Status of DAMA/LIBRA

A. Leoncini [1,2], P. Belli [1,2], R. Bernabei [1,2], F. Cappella [3,4], V. Caracciolo [1,2], R. Cerulli [1,2], C. J. Dai [5], A. D'Angelo [3,4], A. Incicchitti [3,4], X. H. [5], V. Merlo [1,2], F. Montecchia [2,6], X. D. Sheng [5], Z. P. Ye [5,7].

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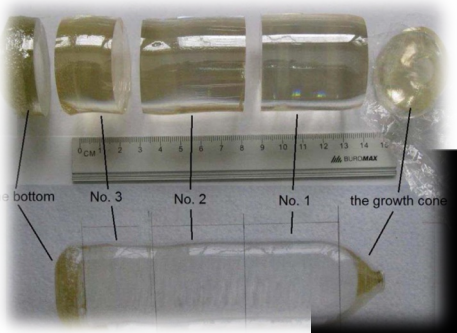
11-15 September 2023

DAMA set-ups

an observatory for rare processes @ LNGS

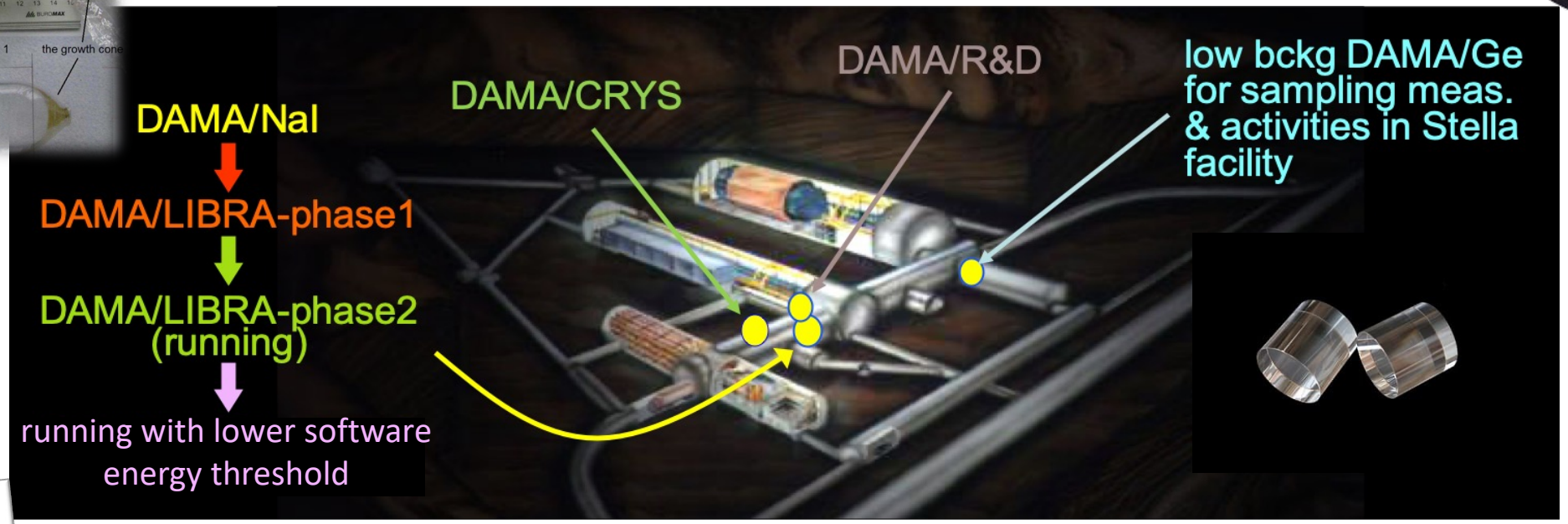


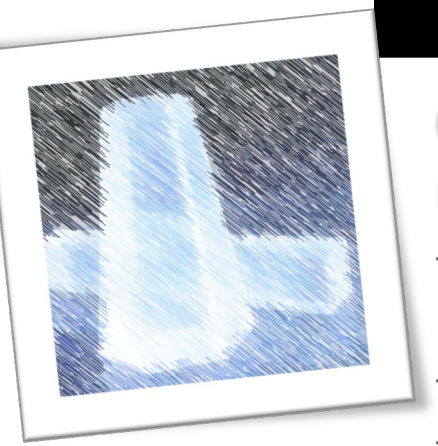
DAMA/NaI

DAMA/LIBRA-phase1

DAMA/LIBRA-phase2 (running)

running with lower software energy threshold





Collaboration:

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

+ by-products and small scale expts.: INR-Kiev + other institutions
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia
+ in some studies on 2β decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

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

Last year (2022-Apr 2023):

- 25 publications on international reviews & volumes of Proc.
- 32 talks at conf. and seminars
- 2 PhD theses in progress

- 339 (53 in the last five years) publications on international reviews
- 427 (93 in the last five years) talks at conf. and seminars
- h-index = 62

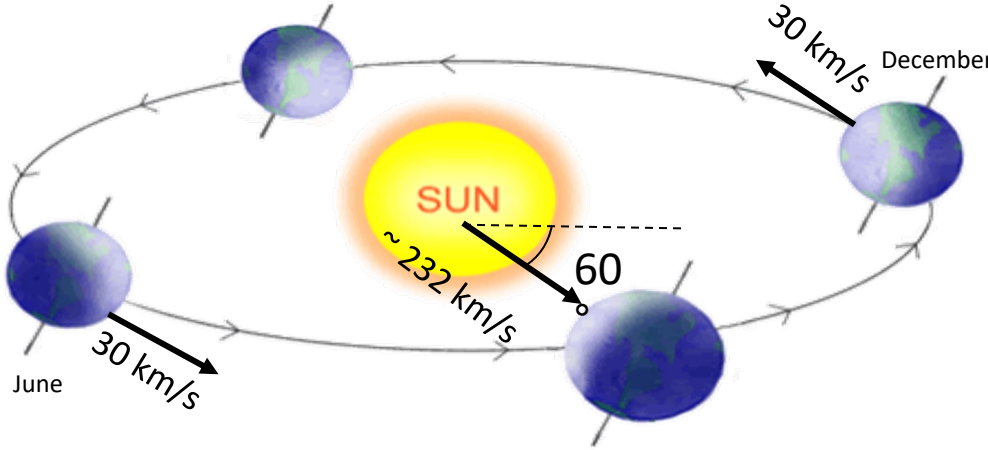
The annual modulation signature for the investigation of DM particles component in the galactic halo

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)
- $\gamma = 2\pi/3$, $\omega = 2\pi/T$, T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

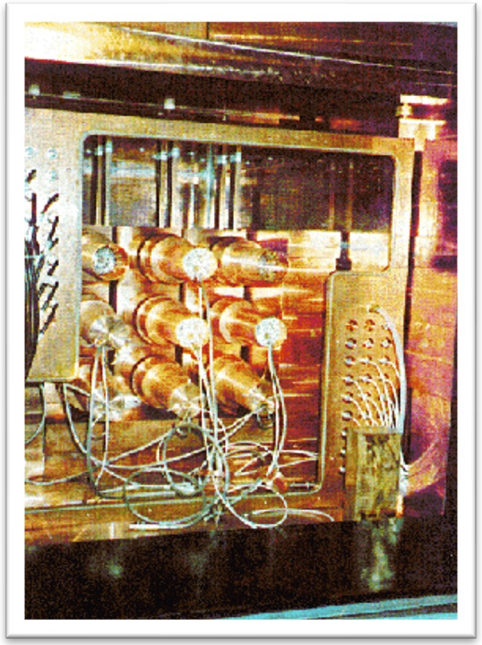
$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

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

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

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

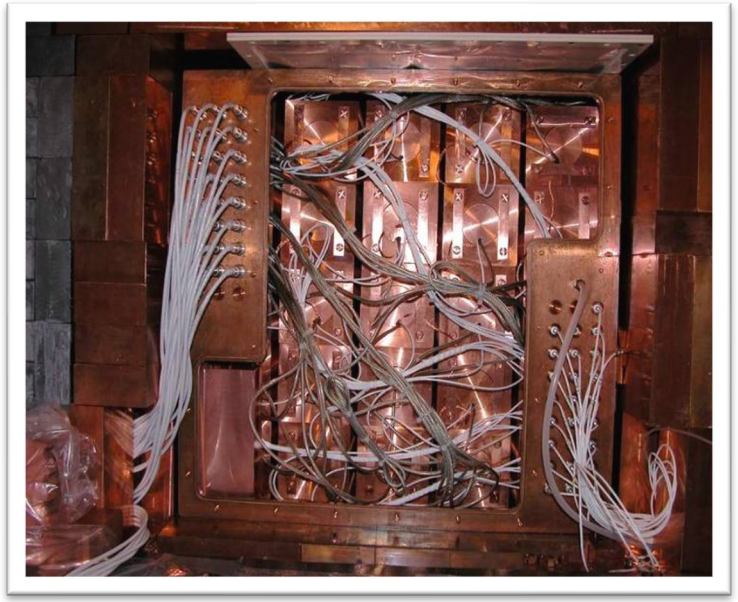
Annual modulation in DAMA



- The pioneer DAMA/NaI: ≈100 kg highly radiopure NaI(Tl)
  - Total exposure (7 annual cycles) 0.29 ton x yr
  - 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



DAMA/LIBRA–phase1:

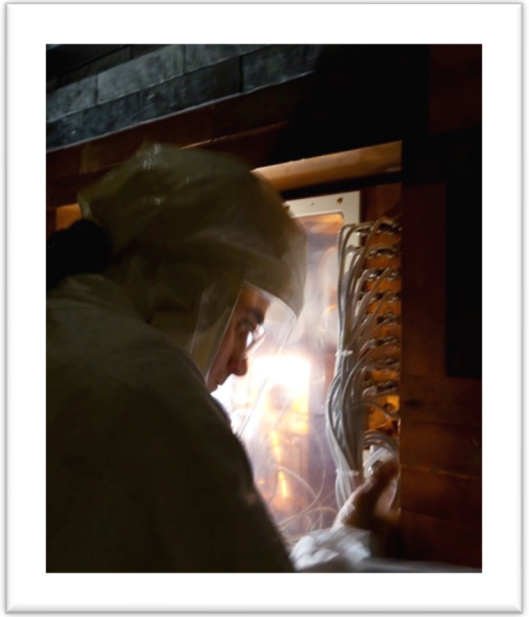
- Total exposure (7 annual cycles) 1.04 ton x yr
- Confirmed the model-independent evidence of DM: reaching 9.3σ C.L.
- Data taking completed on July 2010

DAMA/LIBRA–phase2:

- Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.:
  33 – 39% @ 420 nm
  36 – 44% @ peak
- Goal: software energy threshold at 1 keV – **accomplished**

Empowered DAMA/LIBRA-phase2

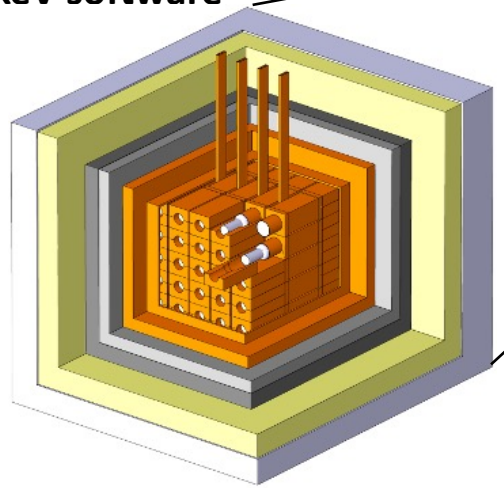
A new stage of the experiment with 0.5 keV energy threshold is running since Dec 1, 2021, see later.

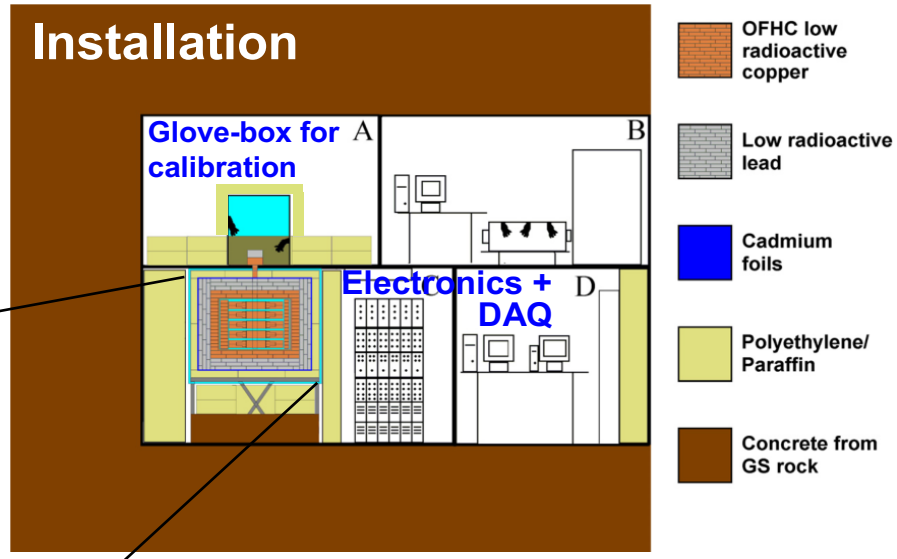


The DAMA/LIBRA–phase2 set-up

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

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- Two Suprasil-B light guides directly coupled to each bare crystal
- Two new high Q.E. PMTs for each crystal working in coincidence at the single ph. el. threshold
- **6-10 phe/keV; 1 keV software energy threshold**





- 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)

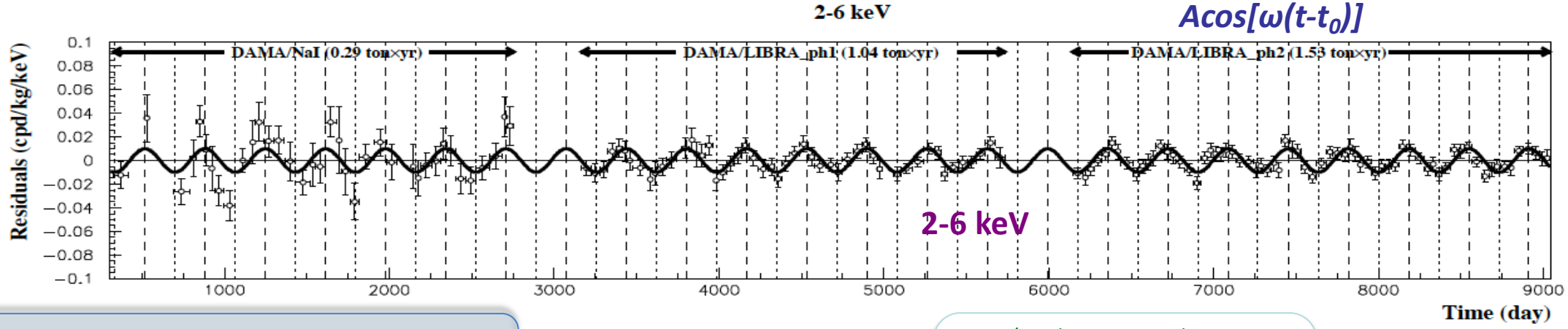
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as prod runs
- Never neutron source in DAMA installations
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data

- Pulse shape recorded by Waveform Analyzer Acqiris DC270 (2chs per detector), 1 *Gs/s,* 8 bit, bandwidth 250 MHz both for single-hit and multiple-hit events
- Data collected from low energy up to MeV region, despite the hardware optimization for low energy
- DAQ with optical readout
- New electronic modules

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}

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

A=(0.00996±0.00074) cpd/kg/keV

χ^2/dof = 130/155 **13.4 σ C.L.**

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.

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

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

Energy distribution of the modulation amplitudes

Max-likelihood analysis

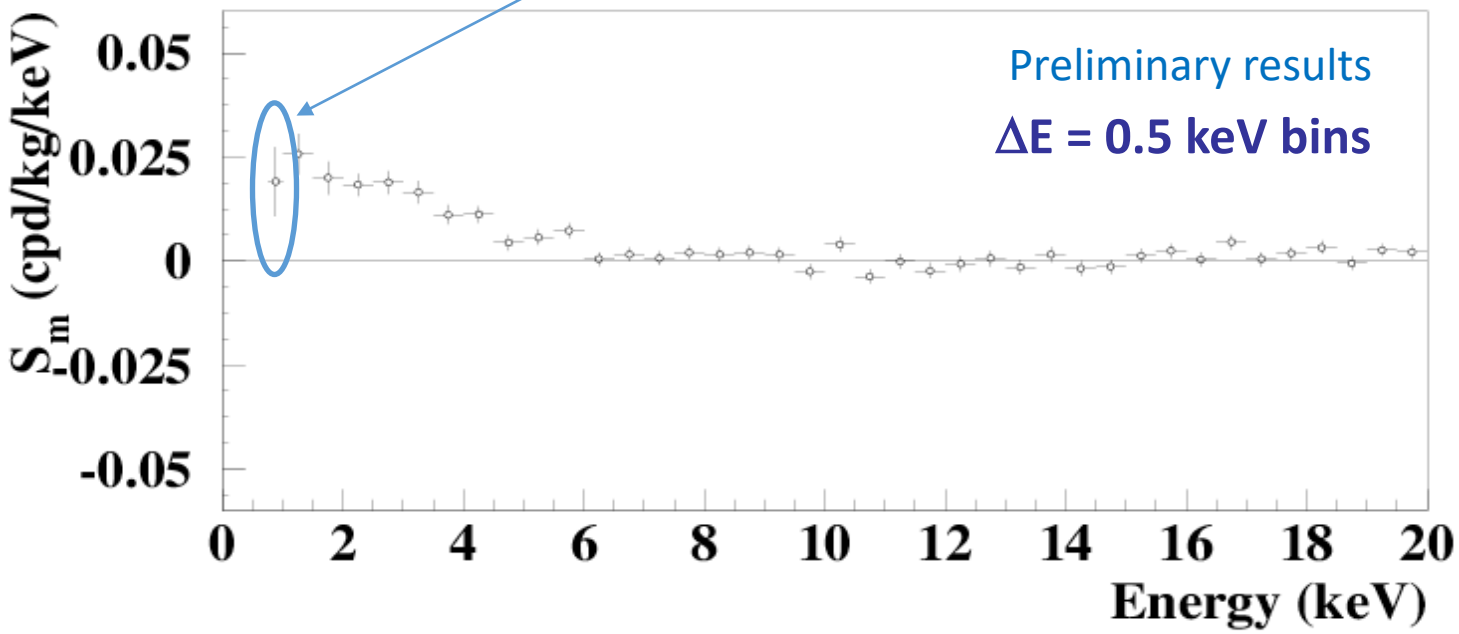
$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right]$$

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

- 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 d.o.f (upper tail probability 21%).

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

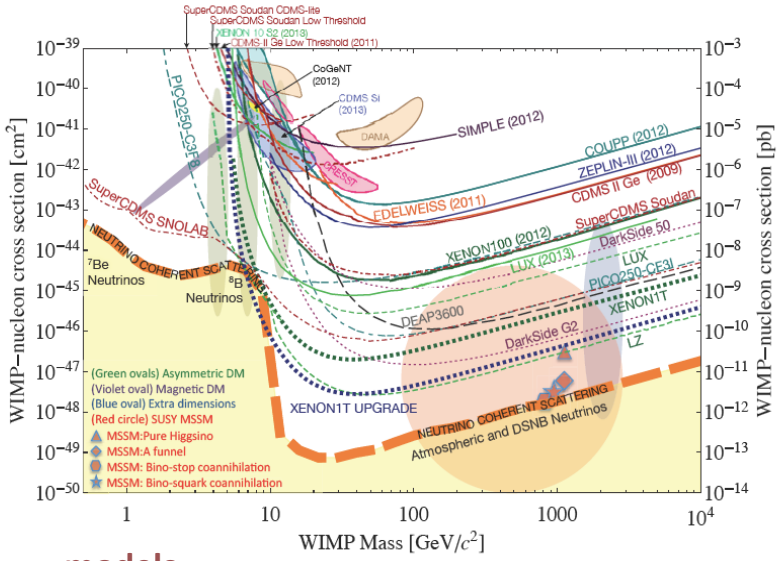
New data point with the 8 a.c. of
DAMA/LIBRA-phase2 (1.53 ton×yr)



- 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

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



…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

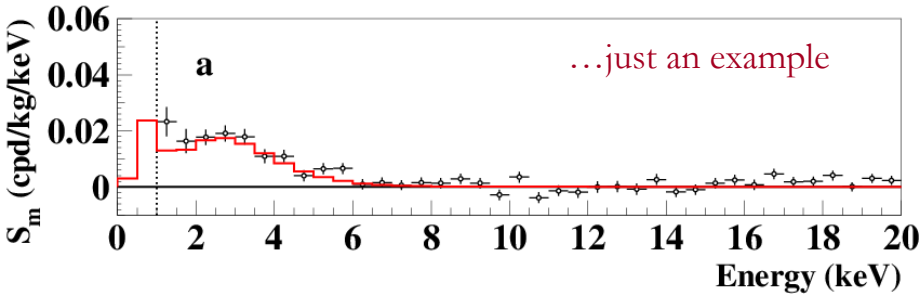
No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

…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**
- …

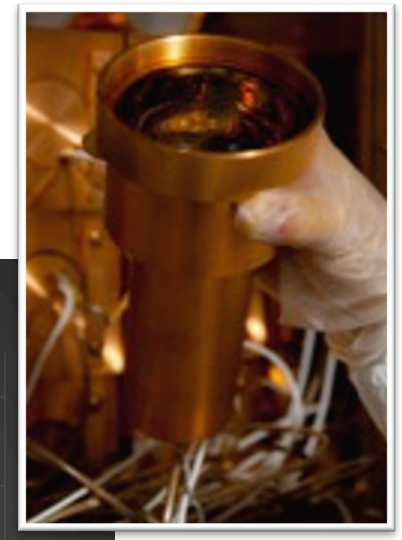
Example: 2 keVee of DAMA ≠2 keVee of COSINE-100 for nuclear recoils

No direct model-independent comparison is possible



Empowered DAMA/LIBRA-phase2 data taking

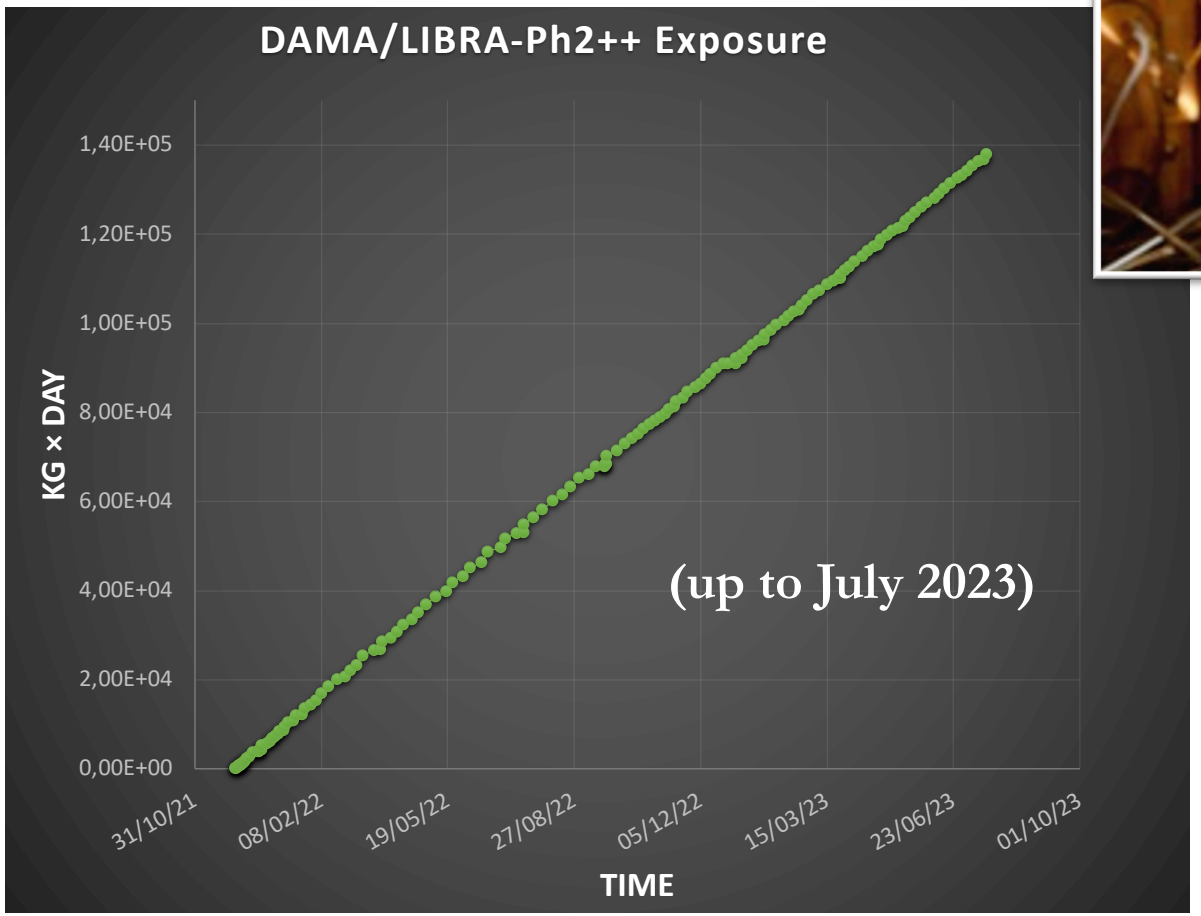
Data taking in this configuration started on December 2021. The data taking has been continued without interruptions, with regular calibration runs.



The upgrade of the whole DAMA/LIBRA–phase2 basically consisted in:

a. equipping the PMTs with new low-background voltage dividers with pre-amps on the same board (named "voltage-divider-plus-preamp") and

b. the use of Transient Digitizers (TD) with higher vertical resolution (14 bits).



✓Calibrations: $\approx 4.75 \times 10^7$ events from sources

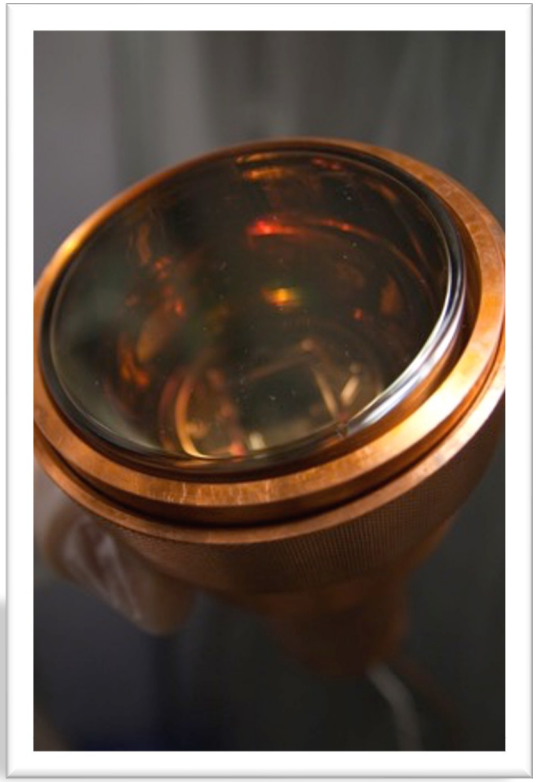
✓Acceptance window eff. per all crystals:
$\approx 2.71 \times 10^7$ events ($\approx 1.1 \times 10^6$ events/keV)

Exposure of empowered DAMA/LIBRA-phase2 up to July 2023:

0.39 ton × yr $\quad (\alpha - \beta^2) \approx 0.498$

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 using 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.

BACKUP

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