
# Status of DAMA/LIBRA-phase2 and its empowered stage

P. Belli
INFN – Roma Tor Vergata

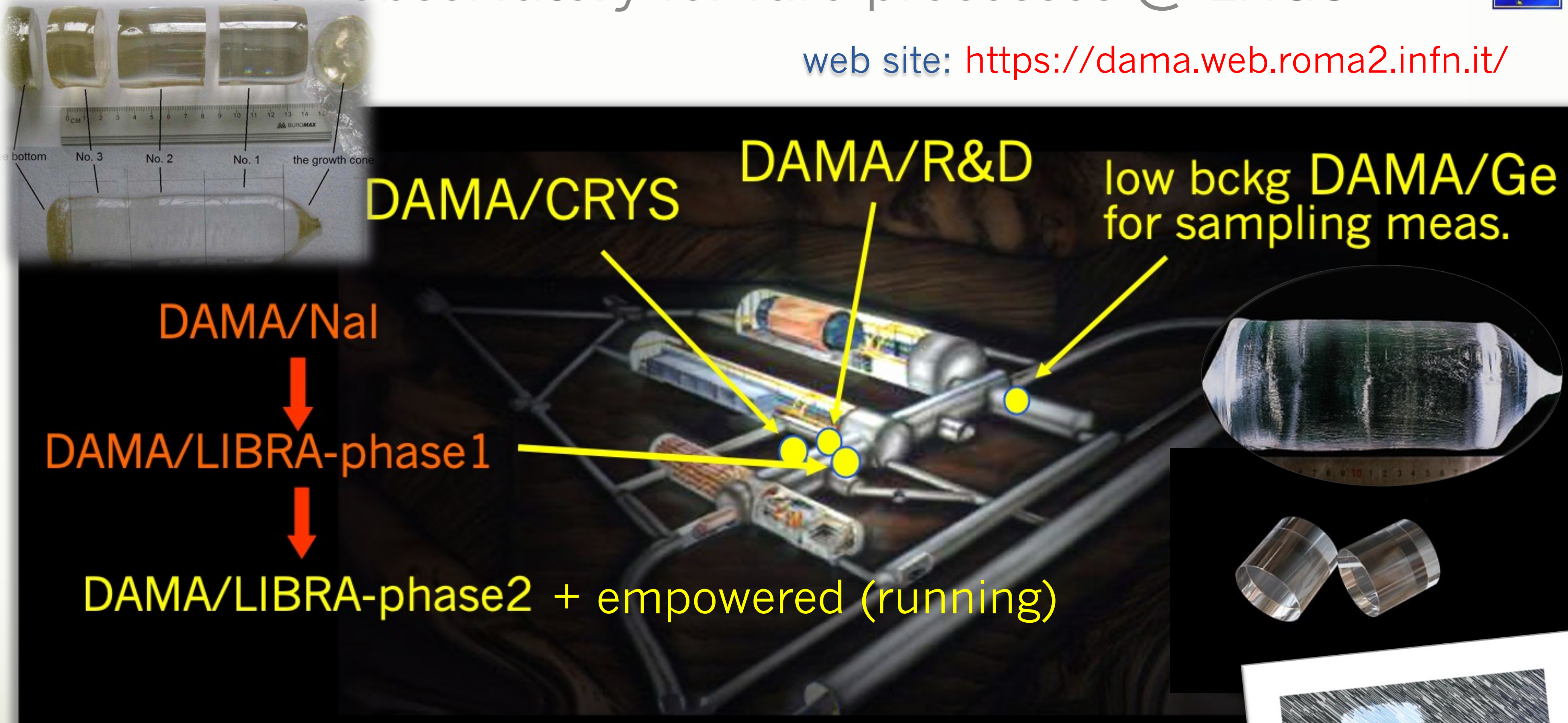
*A Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear physics energy scales in the Cosmic Silence*

ECT*, Trento, Italy
June 3-7, 2024

# DAMA set-ups

## an observatory for rare processes @ LNGS

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




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

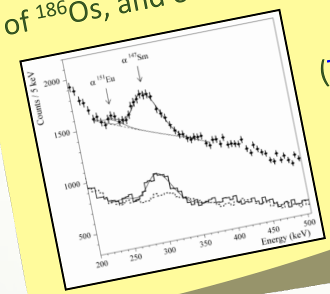
- \+ by-products and small scale expts.: INR-Kiev + other institutions
- \+ neutron meas.: ENEA-Frascati, ENEA-Casaccia
- \+ in some studies, on ββ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

The experimental activities of DAMA will gradually cease at the end of 2024/Spring-2025, according the plans already agreed since years with INFN-CSN2

# Main results obtained by DAMA in the search for rare processes

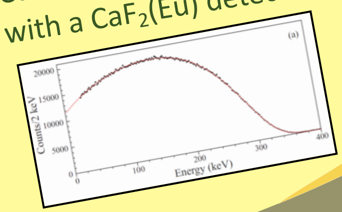
- First or improved results in the search for 2β decays of ~30 candidate isotopes: $^{40}$Ca, $^{46}$Ca, $^{48}$Ca, $^{64}$Zn, $^{70}$Zn, $^{100}$Mo, $^{96}$Ru, $^{104}$Ru, $^{106}$Cd, $^{108}$Cd, $^{114}$Cd, $^{116}$Cd, $^{112}$Sn, $^{124}$Sn, $^{134}$Xe, $^{136}$Xe, $^{130}$Ba, $^{136}$Ce, $^{138}$Ce, $^{142}$Ce, $^{144}$Sm, $^{154}$Sm, $^{150}$Nd, $^{156}$Dy, $^{158}$Dy, $^{162}$Er, $^{168}$Yb, $^{180}$W, $^{186}$W, $^{184}$Os, $^{192}$Os, $^{190}$Pt and $^{198}$Pt (observed 2ν2β decay in $^{100}$Mo, $^{116}$Cd, $^{150}$Nd)
- The best experimental sensitivities in the field for 2β decays with positron emission ($^{106}$Cd)

First observation of α decays of $^{151}$Eu with a $CaF_2$(Eu) scintillator, of $^{190}$Pt to the first excited level ($E_{exc}$=137.2 keV) of $^{186}$Os, and of $^{174}$Hf with CHC crystal




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

Investigations of rare β decays of $^{113}$Cd ($T_{1/2}=8\times10^{15}$yr), $^{113m}$Cd with $CdWO_4$ scintillators and $^{48}$Ca with a $CaF_2$(Eu) detector




Observation of correlated $e^+e^-$ pairs emission in α decay of $^{241}$Am ($A_{e+e-}/A_\alpha \approx 5\times10^{-9}$)

Search for cluster decays of $^{127}$I, $^{138}$La and $^{139}$La

CNC processes, e.g. in $^{127}$I, $^{136}$Xe, $^{100}$Mo and $^{139}$La

Search for $^7$Li solar axions using resonant absorption in LiF crystal

Search for N, NN, NNN decay into invisible channels in $^{129}$Xe and $^{136}$Xe

Search for PEP violating processes in Sodium and in Iodine

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

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

**Dark Matter investigation**

**… many others are in progress**

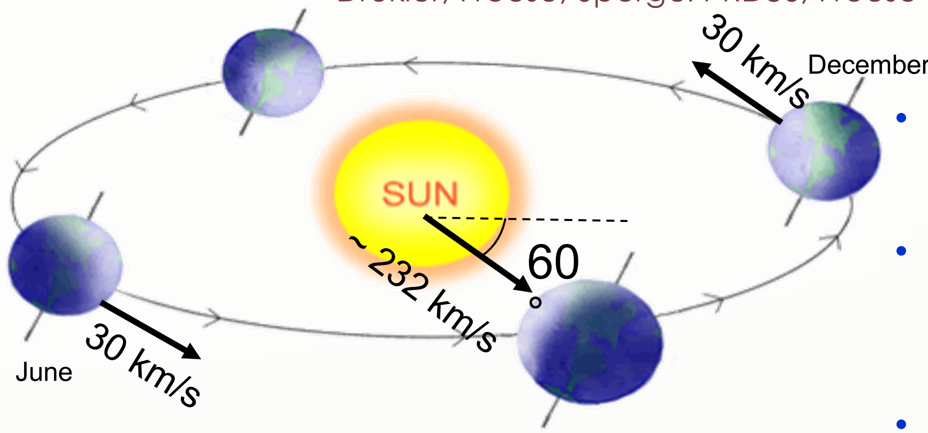
# The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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

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

## Requirements:

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




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

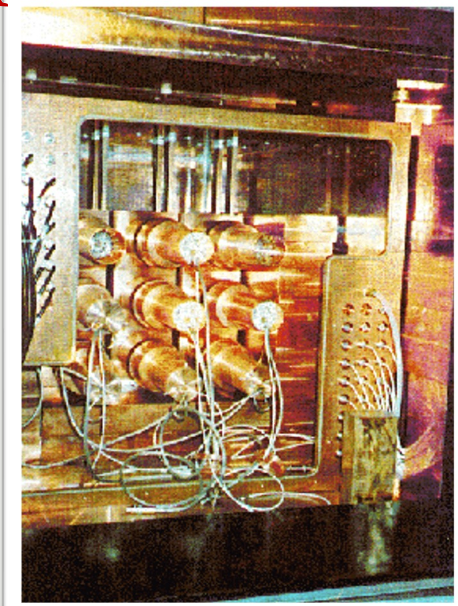
$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

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

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)

Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

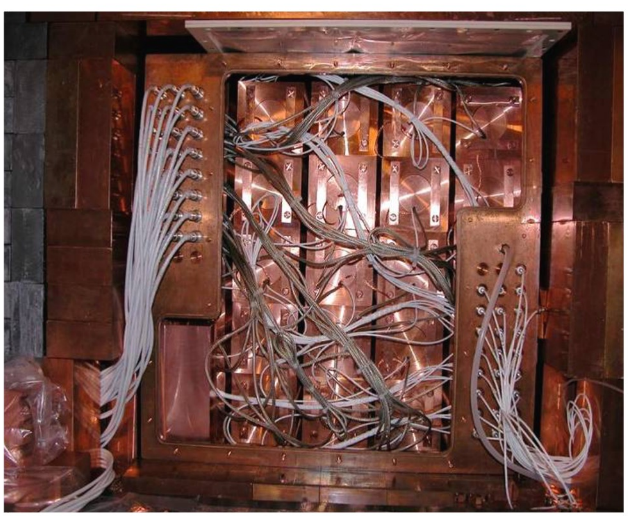
Results on rare processes: PLB408(1997)439, PRC60(1999)065501, PLB460(1999)235, PLB515(2001)6, EPJdirect C14(2002)1, EPJA23(2005)7, EPJA24(2005)51

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

Results on Annual Modulation: PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

Data taking completed on July 2002

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



- As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radio-purification techniques (all operations involving - including photos - in HP Nitrogen atmosphere)
- Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: $^{232}$Th, $^{238}$U and $^{40}$K at level of $10^{-12}$ g/g
  - Performances: NIMA592(2008)297, JINST7(2012)03009

**DAMA/LIBRA–phase1:**

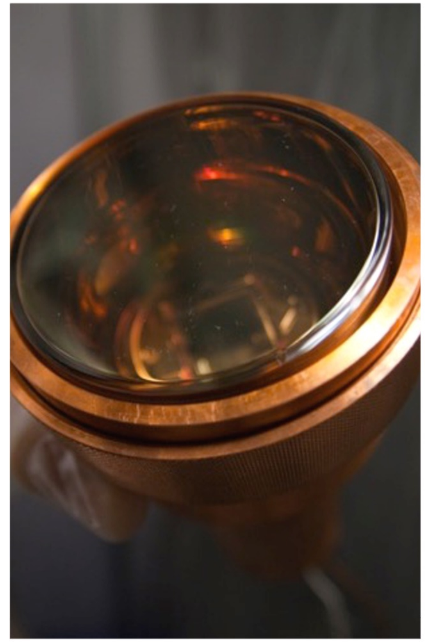
- Results on rare processes: EPJC62(2009)327, EPJC72(2012)1920, EPJA49(2013)64
- Results on DM particles: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28 (2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75 (2015) 239, EPJC75(2015)400, IJMPA31(2016), EPJC77(2017)83
- Results on Annual Modulation: EPJC56(2008)333,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

Data taking completed on July 2010

# DAMA/LIBRA–phase2

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

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

# DAMA/LIBRA–phase2

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

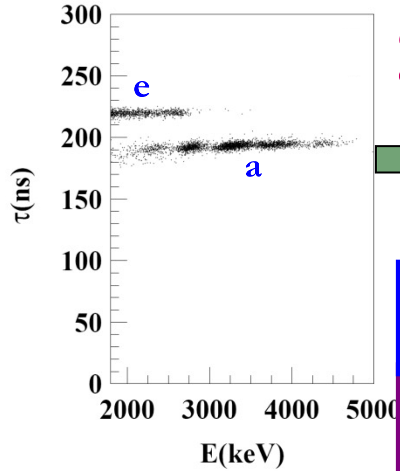
JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4) (2019) 317
PPNP114(2020)103810
NPAE 22(2021) 329

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

Goal: software energy threshold at 1 keV – accomplished

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

# Residual contaminants in the ULB NaI(Tl) detectors




$\alpha$/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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

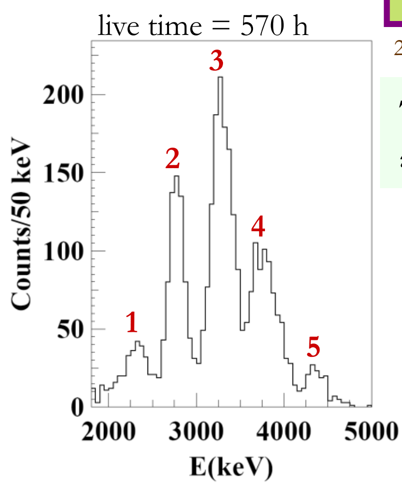
Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling

**$^{232}$Th residual contamination**

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

**$^{238}$U residual contamination**

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



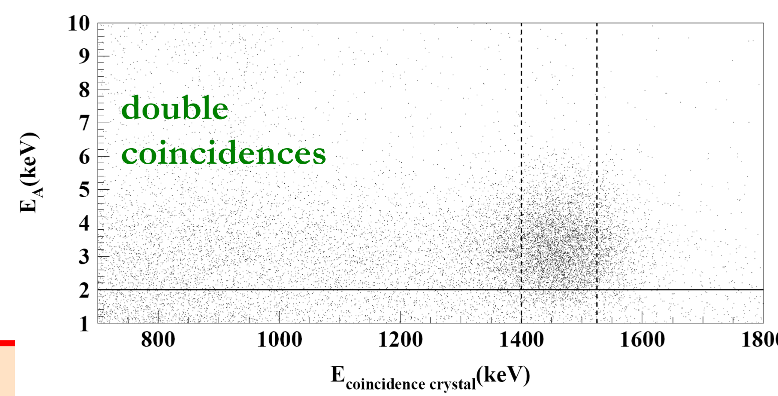

$^{238}$U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

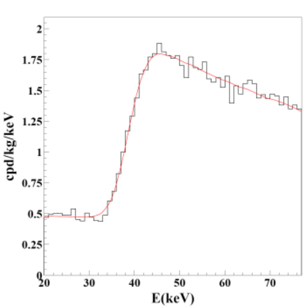
Thus, in this case: (2.1±0.1) ppt of $^{232}$Th; (0.35 ±0.06) ppt for $^{238}$U

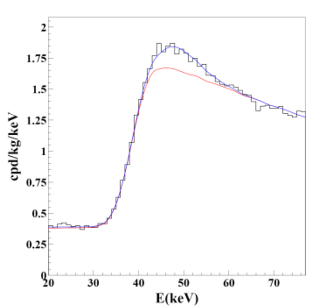
and: (15.8±1.6) μBq/kg for $^{234}$U + $^{230}$Th; (21.7±1.1) μBq/kg for $^{226}$Ra; (24.2±1.6) μBq/kg for $^{210}$Pb.

**$^{nat}$K residual contamination**

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




**$^{129}$I and $^{210}$Pb**

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

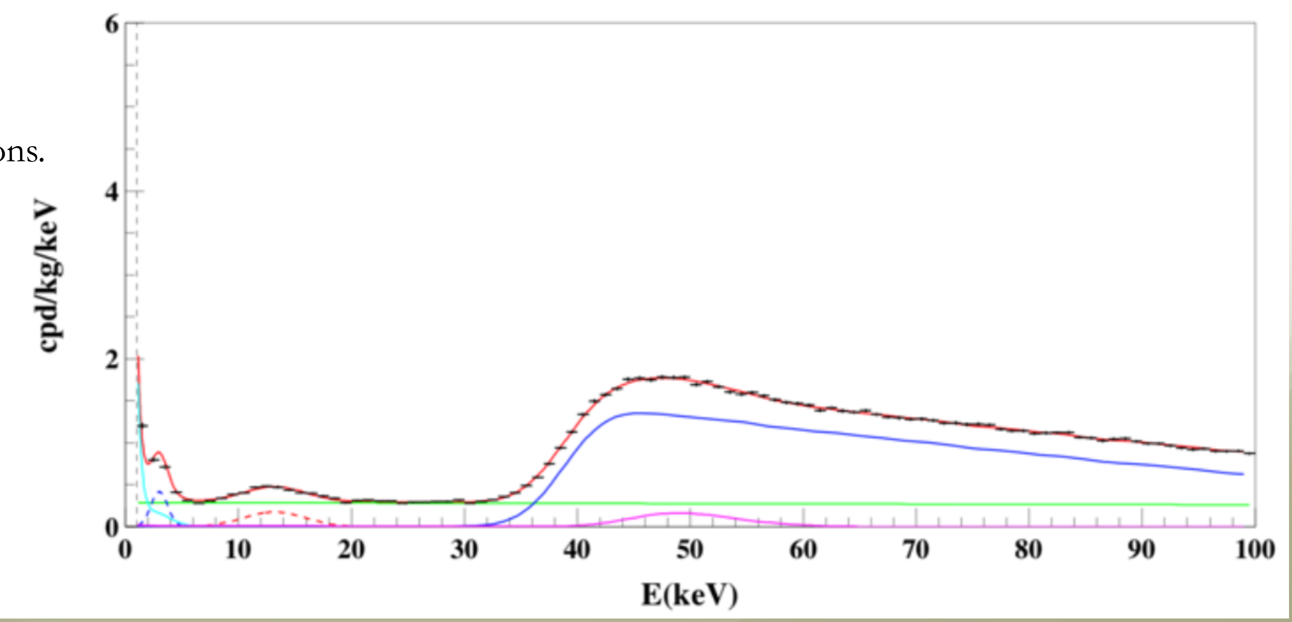
$^{210}$Pb in the new detectors: (5 − 30) μBq/kg.

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

... more on NIMA592(2008)297

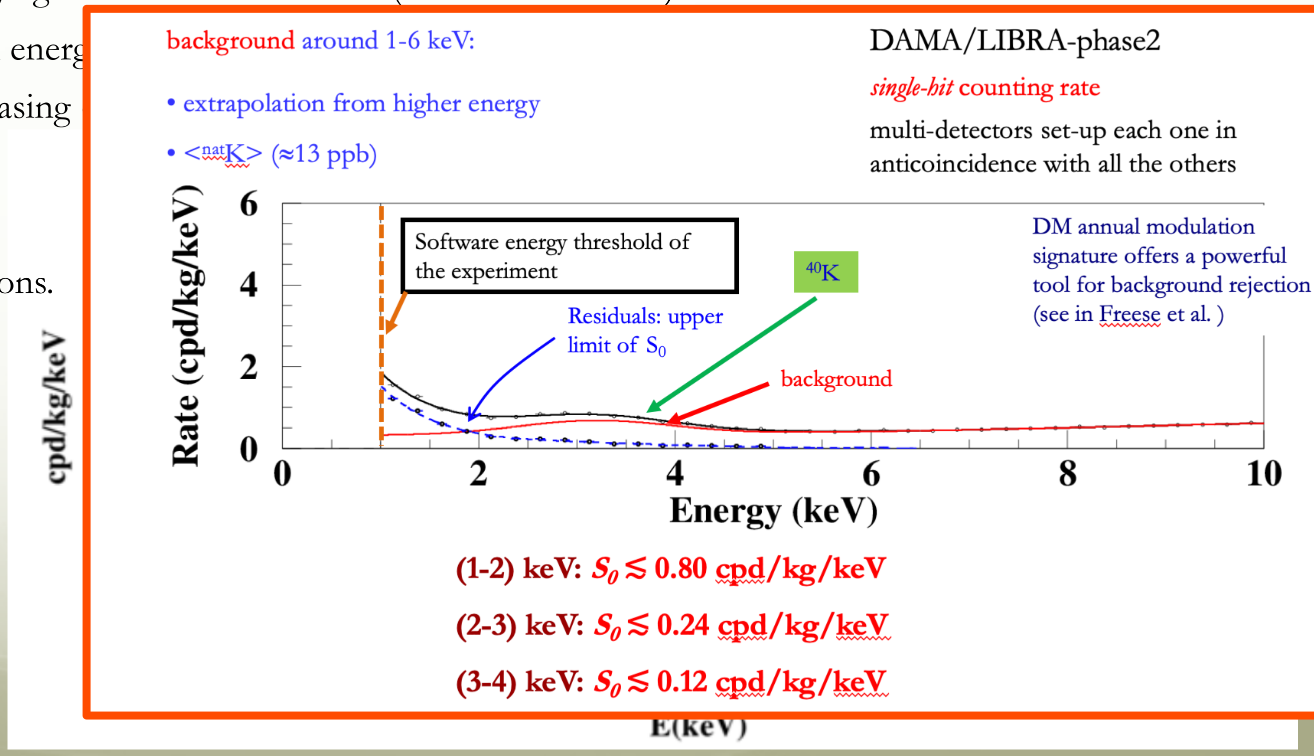
# DAMA/LIBRA energy spectrum

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



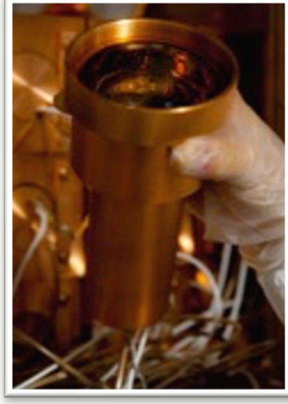
# DAMA/LIBRA energy spectrum

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



# DAMA/LIBRA-phase2 data taking

Upgrade at end of 2010: all PMTs replaced with new ones of higher Q.E.



Energy resolution @ 60 keV mean value:

prev. PMTs 7.5% (0.6% RMS)
new HQE PMTs 6.7% (0.5% RMS)

+ also analyzed with 0.75 keV energy threshold, see later

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

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

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

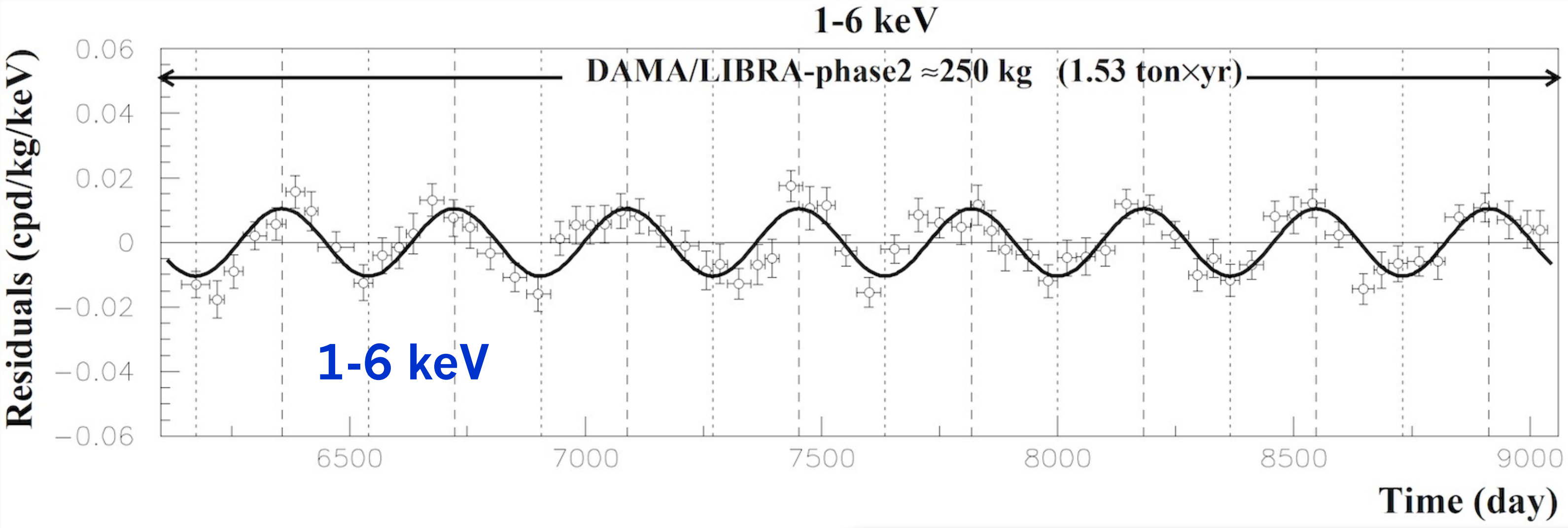
Exposure of DAMA/LIBRA-phase2 with the annual cycles released so far: **1.53 ton × yr**

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

# DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.53 ton × yr)

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




Absence of modulation? No

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

Fit on DAMA/LIBRA-phase2

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

**1-6 keV**

A=(0.01048±0.00090) cpd/kg/keV

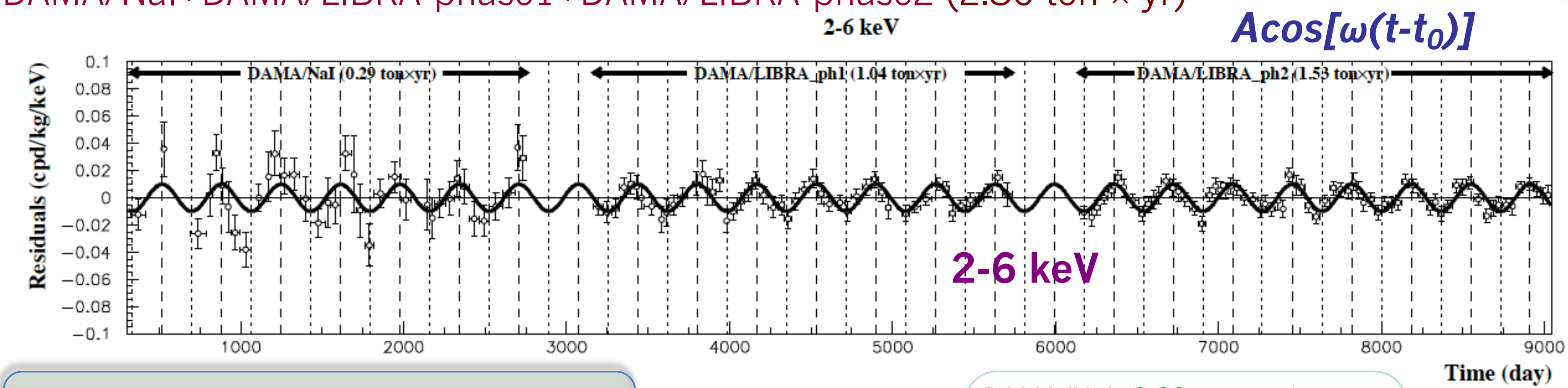
$\chi^2$/dof = 66.2/68 **11.6 σ C.L.**

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

# DM model-independent Annual Modulation Result

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

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




Absence of modulation? No

$\chi^2$/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

$\chi^2$/dof = 130/155 **13.4 σ C.L.**

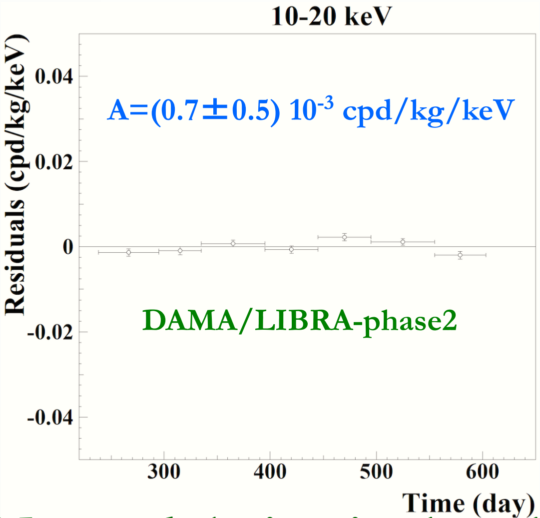
## Releasing period (*T*) and phase ($t_0$) in the fit

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

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

# Examples of consistency: Rate behaviour above 6 keV

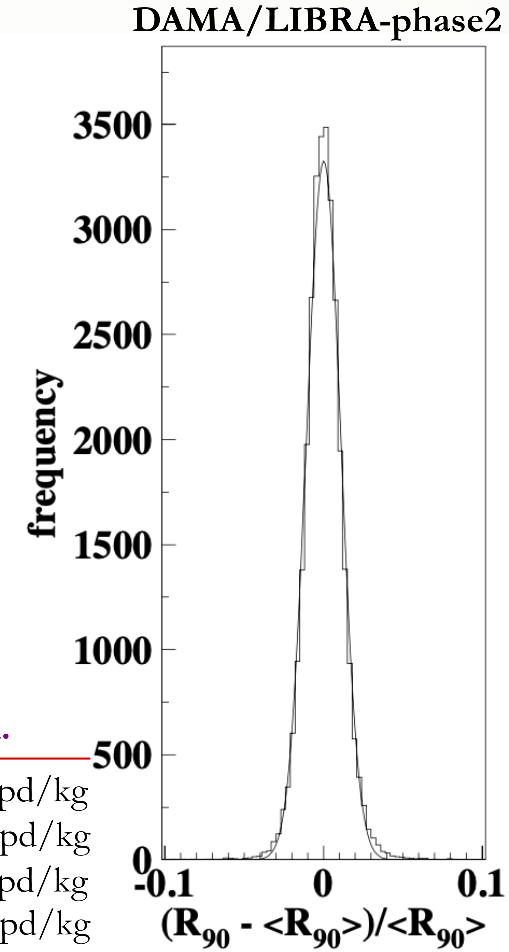
- **No Modulation above 6 keV**




Mod. Ampl. (6-14 keV): cpd/kg/keV

(0.0032 ± 0.0017) DAMA/LIBRA-ph2_2
(0.0016 ± 0.0017) DAMA/LIBRA-ph2_3
(0.0024 ± 0.0015) DAMA/LIBRA-ph2_4
-(0.0004 ± 0.0015) DAMA/LIBRA-ph2_5
(0.0001 ± 0.0015) DAMA/LIBRA-ph2_6
(0.0015 ± 0.0014) DAMA/LIBRA-ph2_7
-(0.0005 ± 0.0013) DAMA/LIBRA-ph2_8
-(0.0003 ± 0.0014) DAMA/LIBRA-ph2_9

→ statistically consistent with zero




σ ≈ 1%, fully accounted by statistical considerations

- **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

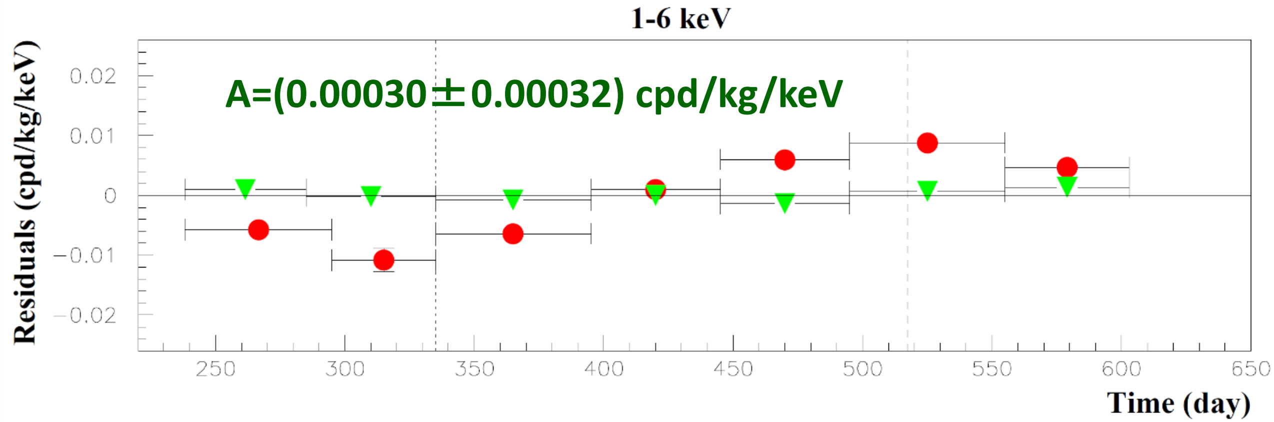
| Period | Mod. Ampl. |
|---|---|
| DAMA/LIBRA-ph2_2 | (0.12±0.14) cpd/kg |
| DAMA/LIBRA-ph2_3 | -(0.08±0.14) cpd/kg |
| DAMA/LIBRA-ph2_4 | (0.07±0.15) cpd/kg |
| DAMA/LIBRA-ph2_5 | -(0.05±0.14) cpd/kg |
| DAMA/LIBRA-ph2_6 | (0.03±0.13) cpd/kg |
| DAMA/LIBRA-ph2_7 | -(0.09±0.14) cpd/kg |
| DAMA/LIBRA-ph2_8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

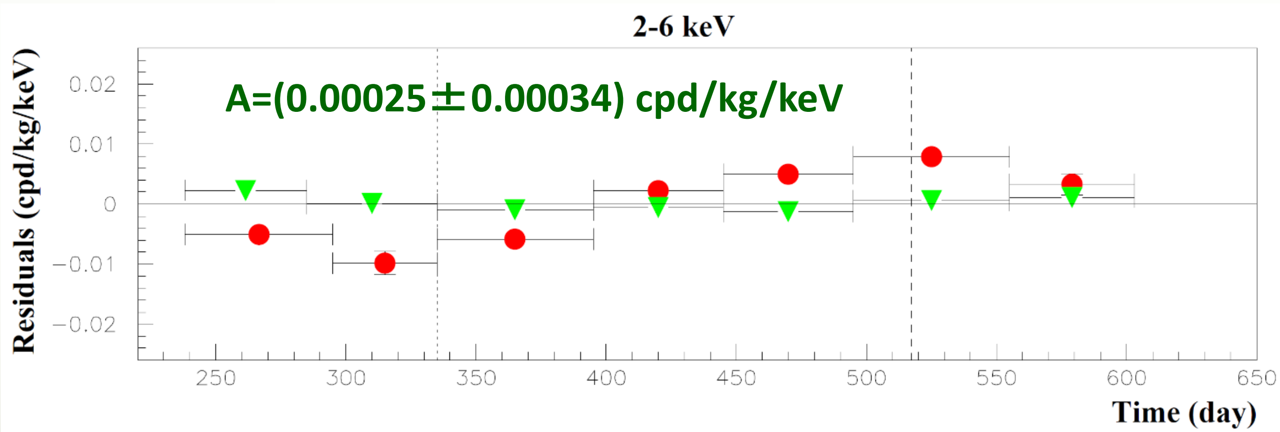
**No modulation above 6 keV**
**This accounts for all sources of bckg and is consistent with the studies on the various components**

# DM model-independent Annual Modulation Result

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

**Multiple hits events = Dark Matter particle "switched off"**




**Single hit residual rate (red)** vs **Multiple hit residual rate (green)**

- Clear modulation in the single hit events;
- No modulation in the residual rate of the multiple hit events

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

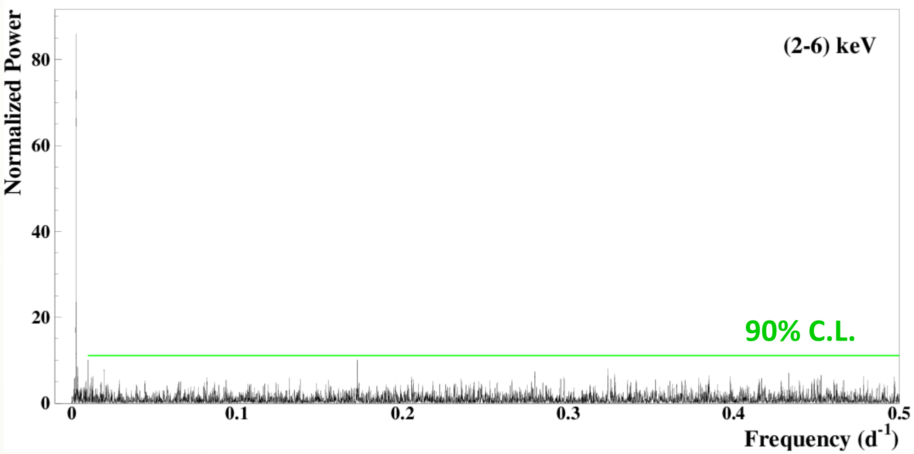
# The analysis in frequency

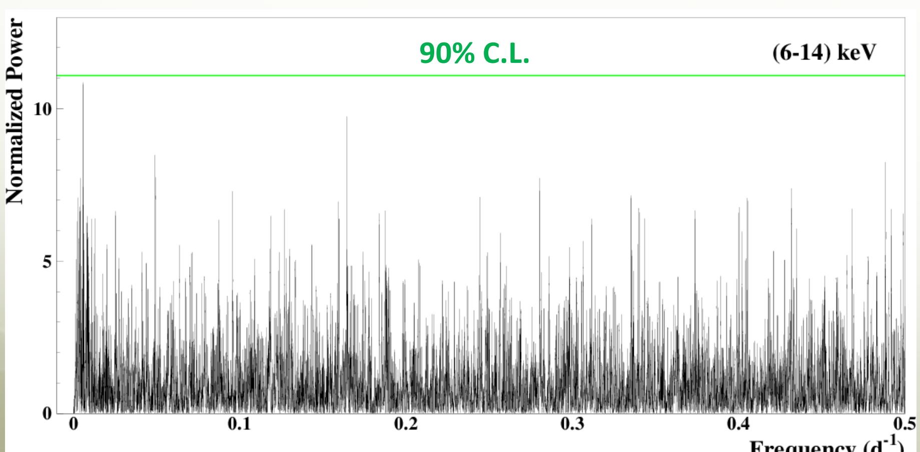
(according to PRD75 (2007) 013010)

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

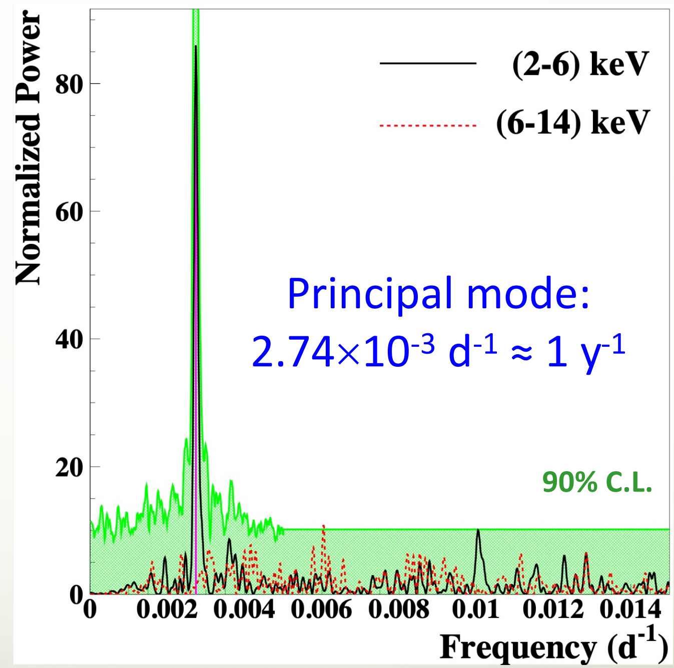
DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (22 yr)
total exposure: 2.86 ton×yr

The whole power spectra up to the Nyquist frequency




Zoom around the 1 y$^{-1}$ peak




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

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

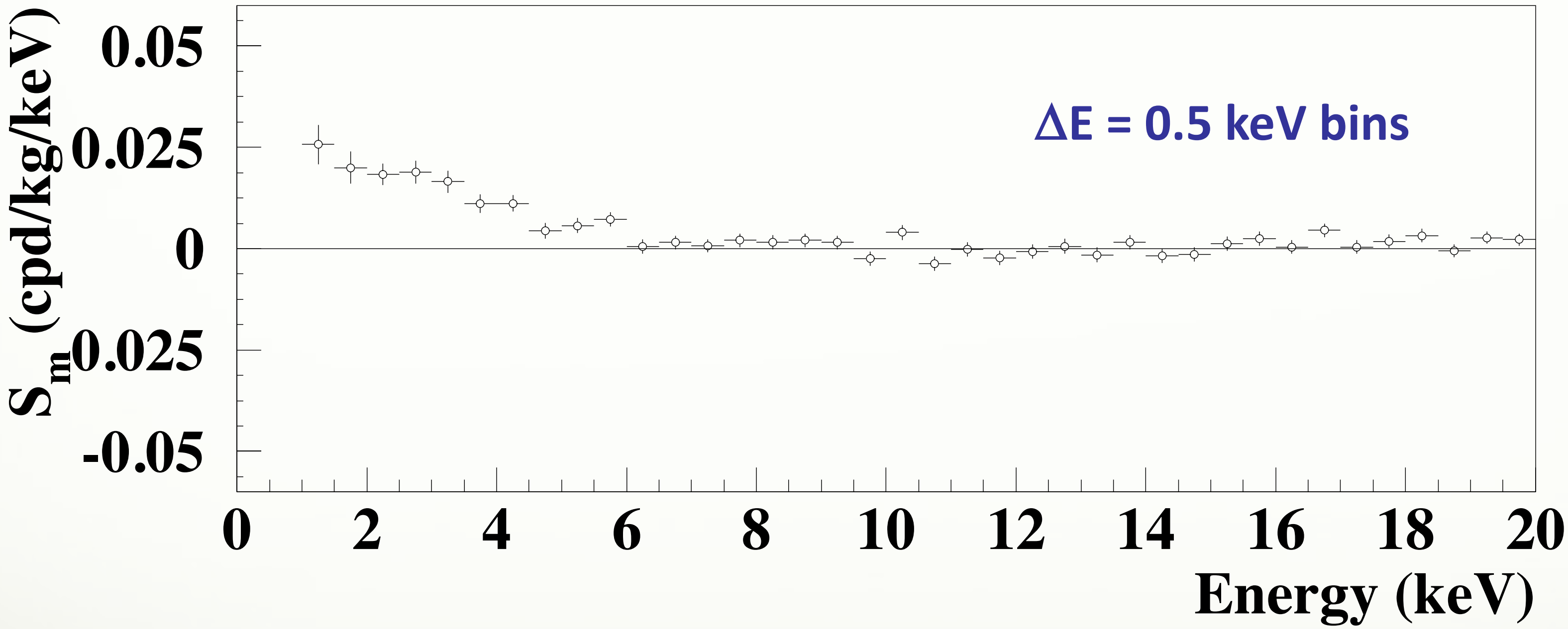
# Energy distribution of the modulation amplitudes

Max-likelihood analysis

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

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

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



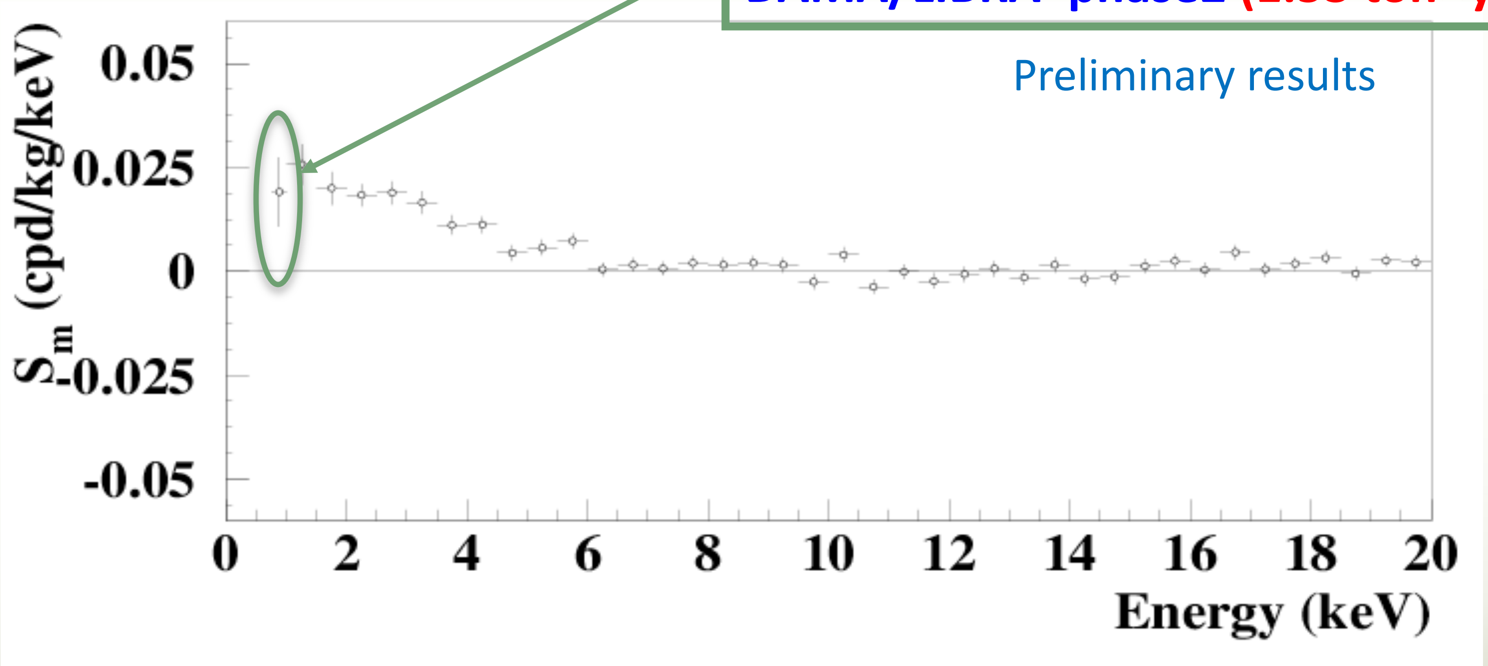

A clear modulation is present in the (1-6) keV energy interval, while $S_m$ values compatible with zero are present just above

- The $S_m$ values in the (6–14) keV energy interval have random fluctuations around zero with $\chi^2$ equal to 20.3 for 16 degrees of freedom (upper tail probability 21%).
- In (6–20) keV $\chi^2$/dof = 42.2/28 (upper tail probability 4%). The obtained $\chi^2$ 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%.

# First attempt towards lower software energy threshold

- decreasing the software energy threshold down to 0.75 keV in the already published exposure of DAMA/LIBRA–phase2
- using the same technique to remove the noise pulses
- evaluating the efficiency by dedicated studies

New data point in 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 suggested the necessity to lower the software energy threshold and to improve the experimental error on the first energy bin

# 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)

**arXiv:2209.00882**

- 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 radio-purity of the set-up

Claims that the DAMA annual modulation signal may be biased by a slow variation only in the low-energy *single-hit* rate, possibly due to bckg increasing with time → already **confuted** quantitatively (see e.g. Prog. Part. Nucl. Phys. 114, 103810, 2020 and here)

For example:

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

- The (2–6) keV *single-hit* residual rates – recalculated considering a possible time–varying background – well **compatible** with those obtained in the *original* analysis

**2) The tail of the $S_m$ distribution case.**

- No **fake modulation amplitudes** on the tail of the $S_m$ distribution above the energy region where the signal is present

**3) The maximum likelihood analysis.**

- The maximum likelihood analysis including a **linear term decreasing with time** yields to results **compatible** with those obtained in the *original* analysis

**4) Multiple-hit events**

- **No modulation** has been found in the ***multiple-hit*** events the same energy region where the annual modulation is present in the *single-hit* events

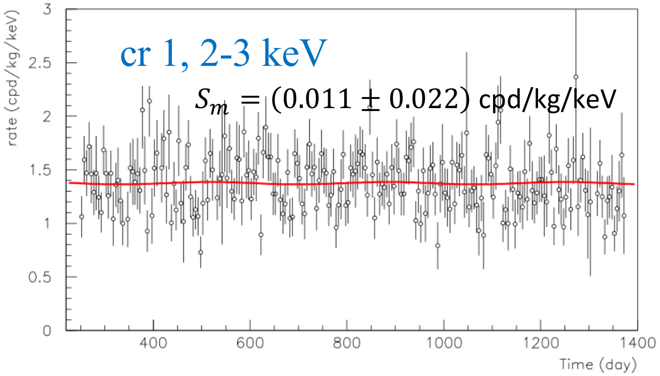
**5) Analysis of the last three years (see next slides)**

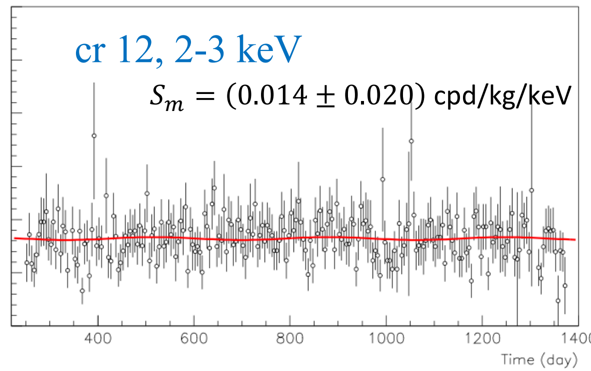
- The **last three published years** of DAMA/LIBRA–phase2 (in which there was continuity between one year and the next) analysed considering the same bckg (w/ and w/o any slope)

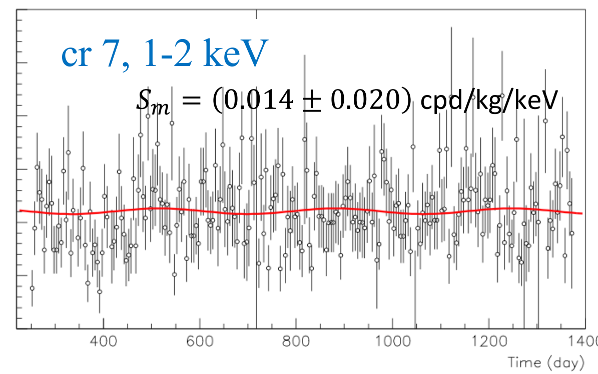
Any effect of long–term time–varying bckg or odd low-energy rate increasing with time ➔ **negligible** in DAMA/LIBRA, thanks to the radiopurity and long-time underground of the ULB DAMA/LIBRA NaI(Tl)

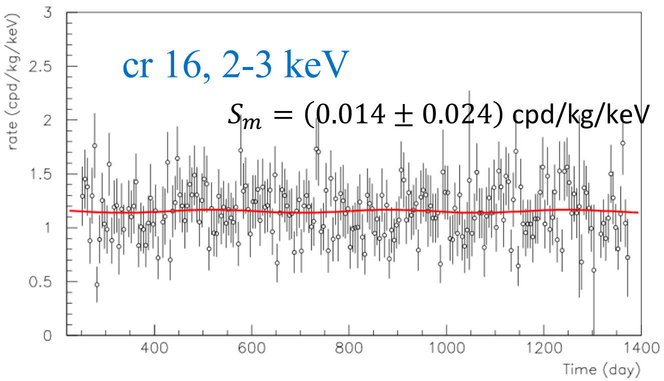
**The original DAMA analyses can be safely adopted**

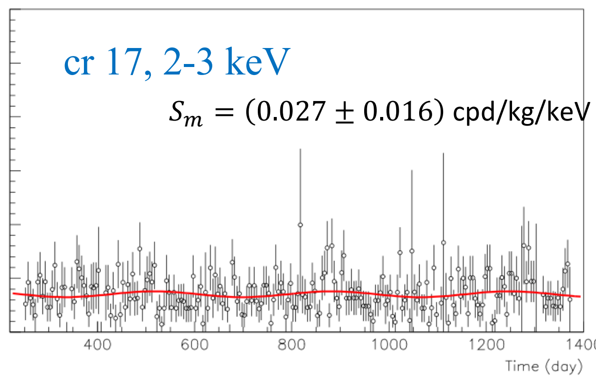
# The **last three published years** of DAMA/LIBRA–phase2 (in which there was continuity between one year and the next) analysed **considering the same bckg**

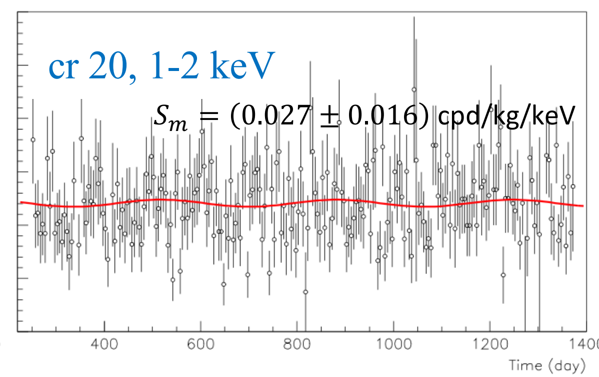


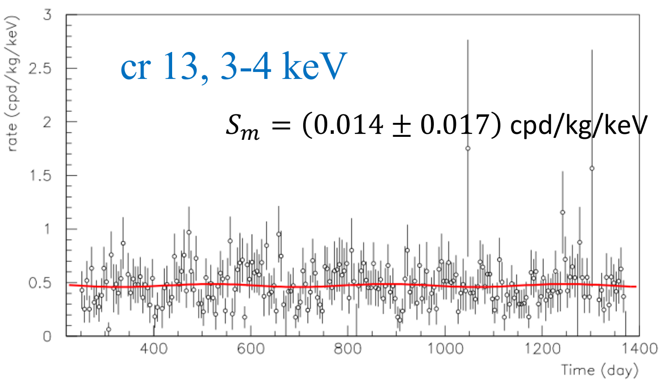



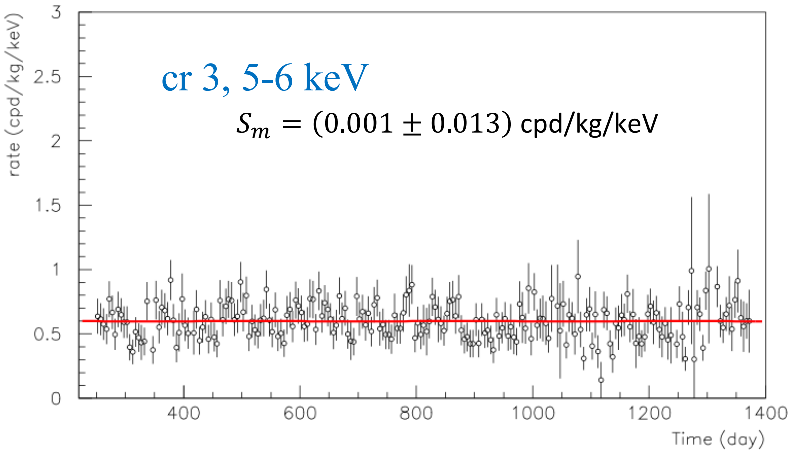



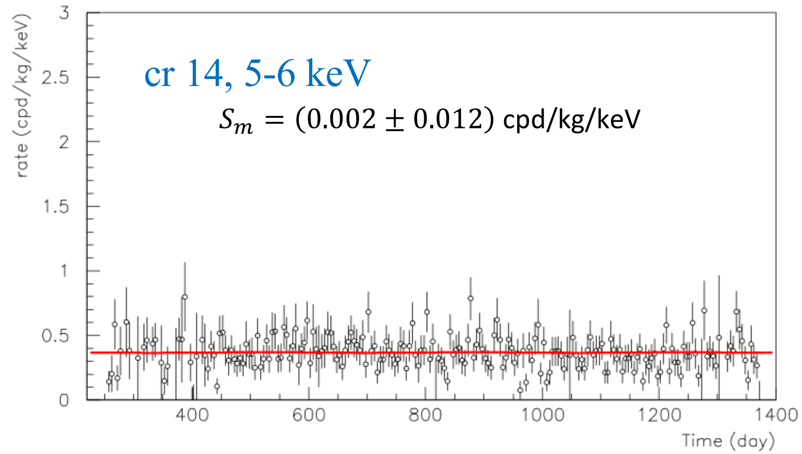

$\sigma_{Sm}(1 \text{ crystal}) \simeq 0.02 \rightarrow \sigma_{Sm}(25 \text{ crystals}) \simeq \frac{0.02}{\sqrt{25}} \simeq 0.004$ cpd/kg/keV

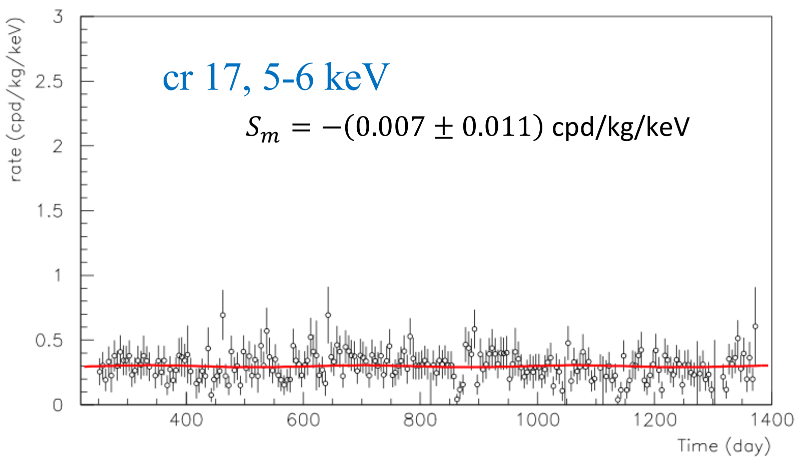
- Time bin: 5 days
- red: maxlik analysis on single crystal with common (constant) background

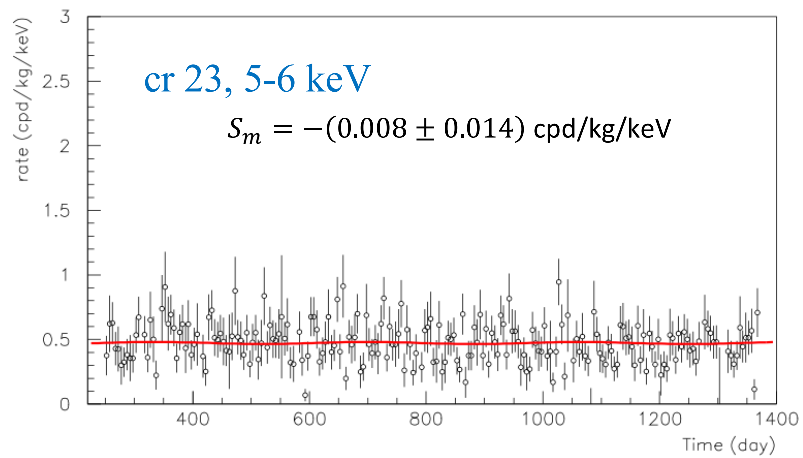
Expected rate over three years: $\mu_{ij} = b_j + S_0 + S_m cos[\omega(t_i - t_0)]$

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**

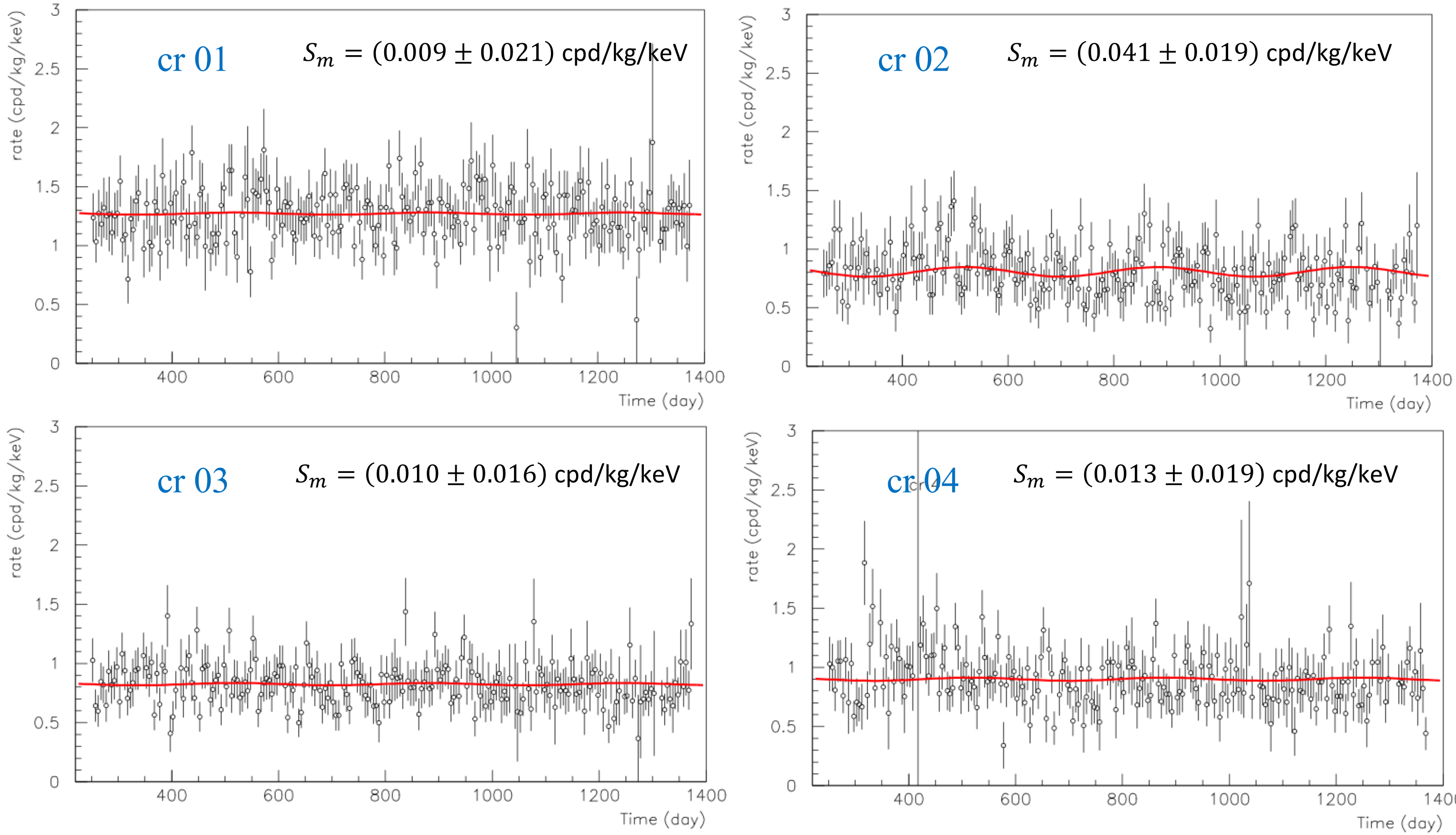


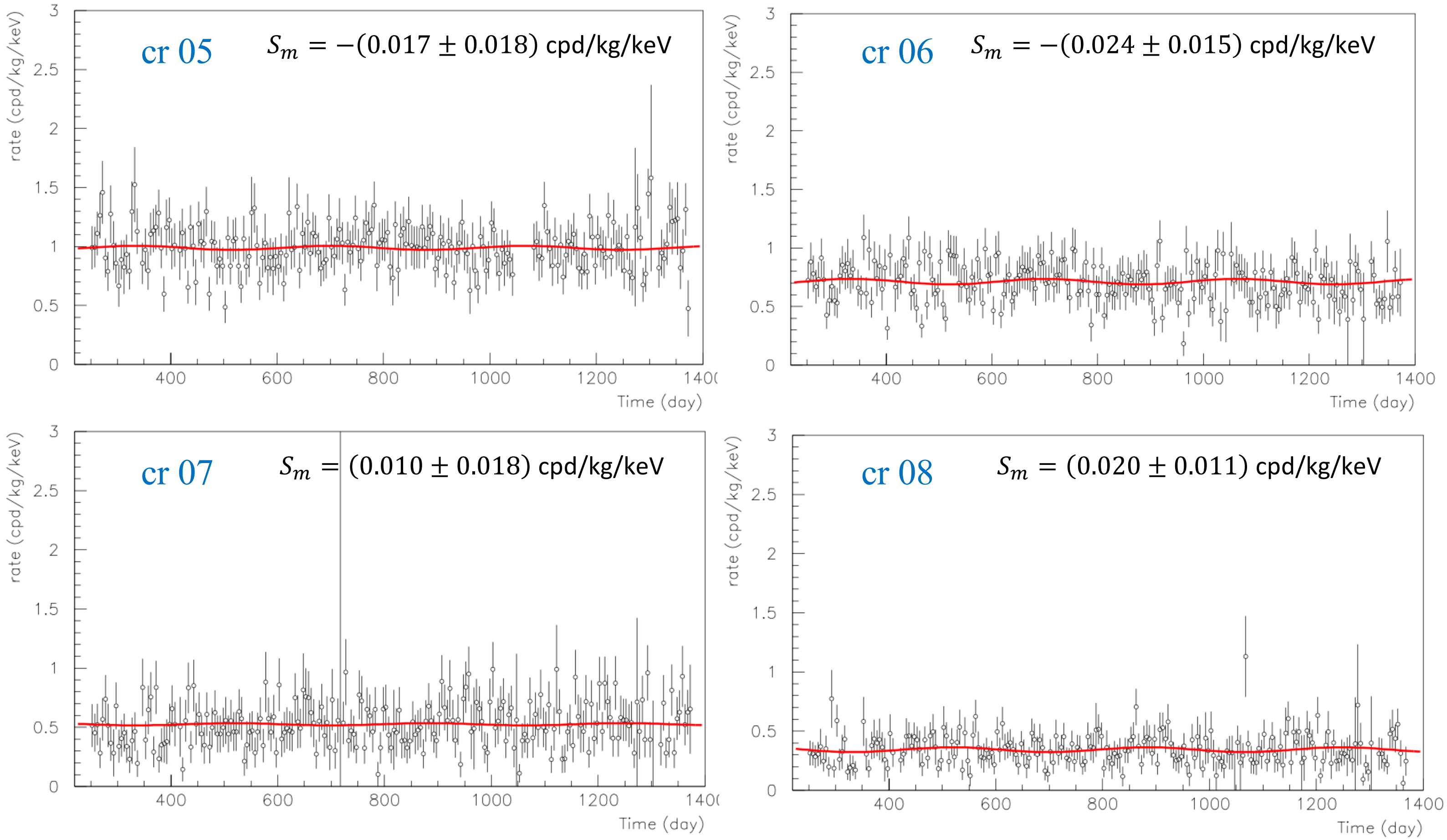
# **A template case:** the energy bin 3-4 keV, for each crystal, along the **last three published years** of DAMA/LIBRA–phase2 (0.61 ton×yr)




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

- Time bin: 5 days
- $S_m$ over all crystals: (0.0092±0.0034) cpd/kg/keV
- $\chi^2$/dof=0.88 – 1.27 (1.52)
- red: maxlik analysis on single crystal

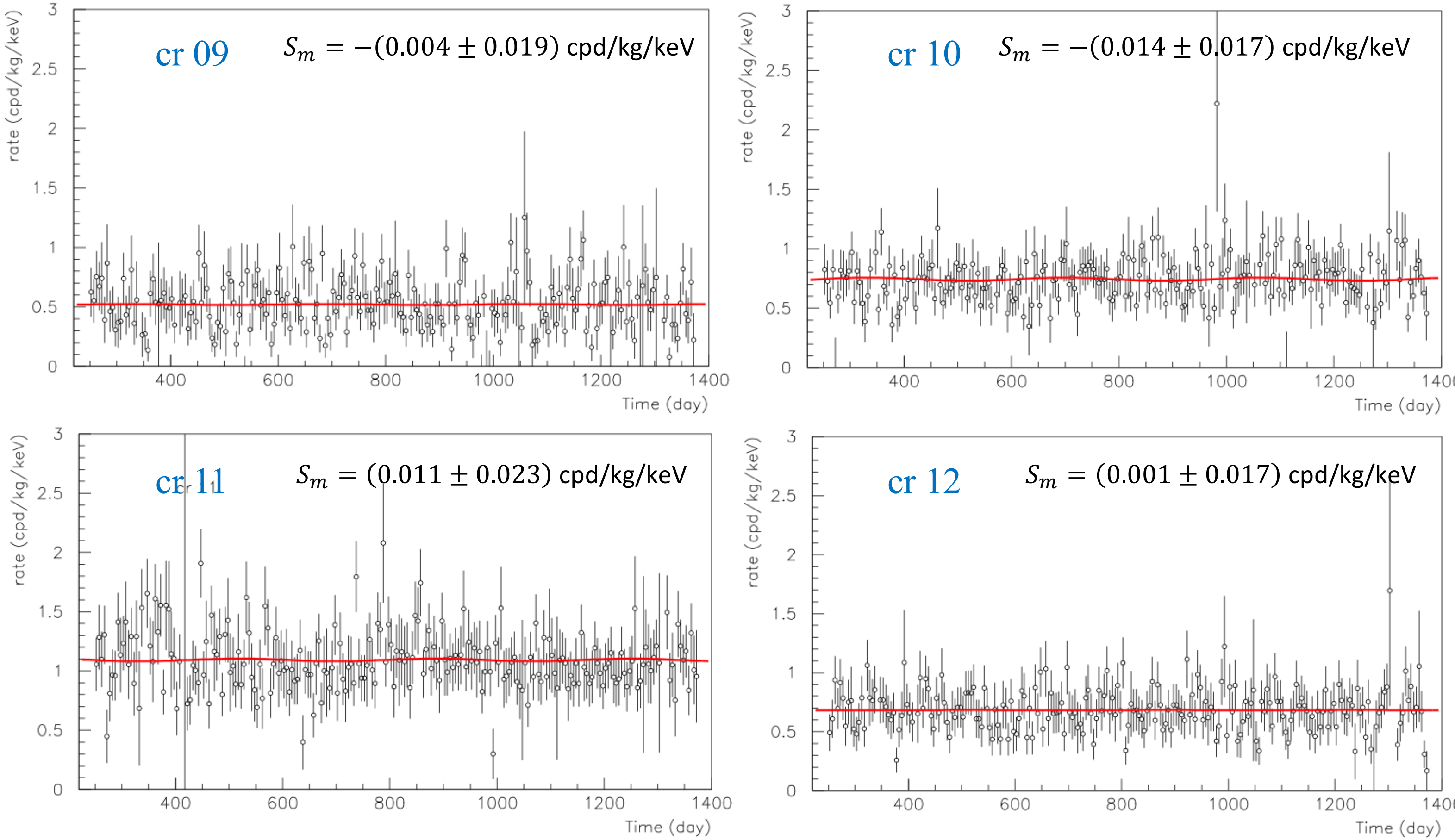
# **A template case:** the energy bin 3-4 keV, for each crystal, along the **last three published years** of DAMA/LIBRA–phase2 (0.61 ton×yr)




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

- Time bin: 5 days
- $S_m$ over all crystals: (0.0092±0.0034) cpd/kg/keV
- $\chi^2$/dof=0.88 – 1.27 (1.52)
- red: maxlik analysis on single crystal

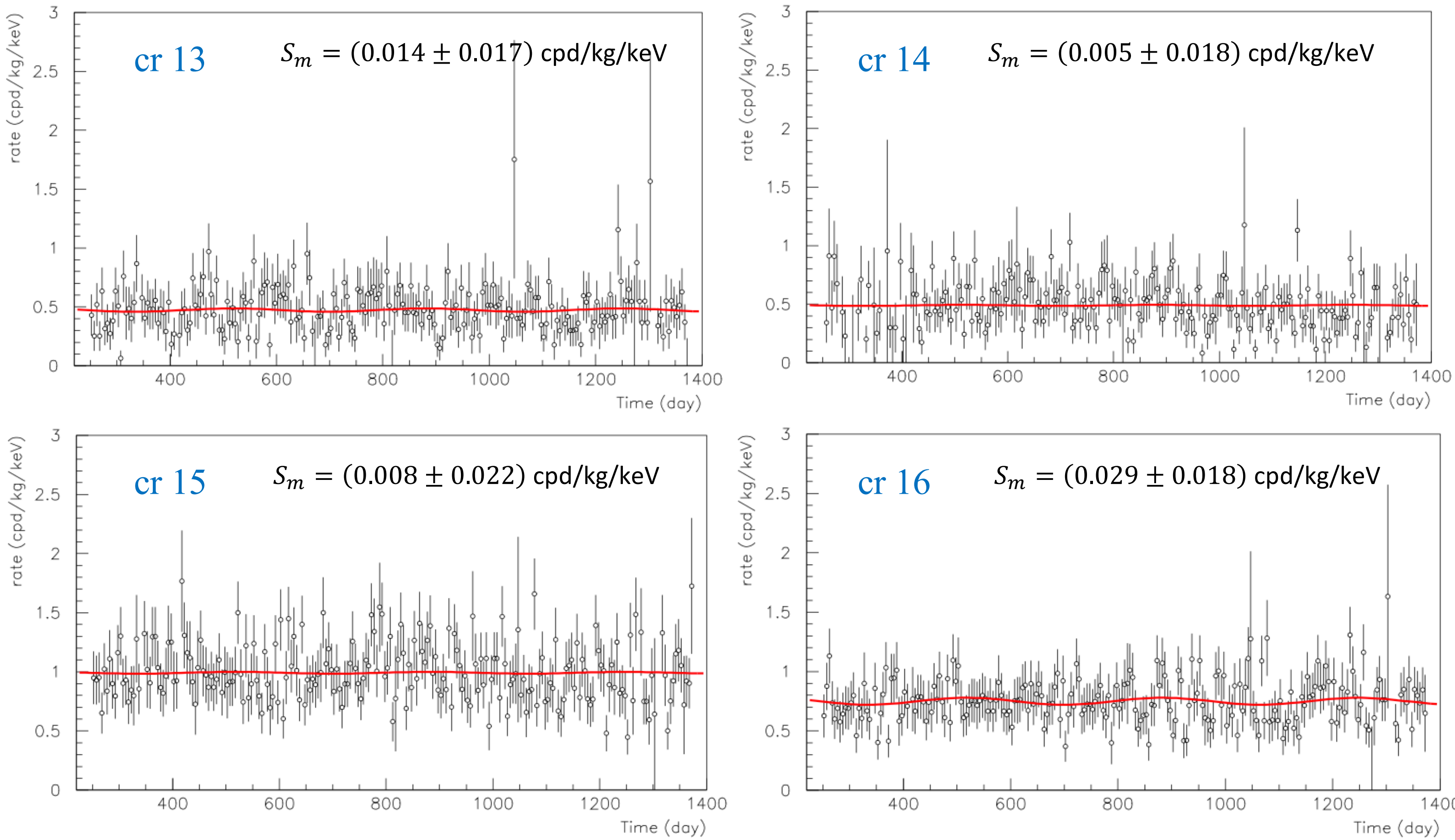
## **A template case:** the energy bin 3-4 keV, for each crystal, along the **last three published years** of DAMA/LIBRA–phase2 (0.61 ton×yr)




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

- Time bin: 5 days
- $S_m$ over all crystals: (0.0092±0.0034) cpd/kg/keV
- $\chi^2$/dof=0.88 – 1.27 (1.52)
- red: maxlik analysis on single crystal

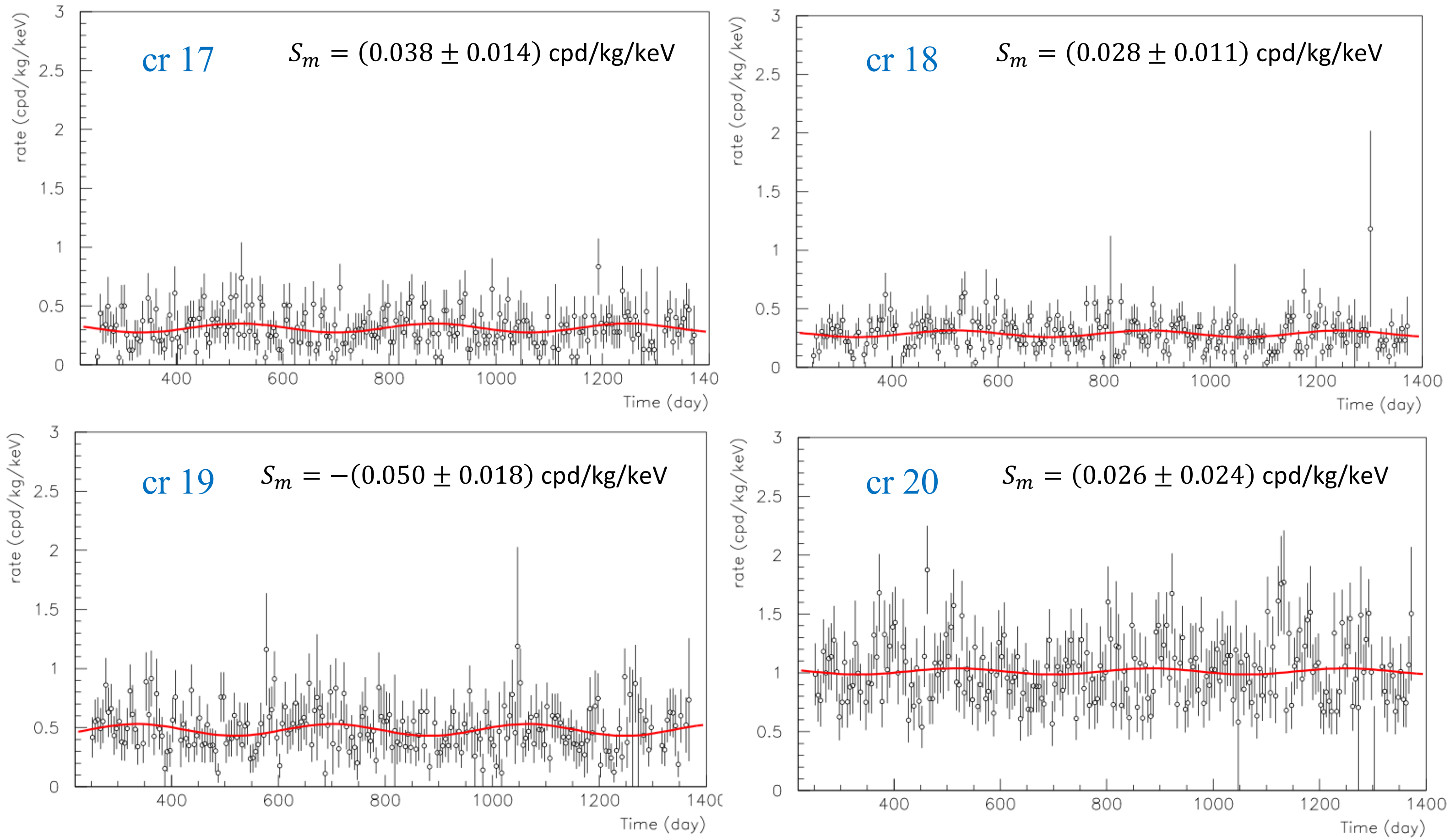
## **A template case:** the energy bin 3-4 keV, for each crystal, along the **last three published years** of DAMA/LIBRA–phase2 (0.61 ton×yr)




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

- Time bin: 5 days
- $S_m$ over all crystals: (0.0092±0.0034) cpd/kg/keV
- $\chi^2$/dof=0.88 – 1.27 (1.52)
- red: maxlik analysis on single crystal

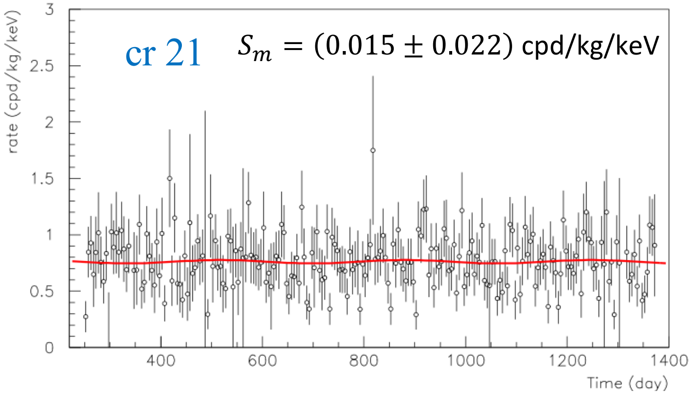
**A template case:** the energy bin 3-4 keV, for each crystal, along the **last three published years** of DAMA/LIBRA–phase2 (0.61 ton×yr)

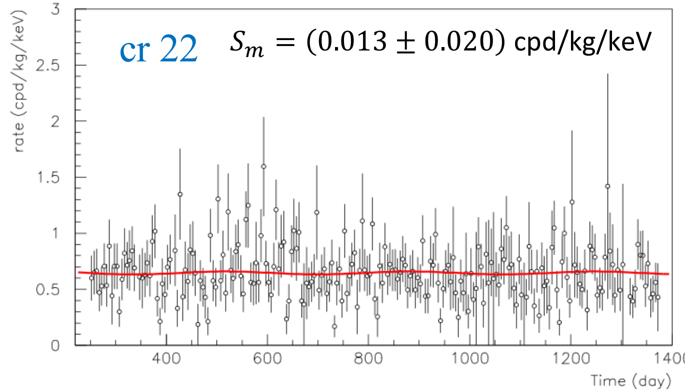


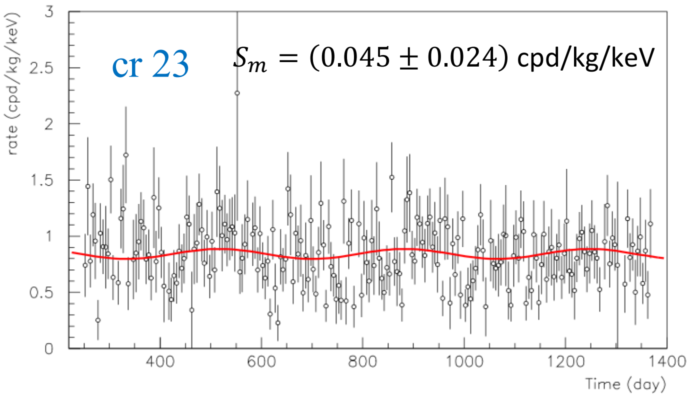

$$\sigma_{Sm}(1 \text{ crystal}) \simeq 0.02 \rightarrow \sigma_{Sm}(25 \text{ crystals}) \simeq \frac{0.02}{\sqrt{25}} \simeq 0.004 \text{ cpd/kg/keV}$$

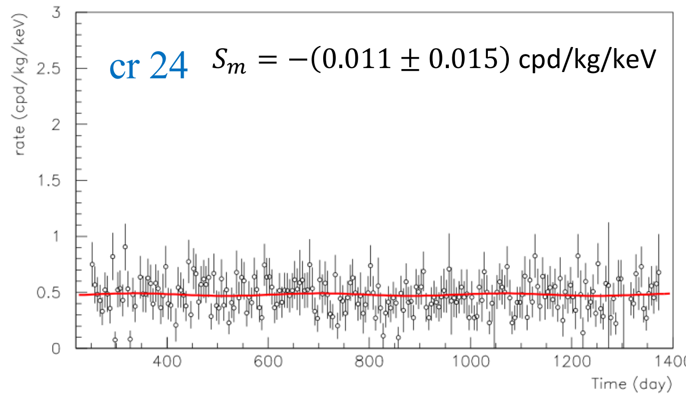
- Time bin: 5 days
- $S_m$ over all crystals: (0.0092±0.0034) cpd/kg/keV
- $\chi^2$/dof=0.88 – 1.27 (1.52)
- red: maxlik analysis on single crystal

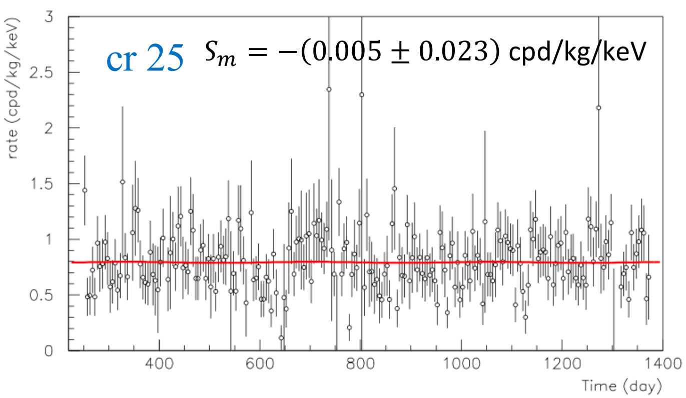
**A template case:** the energy bin 3-4 keV, for each crystal, along the **last three published years** of DAMA/LIBRA–phase2 (0.61 ton×yr)




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

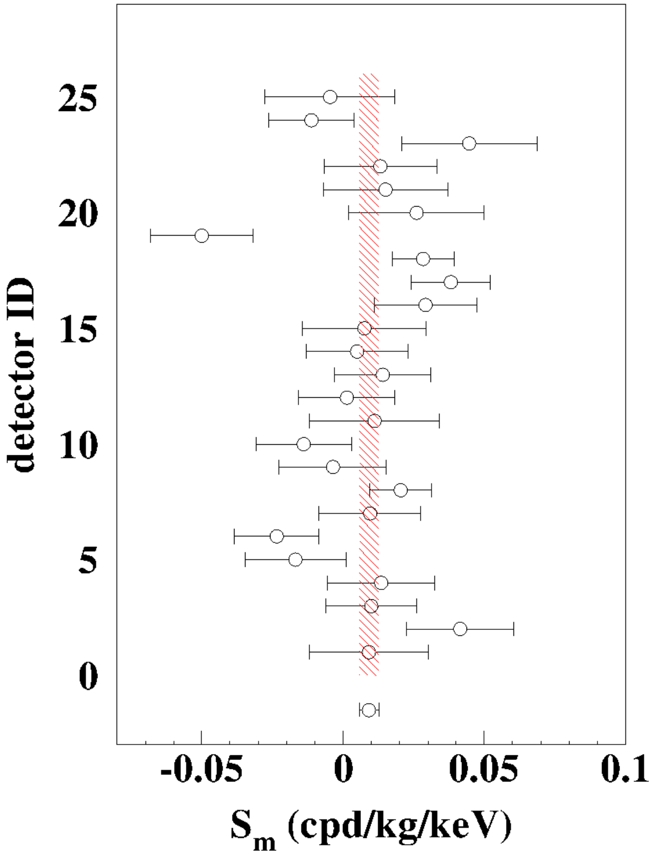
- Time bin: 5 days
- $S_m$ over all crystals: (0.0092±0.0034) cpd/kg/keV

- $\chi^2$/dof=0.88 – 1.27 (1.52)
- red: maxlik analysis on single crystal

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

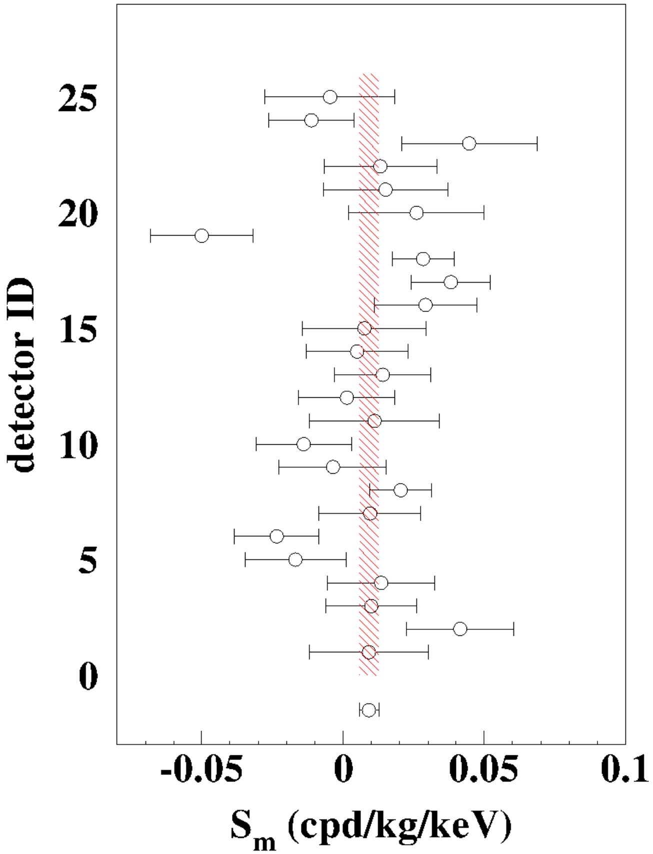
$\sigma_{Sm}(1 \text{ detector}) \simeq 0.02 \rightarrow \sigma_{Sm}(25 \text{ detectors}) \simeq \frac{0.02}{\sqrt{25}} \simeq 0.004$ cpd/kg/keV

- $S_m$ over all: (0.0092±0.0034) cpd/kg/keV

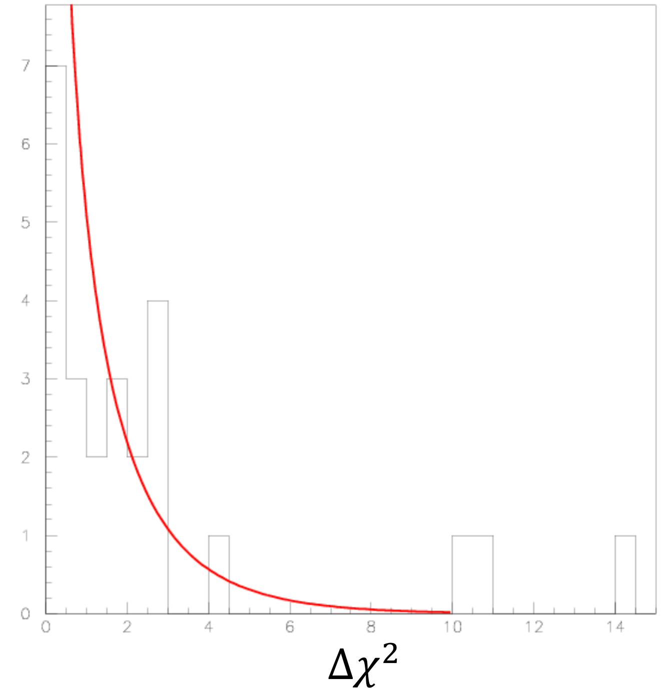


**A template case:** the energy bin 3-4 keV, for each crystal, along the **last three published years** of DAMA/LIBRA–phase2 (0.61 ton×yr)

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

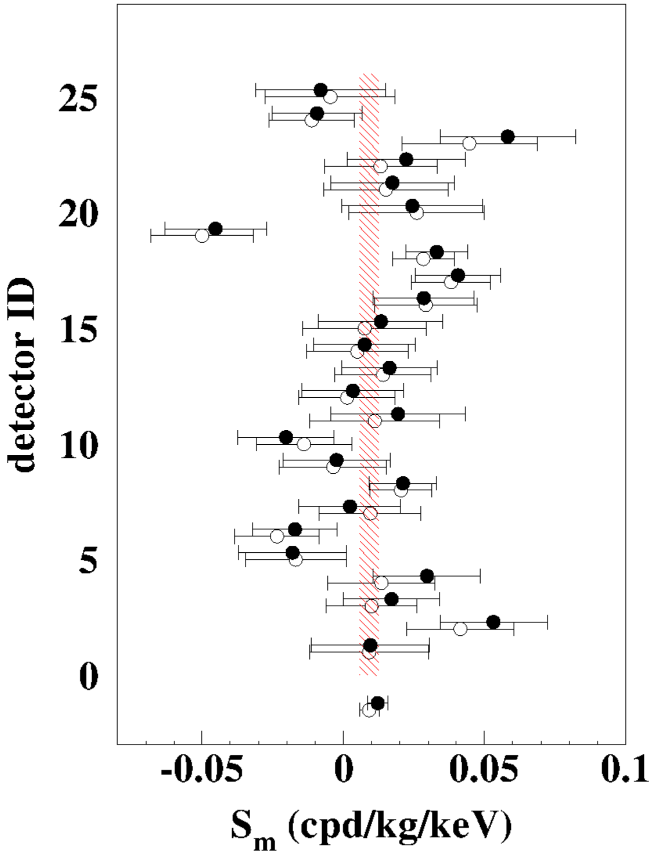



- Plot of $\Delta\chi^2$ for each detector
- It follows a $\chi^2$ distribution with dof=1
- No necessity to enable the slope with time.

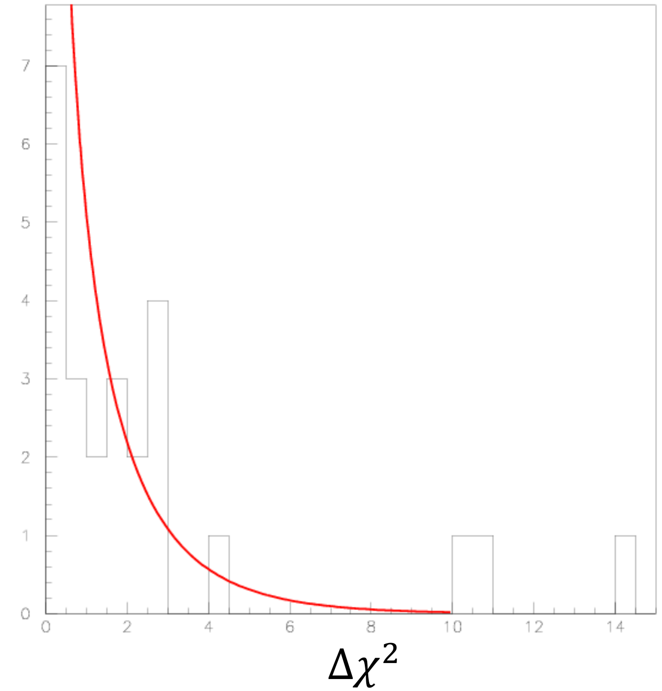


**A template case:** the energy bin 3-4 keV, for each crystal, along the **last three published years** of DAMA/LIBRA–phase2 (0.61 ton×yr)

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



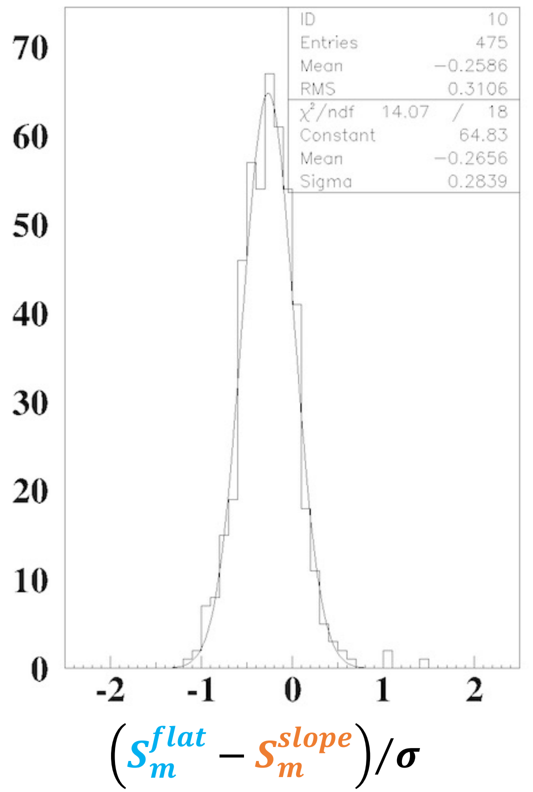

- Plot of $\Delta\chi^2$ for each detector
- It follows a $\chi^2$ distribution with dof=1
- No necessity to enable the slope with time.




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

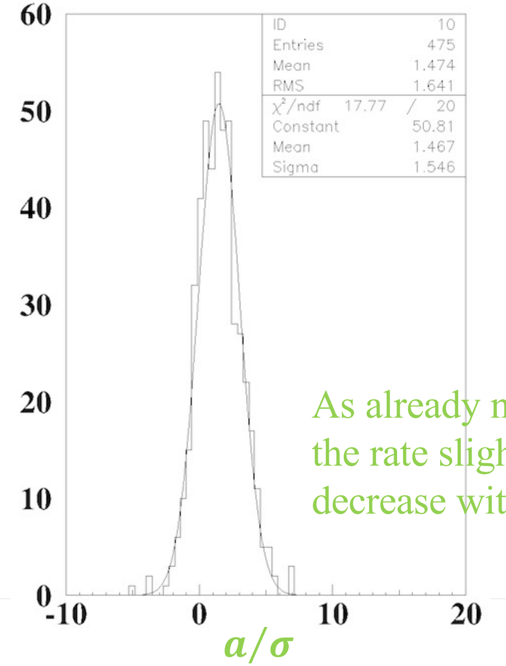
# The general case: the last three published years of DAMA/LIBRA–phase2 (0.61 ton×yr)

- 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

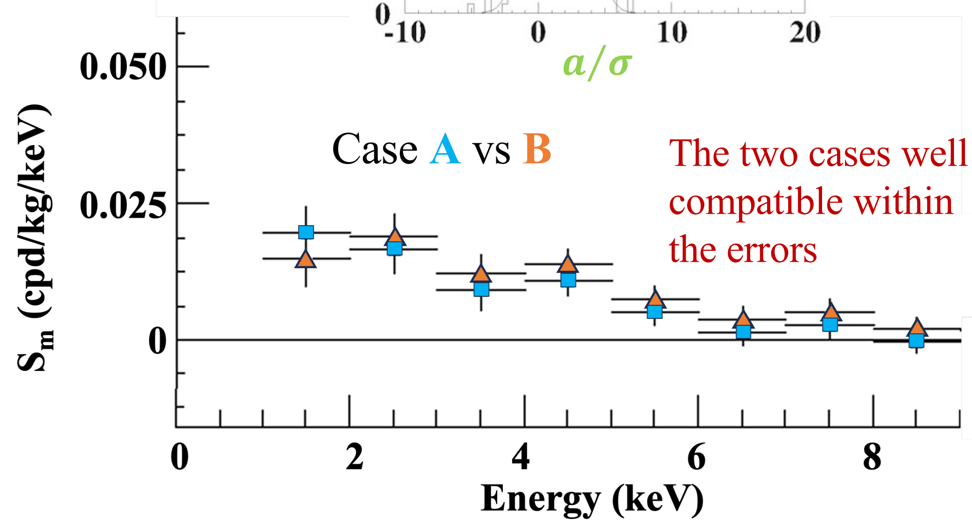



- The mean shift of the modulation amplitudes due to the introduction in the fit of a slope is ≃ $0.27\sigma$

Slope distribution over three annual cycles




As already noted, the rate slightly decrease with time



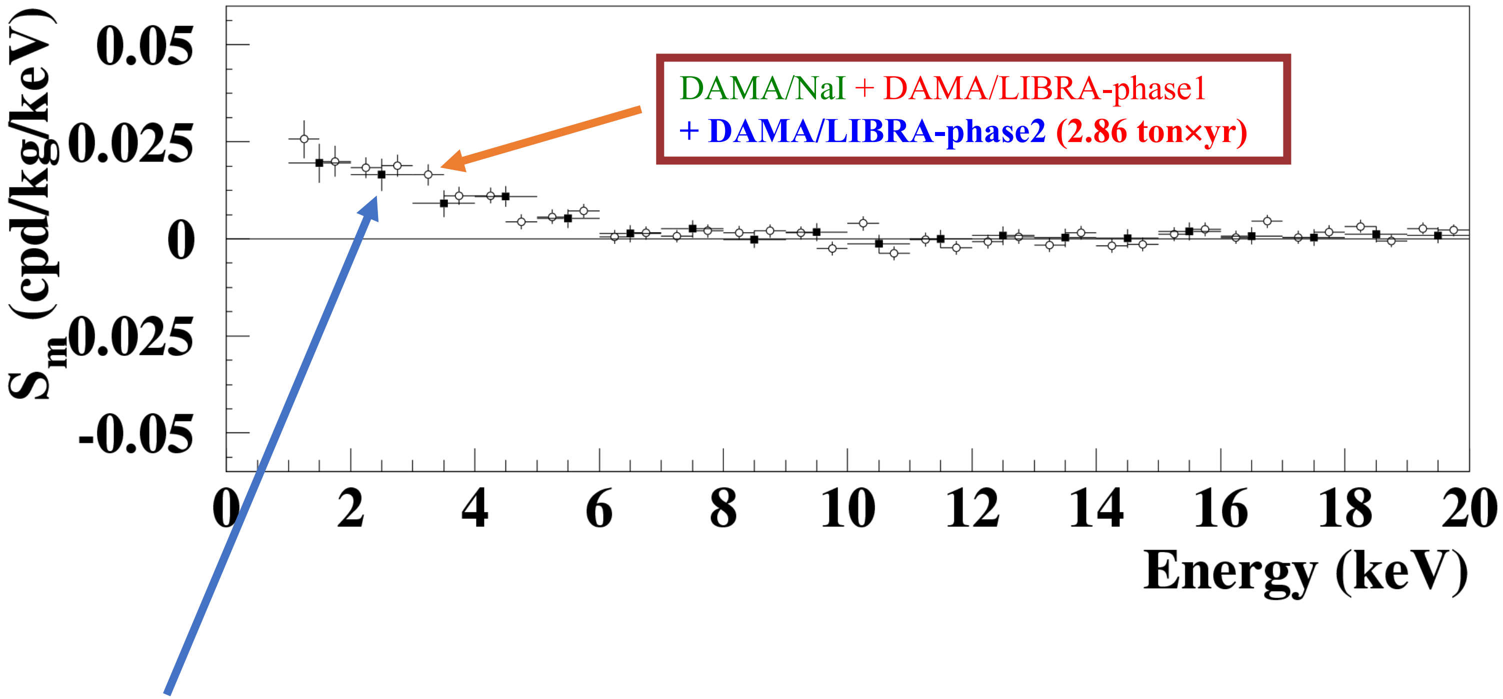

The two cases well compatible within the errors

# 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

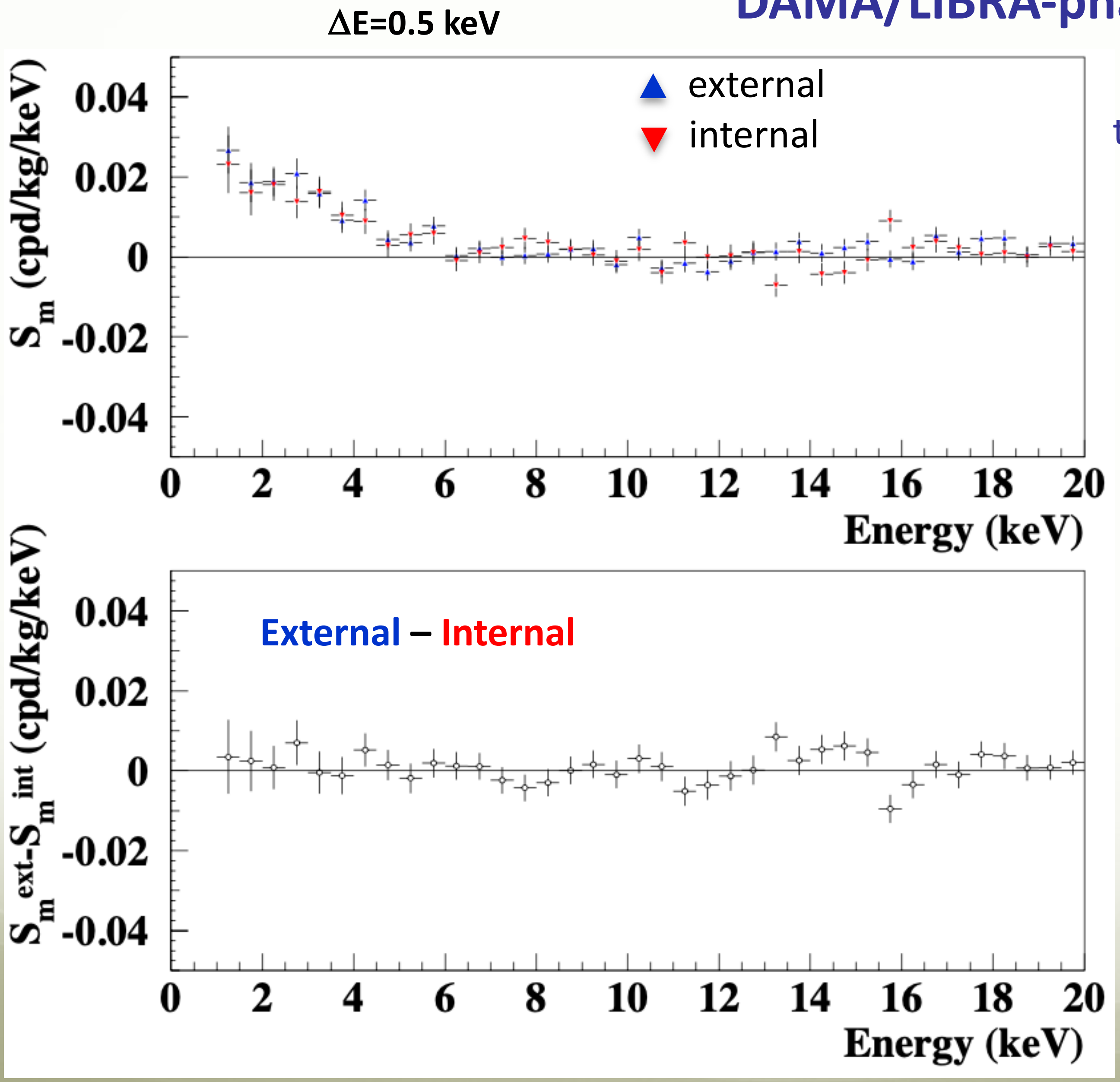



Black squared data points: the **last three published years of DAMA/LIBRA–phase2 (0.61 ton×yr)**, with common (constant) background

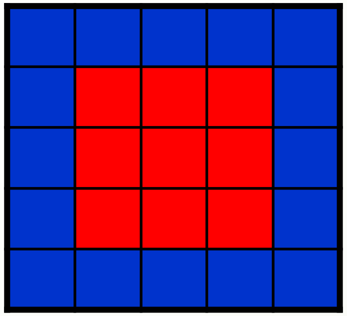
$$\mu_{ijk} = b_{jk} + S_{0,k} + S_{m,k} cos[\omega(t_i - t_0)]$$

# External vs internal detectors:

## DAMA/LIBRA-phase1, -phase2 (8.a.c.)




total exposure: **2.57 ton×yr**



| | |
|---|---|
| 1-4 keV | $\chi^2$/dof =1.9/6 |
| 1-10 keV | $\chi^2$/dof =7.6/18 |
| 1-20 keV | $\chi^2$/dof =36.1/38 |

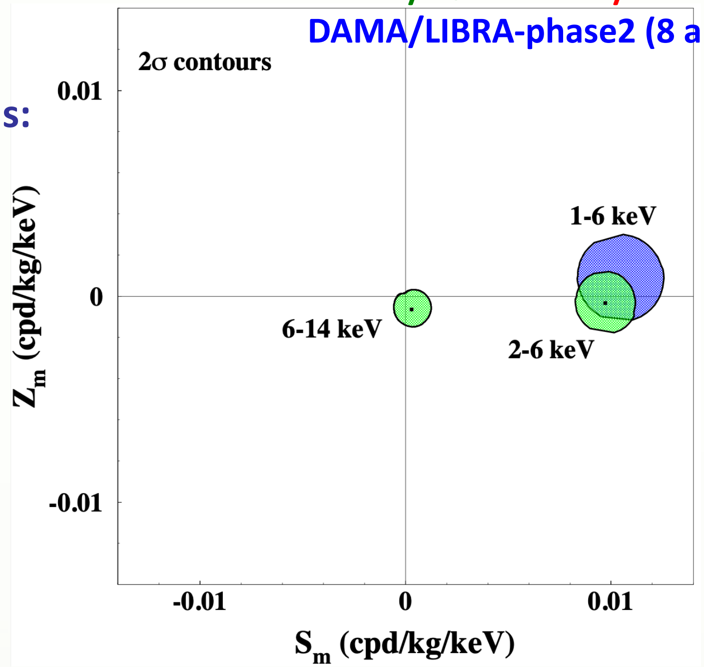
# Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

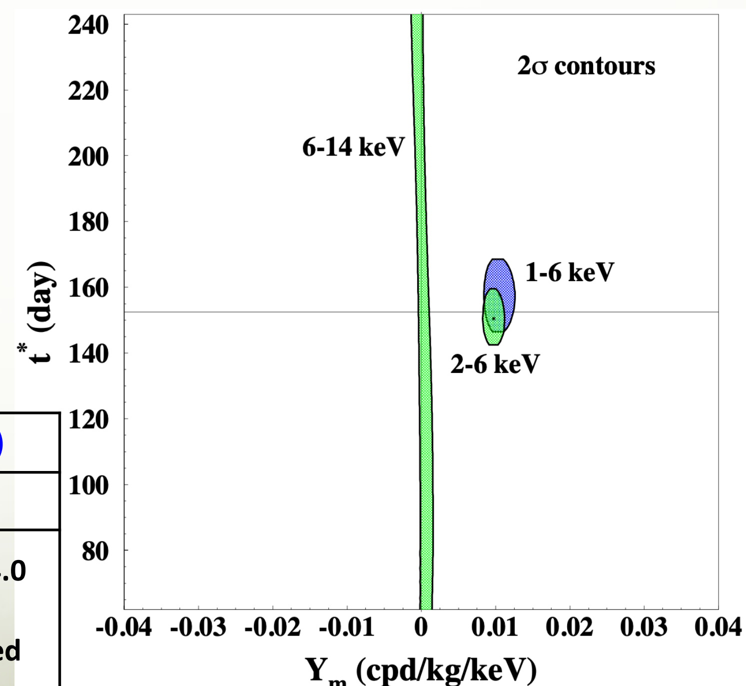
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]

**For Dark Matter signals:**

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




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



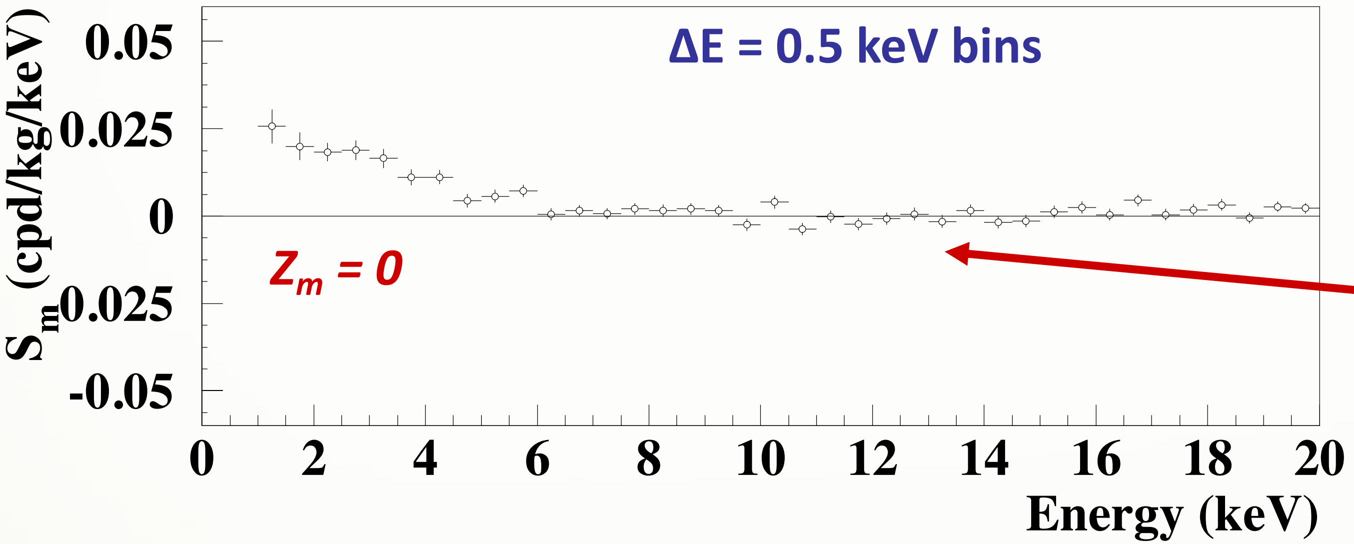

| E (keV) | $S_m$ (cpd/kg/keV) | $Z_m$ (cpd/kg/keV) | $Y_m$ (cpd/kg/keV) | t* (day) |
|---|---|---|---|---|
| DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2 | | | | |
| 2-6 | 0.0097 ± 0.0007 | - 0.0003 ± 0.0007 | 0.0097 ± 0.0007 | 150.5 ± 4.0 |
| 6-14 | 0.0003 ± 0.0005 | -0.0006 ± 0.0005 | 0.0007 ± 0.0010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

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

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

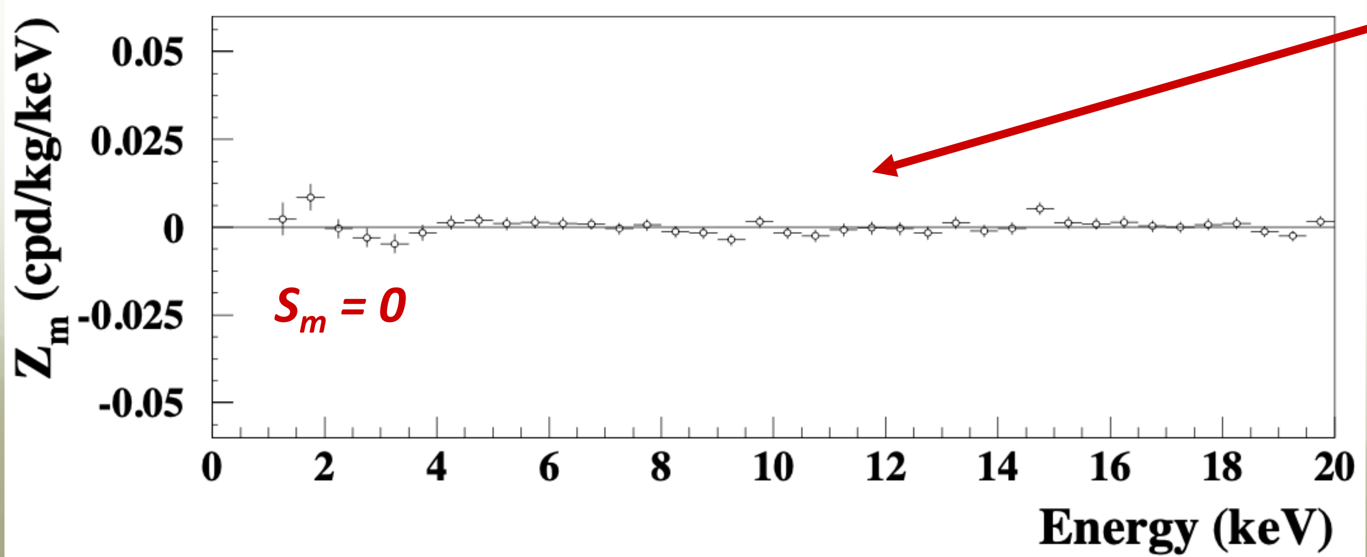
$t_0$ = *152.5 day* (2nd June)

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




*maximum at* 2nd June as for DM particles

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




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

# 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

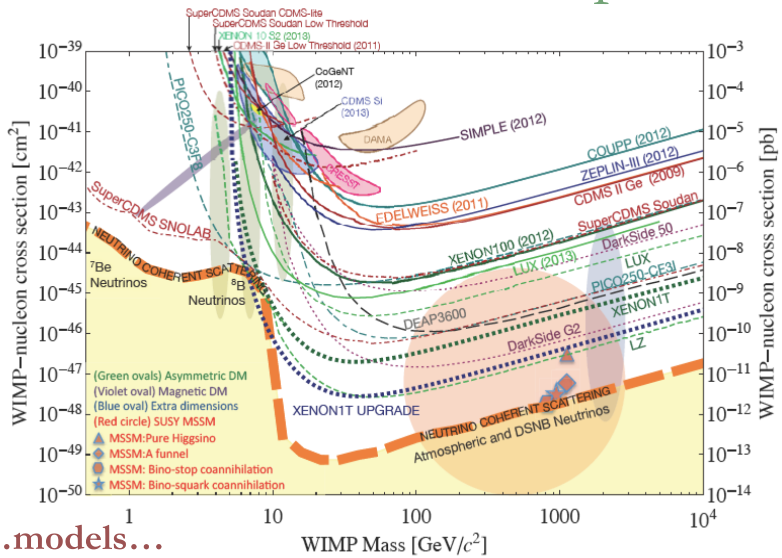
| Source | Main comment | Cautious upper limit (90%C.L.) |
|---|---|---|
| **RADON** | Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc. | **<2.5×10$^{-6}$ cpd/kg/keV** |
| **TEMPERATURE** | Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ 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 ×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 *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**

# About interpretation: is an "universal" and "correct" way to approach the problem of DM and comparisons?

see e.g.: Riv.N.Cim. 26 n.1(2003)1, IJMPD13(2004) 2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84 (2011)055014, IJMPA28 (2013)1330022, NPAE20(4) (2019)317, PPNP114(2020) 103810




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

## …models…

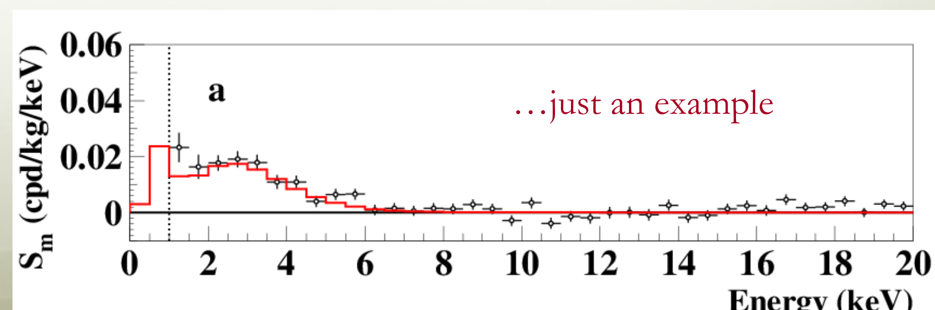
- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

## …and experimental aspects…

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

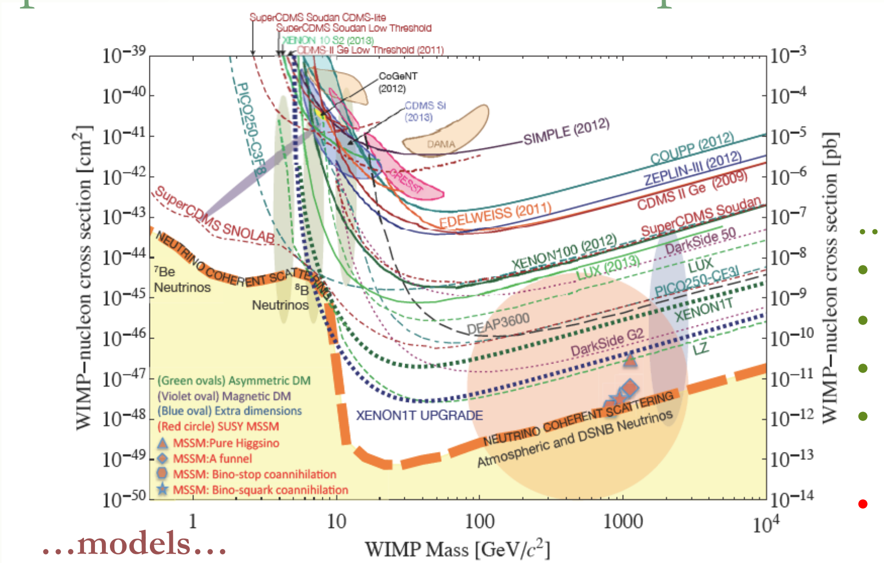
No direct model-independent comparison is possible

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



# 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?
- …

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

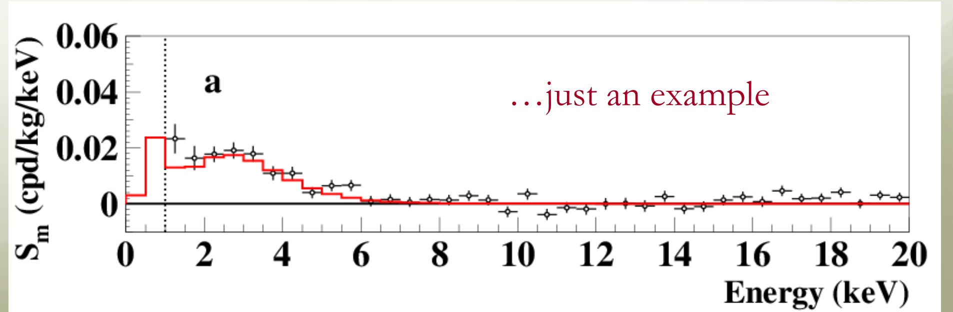
**…and experimental aspects…**

- 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

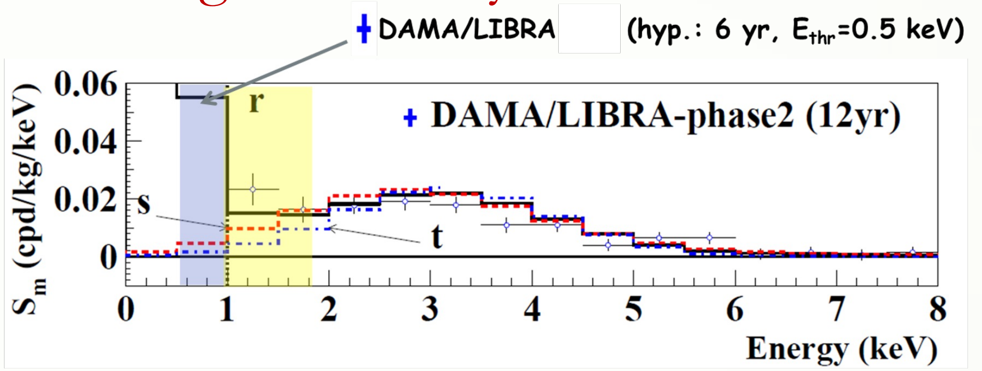
DAMA well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios



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

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

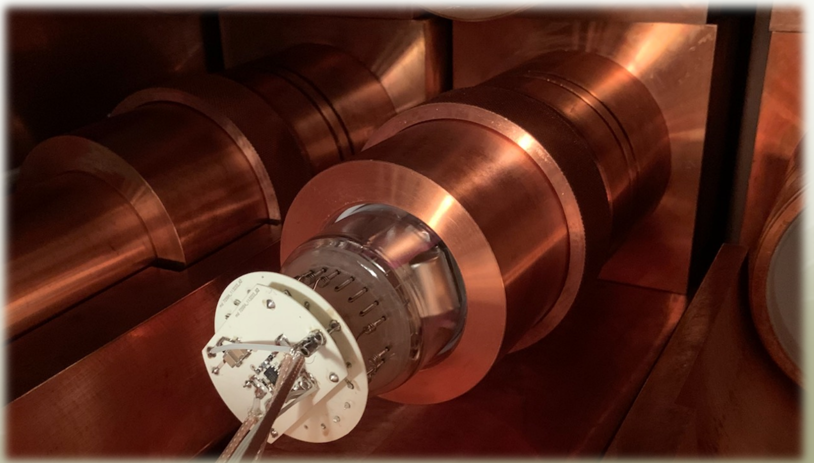
1) During fall 2021, DAMA/LIBRA–phase2 set-up was heavily upgraded
2) The upgrade basically consisted on:
   - new low-background voltage dividers with pre-amps on the same board
   - Transient Digitizers with higher vertical resolution (14 bits)
3) The data taking in this new configuration started on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




The features of the voltage divider+preamp system:

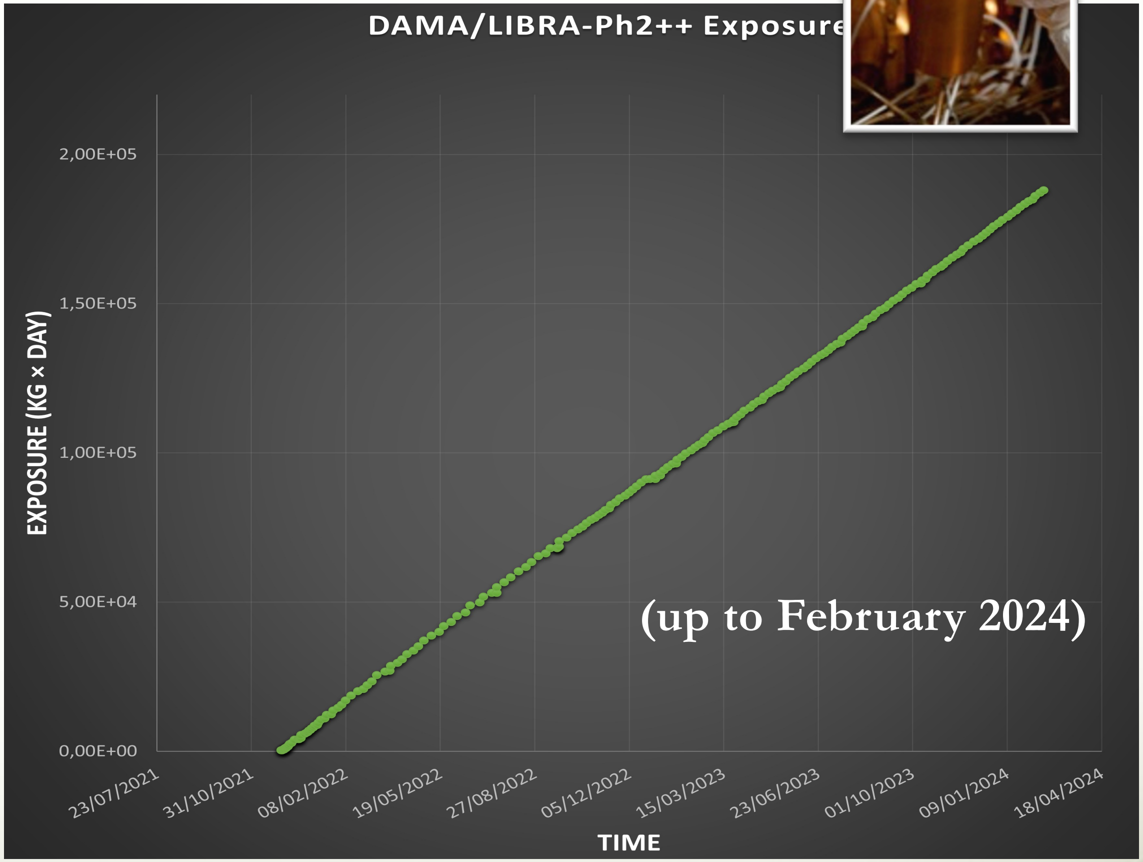
- S/N improvement ≈3.0-9.0;
- discrimination of the single ph.el. from electronic noise: 3 - 8;
- the Peak/Valley ratio: 4.7 - 11.6;
- residual radioactivity lower than that of single PMT

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



# 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.



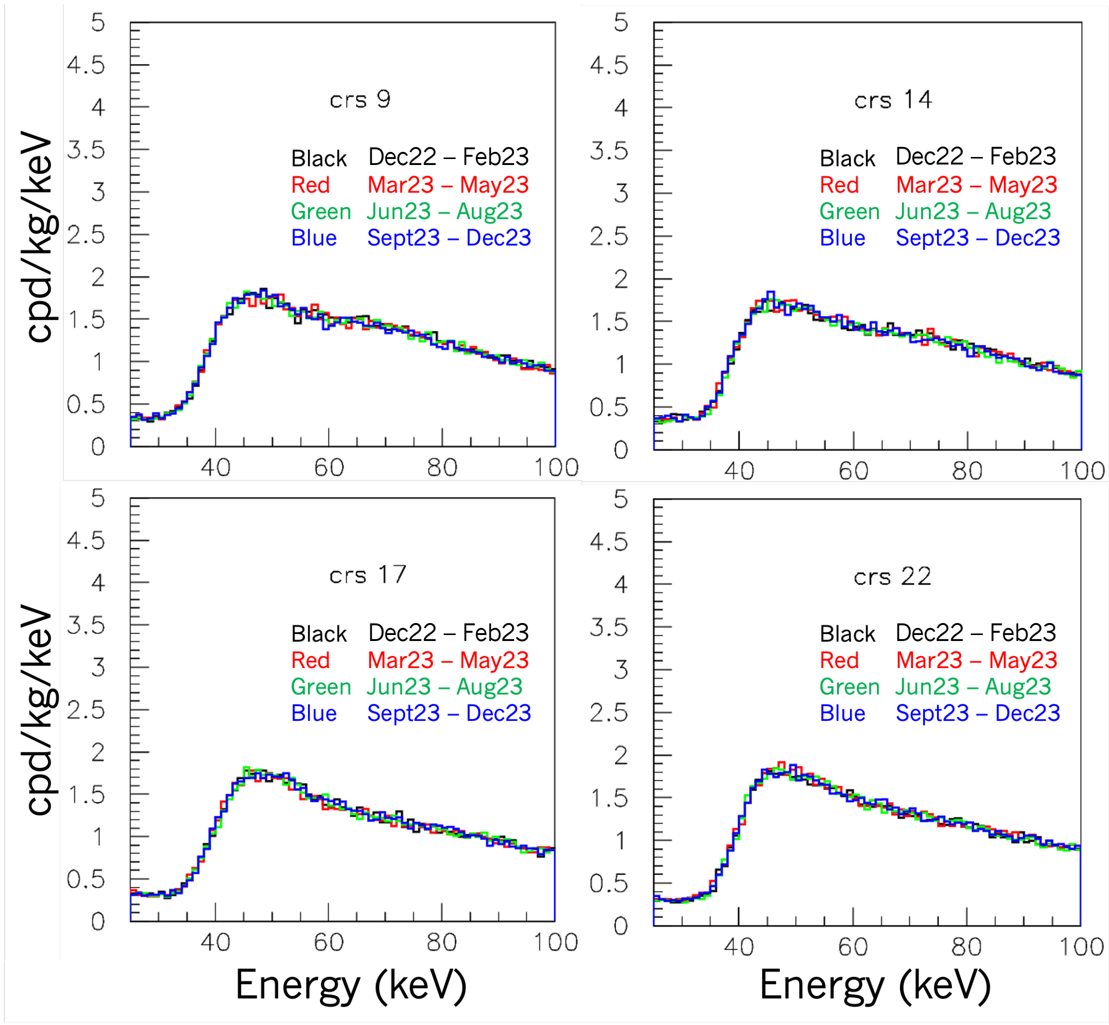

- ✓Calibrations: $\approx 6.38 \times 10^7$ events from sources
- ✓Acceptance window eff. per all crystals: $\approx 3.60 \times 10^7$ events ($\approx 1.4 \times 10^6$ events/keV)

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

**0.478 ton × yr** $\quad (\alpha - \beta^2) \approx 0.488$

# Example: stability of the energy scale

- Monitor of the energy scale in the region of $^{210}Pb + ^{129}I$
- The data in the period dec2022-dec2023 are divided in four time-intervals



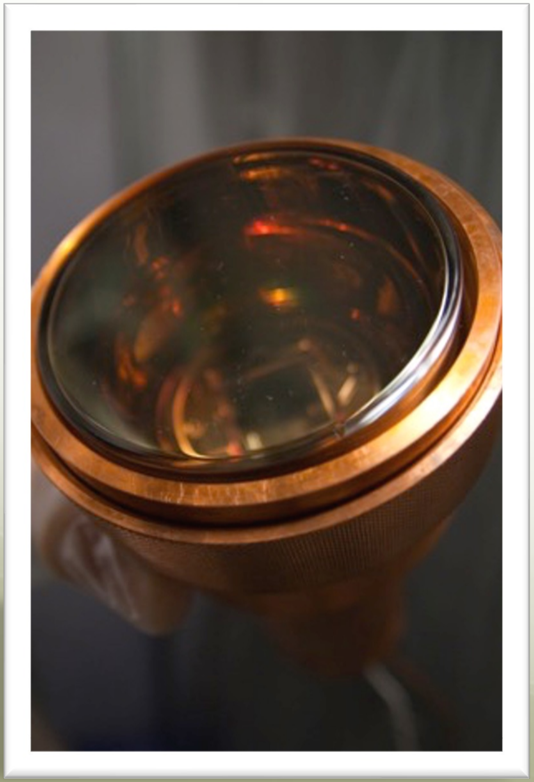

- Just few examples
- The detectors are underground since decades (*) and the $^{129}I$ contribution is dominant in this energy region

- 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 × yr)
- Modulation parameters determined with **increasing precision**
- New investigations on **different peculiarities** of the DM signal in progress
- Full sensitivity to many kinds of DM candidates and interactions types (both inducing recoils and/or e.m. radiation), **full sensitivity to low and high mass candidates**



- **Model-dependent** analyses improve the C.L. and restrict the allowed parameters' space for the various scenarios
- DAMA/LIBRA–phase2-empowered **running** with lower software **energy threshold of 0.5 keV with suitable efficiency**.
- Continuing investigations of **rare processes** other than DM, also in the other DAMA set-ups ($g_A$, $^{106}Cd$, $^{116}Cd$, $^{150}Nd$, Os, Zr, Hf, …)
- Other pursued ideas: **$ZnWO_4$ anisotropic scintillator** for DM **directionality**. Response to nuclear recoils measured.

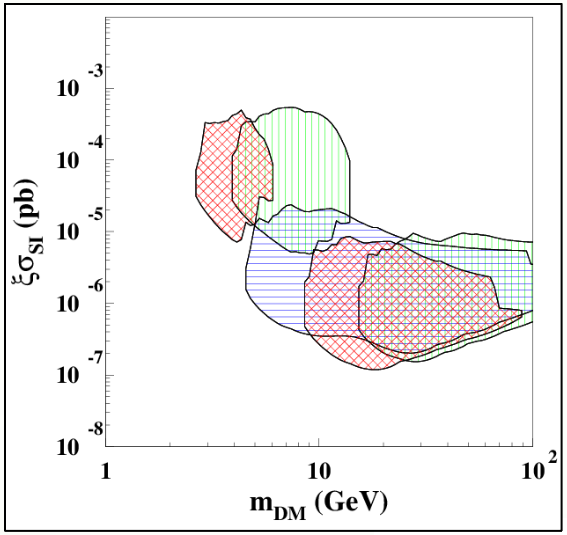
**Thanks to the low background features of all the DAMA set-ups, several rare processes can be investigated: some have already done, some others will be**

# 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

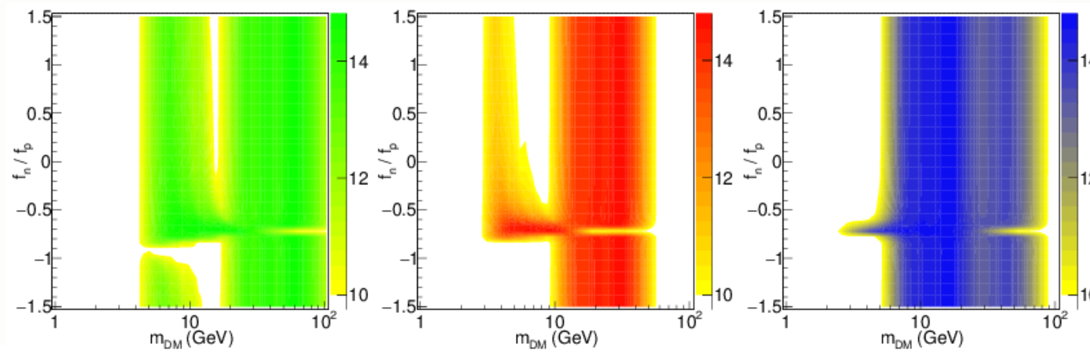


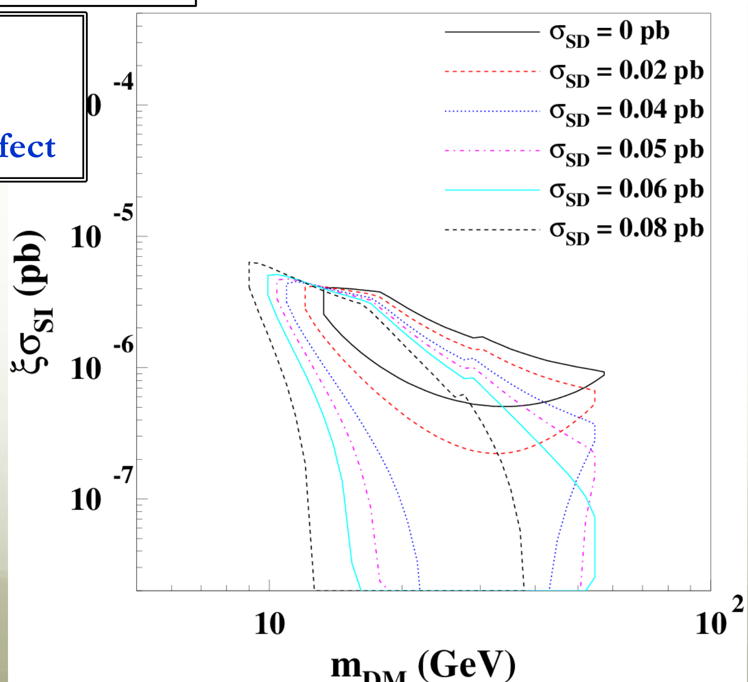

1. Constants q.f.
2. Varying q.f.($E_R$)
3. With channeling effect

DM particles elastically scattering off target nuclei – SI interaction

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

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




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.