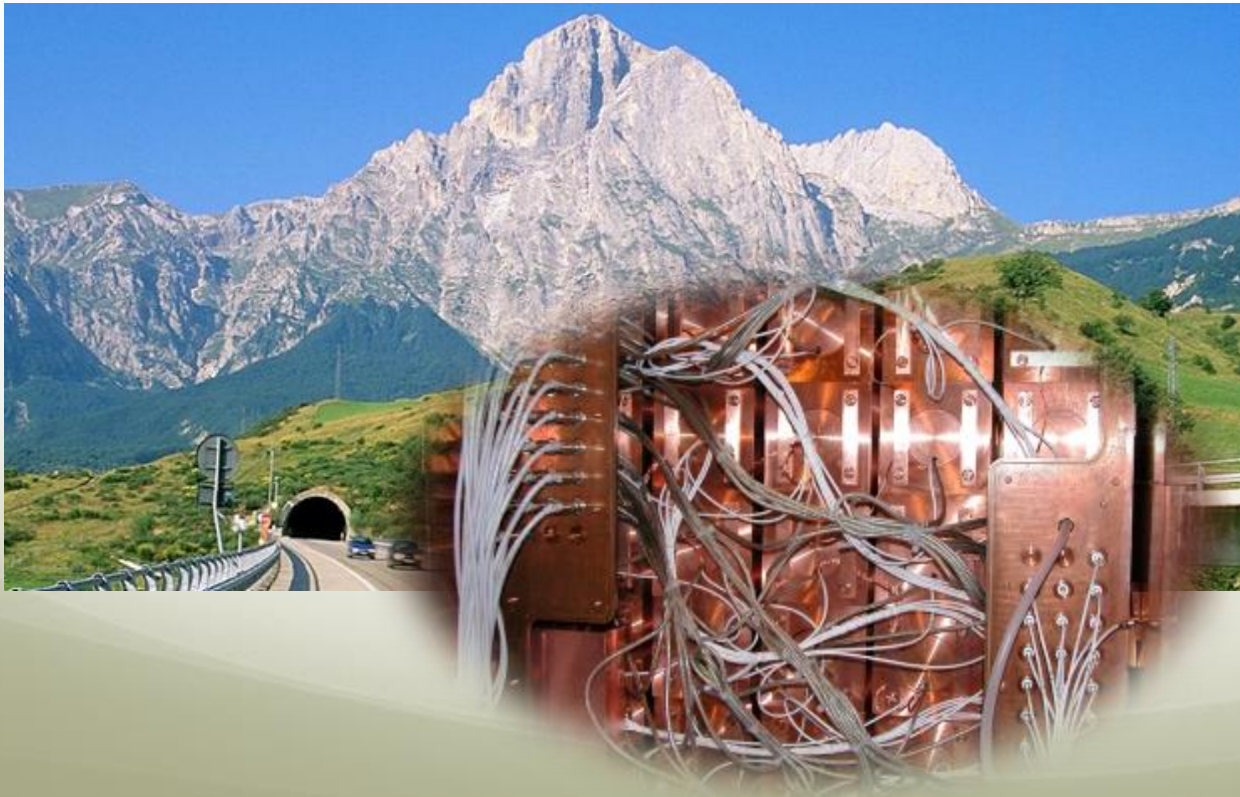


Annual modulation results from DAMA/LIBRA



P. Belli
INFN – Roma Tor Vergata

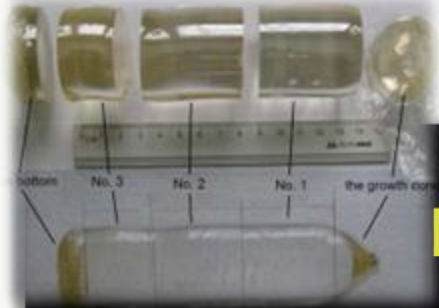
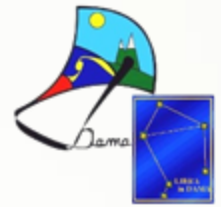


RICAP-24,
Hotel Villa Tuscolana,
Frascati, Sept 23-27, 2024

DAMA set-ups

an observatory for rare processes @ LNGS

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



DAMA/CRYS

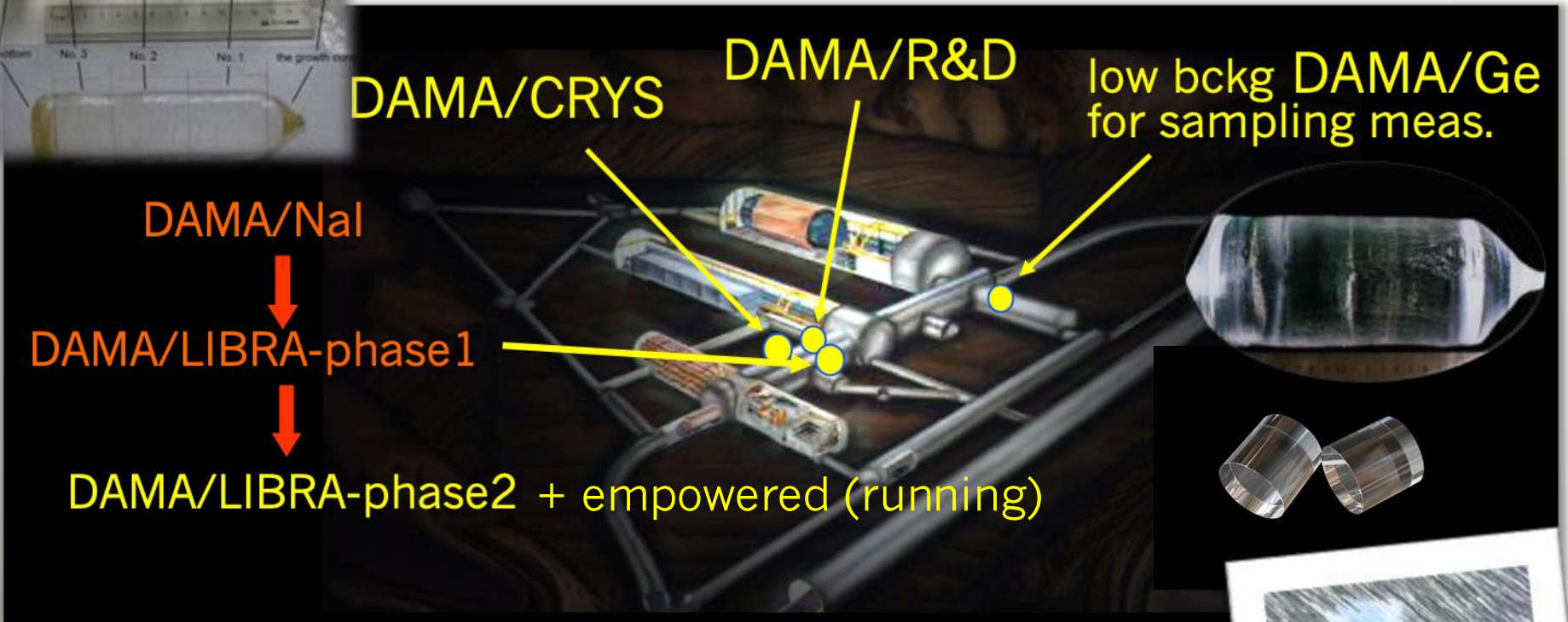
DAMA/R&D

low bckg DAMA/Ge
for sampling meas.

DAMA/NaI

DAMA/LIBRA-phase1

DAMA/LIBRA-phase2 + empowered (running)



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

- + by-products and small scale expts.: INR-Kiev + other institutions
- + neutron meas.: ENEA-Frascati, ENEA-Casaccia
- + in some studies, on $\beta\beta$ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

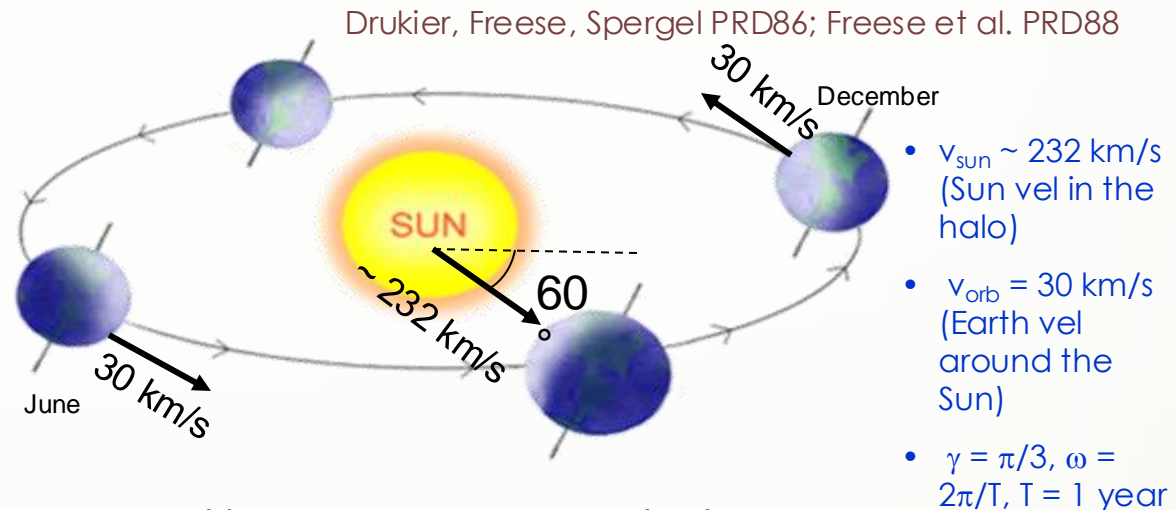
The experimental activities of DAMA will gradually cease in the late 2024/Spring-2025, according to the experiment's long-standing plans

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.

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



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

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

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 **R**Are 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

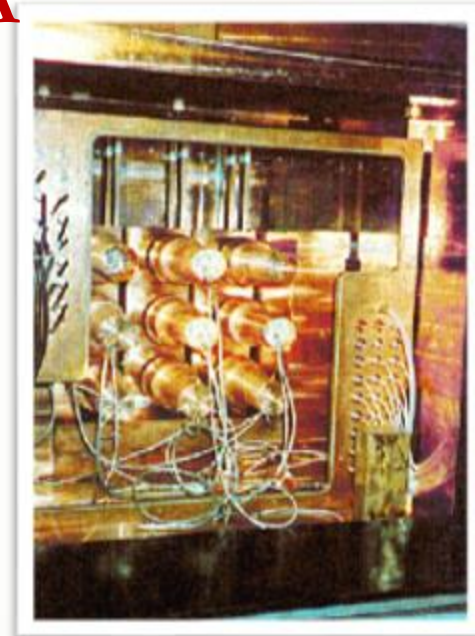
- Results on DM particles:

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

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

- 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



Goal: software energy threshold at 1 keV – accomplished

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

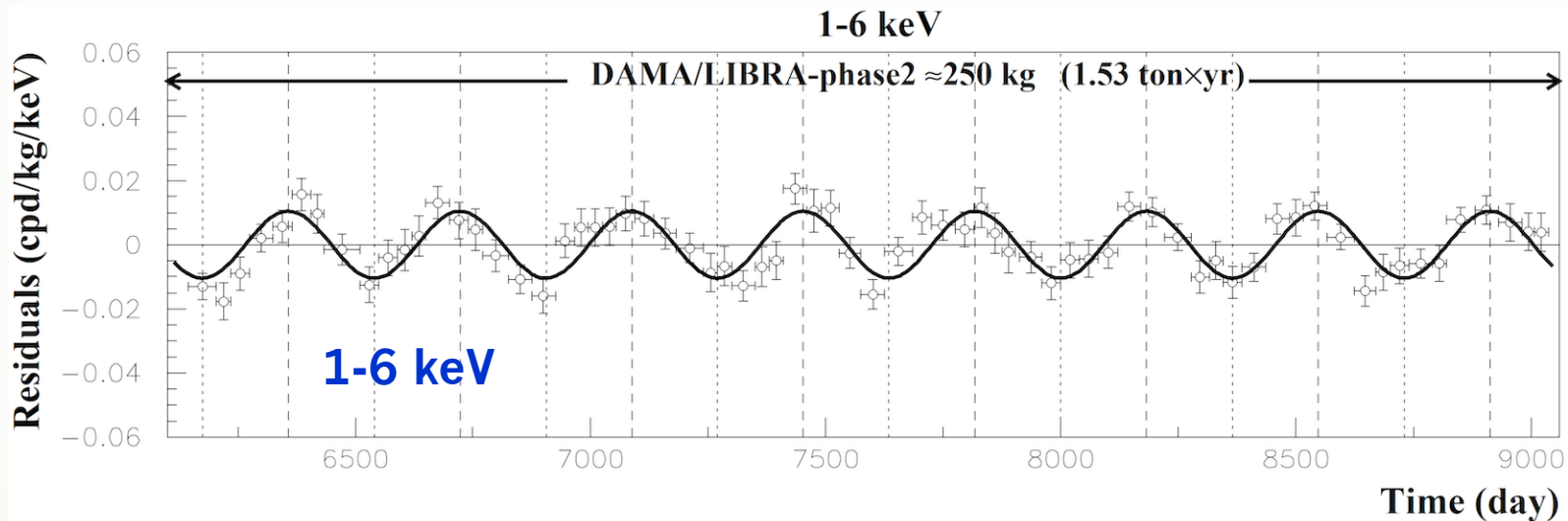
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak



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
 $\chi^2/\text{dof} = 202/69$ (1-6 keV)

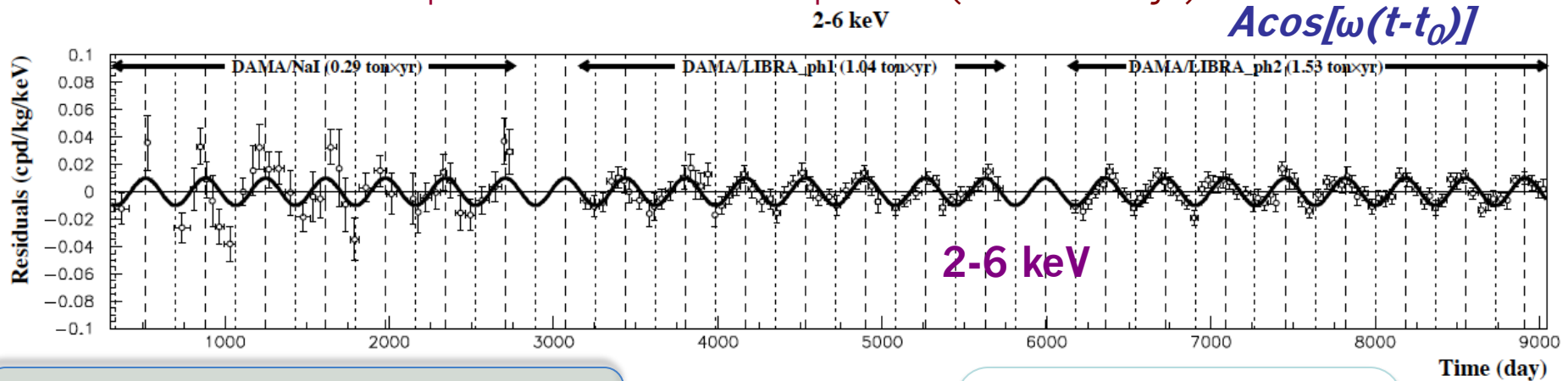
Fit on DAMA/LIBRA-phase2
 $\text{Acos}[\omega(t-t_0)]$; $t_0 = 152.5$ d, $T = 1.00$ y
1-6 keV
 $A = (0.01048 \pm 0.00090)$ cpd/kg/keV
 $\chi^2/\text{dof} = 66.2/68$ **11.6 σ C.L.**

The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6 σ 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

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

DAMA/NaI (0.29 ton × yr)

DAMA/LIBRA-ph1 (1.04 ton × yr)

DAMA/LIBRA-ph2 (1.53 ton × yr)

total exposure = 2.86 ton×yr

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

$$A = (0.00996 \pm 0.00074) \text{ cpd/kg/keV}$$

$$\chi^2/\text{dof} = 130/155 \quad \mathbf{13.4 \sigma \text{ C.L.}}$$

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

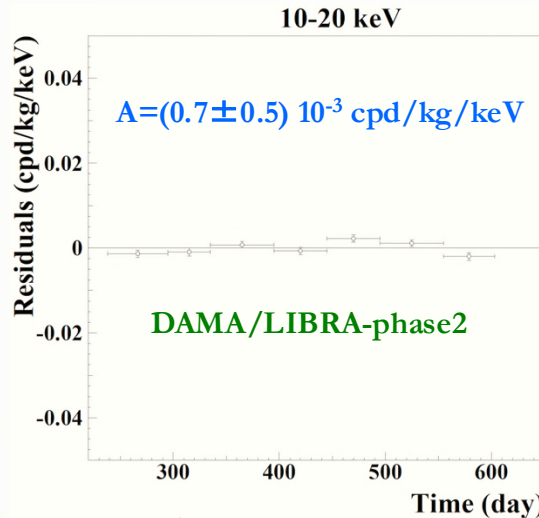
The data of DAMA/NaI +
DAMA/LIBRA-phase1
+DAMA/LIBRA-phase2
favour the presence of a
modulated behaviour with
proper features at 13.7σ
C.L.

	ΔE	$A(\text{cpd/kg/keV})$	$T=2\pi/\omega$ (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

Examples of consistency: Rate behaviour above 6 keV

DAMA/LIBRA-phase2

• 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

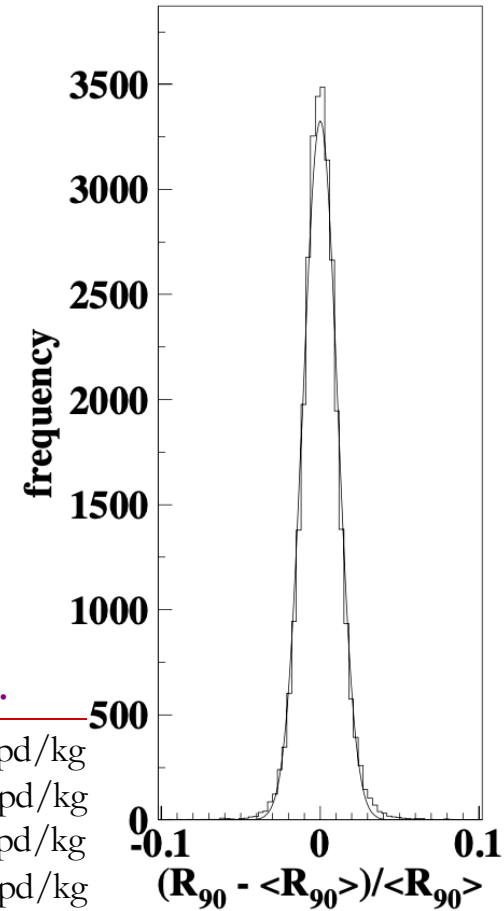
(0.0001 ± 0.0015) DAMA/LIBRA-ph2_6

(0.0015 ± 0.0014) DAMA/LIBRA-ph2_7

$-(0.0005 \pm 0.0013)$ DAMA/LIBRA-ph2_8

$-(0.0003 \pm 0.0014)$ 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 → $R_{90} \sim \text{tens cpd/kg} \rightarrow \sim 100 \sigma$ far away

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

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

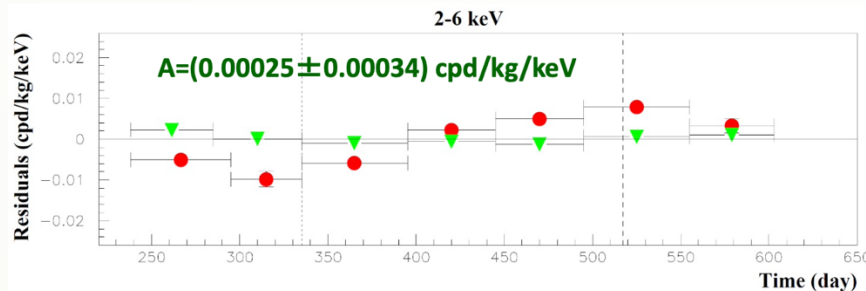
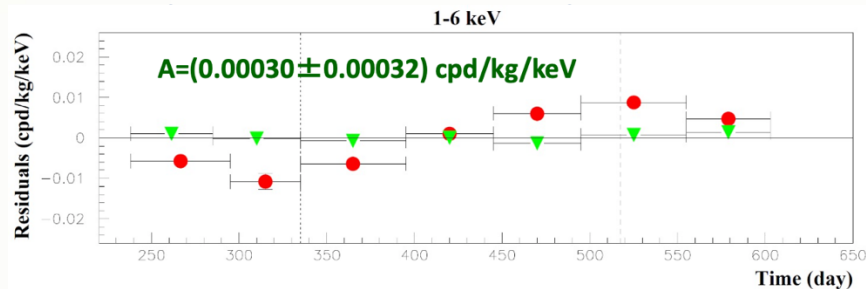
No modulation above 6 keV

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”

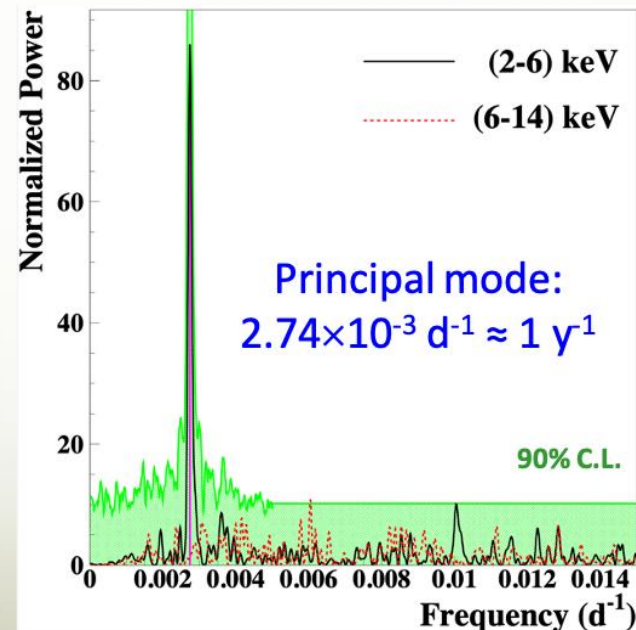


This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

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

Zoom around the 1 yr^{-1} peak



The analysis in frequency

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

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

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

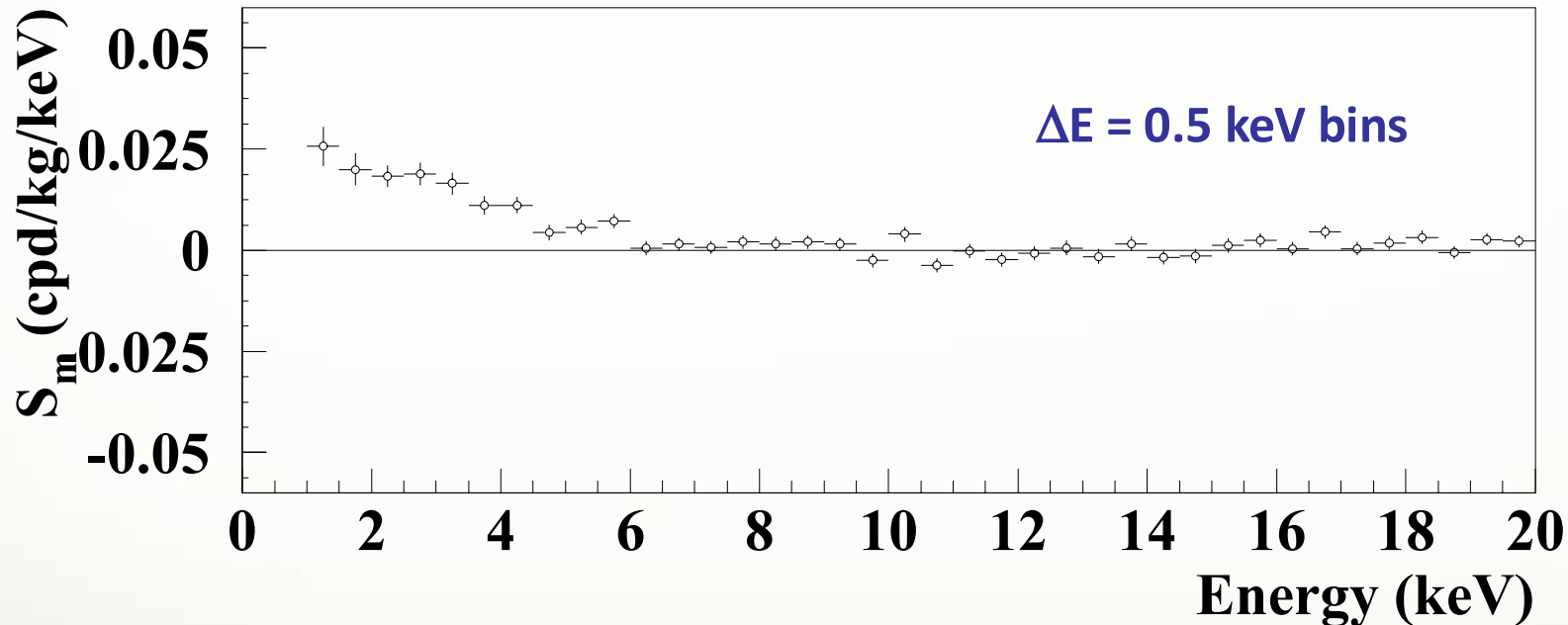
Energy distribution of the modulation amplitudes

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 (2.86 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 $\chi^2/\text{dof} = 42.2/28$ (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%.

Few comments on analysis procedure in DAMA/LIBRA

- 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:
 - ✓ possible decay of **long-term-living isotopes** cannot mimic DM positive signal with all its peculiarities
 - ✓ it may only lead to **underestimate** the observed S_m , depending on the radiopurity of the set-up

Analysis of the last three years (see next slides)

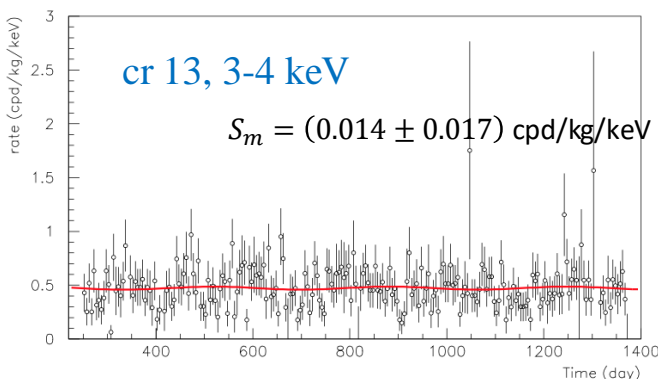
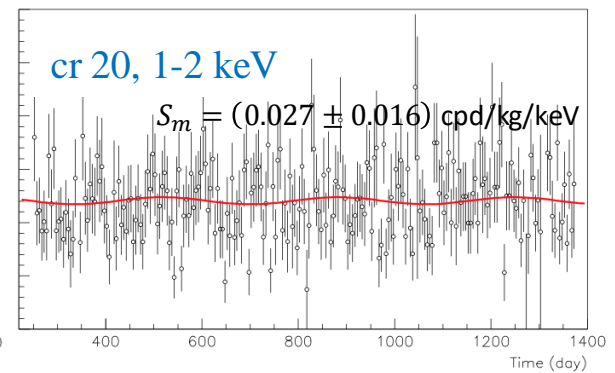
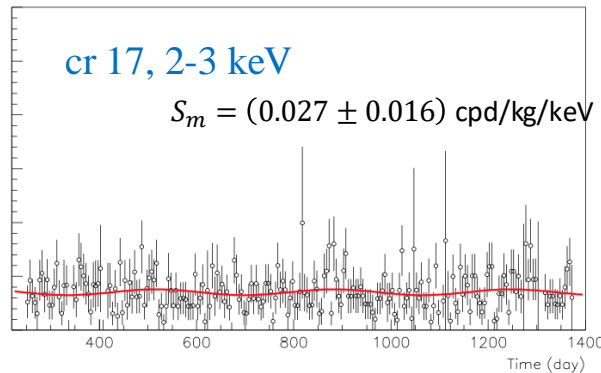
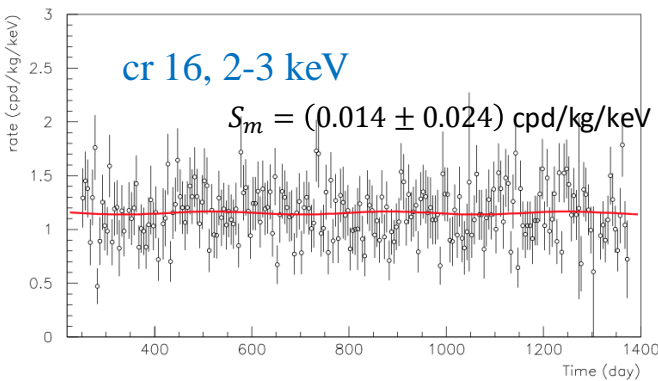
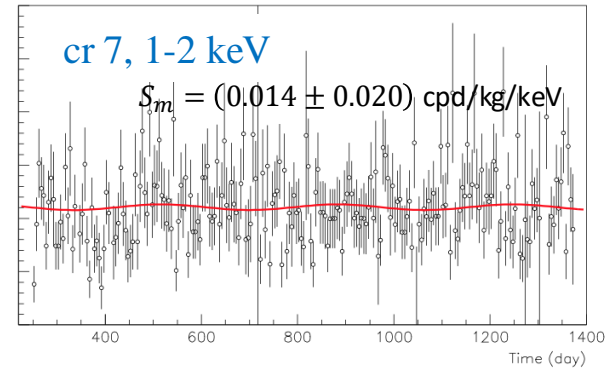
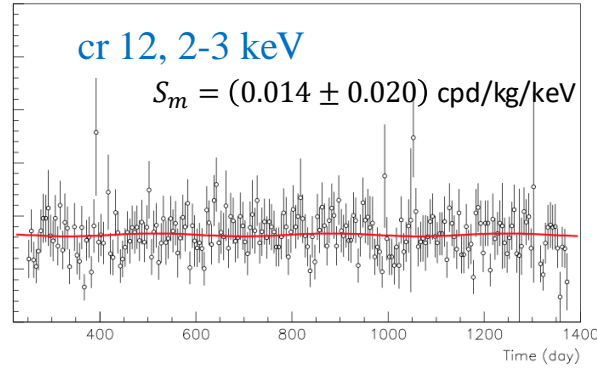
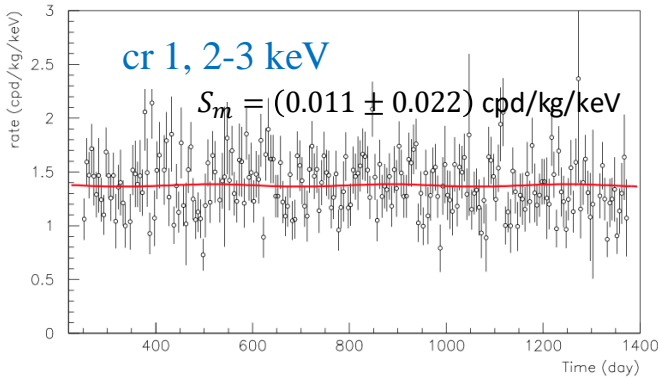
- The **last three published years** of DAMA/LIBRA–phase2 (in which there was continuity between one year and the next) analysed considering the same bckg (w/ and w/o any slope)

Any effect of long-term time-varying bckg
or odd 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)

The original DAMA analyses can be safely adopted

Investigation on the rate dependence

The **last three published years** of DAMA/LIBRA–phase2 (in which there was continuity between one year and the next) analysed **considering the same bckg**



$$\sigma_{S_m}(1 \text{ crystal}) \simeq 0.02 \rightarrow \sigma_{S_m}(25 \text{ crystals}) \simeq \frac{0.02}{\sqrt{25}} \simeq 0.004 \text{ cpd/kg/keV}$$

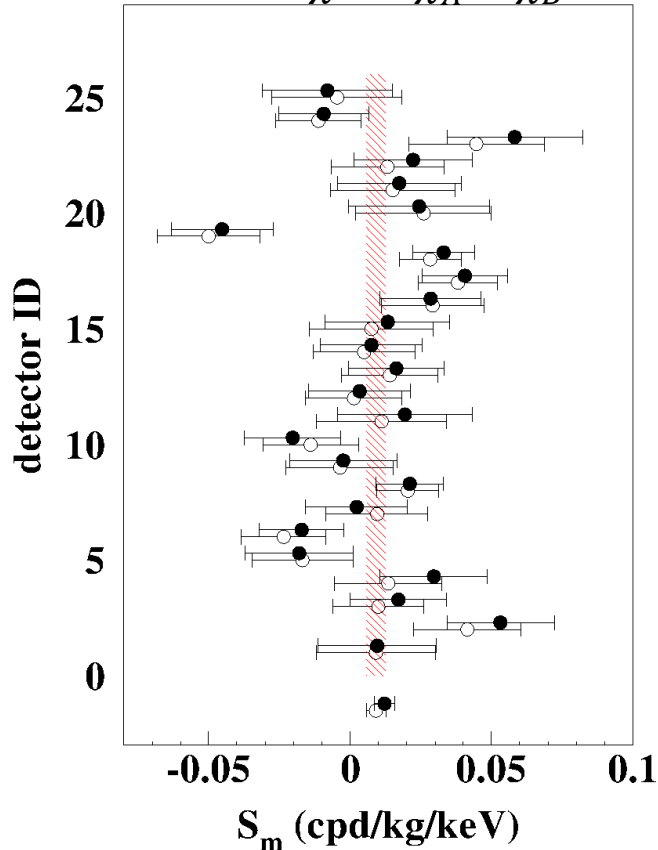
- Time bin: 5 days
- Red: maxlik analysis on single crystal with common (**constant**) background

$$\text{Expected rate over three years: } \mu_{ij} = b_j + S_0 + S_m \cos[\omega(t_i - t_0)]$$

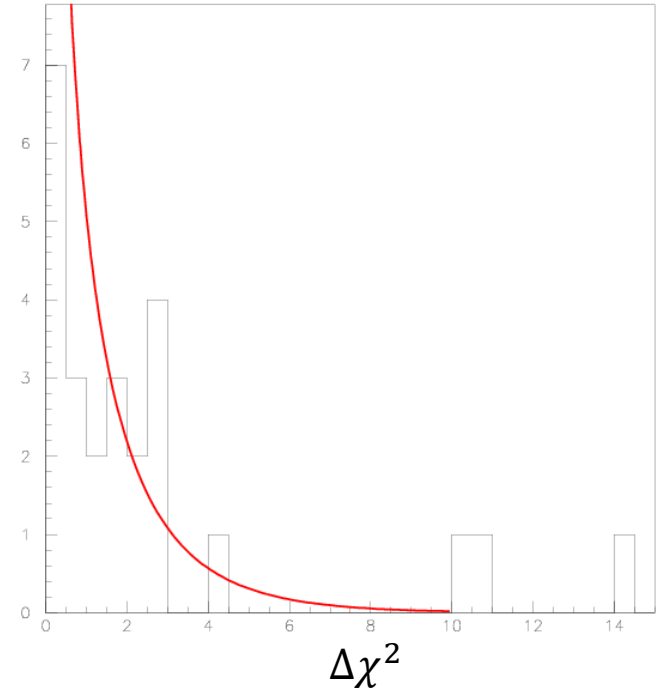
Investigation on the rate dependence

A template case: 3-4 keV, for each crystal, **last three published years** of DAMA/LIBRA-phase2 (0.61 ton×yr)

- For each detector the rates are fitted by MaxLik with case **A**: $b + S_m \cos$
- Then, with case **B**: $b - a \times \text{time} + S_m \cos$
- H_0 hypothesis: flat background \rightarrow case **A**
- Test variable: $\Delta\chi^2 = \chi_A^2 - \chi_B^2$ with dof=1



- Plot of $\Delta\chi^2$ for each detector
- It follows a χ^2 distribution with dof=1
- **No necessity to enable the slope with time.**

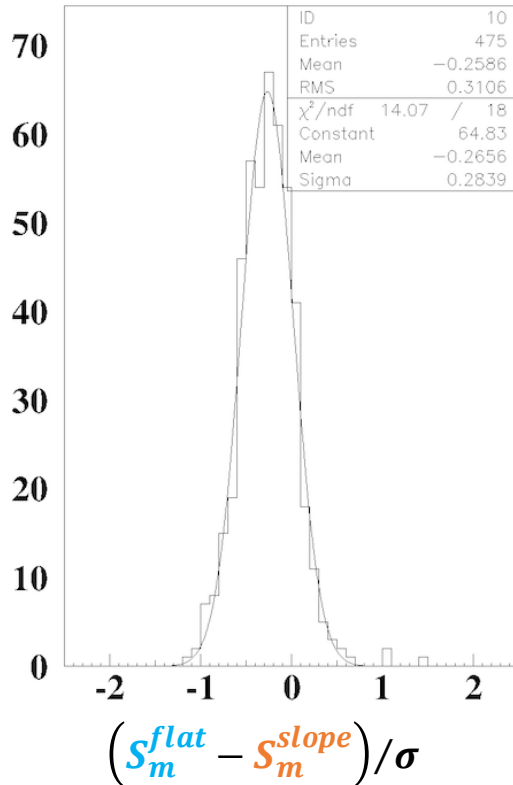


- Modulation amplitudes, S_m , in the two cases
- Case **A**: open points
- Case **B**: black points
- Mean shift between case **B** and **A** is $\simeq 0.26\sigma$

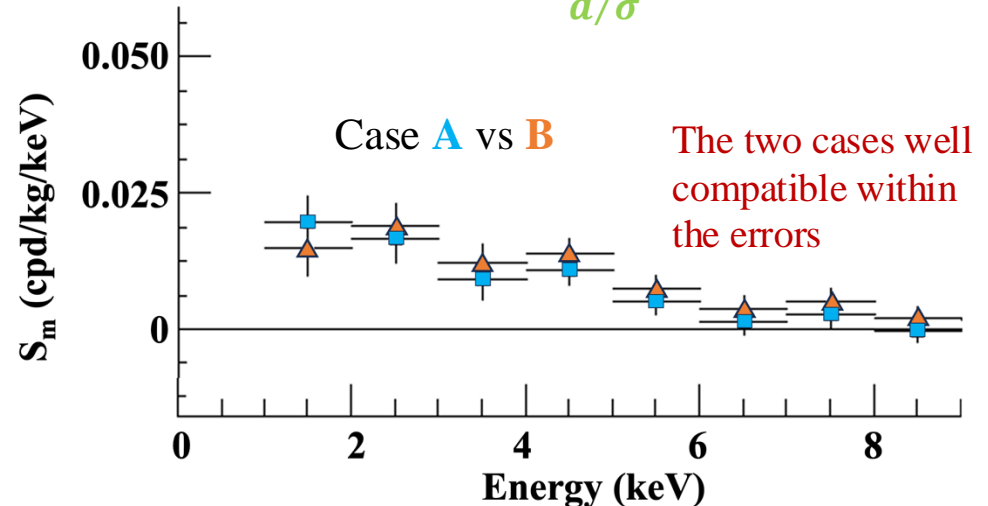
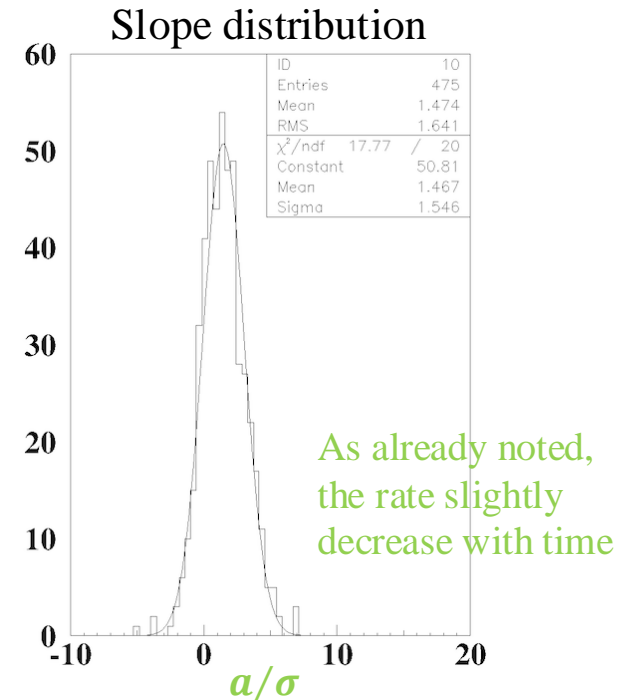
Investigation on the rate dependence

The general case: last three published years of DAMA/LIBRA-phase2

- For each detector the rates are fitted by MaxLik by case **A**: $b + S_m^{flat} \cos$
- and by case **B**: $b - a \times time + S_m^{slope} \cos$
- 475 entries = 25 detectors \times 19 energy bins



- The mean shift of the modulation amplitudes due to the introduction in the fit of a slope is $\approx 0.27\sigma$

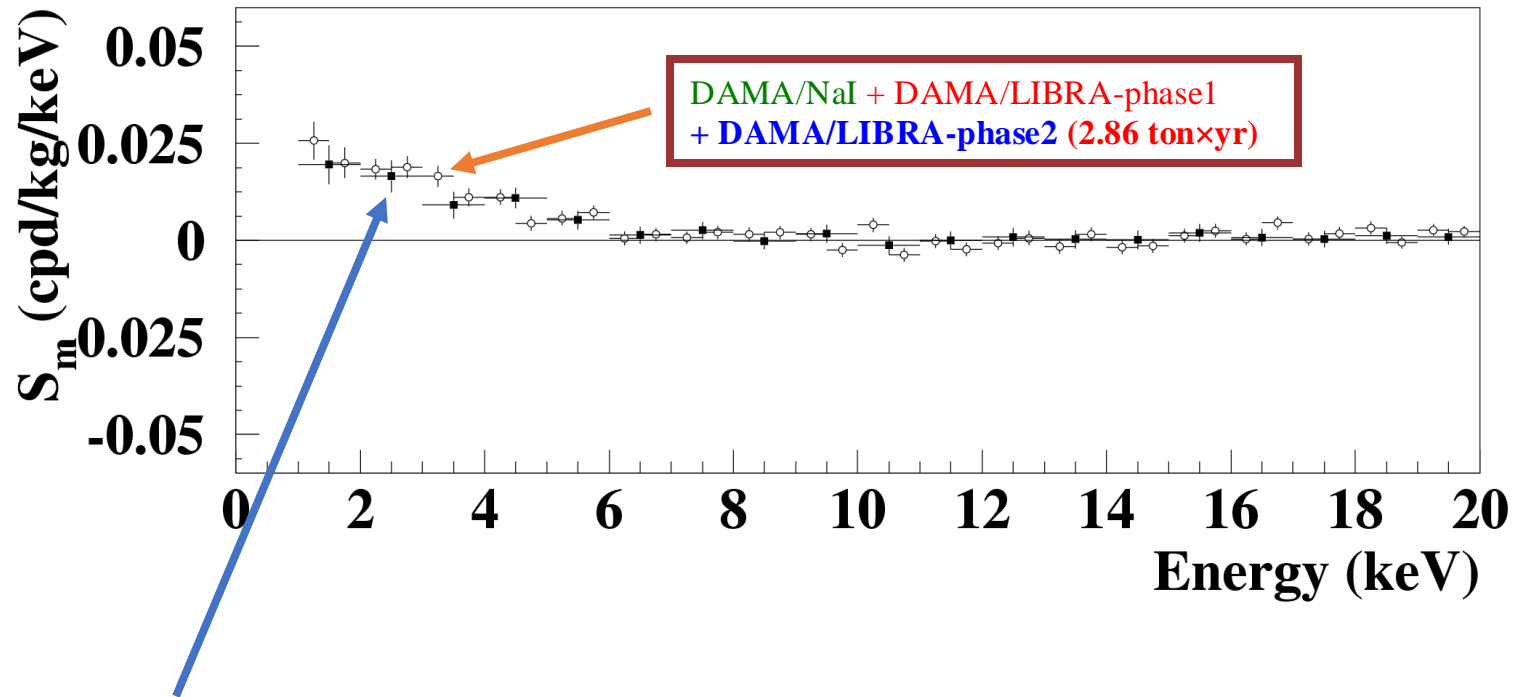


Energy distribution of the modulation amplitudes

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



Black squared data points: the **last three published years of DAMA/LIBRA-phase2 (0.61 ton×yr)**, with common (**constant**) background


$$\mu_{ijk} = b_{jk} + S_{0,k} + S_{m,k} \cos[\omega(t_i - t_0)]$$

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.	$<2.5 \times 10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield → huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1-2 \times 10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV <i>multiple-hits</i> events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured at LNGS	$<3 \times 10^{-5}$ cpd/kg/keV



+ they cannot satisfy all the requirements of annual modulation signature

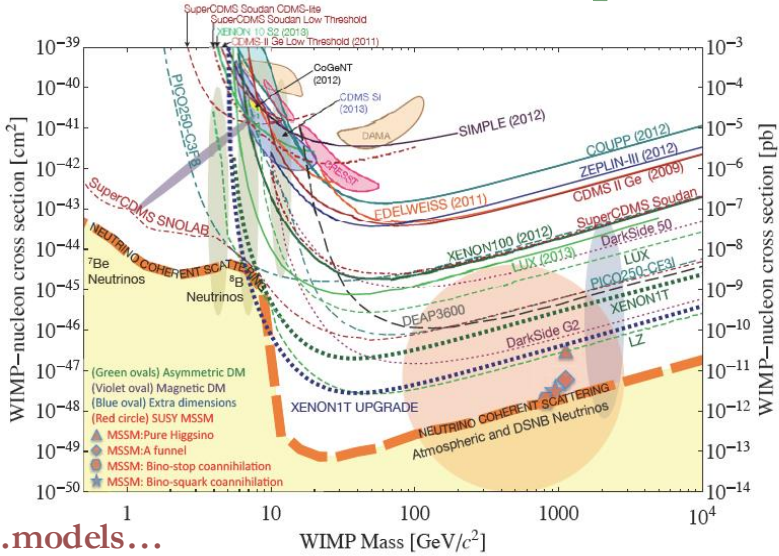


Thus, they cannot mimic the observed annual modulation effect

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, NPAAE20(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?
- ...

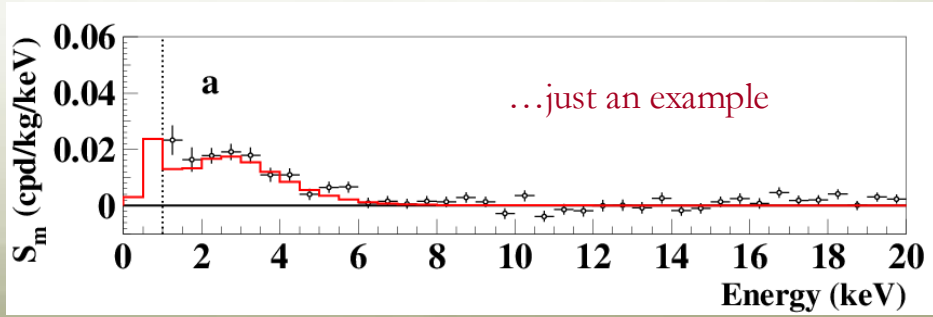
DAMA well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

...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 keV_{ee} of DAMA ≠ 2 keV_{ee} of COSINE-100 for nuclear recoils

No direct model-independent comparison is possible

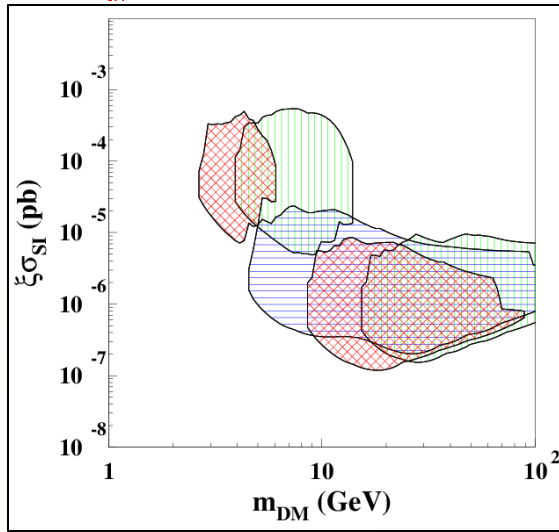


Examples of model-dependent analyses

NPAE 20(4) (2019) 317
PPNP114(2020)103810

A large (but not exhaustive) class of halo models and uncertainties are considered

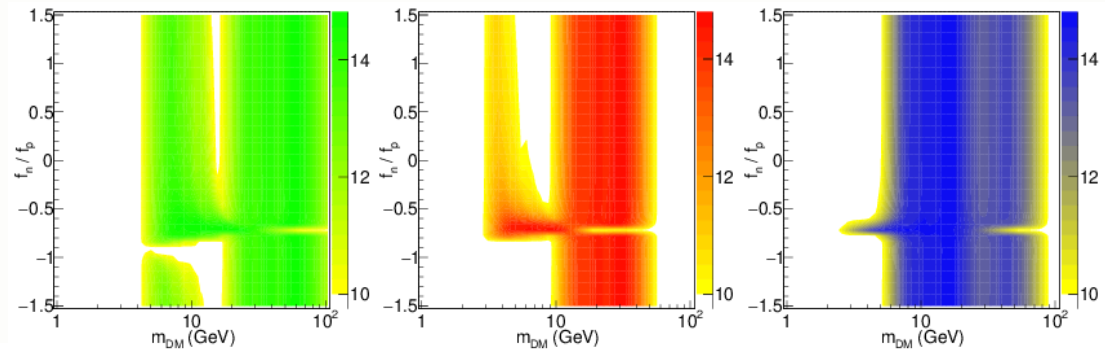
$E_{th}=1$ keV; old data release



DM particles elastically scattering off target nuclei – SI interaction

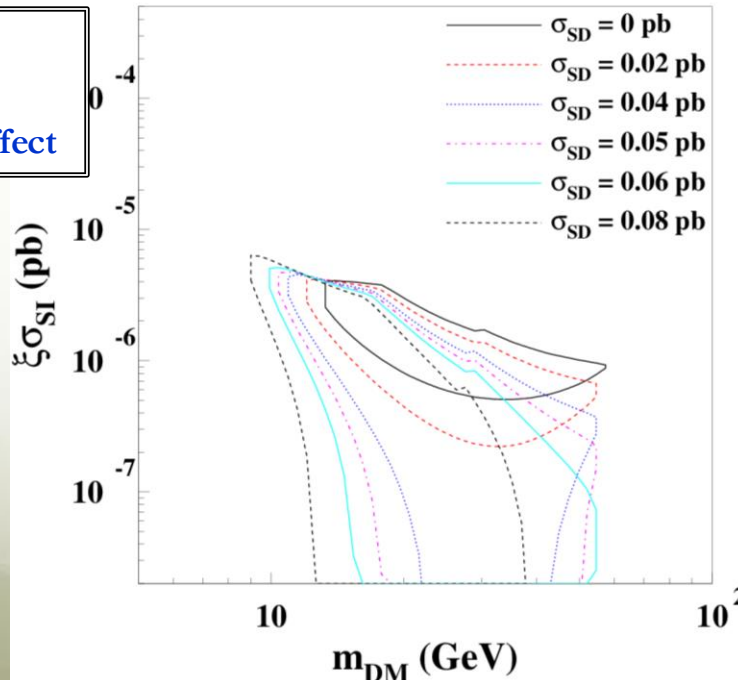
$$S_{SI}(A, Z) \propto m_{red}^2(A, DM) \left[f_p Z + f_n (A - Z) \right]^2$$

Case of isospin violating SI coupling: $f_p \neq f_n$



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

Even a relatively small SD (SI) contribution can drastically change the allowed region in the $(m_{DM}, \xi\sigma_{SI(SD)})$ plane



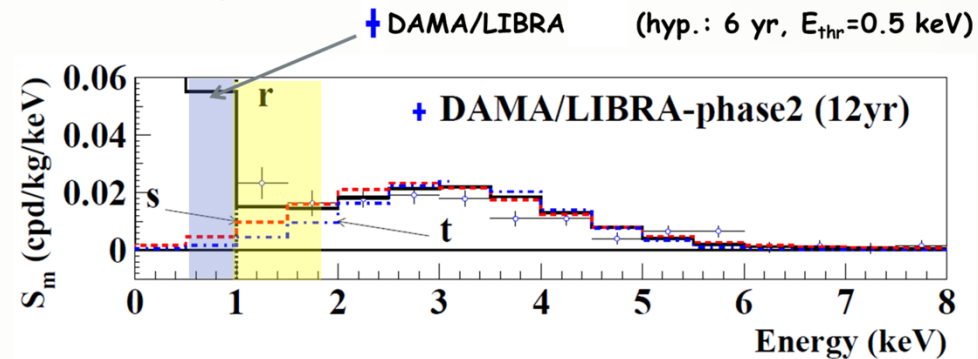
- Two bands at low mass and at higher mass;
- Good fit for low mass DM candidates at $f_n/f_p \approx -53/74 = -0.72$ (signal mostly due to ^{23}Na recoils).
- The inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support for $f_n/f_p=1$ 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.

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**

- 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 μ V**, ranging between 110 and 190 μ V
- 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



The features of the voltage divider+preamp system:

- S/N improvement $\approx 3.0-9.0$;
- 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

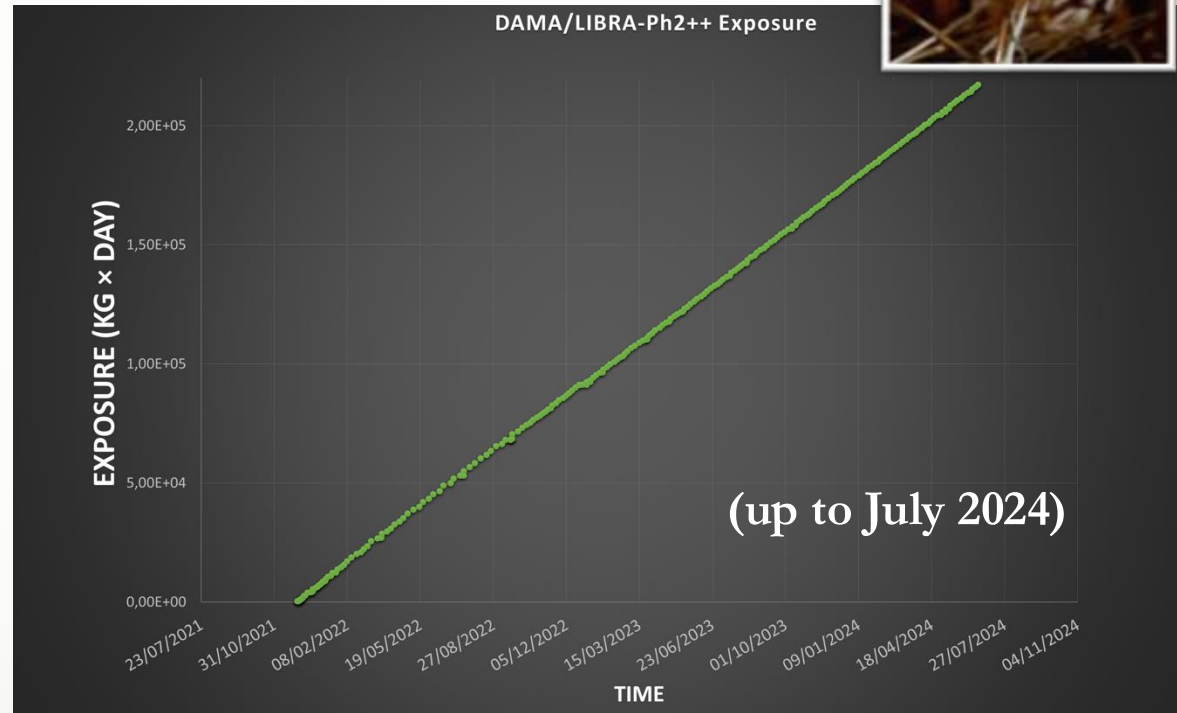


DAMA/LIBRA-phase2-empowered data taking

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



- ✓ Calibrations: $\approx 7.75 \times 10^7$ events from sources
- ✓ Acceptance window eff. per all crystals: $\approx 4.35 \times 10^7$ events ($\approx 1.74 \times 10^6$ events/keV)

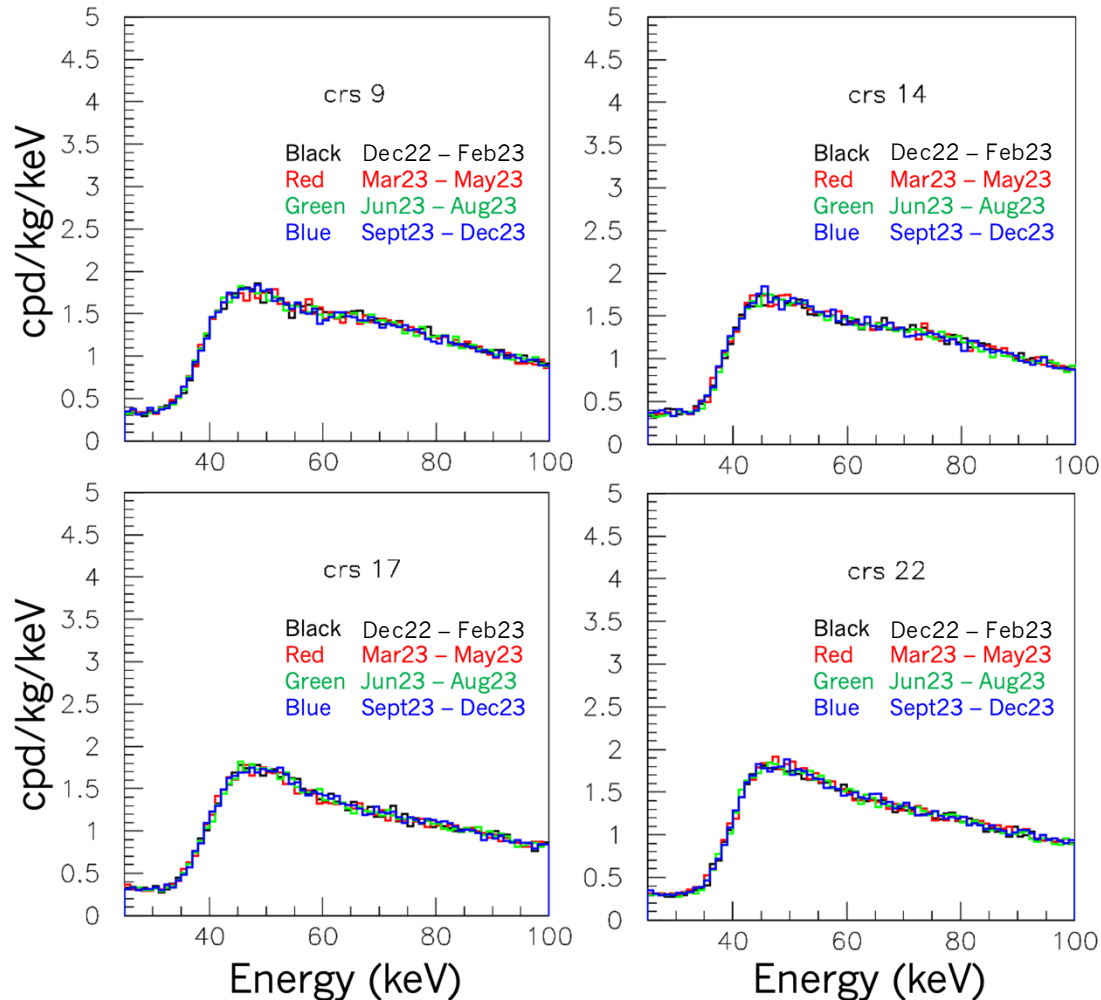


Exposure of DAMA/LIBRA-phase2-empowered up to July 24:

0.558 ton × yr $(\alpha - \beta^2) \approx 0.501$

Example: stability of the energy scale

- Monitor of the energy scale in the region of $^{210}\text{Pb} + ^{129}\text{I}$
- The data in the period dec2022-dec2023 are divided in four 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
- The counting rate is well stable

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

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 \times 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.

Several rare processes investigated, thanks to the low background features of all the DAMA set-ups

The experimental activities of **DAMA** will gradually cease in the late 2024/Spring-2025, according to the experiment's long-standing plans