.L.

Examples of consistency: 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
-(0.0005 ± 0.0013) DAMA/LIBRA-ph2_8
-(0.0003 ± 0.0014) DAMA/LIBRA-ph2_9

→ statistically consistent with zero

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

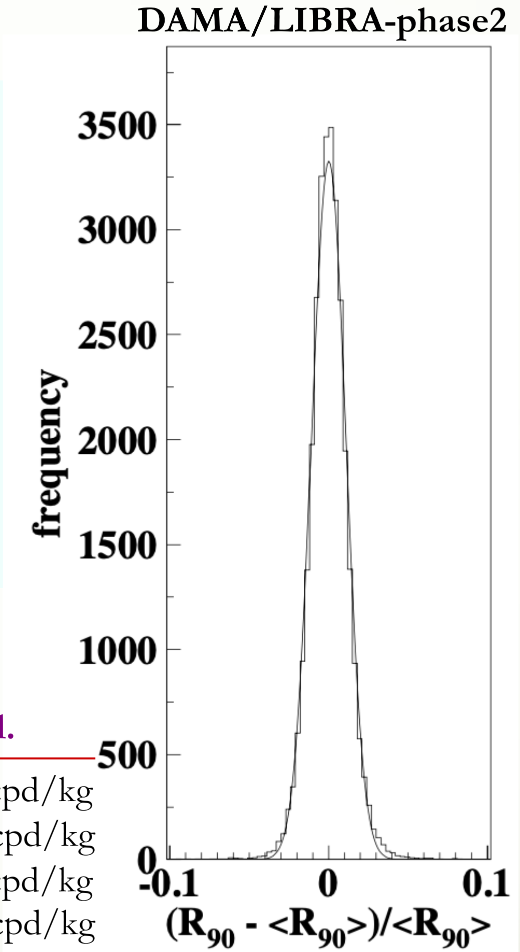
studying integral rate at higher energy, R_{90}

- 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

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

Period	Mod. Ampl.
DAMA/LIBRA-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg
DAMA/LIBRA-ph2_8	-(0.18±0.13) cpd/kg
DAMA/LIBRA-ph2_9	(0.08±0.14) cpd/kg



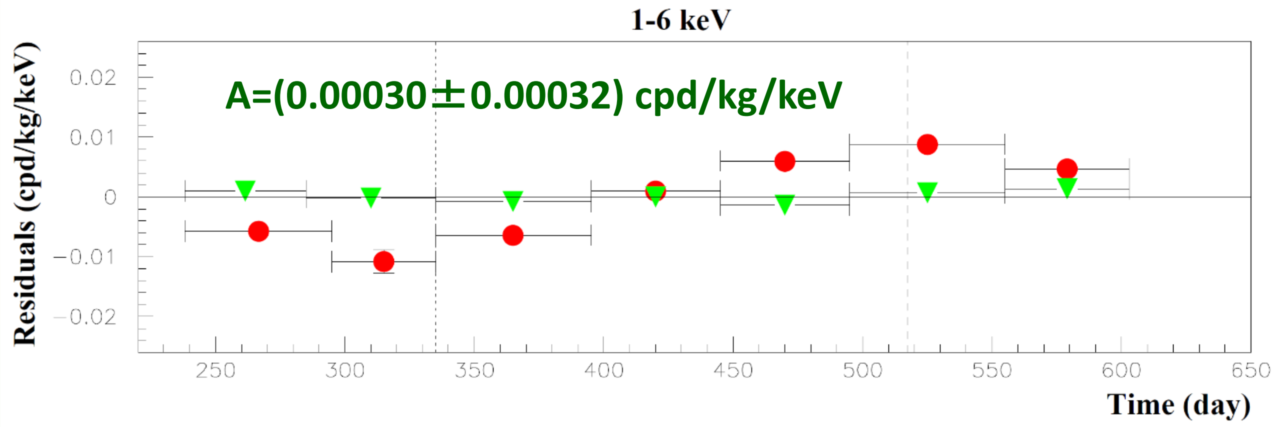
σ ≈ 1%, fully accounted by statistical considerations

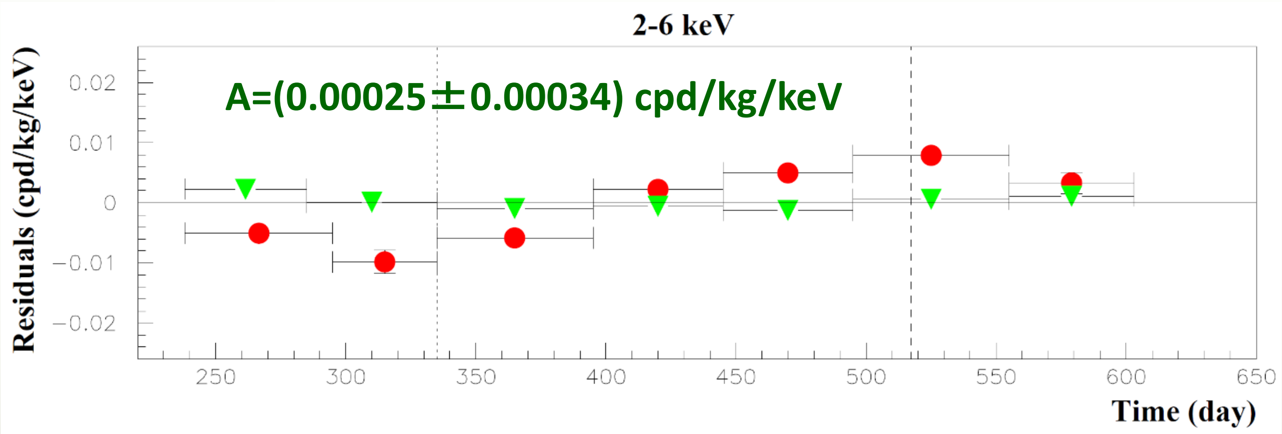
No modulation above 6 keV
This accounts for all sources of bckg and is consistent with the studies on the various components

DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (8 a.c., 1.53 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

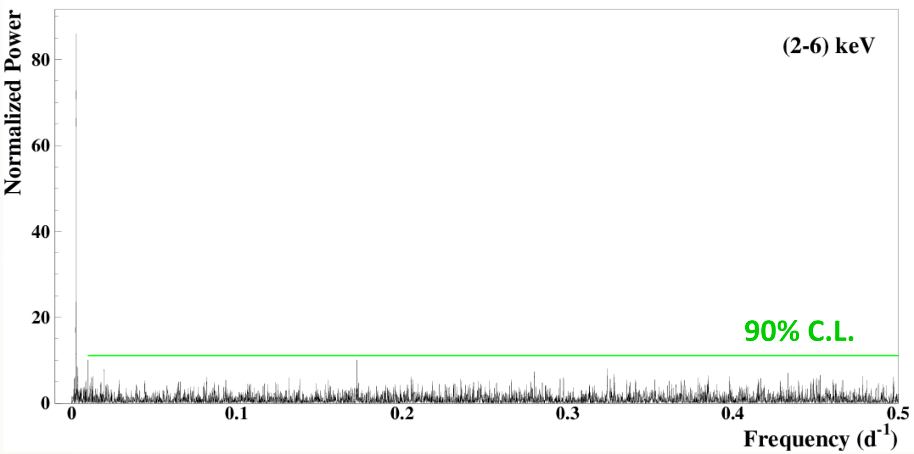
The analysis in frequency

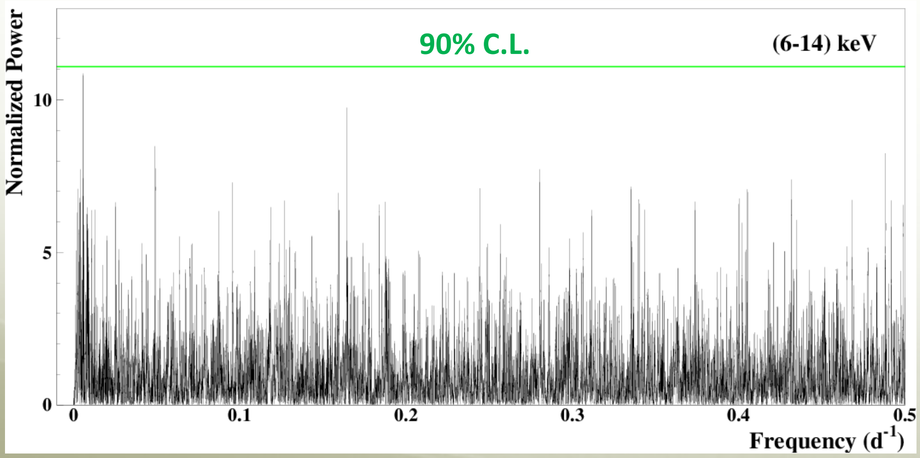
(according to PRD75 (2007) 013010)

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

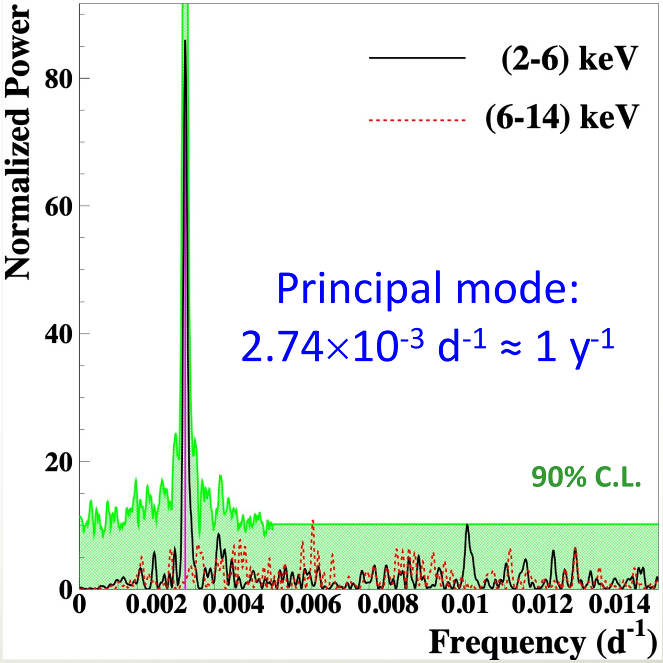
DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (22 yr)
total exposure: 2.86 ton×yr

The whole power spectra up to the Nyquist frequency





Zoom around the 1 y^{-1} peak



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

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

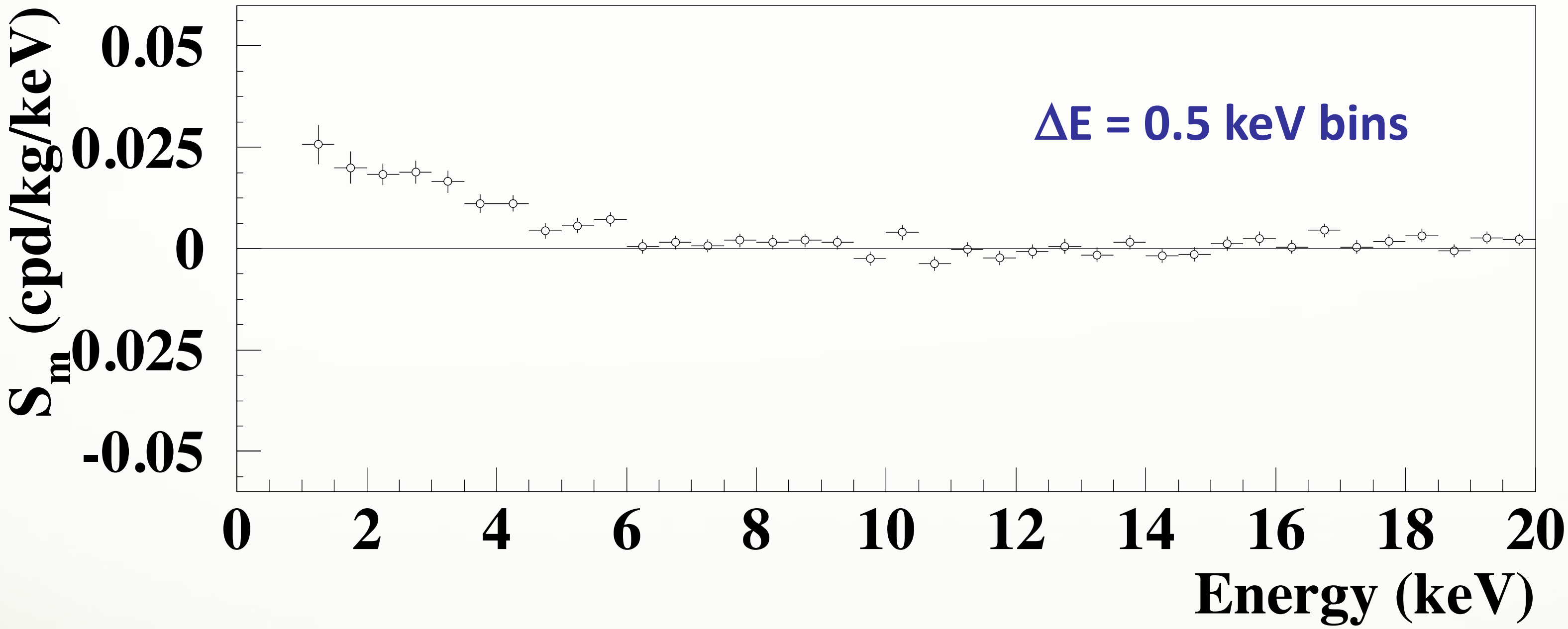
Energy distribution of the modulation amplitudes

Max-likelihood analysis

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

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

DAMA/NaI + DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2 (2.86 ton×yr)

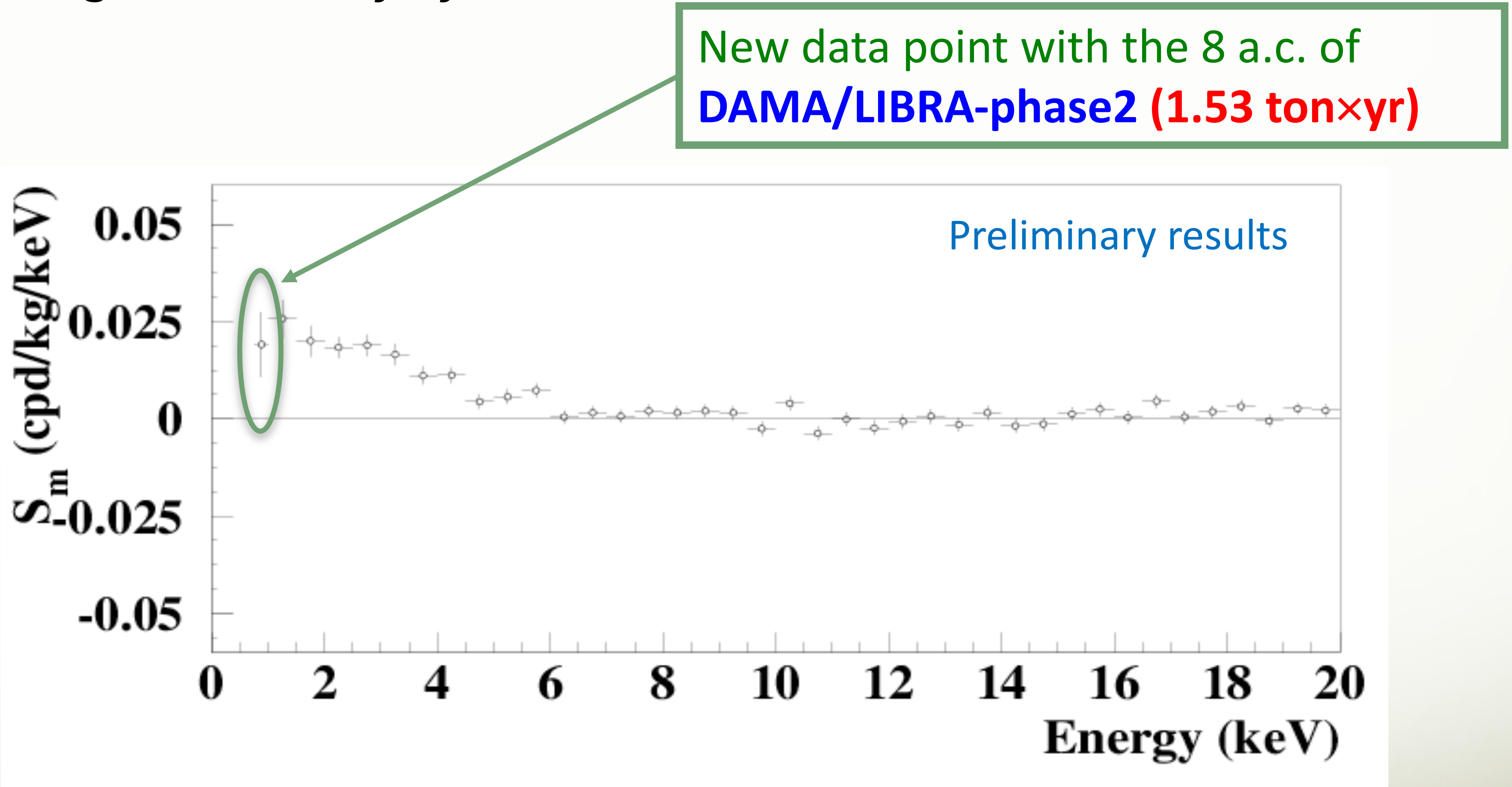


A clear modulation is present in the (1-6) keV energy interval, while S_m values compatible with zero are present just above

- The S_m values in the (6–14) keV energy interval have random fluctuations around zero with χ^2 equal to 20.3 for 16 degrees of freedom (upper tail probability 21%).
- In (6–20) keV χ^2/dof = 42.2/28 (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 14% and 23%.

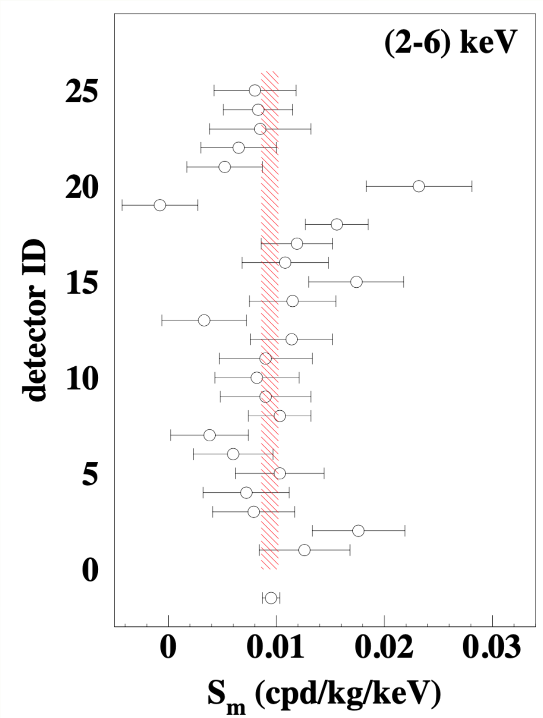
Efforts towards lower software energy threshold

- decreasing the software energy threshold down to 0.75 keV
- using the same technique to remove the noise pulses
- evaluating the efficiency by dedicated studies



- ❑ A clear modulation is also present below 1 keV, from 0.75 keV, while S_m values compatible with zero are present just above 6 keV
- ❑ This preliminary result suggests the necessity to lower the software energy threshold and to improve the experimental error on the first energy bin

S_m for each detector

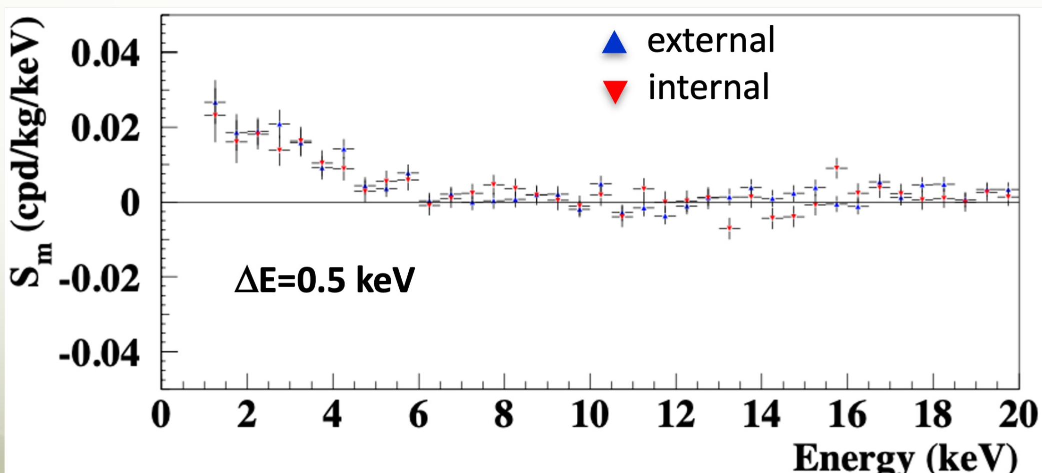


DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2
total exposure: 2.57 ton×yr

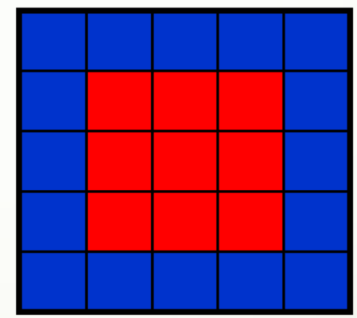
S_m in (2 - 6) keV for each of the 25 detectors (1σ error)

Shaded band = weighted averaged S_m ± 1σ

- χ^2/dof = 38.2/24 d.o.f. (P=3.3%)
- removing C19 and C20: χ^2/dof = 22.1/22 d.o.f.



External vs internal detectors:



1-4 keV χ^2/dof =1.9/6

1-10 keV χ^2/dof =7.6/18

1-20 keV χ^2/dof =36.1/38

- The signal is rather well distributed over all the 25 detectors
- No difference between ext and int detectors

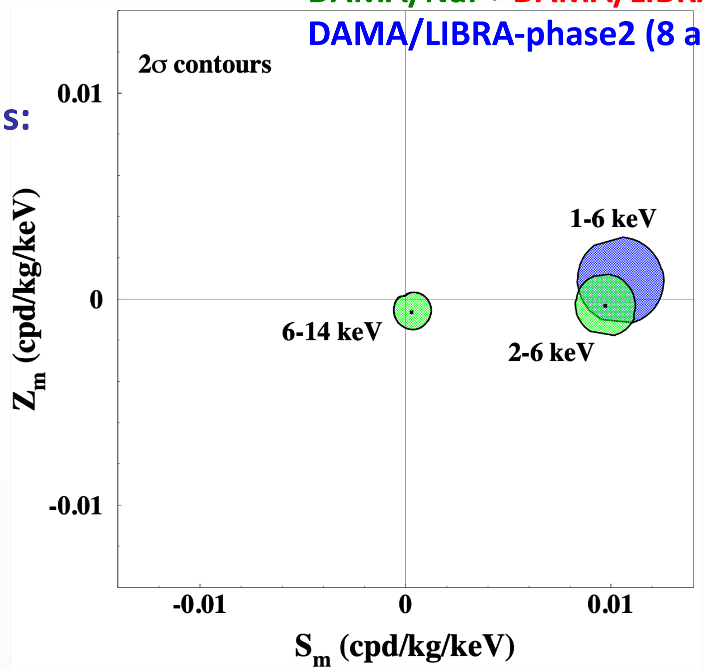
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

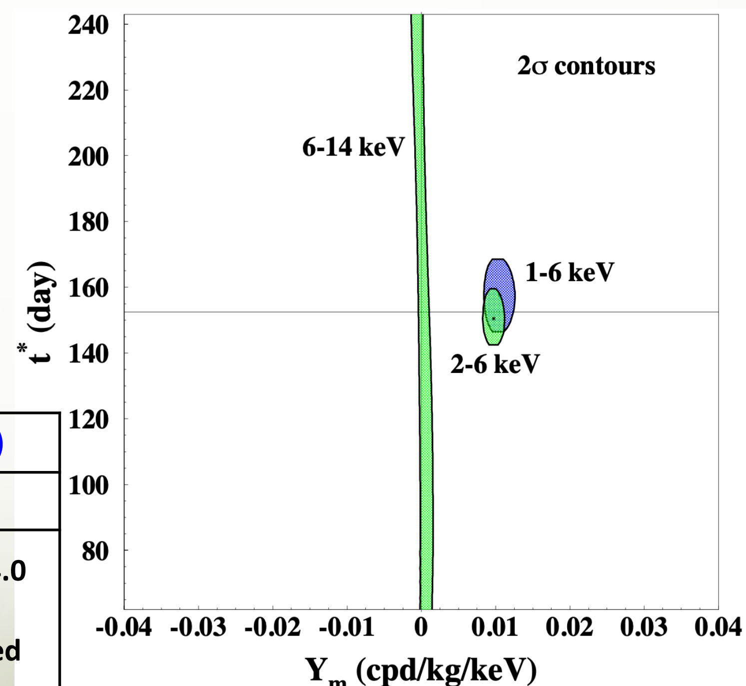
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]

For Dark Matter signals:

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



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



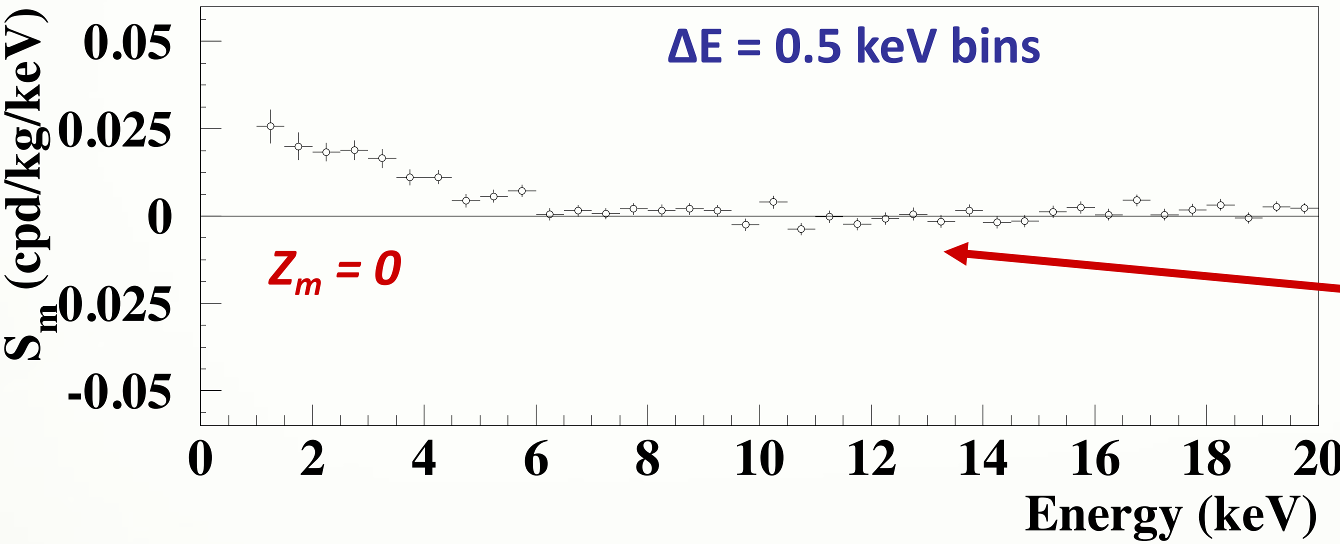
E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0097 ± 0.0007	- 0.0003 ± 0.0007	0.0097 ± 0.0007	150.5 ± 4.0
6-14	0.0003 ± 0.0005	-0.0006 ± 0.0005	0.0007 ± 0.0010	undefined
1-6	0.0104 ± 0.0007	0.0002 ± 0.0007	0.0104 ± 0.0007	153.5 ± 4.0

Energy distributions of cosine (S_m) and sine (Z_m) modulation amplitudes

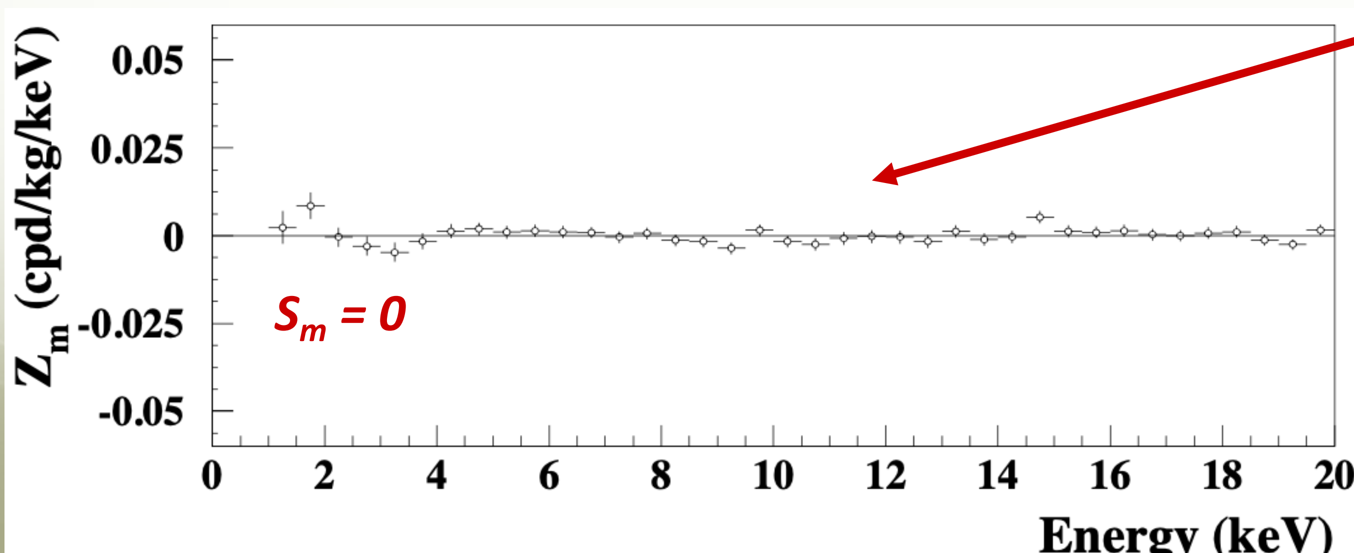
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)]$$

t_0 = *152.5 day* (2^{nd} June)

DAMA/NaI +
DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2 (8 a.c.)
(2.86 ton × yr)



maximum at 2^{nd} June as for DM particles



maximum at 1^{st} September, that is *T/4* days after 2^{nd} June

The χ^2 test in (1-20) keV energy region (χ^2/dof = 40.6/38 probability of 36%) supports the hypothesis that the Z_m values are simply fluctuating around zero.

Few comments on analysis procedure in DAMA/LIBRA

arXiv:2209.00882

- Data taking of each annual cycle starts before the expected **minimum** (Dec) of the DM signal and ends after its expected **maximum** (June)
- Thus, assuming a **constant background** within each annual cycle:
  - ✓ any possible decay of **long–term–living isotopes** cannot mimic a DM positive signal with all its peculiarities
  - ✓ it may only lead to **underestimate** the observed S_m, depending on the radio-purity of the set-up

Claims (JHEP2020,137, arXiv:2208.05158) that the DAMA annual modulation signal may be biased by a slow variation only in the low-energy *single-hit* rate, possibly due to *some background* with odd behaviour increasing with time

already **confuted** quantitatively (see e.g. Prog. Part. Nucl. Phys. 114, 103810, 2020 and here)

- arXiv:2208.05158 claims that an annual modulation in the **COSINE–100** data can appear if they use an analysis method somehow similar to DAMA/LIBRA. However, they get a modulation with reverse phase (**NEGATIVE modulation amplitude if phase = 2 June**) ⇒ **NO SURPRISE!!**
  - → This is expected by the elementary consideration that their rate is very–decreasing with time.

- COSINE-100: **different** NaI(Tl) crystal manufacturing wrt DAMA, different starting powders, different purification, different growing procedures and protocols; different electronics and experimental set-up, all stored underground since decades. Different quenching factor for alpha's and nuclear recoils

- Odd idea that low-energy rate might increase with time due to spill out of noise ⇒ deeply **investigated**:
  - ✓ the stability with time of noise and rate
  - ✓ remaining noise tail after the noise rejection procedure <1%

Any effect of long–term time–varying background or low-energy rate increasing with time ➔ negligible in DAMA/LIBRA thanks to the radiopurity and long-time underground of the ULB DAMA/LIBRA NaI(Tl)

Excluding any effect of long-term decay or odd low-energy rate increasing with time in DAMA/LIBRA

Prog. Part. Nucl. Phys. 114, 103810 (2020)
arXiv:2209.00882

1) The case of low-energy *single-hit* residual rates.

- We recalculate the (2–6) keV *single-hit* residual rates considering a possible time–varying background. They provide modulation amplitude, fitted period and phase well **compatible** with those obtained in the *original* analysis, showing that the effect of long–term time–varying background – if any – is marginal

2) The tail of the S_m distribution case.

- Any possible long–term time–varying background would also induce a (either positive or negative) **fake modulation amplitudes (Σ)** on the tail of the S_m distribution above the energy region where the signal has been observed.
- The analysis shows that $|\Sigma| < 1.5 \times 10^{-3}$ cpd/kg/keV.
- Observed *single-hit* annual modulation amplitude at low energy is order of 10^{-2} cpd/kg/keV
- Thus, the effect – if any – is marginal.

3) The maximum likelihood analysis.

- The maximum likelihood analysis has been repeated including a **linear term decreasing with time**.
- The obtained S_m averaged over the low energy interval are **compatible** with those obtained in the original analysis

4) Multiple-hit events

- No modulation has been found in the *multiple-hit* events the same energy region where the annual modulation is present in the *single-hit* events, strongly **disfavours** the hypothesis that the counting rate has significant long–term time–varying contributions.

Any effect of long–term time–varying background or odd low-energy rate increasing with time ➔ **negligible** in DAMA/LIBRA

The original DAMA analyses can be safely adopted

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)116, Bled19(2018)27, NPAE19(2018)307, PPNP114(2020)103810

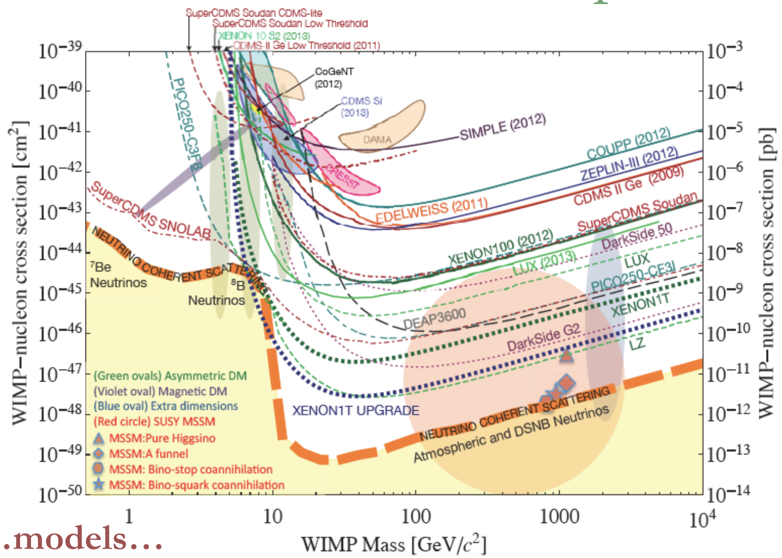
Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5\times10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously 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

About interpretation: is an "universal" and "correct" way to approach the problem of DM 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, NPAE20(4) (2019)317, PPNP114(2020) 103810



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

…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?
- …

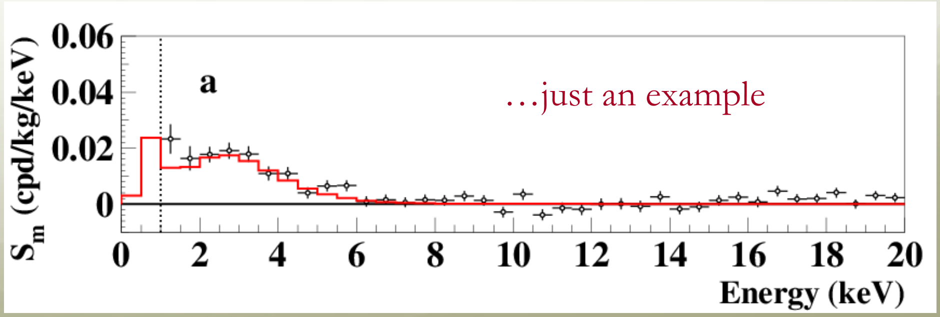
…and experimental aspects…

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

Example: 2 keVee of DAMA ≠2 keVee of COSINE-100 for nuclear recoils

No direct model-independent comparison is possible

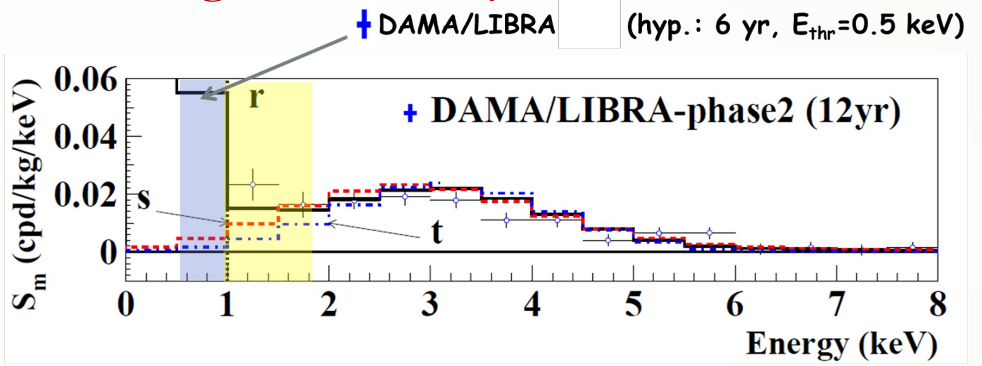
DAMA well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios



Running **phase2-empowered** with software energy threshold of **0.5 keV** with suitable high efficiency

Enhancing experimental sensitivities and improving DM corollary aspects, other DM features, second order effects and other rare processes

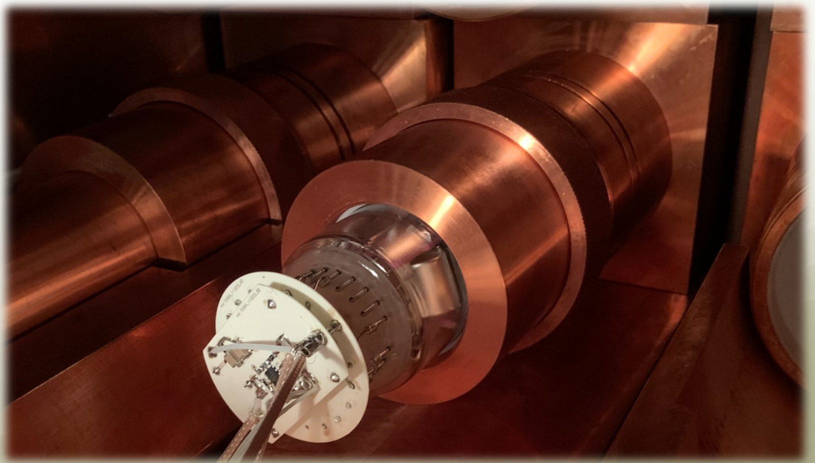
1) During fall 2021, DAMA/LIBRA–phase2 set-up was heavily upgraded
2) The upgrade basically consisted on:
   - new low-background voltage dividers with pre-amps on the same board
   - Transient Digitizers with higher vertical resolution (14 bits)
3) The data taking in this new configuration started on Dec, 1 2021



The features of the voltage divider+preamp system:

- S/N improvement ≈3.0-9.0;
- discrimination of the single ph.el. from electronic noise: 3 - 8;
- the Peak/Valley ratio: 4.7 - 11.6;
- residual radioactivity lower than that of single PMT

- Higher resolution of TDs makes appreciable the improvements coming from the new voltage-dividers-plus-preamps on the same board
- very stable operational feature
- The baseline fluctuations are more than a factor two lower than those of the previous configuration; RMS of baseline distributions is around 150 μV, ranging between 110 and 190 μV
- Software Trigger Level (**STL) decreased** in the offline analysis
- The "noise" events due to single p.e. with the same energy have evident different structures than the scintillation pulses. This feature is used to discriminate them



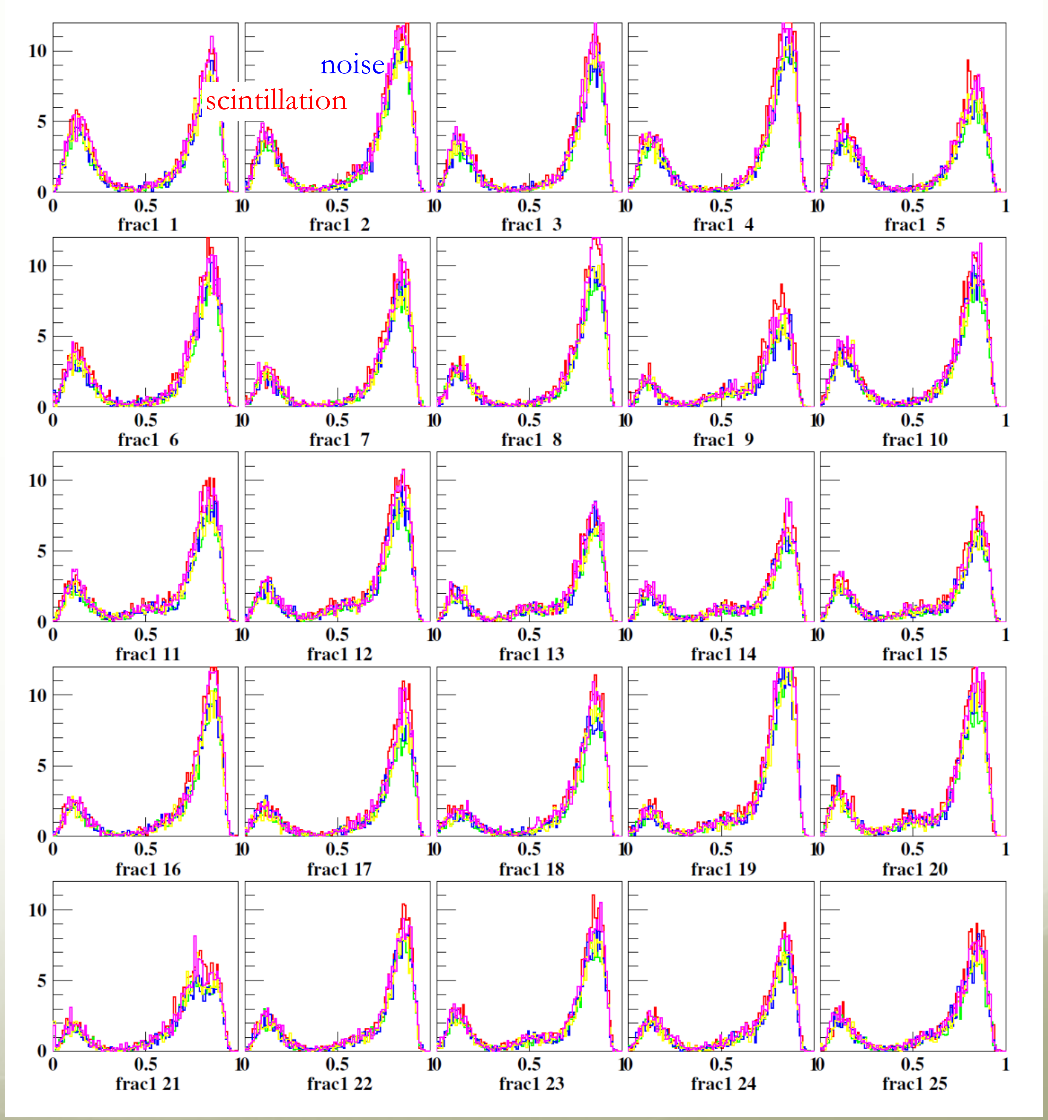
Applying the STL

*frac*3 = Area(from 100 to 600 ns)/Area(from 0 to 600 ns)

frac1 = Area(from 0 to 50 ns)/Area(from 0 to 600 ns)

- *frac3* is distributed around 0 for noise events and around 0.63 for scintillation pulses (assuming a pure exponential behaviour);
- *frac1* is distributed around 1 for noise and around 0.20 for scintillation events (assuming a pure exponential behaviour).

Production runs: **frac1**

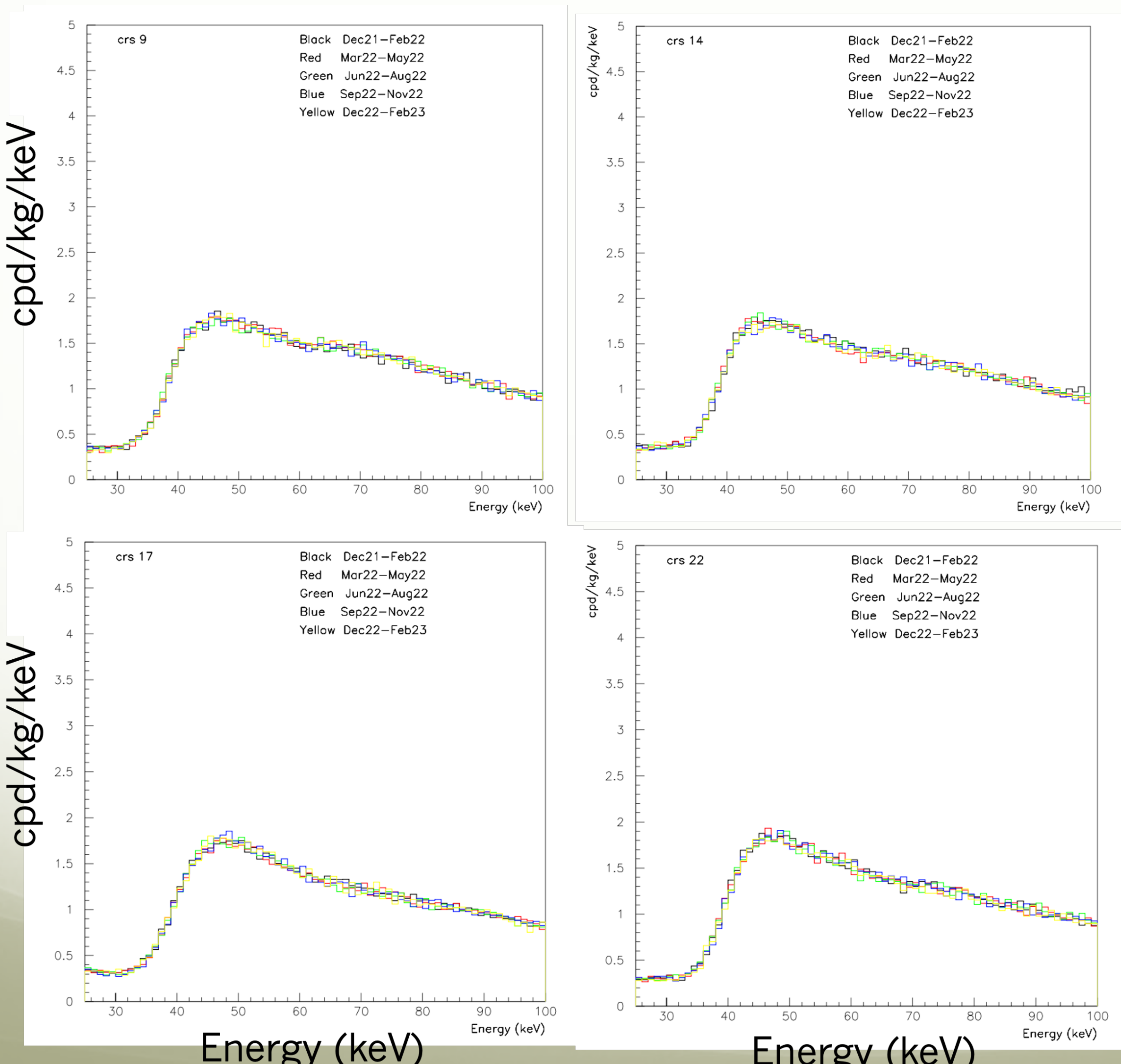


- Distributions of the *tm600* (in ns), *frac1* and *frac3* variables in the 0.5-5 keV energy range;
- Stability along the 2022 (colours correspond to five different periods of the considered data set: Dec 2021 – Feb 2023).

see also JINST 7 (2012) P03009

Stability of the energy scale

- Monitor of the energy scale in the region of ^{210}Pb + ^{129}I
- The data in the period dec 2021-feb2023 are divided in five time intervals

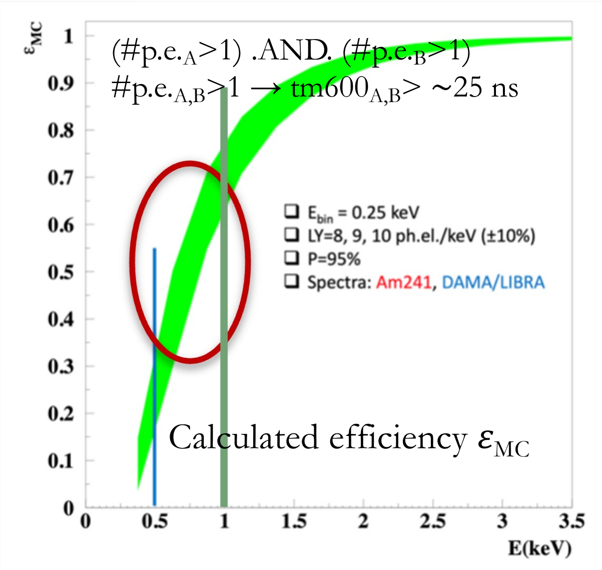


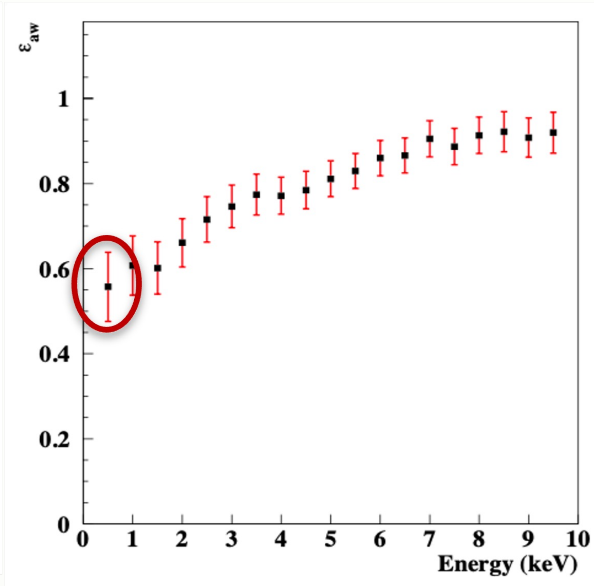
- Just few examples
- The detectors are underground since decades (*) and the ^{129}I contribution is dominant in this energy region

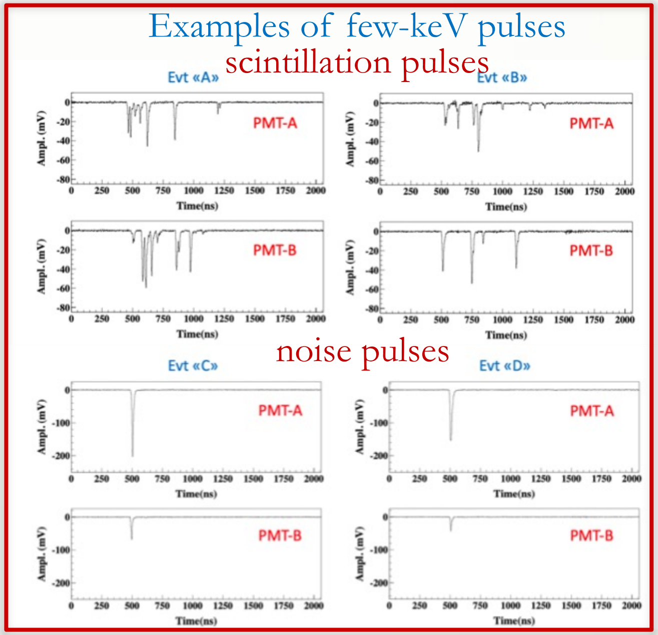
The energy scale is well stable

(*) as the other components of the set-up, always kept in HPN_2 and without exposure to neutron sources

Running **phase2-empowered** with software energy threshold of **0.5 keV** with suitable high efficiency

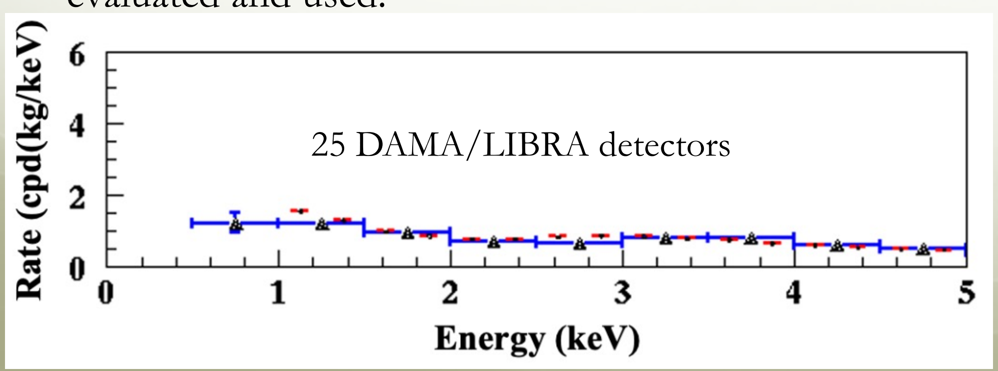






- ε_{aw} efficiencies for the used acceptance windows, measured by applying the same acceptance windows to events by ^{241}Am in the same experimental conditions as the production data.
- Very stringent acceptance windows, which assure the absence of any noise tail, can be considered and related efficiencies can be properly evaluated and used.

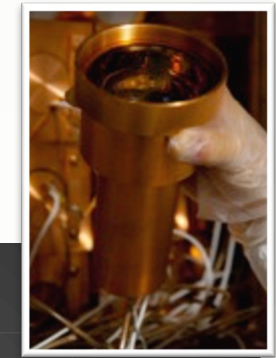
A suitable efficiency below 1 keV is possible in the new configuration

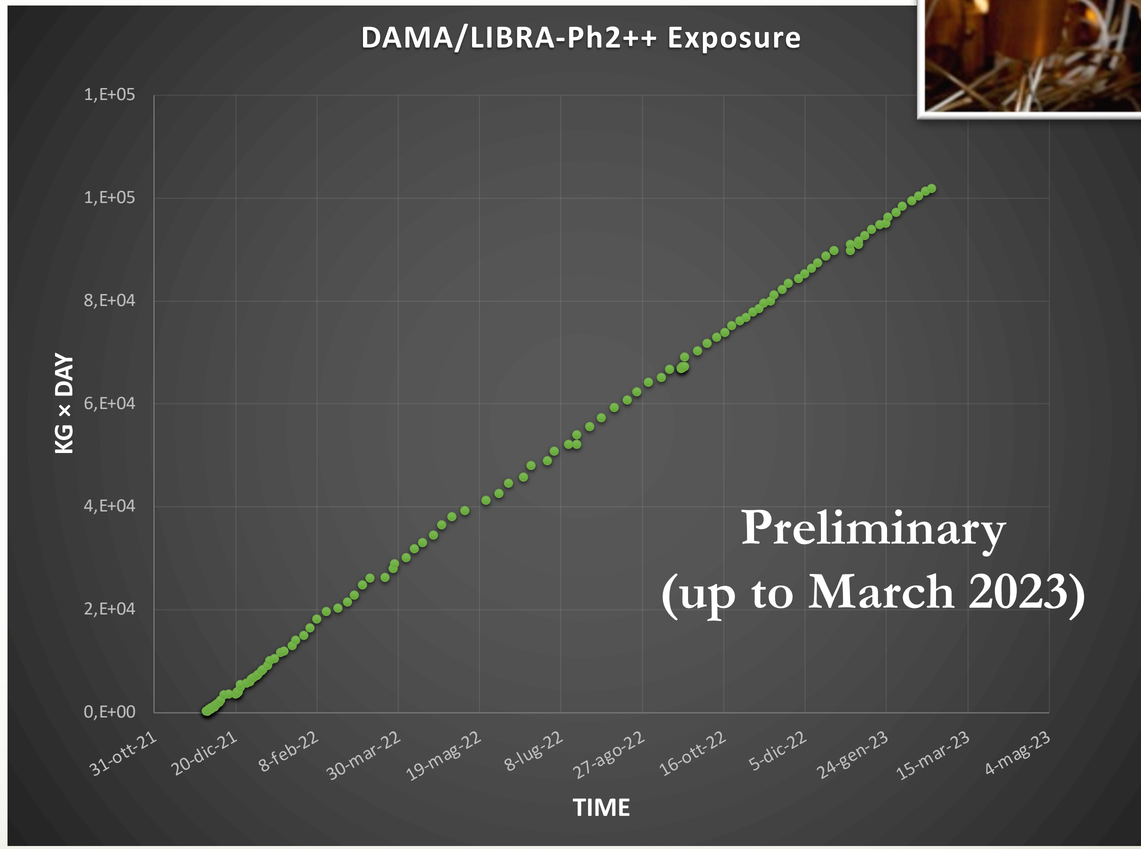


Energy spectrum of the *single-hit* scintillation events – already corrected for the efficiencies – in the new configuration (blue, exposure 2350 kg×d) and in DAMA/LIBRA–phase2 (red, the energy threshold was 1 keV, 1.53 ton×yr).

Empowered DAMA/LIBRA-phase2 data taking

Data taking in this configuration started on December 2021. The data taking has been continued without interruptions, with regular calibration runs.





- ✓Calibrations: $\approx 3.5 \times 10^7$ events from sources
- ✓Acceptance window eff. per all crystals: $\approx 1.95 \times 10^7$ events ($\approx 7.8 \times 10^5$ events/keV)

Exposure of empowered DAMA/LIBRA-phase2 up to now: **0.28 ton × yr.**

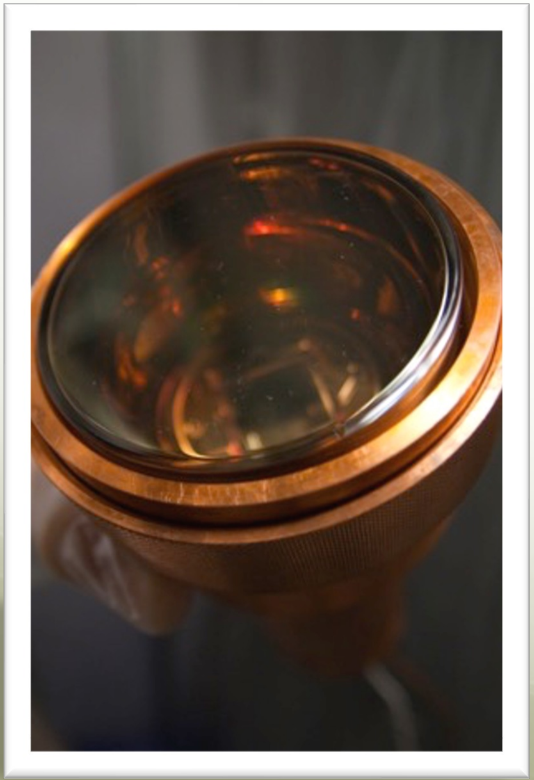
$(\alpha - \beta^2) \approx 0.488$

Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2+empowered-phase2:

3.14 ton × yr

Conclusions

- **Model-independent** evidence for a signal that satisfies all the requirements of the DM annual modulation signature at **13.7σ** C.L. (22 independent annual cycles with 3 different set-ups: 2.86 ton × yr)
- Modulation parameters determined with **increasing precision**
- New investigations on **different peculiarities** of the DM signal 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 improve the C.L. and restrict the allowed parameters' space for the various scenarios
- DAMA/LIBRA–phase2-empowered **running** with lower software **energy threshold of 0.5 keV with suitable efficiency**.
- Continuing investigations of **rare processes** other than DM, also in the other DAMA set-ups (g_A, ^{106}Cd, ^{116}Cd, ^{150}Nd, Os, Zr, Hf, …)
- Other pursued ideas: **$ZnWO_4$ anisotropic scintillator** for DM **directionality**. Response to nuclear recoils measured.

Thanks to the low background features of all the DAMA set-ups, several rare processes can be investigated: some have already done, some others will be