Annual Modulation Results from DAMA/LIBRA

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Identification of Dark Matter 2024
L'Aquila, July 8-12, 2024

DAMA set-ups

an observatory for rare processes @ LNGS

- DAMA/LIBRA (DAMA/NaI)
- DAMA/LXe
- DAMA/R&D
- DAMA/Crys
- DAMA/Ge

Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur and Ropar, India

Web Site: dama.web.roma2.infn.it/

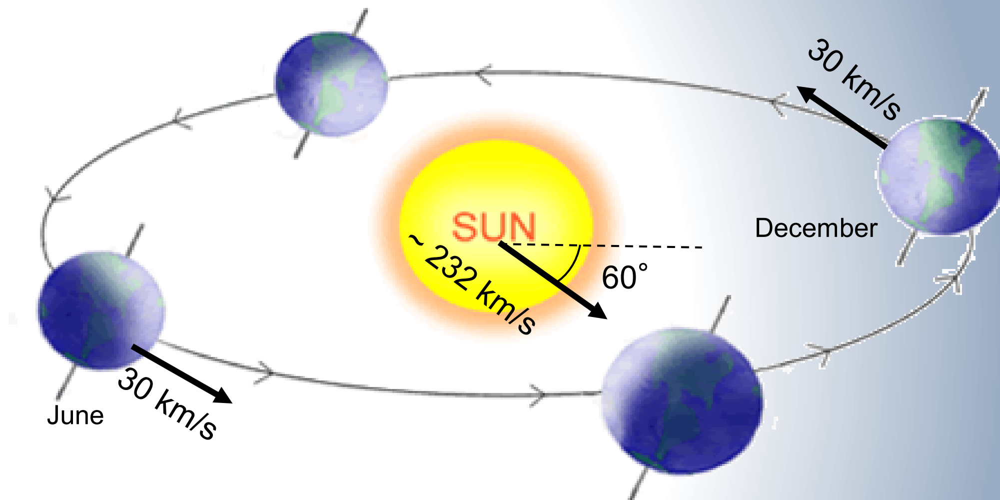
The **annual modulation**: a model independent signature for the investigation of DM particles

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) Cosine-like modulation of the rate
2) In low energy range
3) Period of 1 year
4) Phase at about June 2nd
5) 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

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



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

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

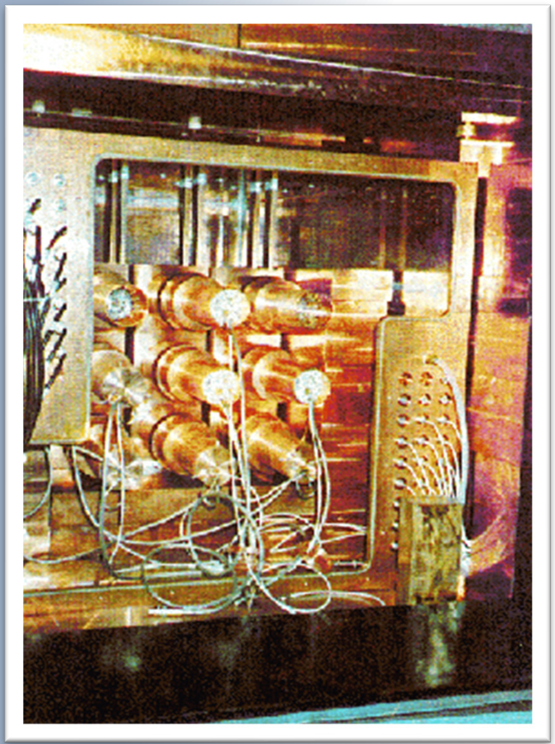
the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

To mimic this signature, spurious effects and side reactions must be able to account for the whole observed modulation amplitude, and also to satisfy simultaneously all the requirements

Highly radiopure NaI(Tl) experiment in DAMA

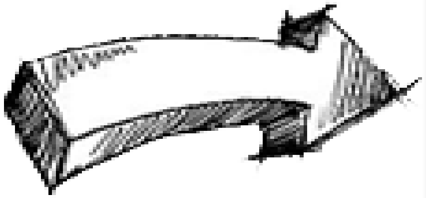
DAMA/NaI

Concluded on July 2002; 7 annual cycles collected; exposure 0.29 ton×yr



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

+ many results on other rare processes



DAMA/LIBRA

New NaI(Tl) detectors with better radiopurity features

Residual contaminations: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

- DAMA/LIBRA-phase1: 7 annual cycles, 1.04 ton × yr
- Model independent evidence of a particle DM component in the galactic halo at 9.3σ C.L.
- DAMA/LIBRA-phase2: lowering software energy threshold below 2 keV; 8 annual cycles released so far (1.53 ton × yr)

DAMA/LIBRA–phase2

- Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.
  ⇒ 1 keV threshold
- Empowered new stage in 2021, running
  ⇒ 0.5 keV threshold

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

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

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)

- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 8 a.c.: ≈ 1.6×10^8 events from sources
- ✓ Acceptance window eff. 8 a.c.: ≈ 4.2×10^6 events (≈ 1.7×10^5 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

Exposure with this data release of DAMA/LIBRA-phase2: **1.53 ton × yr**

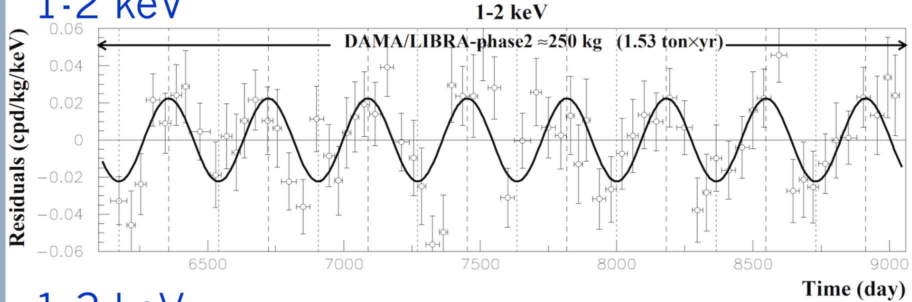
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.86 ton × yr**

Model Independent Annual Modulation Result

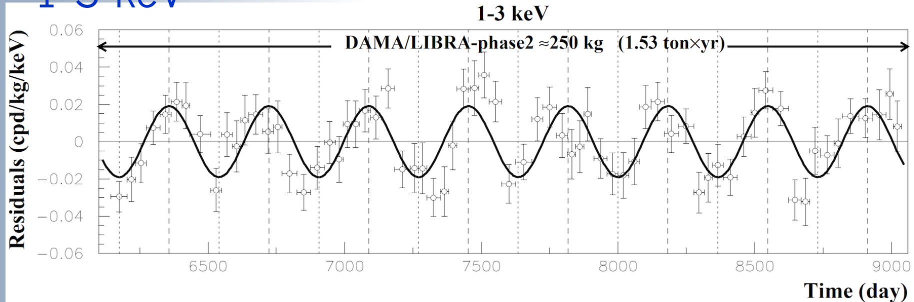
DAMA/LIBRA-phase2 (8 a.c. , 1.53 ton × yr)

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

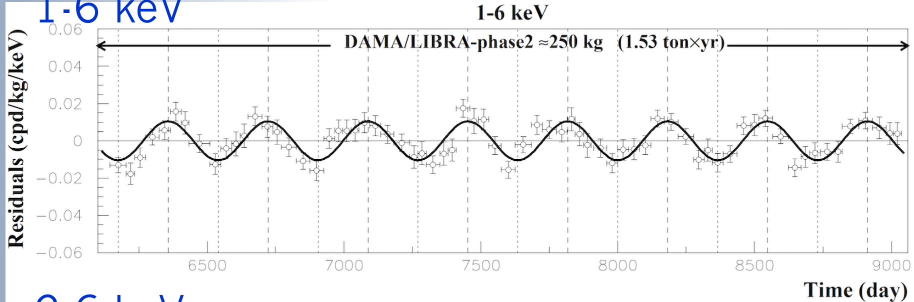
1-2 keV



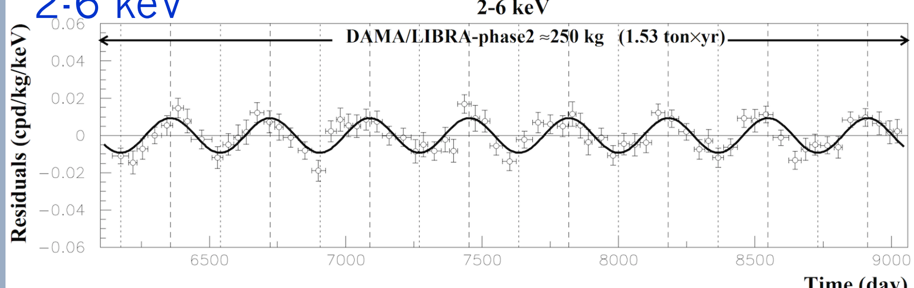
1-3 keV



1-6 keV



2-6 keV



Absence of modulation? No

χ^2/dof = 130/69 (1-2 keV); 176/69 (1-3 keV); 202/69 (1-6 keV); 157/69 (2-6 keV)

Fit on DAMA/LIBRA-phase2

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

1-2 keV

A=(0.0224±0.0030) cpd/kg/keV
χ^2/dof = 75.8/68 **7.4 σ C.L.**

1-3 keV

A=(0.0191±0.0020) cpd/kg/keV
χ^2/dof = 81.6/68 **9.7 σ C.L.**

1-6 keV

A=(0.01048±0.00090) cpd/kg/keV
χ^2/dof = 66.2/68 **11.6 σ C.L.**

2-6 keV

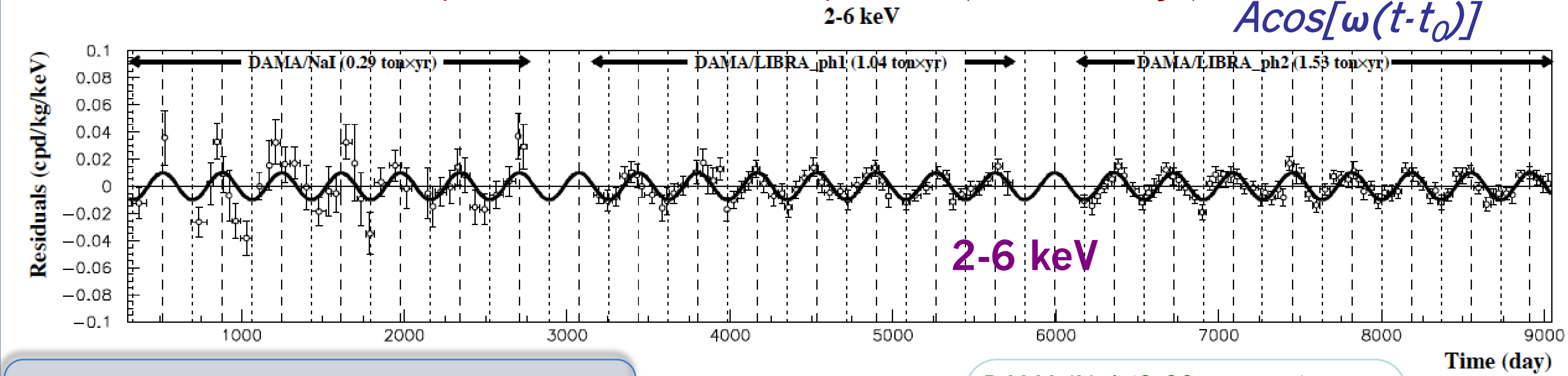
A=(0.00933±0.00094) cpd/kg/keV
χ^2/dof = 58.2/68 **9.9 σ C.L.**

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

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 ⇒ 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.**

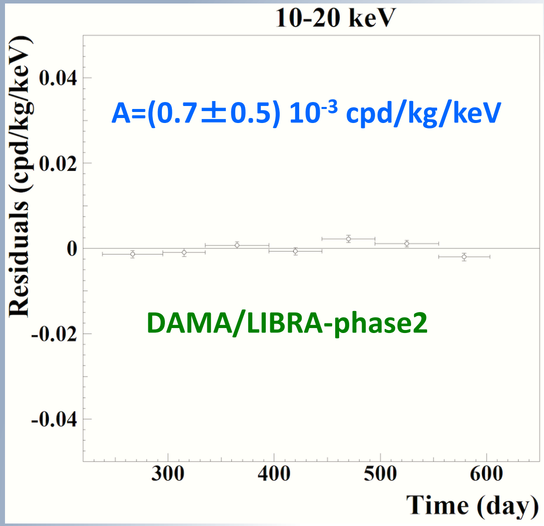
Releasing period (*T*) and phase (t_0) in the fit

	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.

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

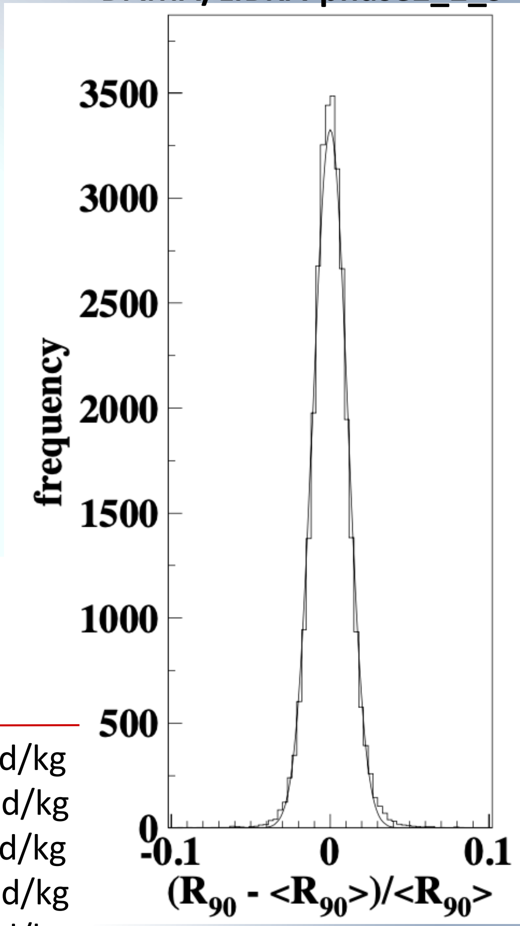
- **No modulation in the whole energy spectrum:** studying integral rate at higher energy, R_{90}
  - R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods
  - Fitting the behaviour with time, adding a term modulated with period and phase 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

DAMA/LIBRA-phase2_2_9



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

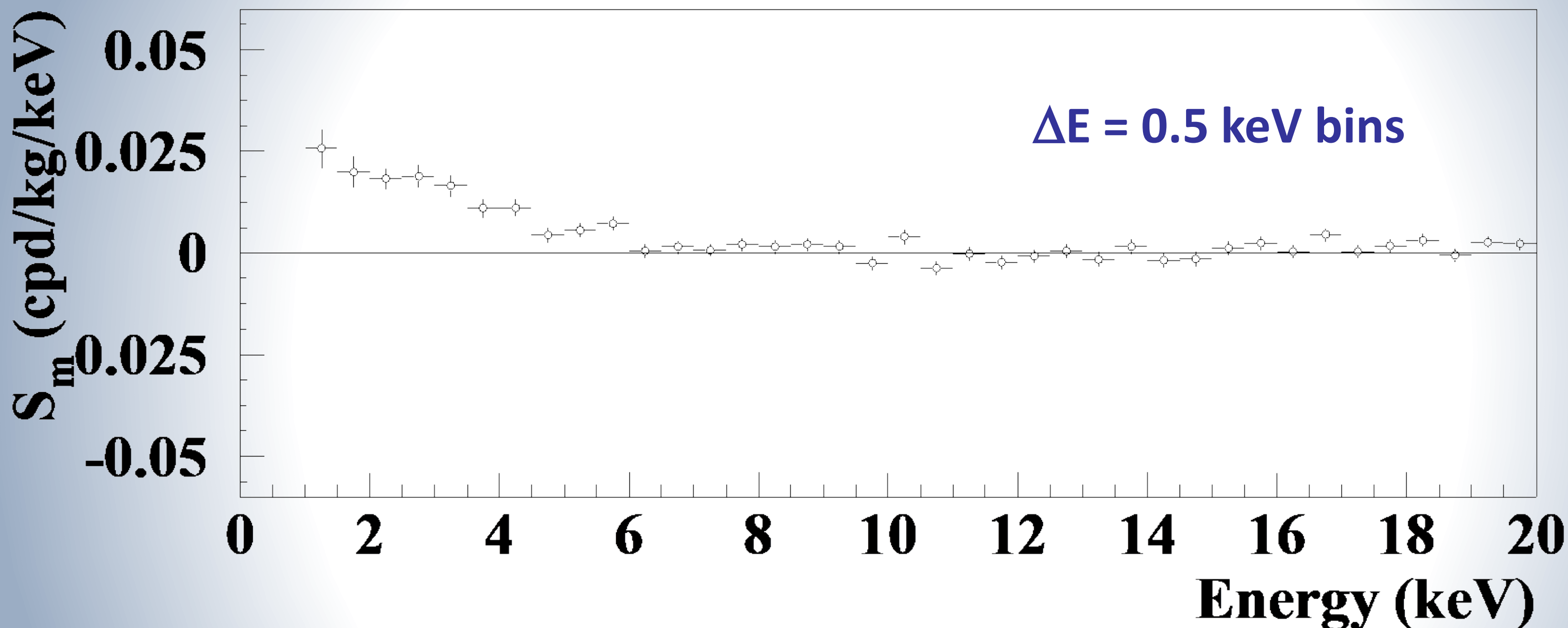
Energy distribution of the modulation amplitudes

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

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

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

max-likelihood analysis of the single hit scintillation events



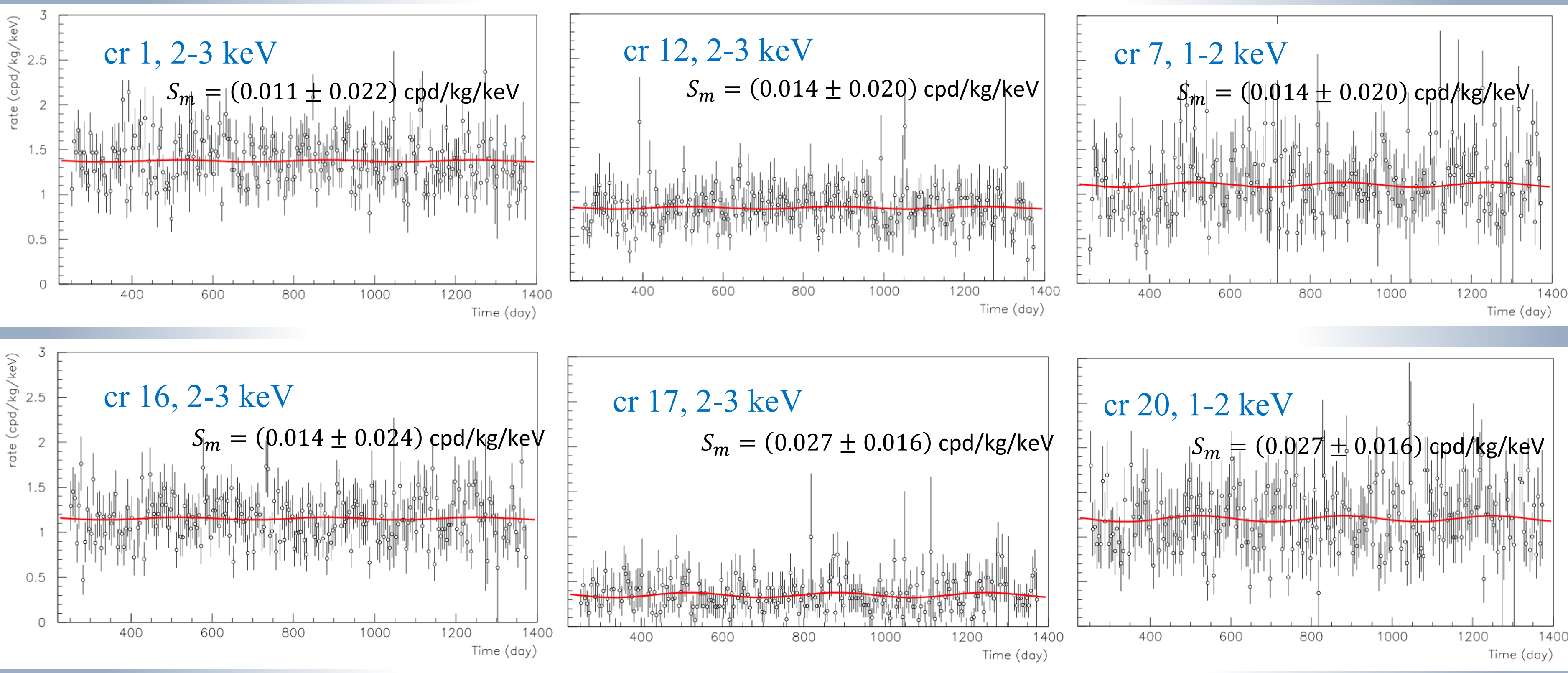
A clear modulation is present in the (1 -6) keV energy interval, while S_m values compatible with zero are present just above

- S_m in (6–14) keV random fluctuate around zero; χ^2=20.3/16 dof (P=21%)
- In (6–20) keV χ^2/dof = 42.2/28 (P=4%)*

*The obtained χ^2 value is rather large due mainly to two data points 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%.

Investigation on the rate time 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**



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

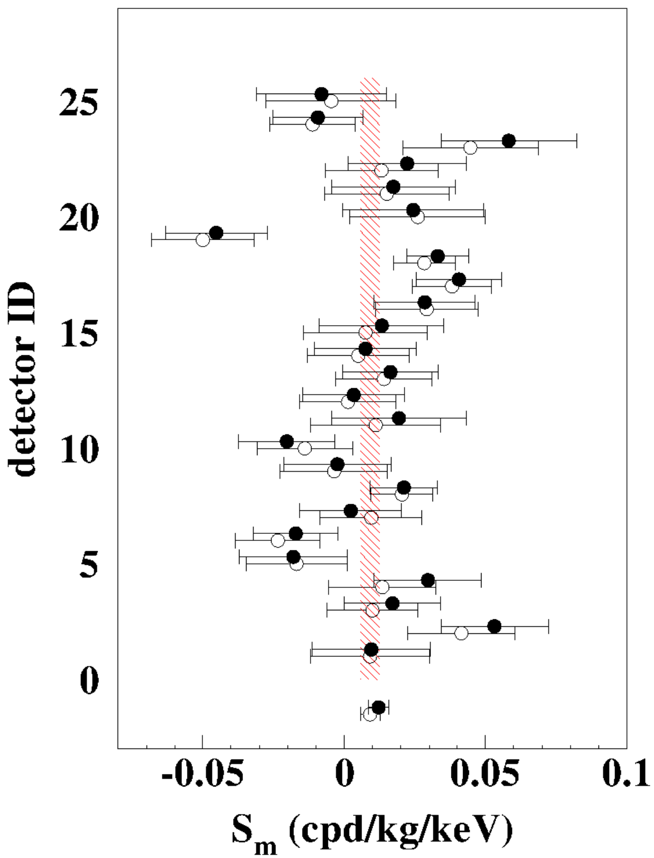
- Time bin: 5 days
- Red: maxlik analysis on single crystal with common (constant) background

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

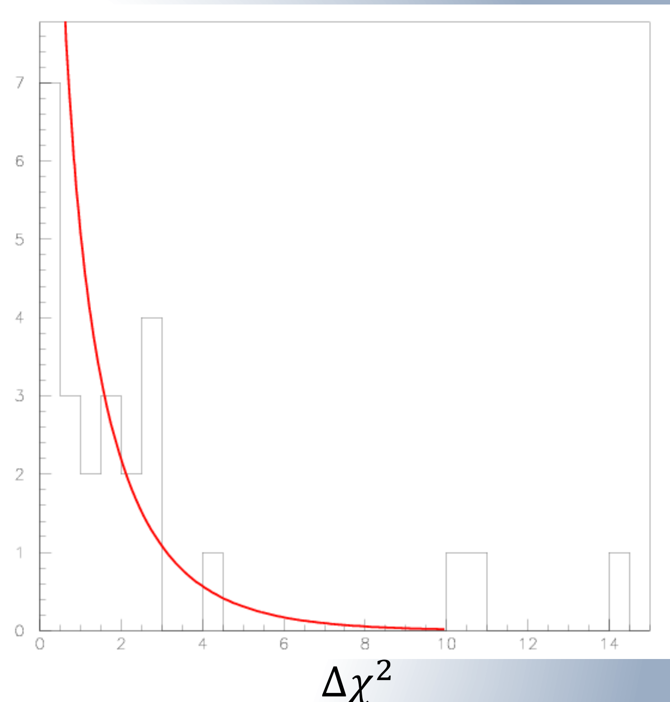
Investigation on the rate time dependence

A template case: 3-4 keV, 25 crystal, **last three 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**: $b - a \times time + S_m cos$
- H_0 hypothesis: flat background → case **A**
- Test variable: $\Delta\chi^2 = \chi^2_A - \chi^2_B$ with dof=1



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



- Plot of $\Delta\chi^2$ for each detector
- It follows a χ^2 distribution with dof=1

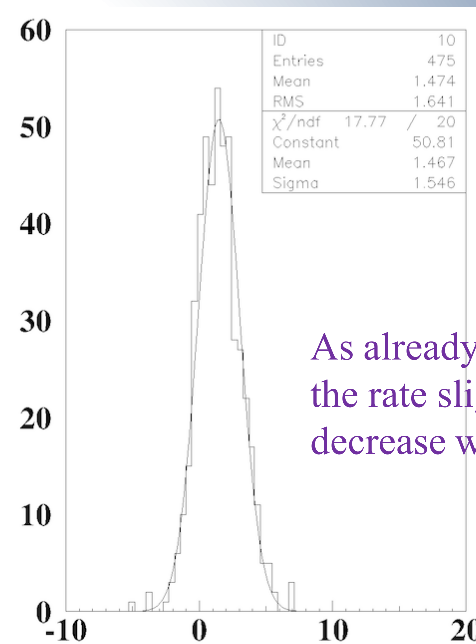
There is no need to enable the background slope over time

Investigation on the rate time dependence

The general case: last three published years of DAMA/LIBRA–phase2 (0.61 ton×yr)

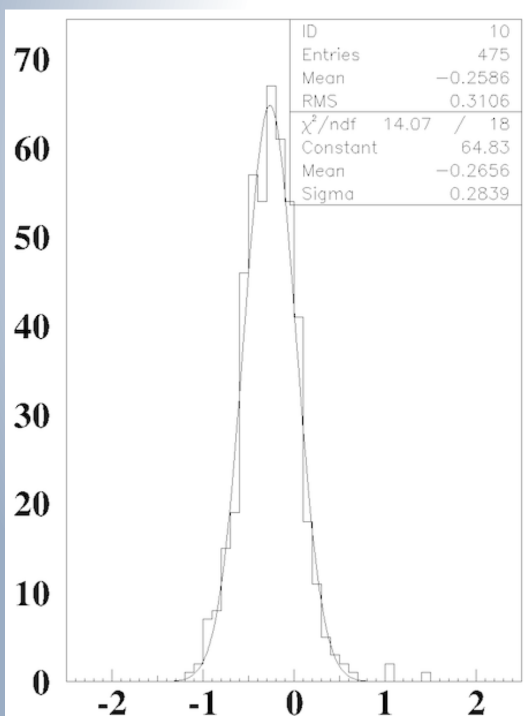
- For each detector the rates are fitted by MaxLik by case A: $b + S_m^{flat} \cos$
- and by case B: $b - a \times time + S_m^{slope} \cos$
- 475 entries = 25 detectors × 19 energy bins

Slopes distribution



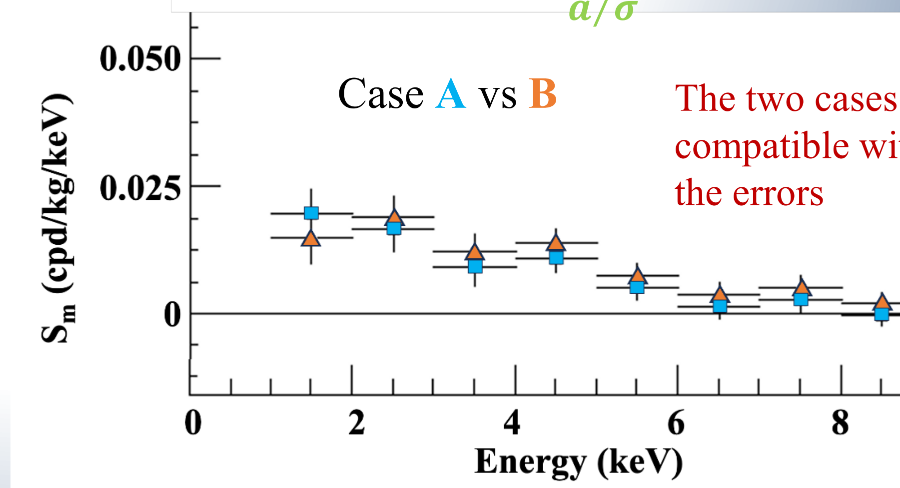
a/σ

As already noted, the rate slightly decrease with time



$\left(S_m^{flat} - S_m^{slope}\right)/\sigma$

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

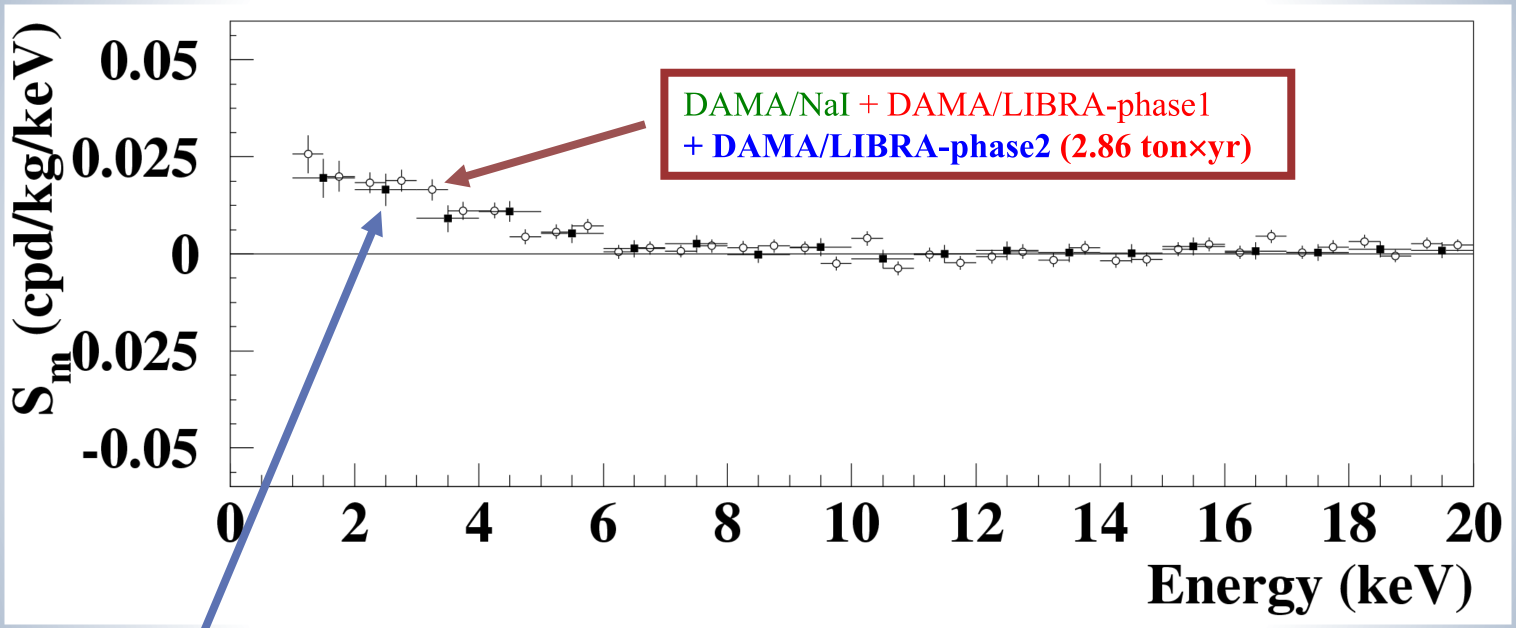


Energy distribution of the modulation amplitudes

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

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

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.	**<2.5×10^{-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 $\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**<10^{-4} cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**<10^{-4} cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**<3×10^{-5} cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

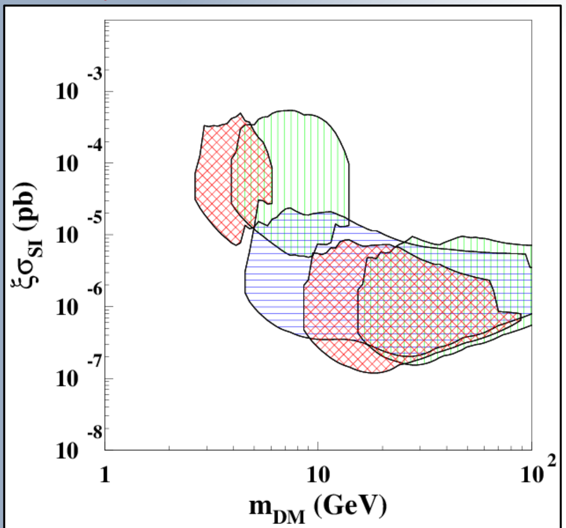
→ **Thus, they cannot mimic the observed annual modulation effect**

Examples of model-dependent analyses

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

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

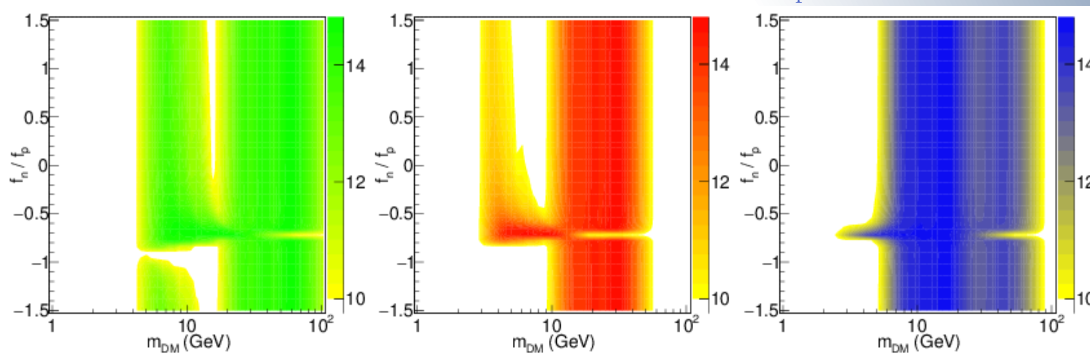
E_{th}=1 keV; old data release



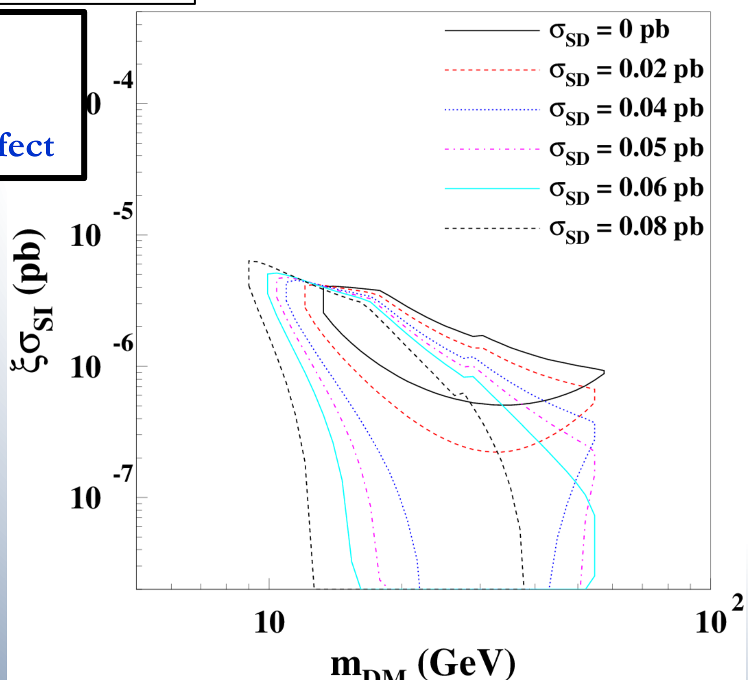
DM particles elastically scattering off target nuclei – SI interaction

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

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

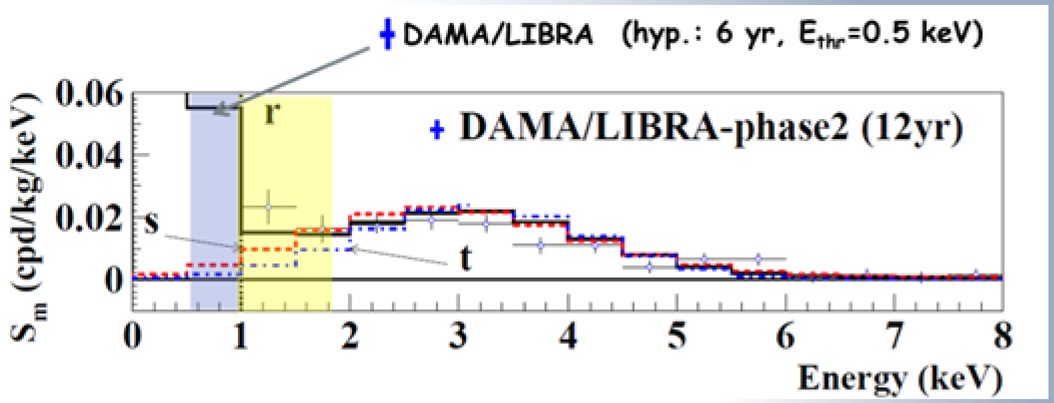


Even a relatively small SD (SI) contribution can drastically change the allowed region in the (m_{DM}, $\xi\sigma_{SI(SD)}$) plane

- 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 lower software energy threshold below 1 keV with high efficiency

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

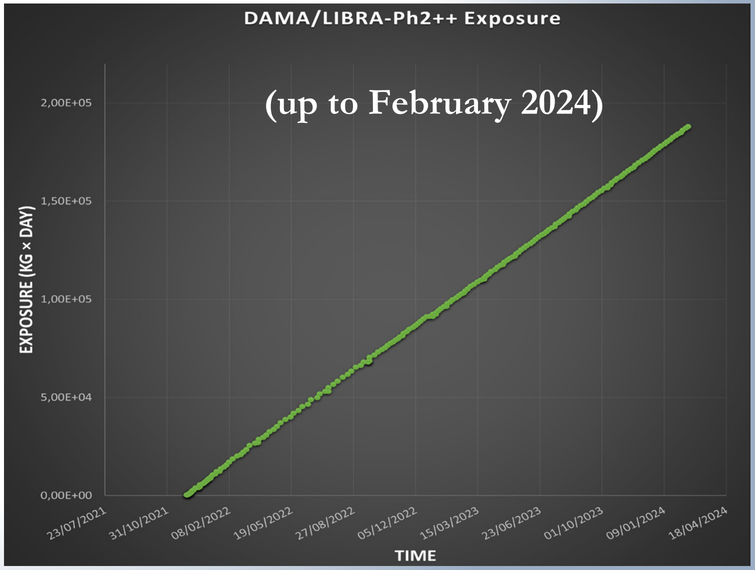


2021 upgrade:

- ✓ PMTs with new low-background voltage dividers with pre-amps on the same board
- ✓ use of 14 bits Transient Digitizers

→ very low values of the software trigger level on each PMT

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



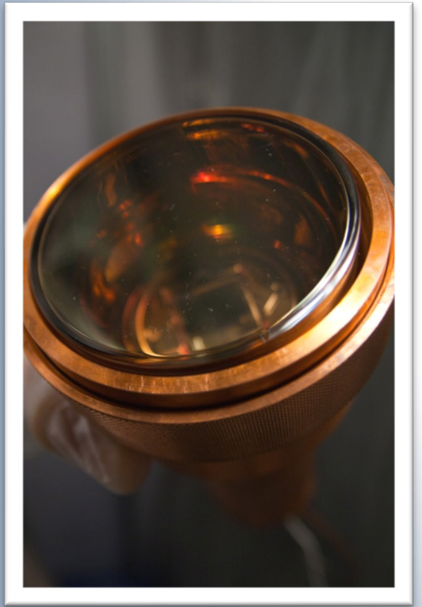
✓Calibrations: $\approx 6.38 \times 10^7$ events from sources

✓Acceptance window eff. per all crystals: $\approx 3.60 \times 10^7$ events (≈ 1.4×10^6 events/keV)

Exposure of DAMA/LIBRA-phase2-empowered up to February 24: 0.478 ton × yr $(\alpha - \beta^2) \approx 0.488$

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 **high precision**
- Full sensitivity to many kinds of DM candidates and interactions types



- Model-dependent analyses improve the C.L. and restrict the allowed parameters' space for the various scenarios
- DAMA/LIBRA–phase2-empowered **running** until the end of 2024 with lower software **energy threshold of 0.5 keV** with suitable efficiency.
- Investigations of **rare processes** other than DM
- DAMA set-ups: **decommissioning in 2025**