MODEL-INDEPENDENT RESULTS FROM DAMA/LIBRA-PHASE2-EMPOWERED

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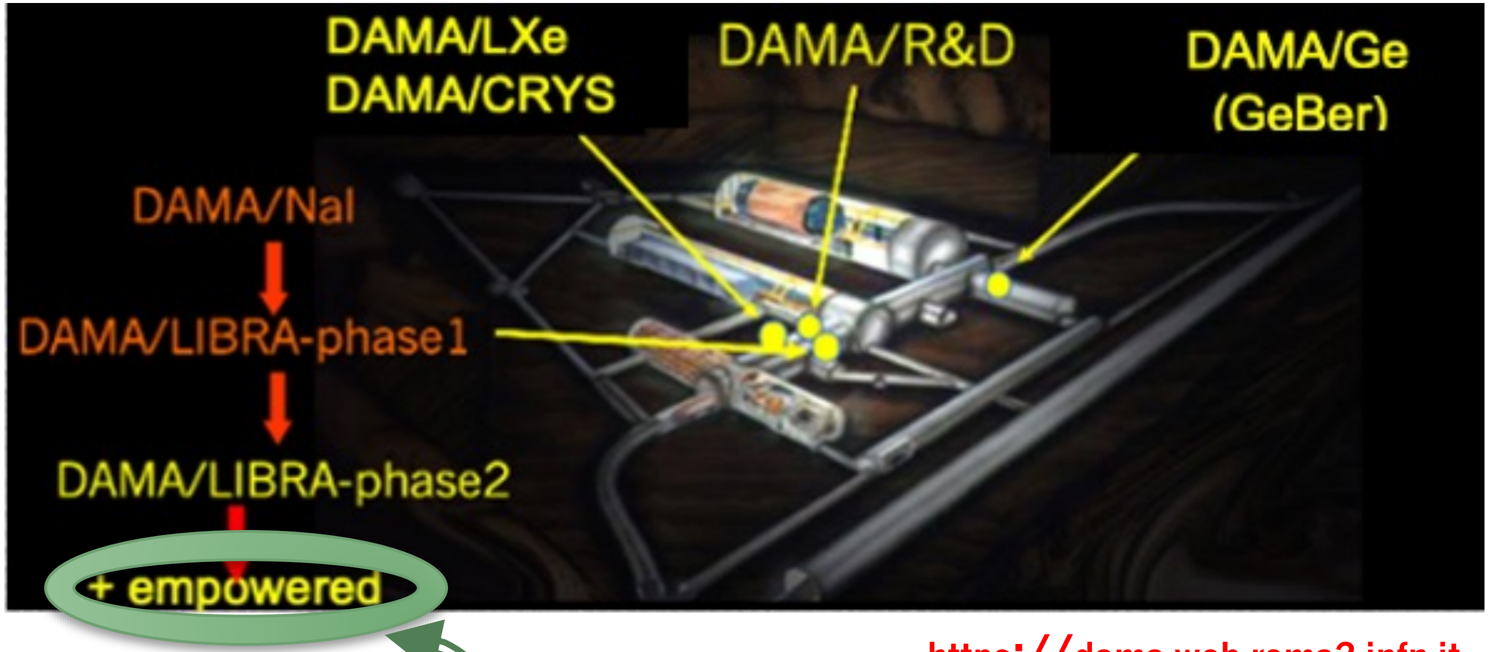
29[9h] Int. workshop ''What comes beyond the standard models'', virtual, July 6-16, 2026

Developing and using new and low background crystal scintillators & set-ups for rare events searches



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

- 1 experiment for many set-ups & measurements since the proposal to INFN in 1990
- End of running fall 2024
- Analyses and papers on various topics under completion

NUCL. PHYS. AT. ENERGY 27 (2026) 105-117

In numbers:

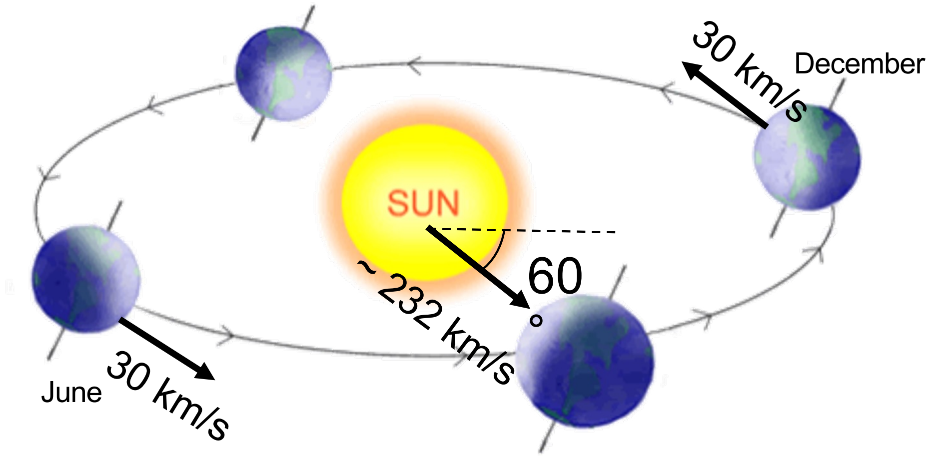
- 370 (49 in the last five years) publications on international reviews
- 450 (67 in the last five years) talks at conf. and seminars
- DAMA h-index=64
- Theses (various levels): about 30

A model independent signature for DM particles in the galactic halo

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

Presence of DM induces:

- cosine-like modulated rate
- in low energy range
- with a proper period (1 year)
- with proper phase (about 2 June)
- just for single hit events in a multi-detector set-up
- 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



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

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

- $v_{sun} \sim 232$ 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)

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

&

- **to point out the presence of DM particle in the galactic halo No uncertain hypothesized background model is necessary as in some other expts. The signature itself acts as an effective background rejection.**
- **No discrimination – always statistical - between electron and nuclear recoils applied → the experiment sensitive to DM candidates producing either electron or nuclear or both recoils.**
- **High and low mass taget nuclei, I (and Tl) and Na → sensitive to low and high mass DM, and to many scenarios**

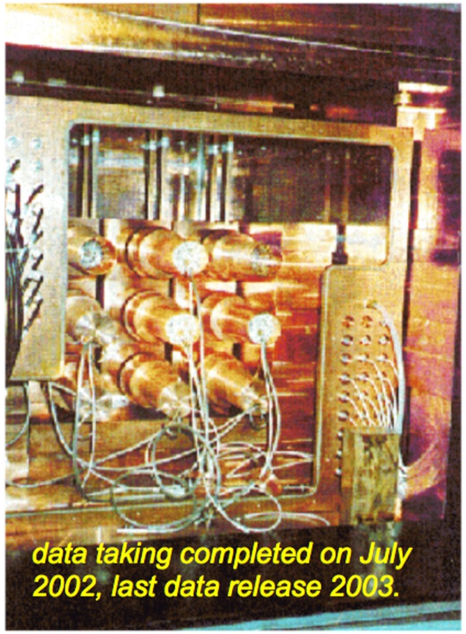
The pioneer DAMA/NaI: ≈100 kg highly radiopure NaI(Tl)

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 6.3σ C.L.

total exposure (7 annual cycles) 0.29 ton×yr

The pioneer DAMA/NaI:

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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.

The pioneer DAMA/NaI:

The DAMA/LIBRA set-up ~250 kg Na (Tl)
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As a result of a 2nd generation R&D for more radiopure NaI(Tl) by

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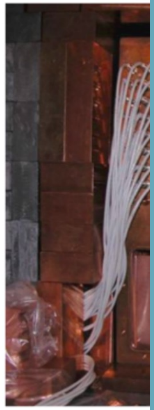
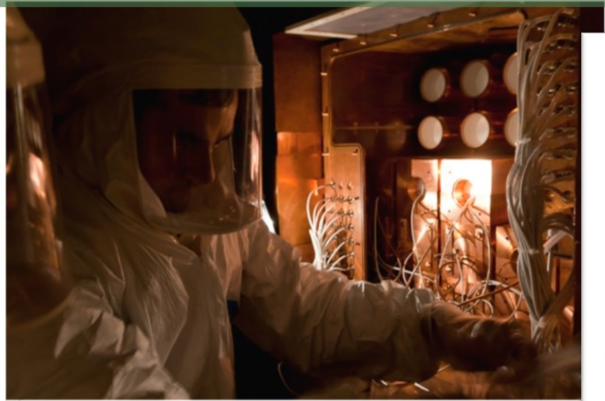
Residual
DAMA/LI
^{238}U and

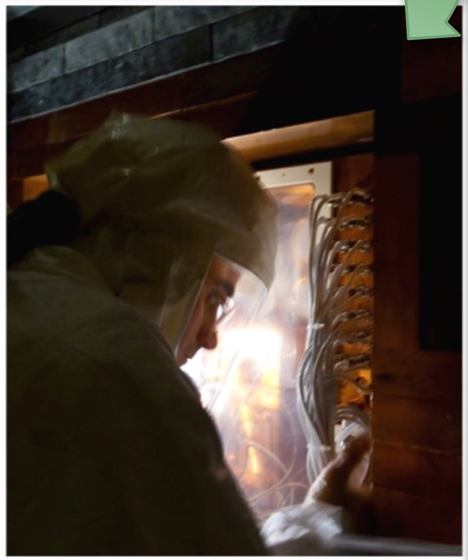


DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4)(2019)317
PPNP114(2020)103810

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

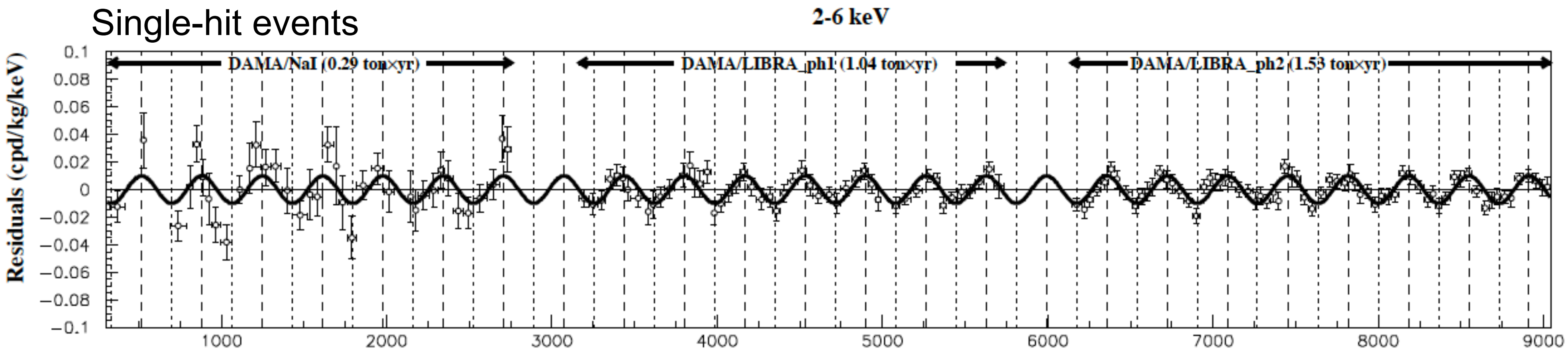




Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak


The pioneer DAMA/NaI:
The DAMA/LIBRA set-up ~250 kg Na (Tl)
(Large sodium Iodide Bulk for RAre pr cesse
As a result of a 2nd generation R&D for more radiopure NaI(Tl) by
DAMA/LIBRA–phase2
JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
NPAE 20(4)(2019)317
Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.
A new stage of the experiment:
DAMA/LIBRA-phase2- empowered with 0.5 keV
energy threshold from Dec 1, 2021 to 2024
NPAE 27 (2026) 105-117
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak

Synthetizing until beginning 2026



P(A=0) =2.3×10^{-12} total exposure = 2.86 ton × yr 13.4 σ C.L.

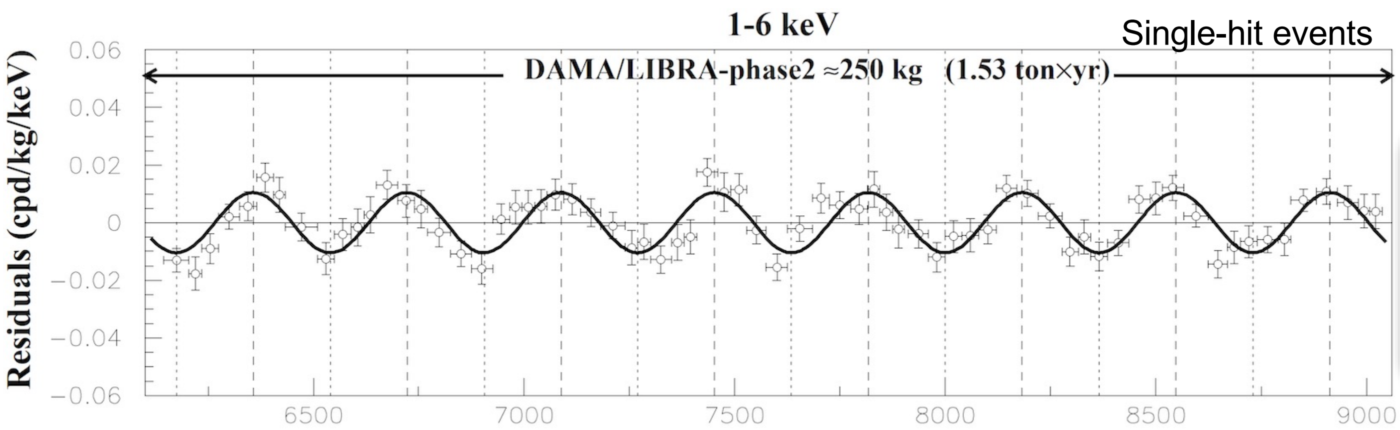
phase and period well compatible with expectations for DM

- Multiple different and independent analyses give completely consistent results
- All the many peculiarities of the DM annual modulation signature satisfied
- No competing systematics or reactions capable of mimicking the signature
- Result compatible with many different phenomenological scenarios

Further exposure and lower software thresholds increased with time the sensitivity and allowed a more precise determination of the parameters to investigate:

- The nature of Dark Matter particles
- Possible diurnal effects with sidereal time
- Astrophysical models

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.**

P(A=0) =10^{-14} total exposure = 1.53 ton × yr

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

After DAMA/LIBRA-phase1, the increasing sensitivity in the model-independent DM annual modulation signature pursued by lowering the software energy threshold

The sensitivity of the DM annual modulation signature depends – apart from the counting rate – on the product:

$\varepsilon \times \Delta E \times M \times T \times (\alpha\text{-}\beta^2)$

increased in DAMA/LIBRA-phase2

increased in DAMA/LIBRA-phase2

increased with DAMA/LIBRA-phase2

→ equivalent to have enlarged the exposed mass

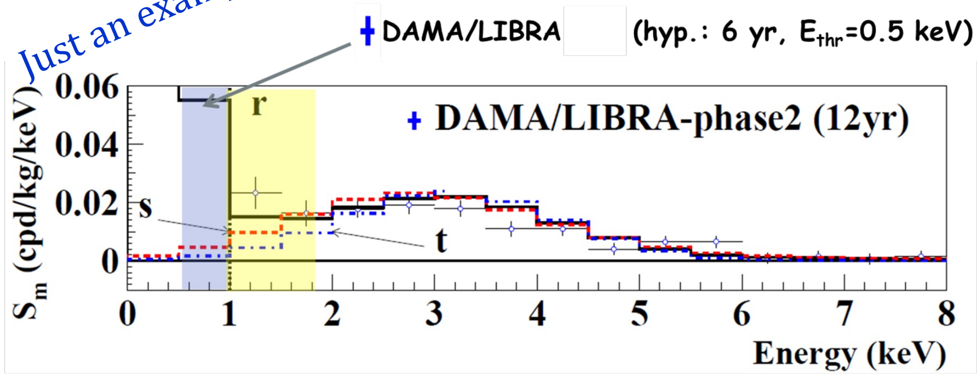
Further improvement: DAMA/LIBRA-phase2-empowered

&: this signature acts itself as a strong bckg reduction strategy as pointed out in the original paper by Freese et al.

&: 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

.... improvement in model-dependent corollary analyses

Just an example

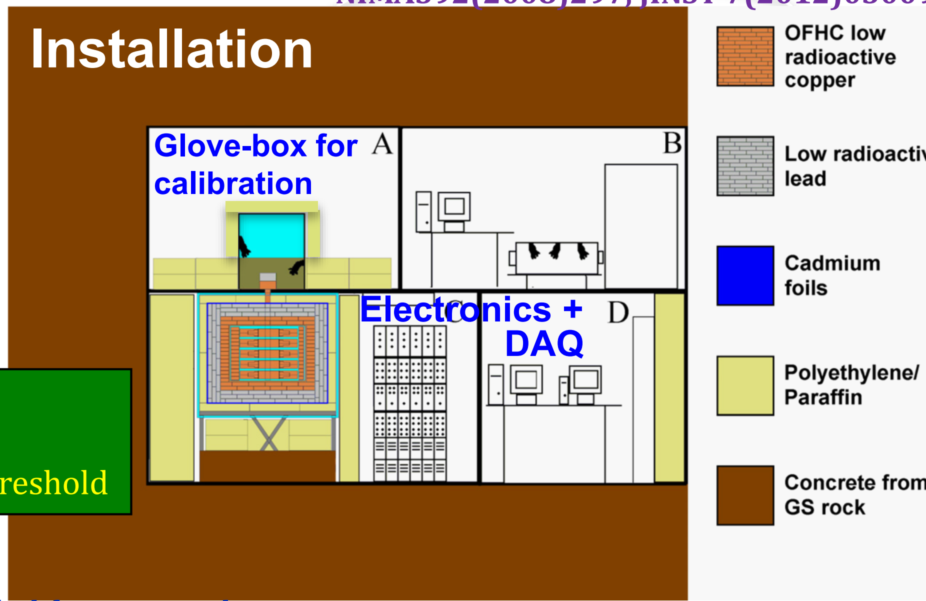


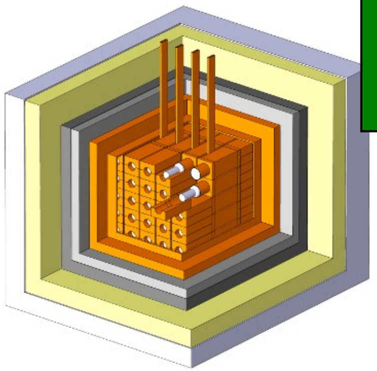
- the nature of the DM candidates
- possible diurnal effects on sidereal time
- astrophysical models
- ....

FROM DAMA/LIBRA-phase2 set-up ...

For details, radiopurity, performances, procedures, etc.
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 working in coincidence at the single ph. el. threshold





Typical :
6-10 phe/keV;
1 keV software energy threshold

- Whole setup decoupled from ground
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- Dismounting/Installing protocol in HPN_2
- All the materials selected for low radioactivity
- Multiton-multicomponent passive shield (>10 cm of OFHC Cu, 15 cm of boliden Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)

- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Never neutron source in DAMA installations
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waweform Analyzer Acqiris DC270 (2chs per detector), 1 *Gsample/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 was done for the low energy
- DAQ with optical readout & some new electronic modules

… to DAMA/LIBRA-phase2-empowered

→ software energy threshold of **0.5 keV** with suitable high efficiency

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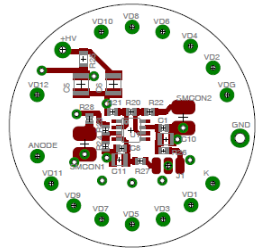
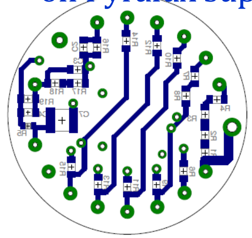
Enhancing experimental sensitivities and improving DM corollary aspects, other DM features, 2nd order effects

During fall 2021, DAMA/LIBRA–phase2 set-up was heavily upgraded to -empowered:

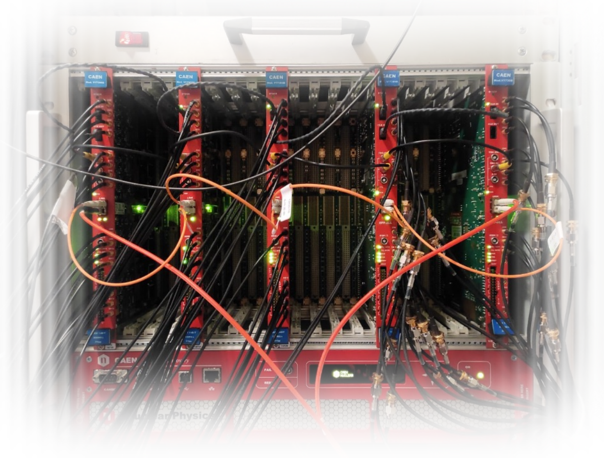
- new low-background voltage dividers with pre-amps on the same board



Voltage divider + preamp on Pyralux support



- Transient Digitizers with higher vertical resolution (14 bits)



DAQ is composed by 5 TD's, CAEN VME VX1730, dynamic range of 14 bit (that is vertical resolution of 0.122 mV/digit), vertical window of 2 V, sampling frequency of 500 MSa/s, 16 chs. It acquires three traces for each detector (the two PMTs and the high-energy sum). The read-out is made by a daisy-chain of optical fibers directly connected to the DAQ pc

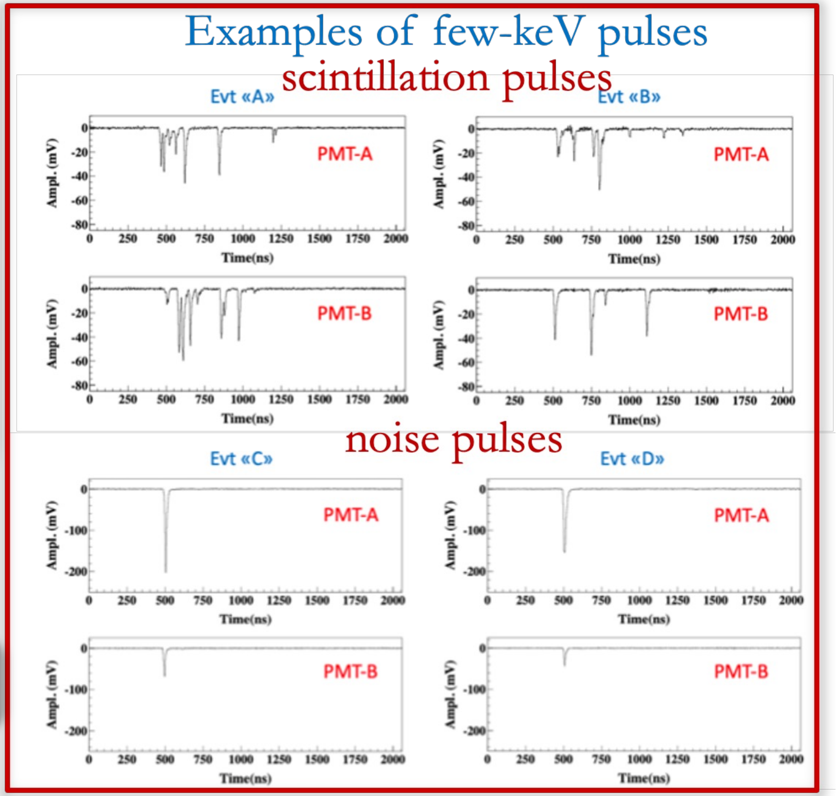
Higher resolution of TDs makes appreciable the improvements coming from the new voltage-dividers-plus-preamps on the same board:

- 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

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

Data taking in this new configuration started on Dec, 1 2021

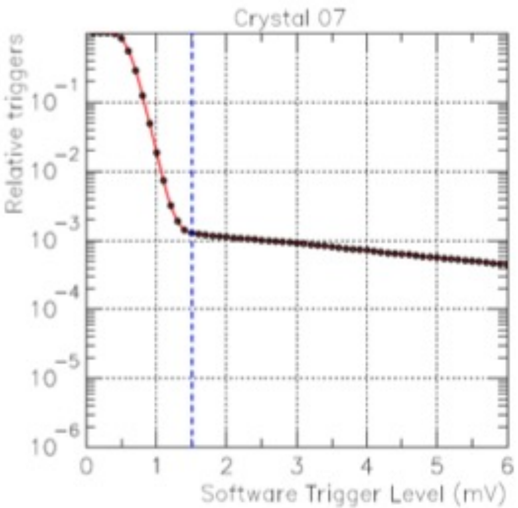


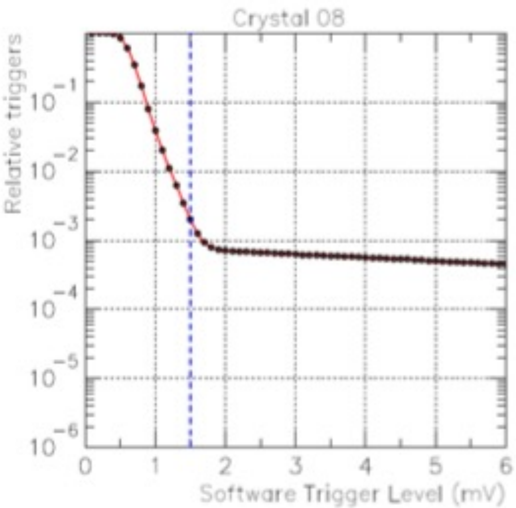
Software Trigger Level (STL)

The new configuration allows a significantly lower STL in the offline waveforms analysis, giving :

- improvement of the effectiveness of the software trigger algorithm that determines the start time of the pulses also below 1 keV;
- very good evaluation of the energy of events near energy threshold;
- improved capability to discriminate the single p.e. in each channel;
- improved efficiency of the acceptance windows used to reject noise events (single p.e.)

→ It allows us to set STL values factor 3-4 lower than in the previous data taking.





- Fraction of events recognized in a run of pure baselines (null traces)
- STL values lower than 1.5 mV produce a higher rate of fake events
- Above 1.5 mV a fraction of events less than 10^{-3} is identified: they are single p.e. randomly present within the acquiring time window. However, these events are rejected by the standard analysis

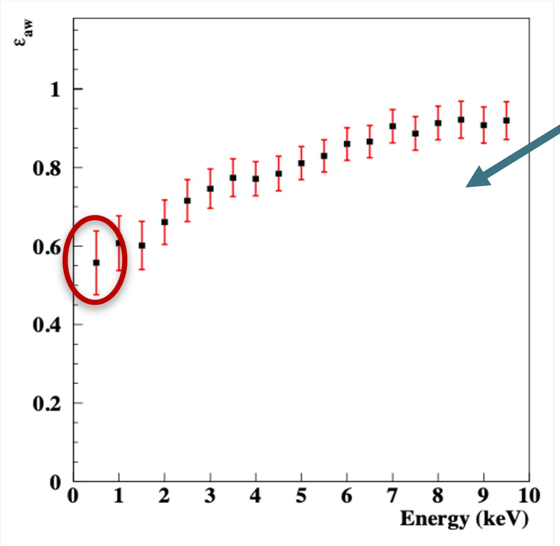
STLs determined by the analysis of the collected waveforms

	STL	
	to determine t_0	to determine the other parameters
A, B	1.5 mV	5.0 mV
SUM	2.2 mV	2.2 mV
SUM-HE	1.0 mV	1.0 mV

- With these values of STL the starting point (t_0) of each pulse can be safely determined.
- For the determination of the other parameters (*frac1*, *frac3*, *area*, *tm600*, etc.) larger STL is used for A,B. This choice allows a better discrimination of the single p.e. in the $tm600_A$ e $tm600_B$
- In fact, $tm600_A$, $tm600_B$> 25 ns is equivalent to the condition where only events with at least two p.e. (#p.e.>1) in each of the two PMTs of a detector are accepted.

The energy threshold is 0.5 keV with suitable efficiency

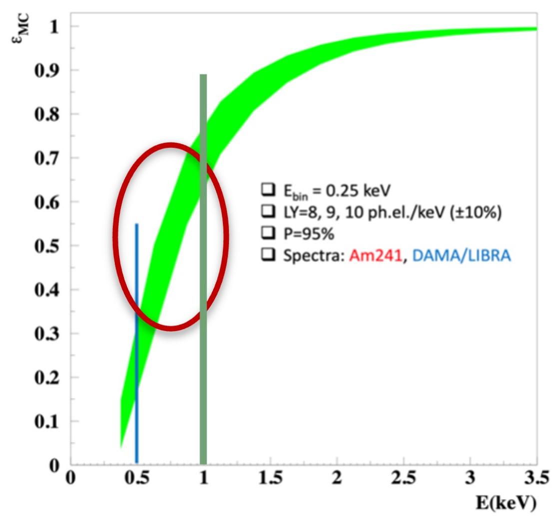
- ❑ The adopted procedure and the acceptance windows are the same, unchanged along all the DAMA/LIBRA-phase2 and DAMA/LIBRA-phase2-empowered, throughout the months and the annual cycles (see e.g. JINST 7 (2012) P03009)



- Typical behaviour of the measured ε_{aw} efficiencies for the used acceptance windows
- Measured by applying the same acceptance windows to events by ^{241}Am source in the same experimental conditions and energy range 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.

→ suitable efficiency below 1 keV is possible in the new configuration.

- ❑ Below 1 keV, to take into account the overall detection efficiency, an additional efficiency for the hardware trigger and for the new requirement below was evaluated by MC. The hardware trigger of a detector is produced by the electronic chain when a signal above the single p.e. level, i.e. the hardware energy threshold, is detected in both the PMTs within a coincidence window of 100 ns.



- (#p.e.$_A$>1) .AND. (#p.e.$_B$>1)
- #p.e.$_{A,B}$>1 → tm600$_{A,B}$> ~25 ns
- This condition allows the removal of a large part of the noise events near energy threshold
- Calculated efficiency ε_{MC}. The band considers light yields 9 p.e./keV (±10%)
- The spread of the band is used to evaluate the uncertainty of the ε_{MC}

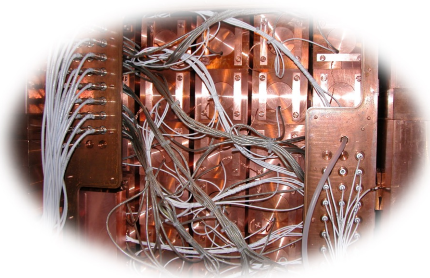
Data taking with DAMA/LIBRA-phase2-empowered

≃ 3 annual cycles:

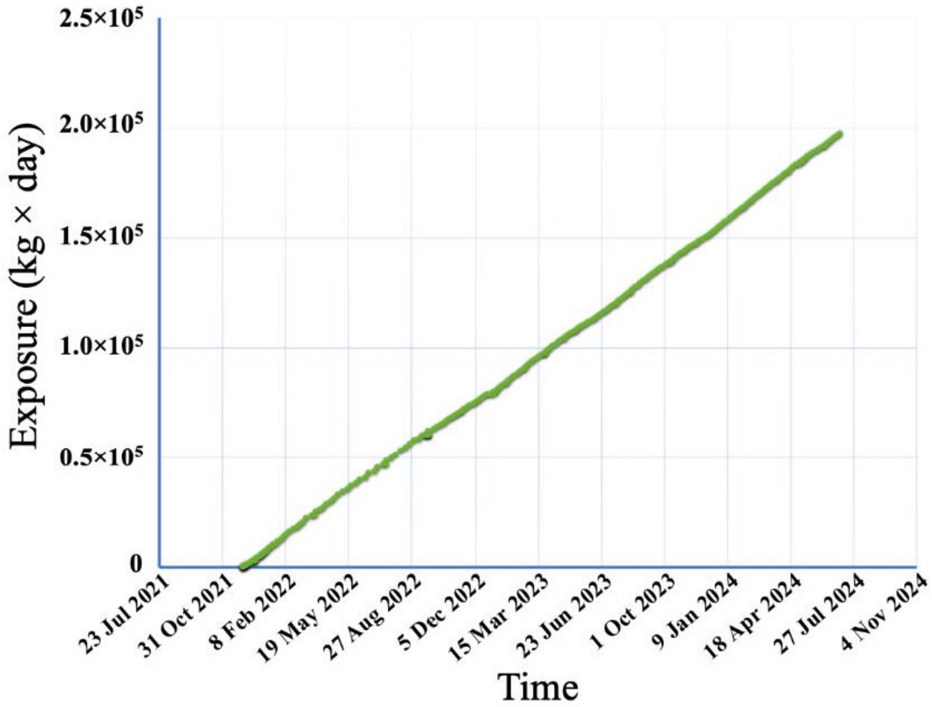
DL2-empowered annual cycles	Period	Exposure, kg·day	$(\alpha-\beta^2)$
1	Dec. 2, 2021 – Oct. 5, 2022	63294	0.410
2	Oct. 6, 2022 – Sept. 5, 2023	68139	0.500
3	Sept. 6, 2023 – July 9, 2024	66064	0.531
DL2-empowered	Dec. 2, 2021 – July 9, 2024	197497 = 0.541 t·yr	0.482
DL2 + DL2-empowered:		2.07 t·yr	
DAMA/NaI + DL1 + DL2 + DL2-empowered:		3.40 t·yr	

For simplicity, DL1, and DL2 indicate DAMA/LIBRA-phase1, and DAMA/LIBRA-phase2, respectively.

Total exposure: 0.541 t·yr for DAMA/LIBRA-phase2-empowered and variance of the cosine, $(\alpha-\beta^2) \simeq 0.5$ → detectors were operational evenly throughout the year. Duty cycle 85–90 %, mainly affected by routine calibrations and data collection for the acceptance windows efficiency near the software energy threshold.

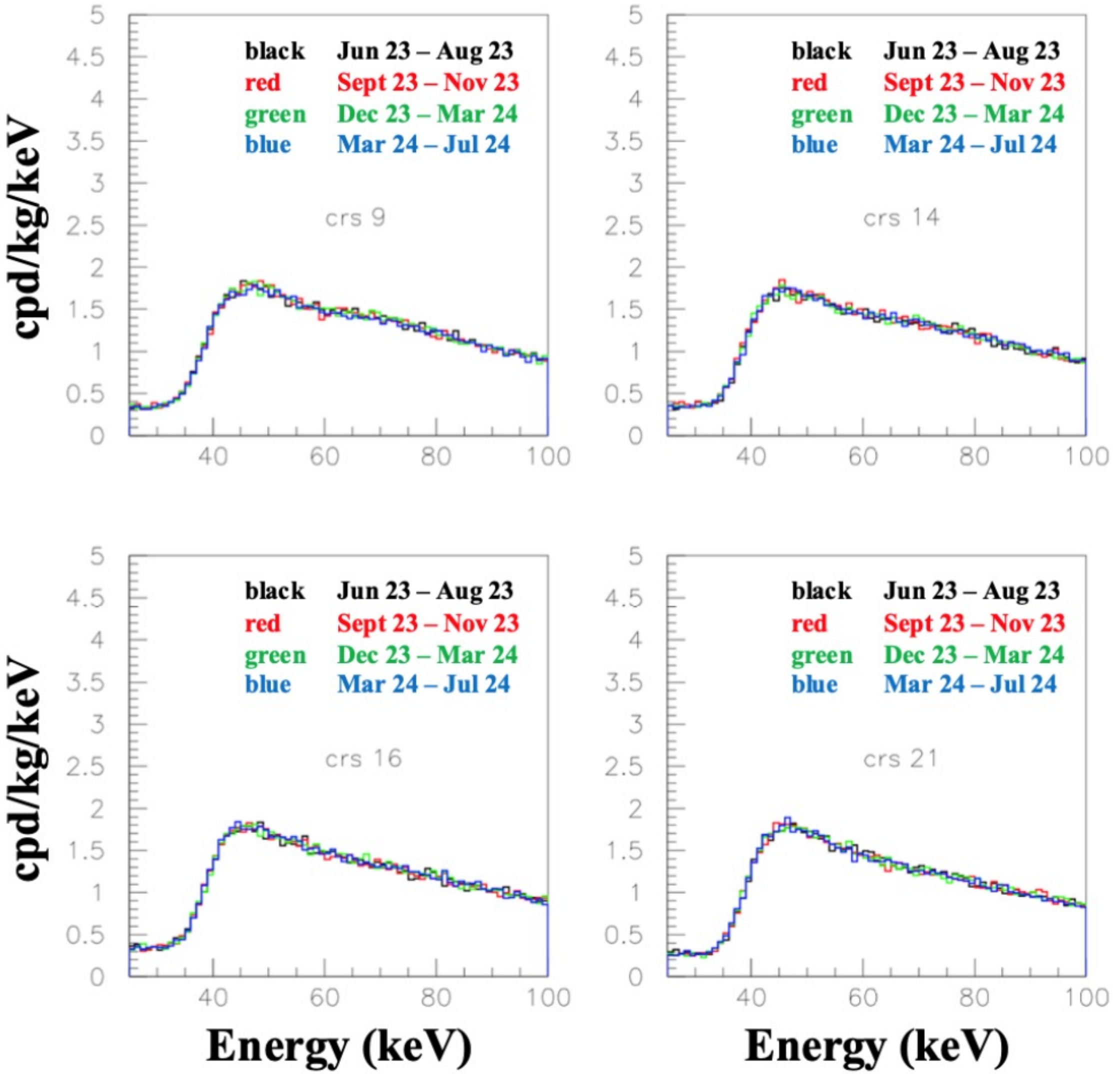


data-taking continuous without long interruptions, apart from the periods dedicated to routine calibrations, performed exactly under the same conditions as the production runs



- Total number of events collected for energy calibrations in DAMA/LIBRA-phase2-empowered $\simeq 7.8 \cdot 10^7$
- $\simeq 6.9 \cdot 10^4$ events/keV were collected for each crystal to evaluate the acceptance window efficiency for noise rejection near software energy threshold.

The operational features of the upgraded system have proven to be very stable.



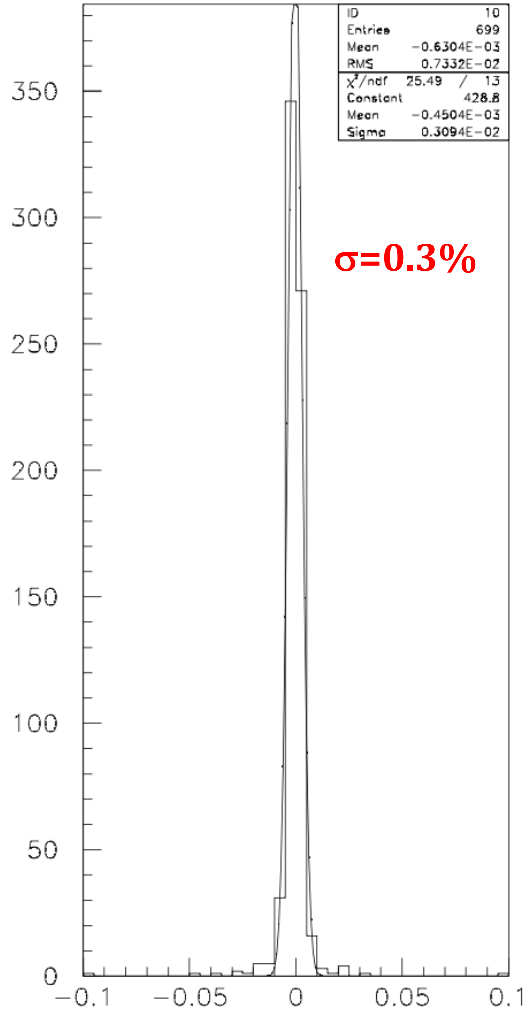
Examples of stability of the counting rate and energy scale of four detectors in the energy region where the ^{210}Pb and the ^{129}I contaminations are dominant.

Data collected in the last annual cycle are grouped in four-time intervals.

Example of stability of the energy scale

- Distribution of the percentage variations (ε_{tdcal}) of each energy scale factor ($tdcal_k$) with respect to the value measured in the previous calibration ($tdcal_{k-1}$)
- From Dec 1, 2021 to Feb 23, 2023
- Gaussian behaviour

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



Low-Energy calibration factors (ε_{tdcal})

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

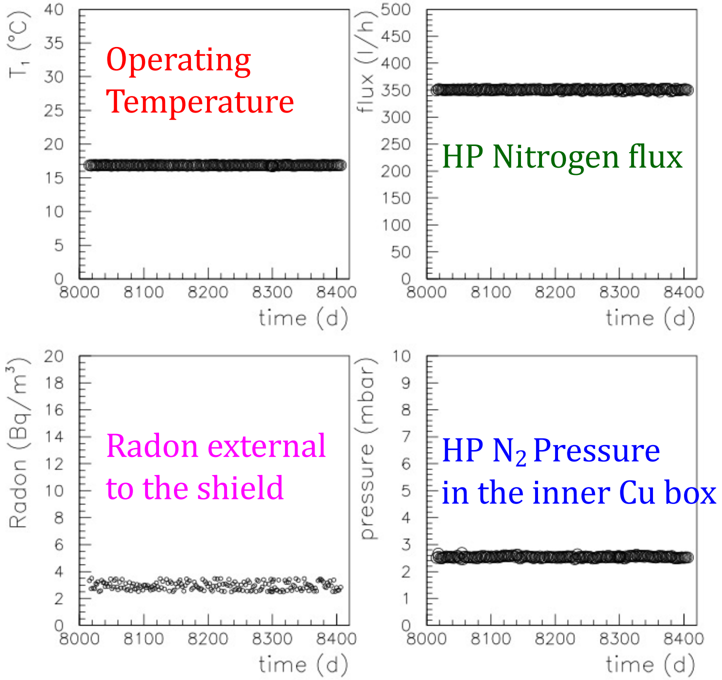
$$\sigma = \sqrt{\sigma_{res}^2 + \sigma_{cal}^2} \approx \sigma_{res} \cdot \left[1 + \frac{1}{2}\left(\frac{\sigma_{cal}}{\sigma_{res}}\right)^2 \right]; \frac{1}{2}\left(\frac{\sigma_{cal}/E}{\sigma_{res}/E}\right)^2 \le 7.5 \cdot 10^{-4} \frac{E}{20keV}$$

Negligible effect considering routine calibrations and energy resolution at **low energy**

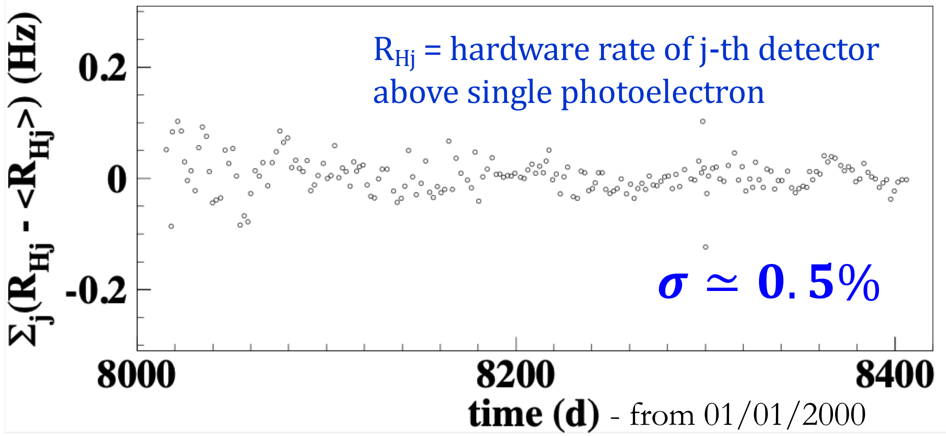
Confirmation from MC: maximum relative contribution to annual modulation amplitude $< 1 - 2 \times 10^{-4}$ cpd/kg/keV

No modulation in the energy scale
+ cannot mimic the signature

Example of Stability Parameters



Period: Dec 10, 2021 – Gen 7, 2023

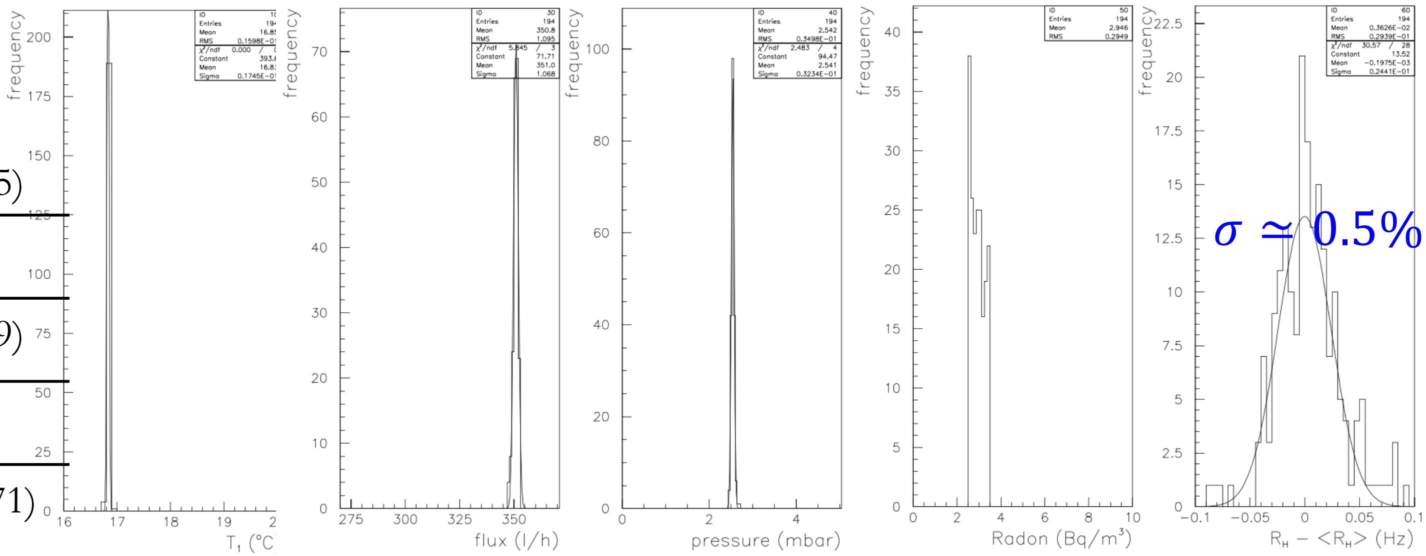


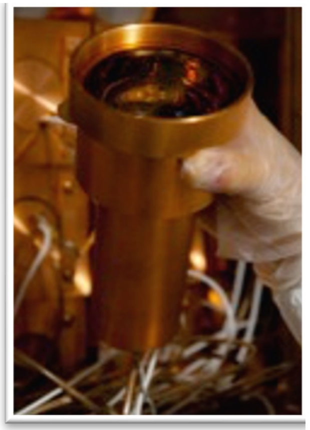
Running conditions stable at level < 1%

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

Temperature (°C)	(0.0003±0.0025)
Flux N_2 (l/h)	-(0.01±0.11)
Pressure (mbar)	(0.0002±0.0029)
Radon (Bq/m^3)	(0.003±0.029)
Hardware rate above single ph.e. (Hz)	-(0.0050±0.0071)

Parameters distributions





DM model-independent Annual Modulation Result in DAMA/LIBRA-phase2-empowered

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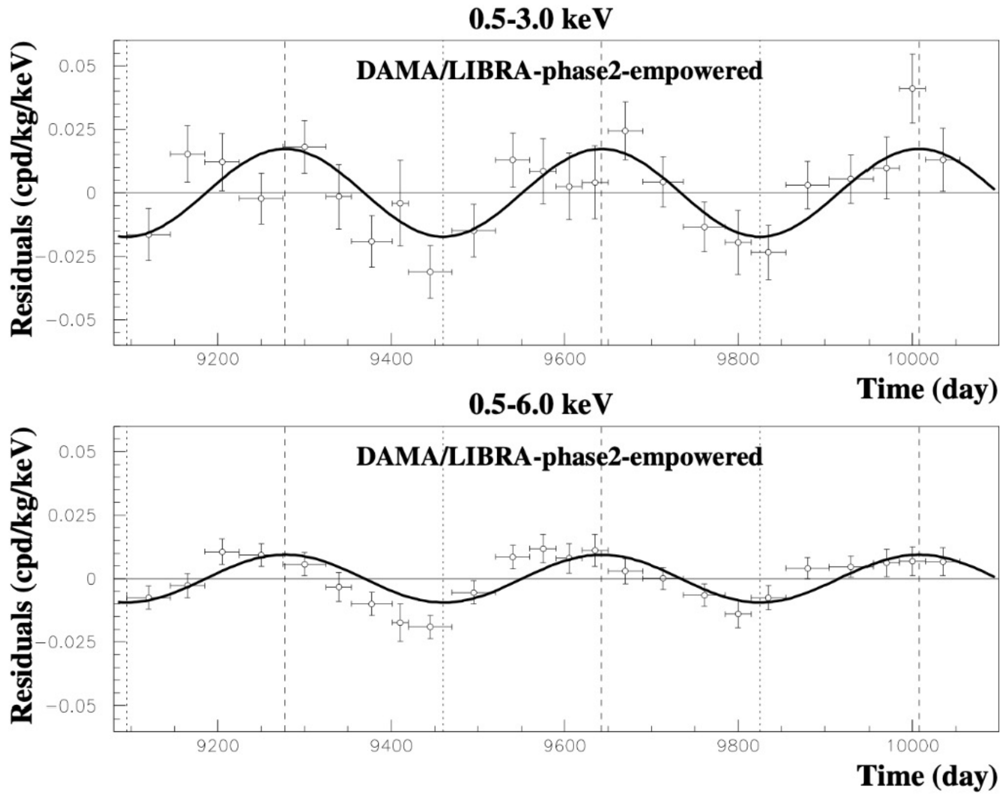
exposure: 0.541 t·yr

$P(A=0) = 1.2\cdot10^{-3}$ and $5.5\cdot10^{-7}$

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



Superimposed curves are the cosinusoidal functional: $A \cos \omega(t - t0)$ with a period $T = 2\pi/\omega = 1$ yr, a phase $t_0 = 152.5$ days (June 2), and amplitude, A.

Dashed vertical lines correspond to the maximum expected for the DM signal (June 2), while dotted vertical lines correspond to the expected minimum.

Experimental residual rate of the *single-hit* scintillation events in DAMA/LIBRA-phase2 and DAMA/LIBRA-phase2-empowered

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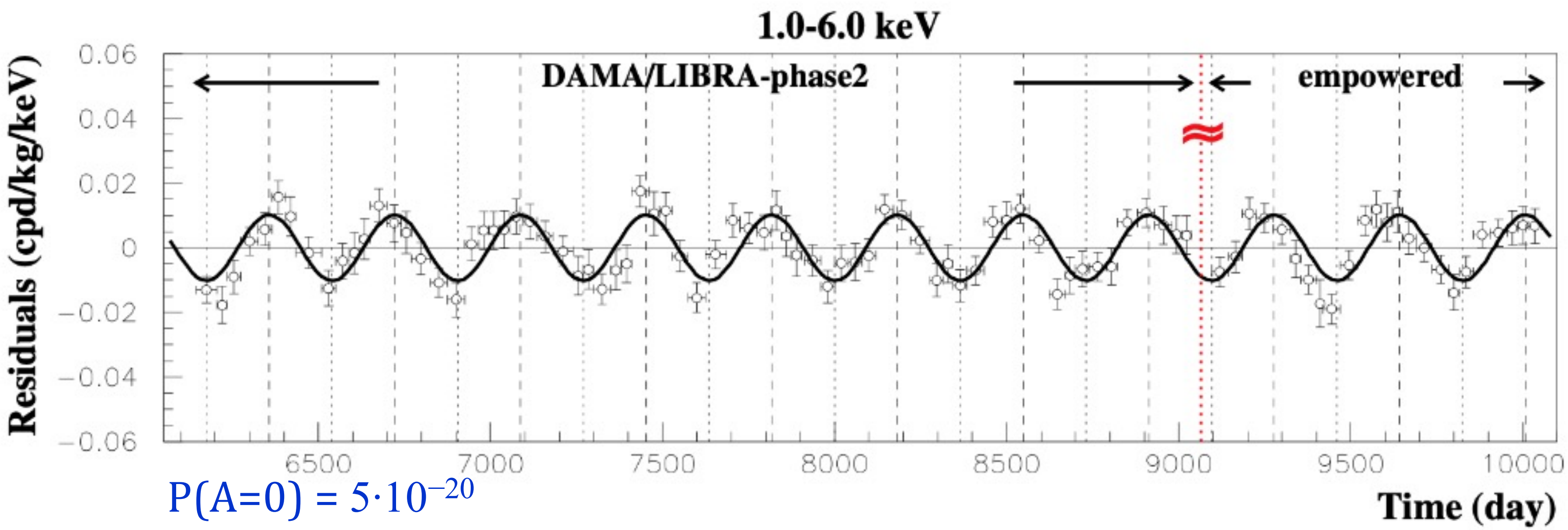

$P(A=0) = 5 \cdot 10^{-20}$

Superimposed curve = cosinusoidal functional form $A \cos \omega (t - t_0)$ with a period $T = 2\pi/\omega$, a phase t_0 = 152.5 days (June 2) and the modulation amplitude, A, reported in in next Table.

The interruption between the two experimental configurations is highlighted by the vertical dotted red line with proper symbol

Modulation amplitudes from fits of the *single-hit* residual rate

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The goodness of the fits is well supported by the χ^2 tests. The results of DAMA/LIBRA-phase2-empowered (there DL2-empowered) are well compatible with expectations for the DM annual modulation signal.

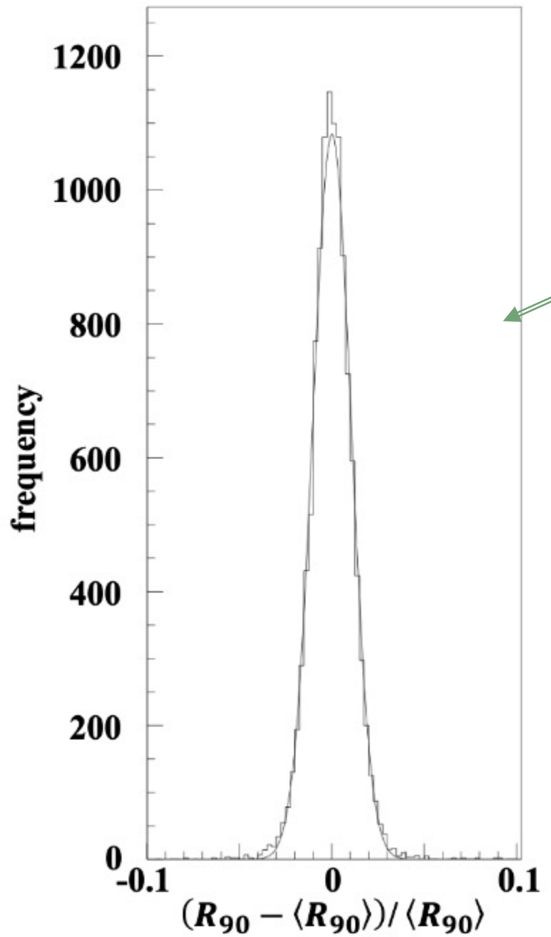
Energy intervals, keV	A, cpd/kg/keV	$T = \frac{2\pi}{\omega}$, yr	t_0, days	C.L.	χ^2 / d.o.f
DL2-empowered:					
0.5–3	0.0173 ± 0.0033	1	152.5	5.2 σ	23.2/23
0.5–6	0.0094 ± 0.0015	1	152.5	6.3 σ	31.9/23
0.5–3	0.0187 ± 0.0033	0.998 ± 0.003	148 ± 30	5.7 σ	19.3/21
0.5–6	0.0116 ± 0.0015	0.996 ± 0.003	155 ± 20	7.7 σ	12.4/21
DL2 + DL2-empowered:					
1–6	0.01018 ± 0.00076	1	152.5	13.4 σ	98.4/92
1–6	0.01069 ± 0.00077	0.998 ± 0.001	154.1 ± 4.1	13.9 σ	81.0/90
DAMA/NaI + DL1 + DL2 + DL2-empowered:					
2–6	0.00976 ± 0.00066	1	152.5	14.8 σ	162.9/179
2–6	0.01028 ± 0.00067	0.99748 ± 0.00053	153.5 ± 3.8	15.3 σ	141.1/177

Fits where period and phase are left free are reported, as well as those when including the earlier data of DAMA/NaI, DAMA/LIBRA-phase1 (DL1), and DAMA/LIBRA-phase2 (DL2)

No modulation in the background

- Background in the lowest energy region is essentially due to "Compton" electrons, X-rays and/or Auger electrons, muon induced events, etc., strictly correlated with events in the higher energy region → if a modulation detected in the lowest energy region were due to a modulation of the background (rather than to signal), an equal or larger modulation in the higher energy regions should be present.

Absence of any significant background modulation for energy regions not of interest for DM verified by analyzing the measured rate integrated above 90 keV, R_{90}, as a function of time



Distribution of the percentage variations of R_{90} with respect to the mean values for all the detectors in DAMA/LIBRA-phase2-empowered

Cumulative behavior is Gaussian with $\sigma \simeq 1$ %, well accounted for by the statistical spread provided by the sampling time used.

DAMA/LIBRA-phase2-empowered annual cycle	A_{R90}, cpd/kg
1	(0.15 ± 0.14)
2	$-(0.15 \pm 0.12)$
3	(0.01 ± 0.12)
1 – 3	$-(0.011 \pm 0.073)$

When fitting the time behavior of R_{90}, including a term with phase and period as for DM particles → modulation amplitude, A_{R90}, compatible with zero for all the annual cycles

This also excludes presence of any background modulation in the whole energy spectrum at a level much lower than the effect measured in the lowest energy region for the *single-hit* scintillation events → otherwise, considering the R_{90} mean values, a modulation amplitude of the order of tens cpd/kg would be present for each annual cycle, that is $\simeq 100\ \sigma$ far away from the measured values.

- Analyses performed in other energy regions above 6 keV give similar results.
- *multiple-hit* sample does not show any annual modulation in the low-energy intervals as in previous data release.

Finally, no background process able to mimic the DM annual modulation signature (ie. able to simultaneously satisfy all the peculiarities of the signature and to account for the measured modulation amplitude) has been found or suggested by anyone throughout some decades thus far

Maximum likelihood modulation amplitudes

Annual modulation present at low energy can be pointed out by depicting the energy dependence of the modulation amplitude, $S_m(E)$, obtained by the maximum likelihood method, considering a fixed period and phase: T = 1 yr and t_0 = 152.5 days, respectively.

For this purpose, the likelihood function of the *single-hit* experimental data can be constructed considering that the number of events collected in the *i*-th time interval (hereafter 1 day), by the *j*-th detector and in the *k*-th energy bin follows a Poisson's distribution with expectation value:

$$\mu_{ijk} = \left[b_{jk} + S_{ik} \right] M_j \Delta t_i \Delta E \varepsilon_{AW,jk} \varepsilon_{MC,jk}.$$

b_{jk} = background contributions,
M_j = mass of the *j*-th detector,
Δt_i = detector running time during the *i*-th time interval,
ΔE = chosen energy bin,
ε_{AWjk} = acceptance window efficiency,
ε_{MCjk} = efficiency for the hardware-trigger and the preliminary offline coincidences,
S_{ik} = signal can be written as: $S_{ik} = S_{0k} + S_{mk} \cos\omega(t_i - t_0).$

S_{0k} = constant part of the signal
S_{mk} = modulation amplitude, in the *k*-th energy bin.

The free parameters of the fit are the $(b_{jk} + S_{0k})$ contributions and the S_{mk} (in the following, the *k*-index will be omitted for simplicity)

DAMA/LIBRA-phase2-empowered vs all

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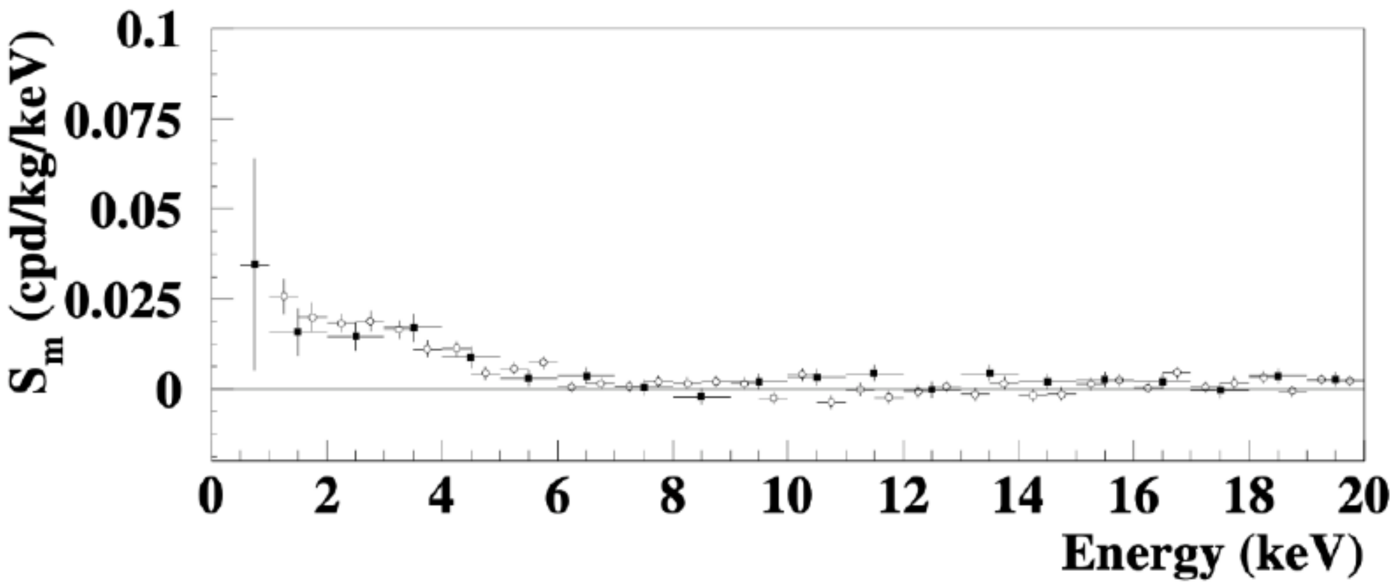
In the data taking typically each annual cycle starts before the expected minimum of the DM signal (about December 2) and ends after its expected maximum (about June 2)
→ adopting in the data analysis a constant background, *bjk*, evaluated within each annual cycle, any possible decay of long-term-living isotopes cannot mimic a DM positive signal with all its peculiarities. On the contrary, it may only lead to underestimating the DM annual modulation amplitude, depending on the radio-purity of the setup.

A positive signal is present in the 0.5–6 keV energy interval, while $S_m(E)$ values compatible with zero are present just above



black filled squares = DAMA/LIBRA-phase2-empowered data set (0.541 t·yr) with an energy threshold of 0.5 keV

Withe open circles = DAMA/NaI, DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 (total exposure: 2.86 t·yr)

They are compatible: χ^2 (1-20 keV) = 39.3, d.o.f. 38 (p-value = 41 %) → they can be combined together.

Combined modulation amplitudes for the whole data sets:

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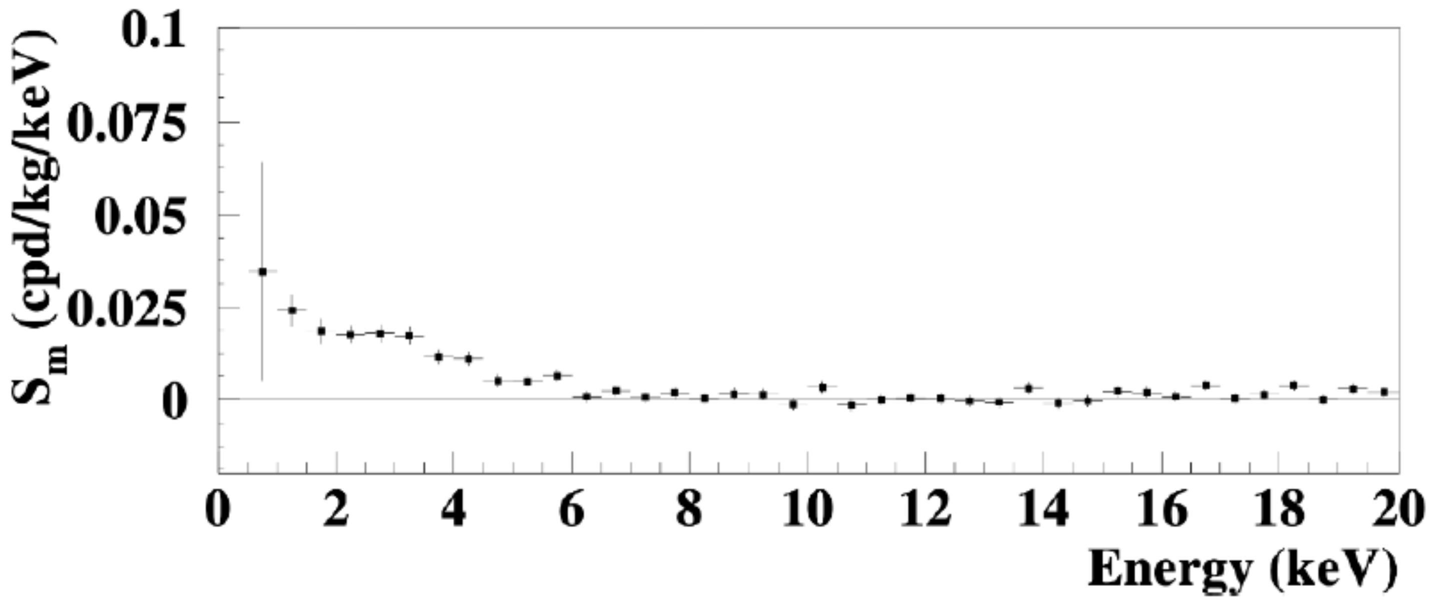
DAMA/NaI, DAMA/LIBRA-phase1, DAMA/LIBRA-phase2, DAMA/LIBRA-phase2-empowered (total exposure 3.40 t·yr)



A positive signal is present in the 0.5–6 keV energy interval, while $S_m(E)$ values compatible with zero are present just above → this confirms other analyses.

The test of the hypothesis that the $S_m(E)$ values e.g. in the (6–14) keV energy range have random fluctuations around zero yields χ^2/d.o.f. = 17.0/16 (p-value = 39 %).

Standard analysis vs common background analysis

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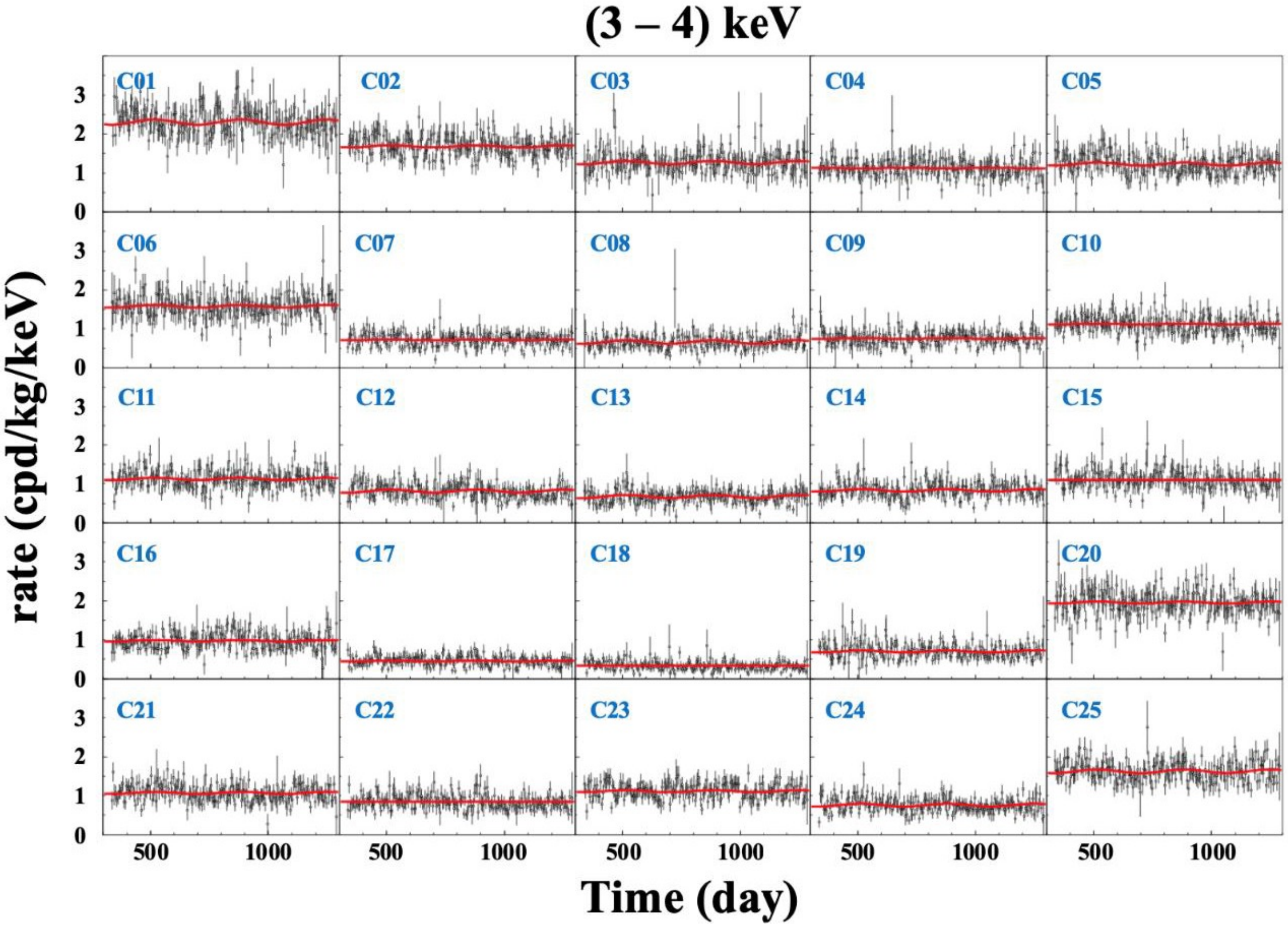
Analysis procedure above assumes a constant background evaluated within each annual cycle → any possible decay of long–lived isotopes cannot mimic a positive DM signal with all its characteristic features. On the contrary, such decays could only lead to underestimate the DM annual modulation amplitude, depending on the radiopurity of the setup.

Here – taking advantage of the fact that the approximately 3 annual cycles of DAMA/LIBRA-phase2-empowered are continuous without any long interruption or upgrade during the three years – the entire DAMA/LIBRA-phase2-empowered data set is also analyzed under the assumption of a common background across all cycles.

Example:
counting rates of all the 25 detectors during the DAMA/LIBRA-phase2-empowered.

- time bin = 5 days
- *red solid curve* = result of the maximum likelihood analysis considering the same background over $\simeq$ 3 annual cycles of data taking.

- The χ^2/d.o.f. ranges from 0.94 to 1.13.



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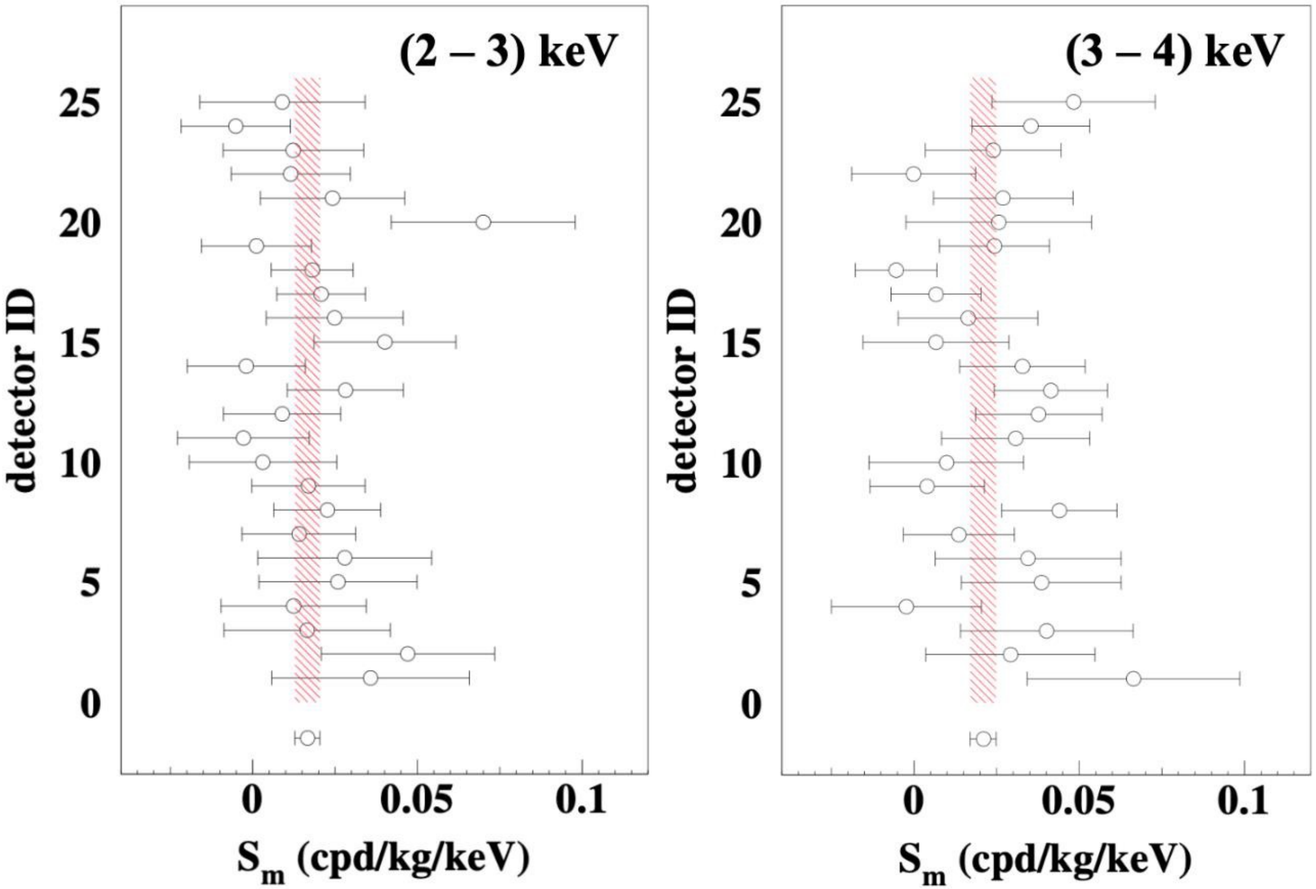
Template cases



Modulation amplitudes S_m in the 2–3 keV (*left panel*) and 3–4 keV (*right panel*) energy intervals for each of the 25 detectors in DAMA/LIBRA-phase2-empowered.

Errors at 1 σ C.L.

Weighted average point and 1 σ band (*shaded area*)

$$\sigma_{Sm}(1\ \text{detector}) \simeq 0.02 \rightarrow \sigma_{Sm}(25\ \text{detectors}) \simeq \frac{0.02}{\sqrt{25}} \simeq 0.004\ \text{cpd/kg/keV}$$

- S_m over all: (0.0166±0.0038) cpd/kg/keV
- Hyp: S_m=0.0166: $\chi^2 = 13.3\ \ dof = 24$ – p-value=96%
- Hyp: S_m=0: $\chi^2 = 31.9\ \ dof = 25$ – p-value=16%
- Hyp: S_m=0 excluded $\Delta\chi^2 = 18.6\ \ dof = 1$

- S_m over all: (0.0210±0.0039) cpd/kg/keV
- Hyp: S_m=0.0210: $\chi^2 = 19.8\ \ dof = 24$ – p-value=71%
- Hyp: S_m=0: $\chi^2 = 48.6\ \ dof = 25$ – p-value=3×10^{-3}
- Hyp: S_m=0 excluded $\Delta\chi^2 = 28.8\ \ dof = 1$

Also supporting the hypothesis that the signal is well distributed over all 25 detectors.

Standard analysis vs common background analysis

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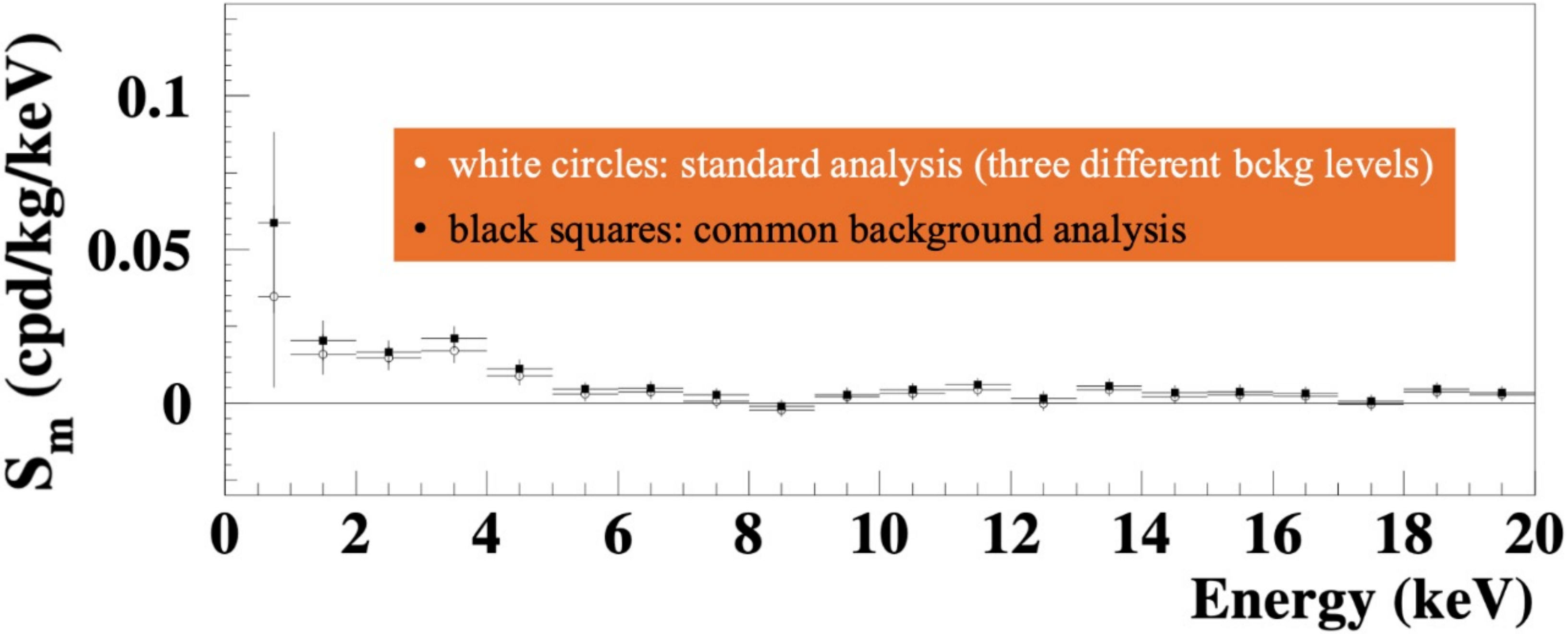


Comparison between the modulation amplitudes, S_m, obtained with the standard analysis (*white open circles*) and with the analysis considering the same background over ≃ 3 annual cycles (*black filled squares*); in both cases, the used data set is the entire DAMA/LIBRA-phase2-empowered.

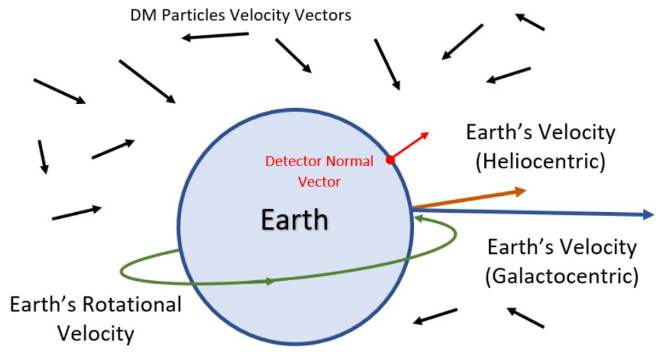
In conclusion the modulation amplitudes obtained by the two methods of analysis are consistent with each other (χ^2/dof = 8.4/20), further confirming that any effects from long-term, time-varying backgrounds – even from any hypothetical slowly increasing low-energy rate – are negligible in DAMA/LIBRA, thanks to the detectors' performances and long-term underground operation → the standard DAMA analysis can be reliably used.

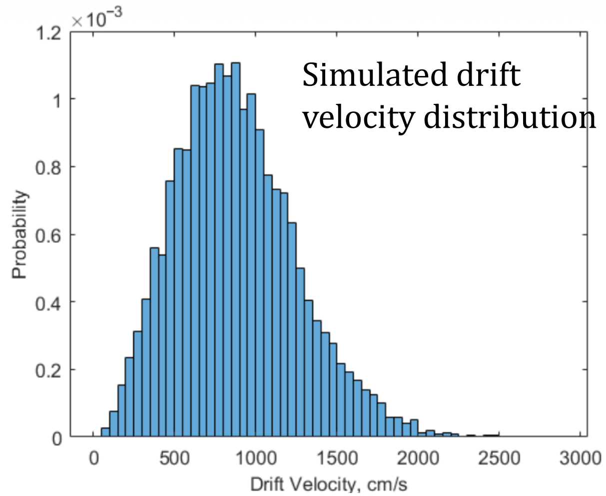
DAMA observed effect compatible with a wide class of theoretical models, particularly in light of the substantial uncertainties that persist in astrophysical, nuclear, and particle-physics aspects.

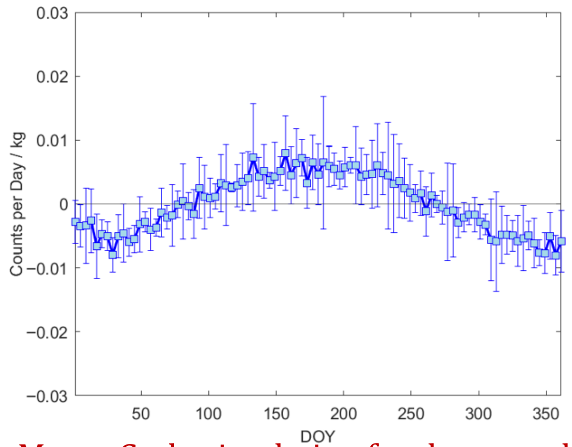
A recent investigation: Dark Atom Scenario in the DAMA/LIBRA results

P. Belli, R. Bernabei, … M. Khlopov et al., Universe 12 (**2026**) 116

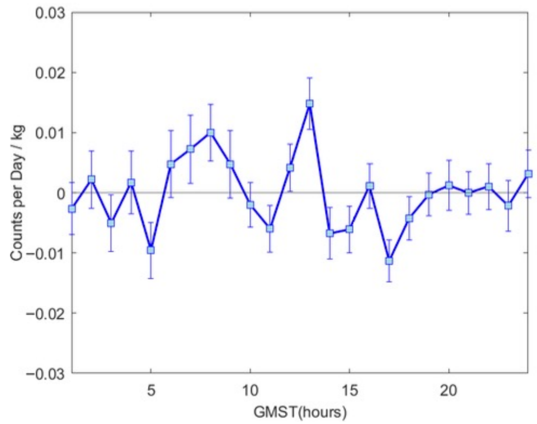
- Dark atoms hypothetical stable lepton-like particles with a charge of $-2n$ ($n \in \mathbb{N}$) that form neutral bound states with n primordial helium nuclei.
- The dark atoms are captured by the Earth, and they drift with drift velocity as in the figure.
- Quantum-mechanical description of bound states between dark atoms and ordinary nuclei
- Procedures for systematic comparisons with this model, which have general interest, are presented considering the DAMA published results on the dark matter annual and diurnal modulation signatures as a benchmark







Monte Carlo simulation for the annual modulation of the residual count rate as a function of the day of the year (DOY), averaged over 11 years for the period from 2011 to 2022.



Monte Carlo simulation for the daily modulation of the residual count rate as a function of Greenwich Mean Sidereal Time.

The dark atom model provides a self-consistent and phenomenologically extensive framework able to account for the published DAMA results on annual and diurnal modulation signatures and on some energy spectrum behavior, as well as for absence of an annual modulation effect in detectors based on heavy nuclei while remaining compatible with other constraints.

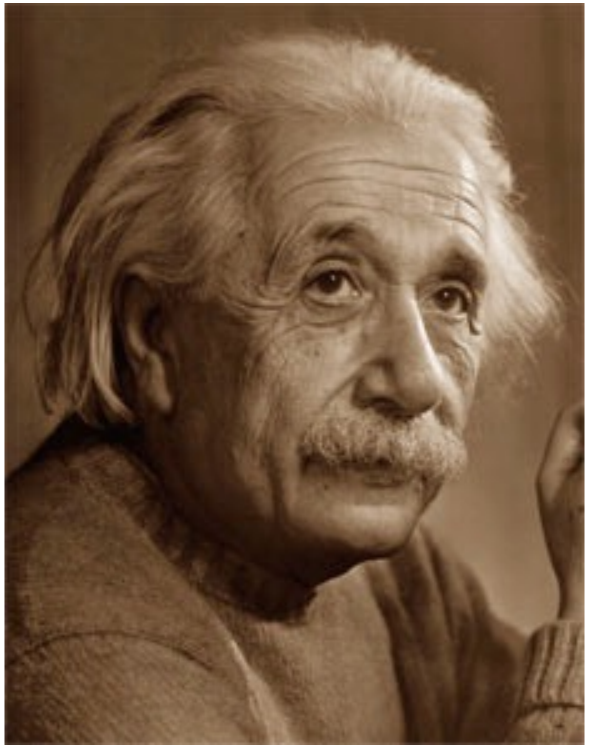
Conclusions

- New results from DAMA/LIBRA-phase2-empowered (exposure: 0.541 t·yr)
- Reduction of the software energy threshold down to 0.5 keV further improving the experimental sensitivity.
- Effect, already observed in previous configurations, is also present in this new configuration.
- Continuous data-taking procedure has allowed us to further demonstrate the robustness of the DAMA standard model-independent analysis and to further exclude any hypothetical effect from a long-term, time-varying background.
- DAMA cumulative model-independent DM annual modulation effect, corresponding to a total exposure of 3.40 t·yr, is observed at 15.3 σ C.L. over 25 independent annual cycles and various experimental configurations

DAMA observed effect remains compatible with a wide class of theoretical models, particularly in light of the substantial uncertainties that persist in astrophysical, nuclear, and particle-physics aspects (latest study on Dark Atoms: *Universe 2026, 12(4), 116).*

Finally, we note that the DAMA project was concluded - as planned - after several decades of operation with several set-ups and many measurements on rare processes performed.

DAMA experimental setups were dismantled in fall 2024.



”… The one who follows the crowd will usually get no further than the crowd. The one who walks alone, is likely to find himself in places no one has ever been.”

Thanks for attention