# Annual Modulation investigation with DAMA/LIBRA

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# DAMA set-ups

an observatory for rare processes @ LNGS

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

## Collaboration:

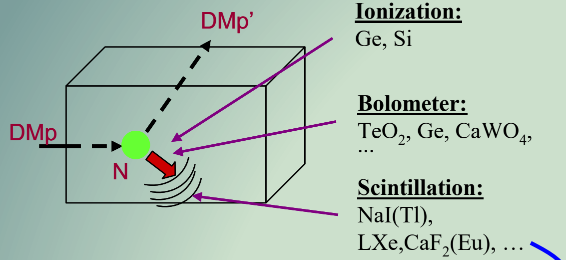
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur and Ropar, India

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

# Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy




- Inelastic Dark Matter: **W + N → W* + N**

  → W has 2 mass states χ+ , χ- with δ mass splitting

  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

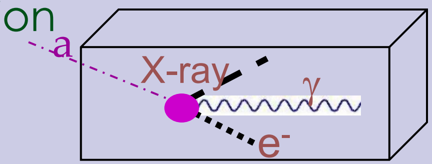
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

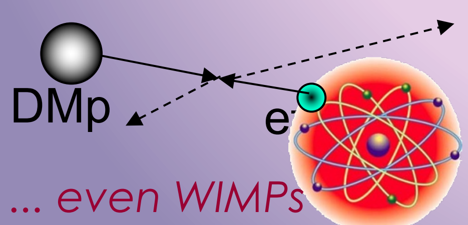
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, $e^-$




- Interaction only on atomic electrons

  → detection of e.m. radiation

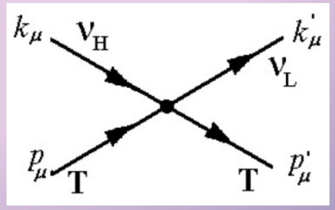



*... even WIMPs*

- Interaction of light DMp (LDM) on $e^-$ or nucleus with production of a lighter particle

  → detection of electron/nucleus recoil energy

*e.g. sterile ν*




… also other ideas …

e.g. signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

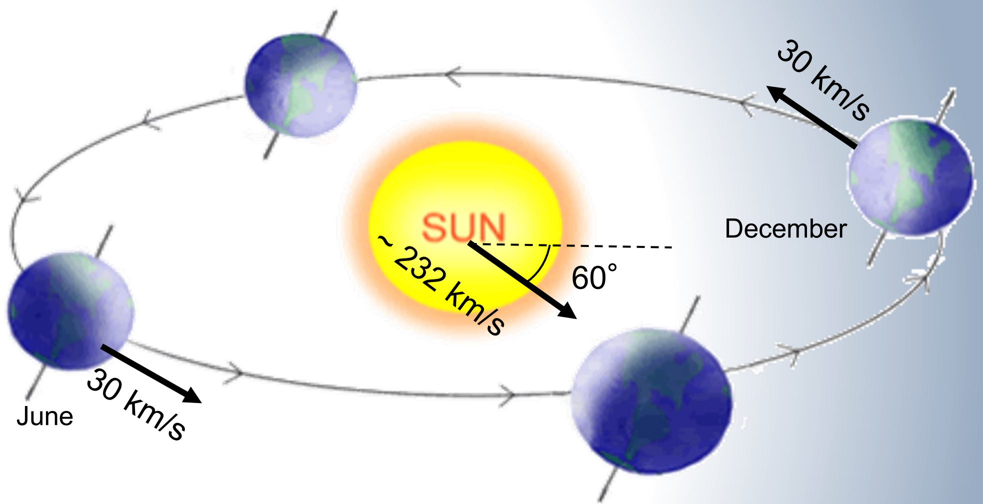
# The **annual modulation**: a model independent signature for the investigation of DM particles

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.

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

## Requirements:

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




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

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

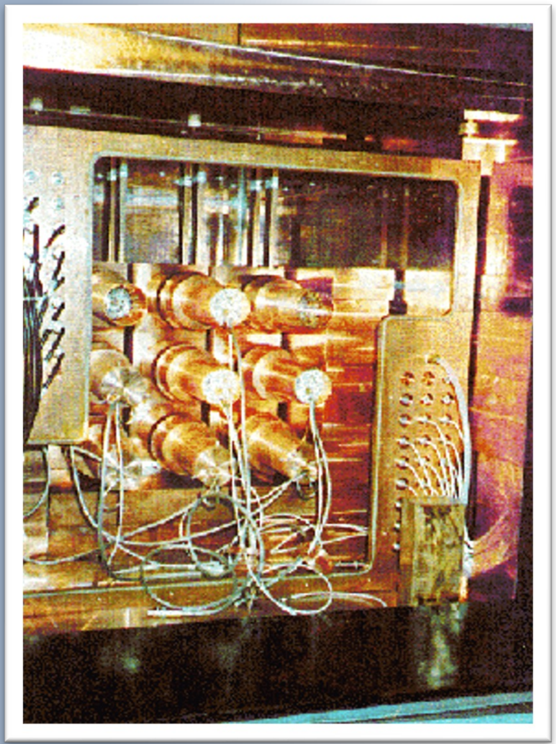
the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

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

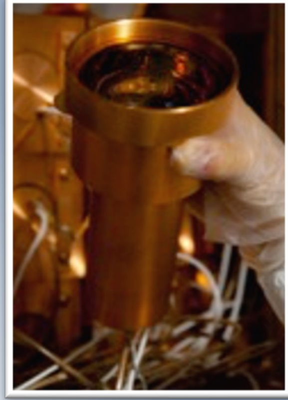
Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.
**⇒ 1 keV threshold**

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.: $\approx 1.6 \times 10^8$ events from sources
- ✓ Acceptance window eff. 8 a.c.: $\approx 4.2 \times 10^6$ events ($\approx 1.7 \times 10^5$ events/keV)

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

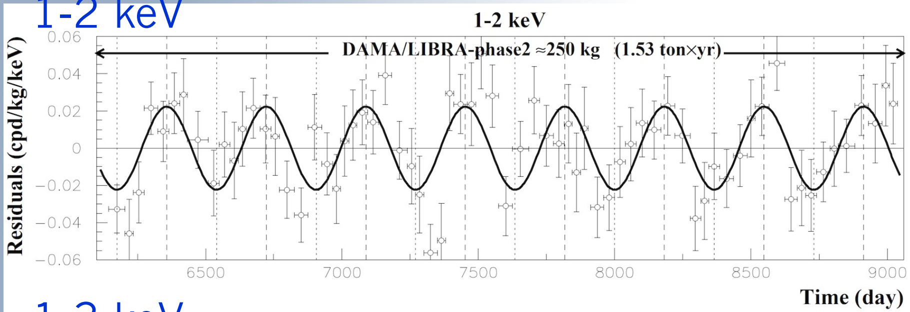
Exposure with this data release of DAMA/LIBRA-phase2: **1.53 ton × yr**

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

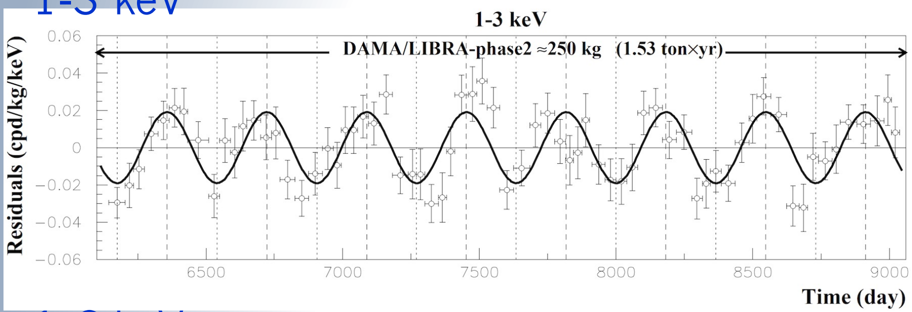
# Model Independent Annual Modulation Result

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

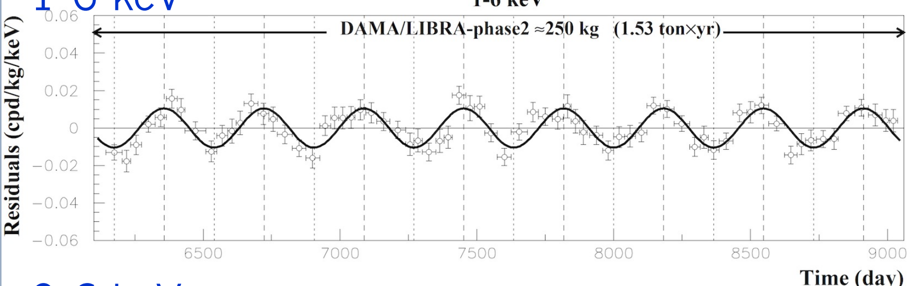
1-2 keV



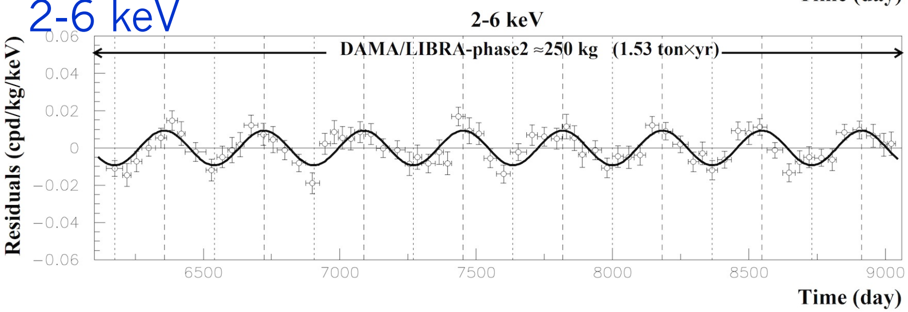

1-3 keV




1-6 keV




2-6 keV




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

Absence of modulation? No

$\chi^2$/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
$\chi^2$/dof = 75.8/68 **7.4 σ C.L.**

**1-3 keV**

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

**1-6 keV**

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

**2-6 keV**

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

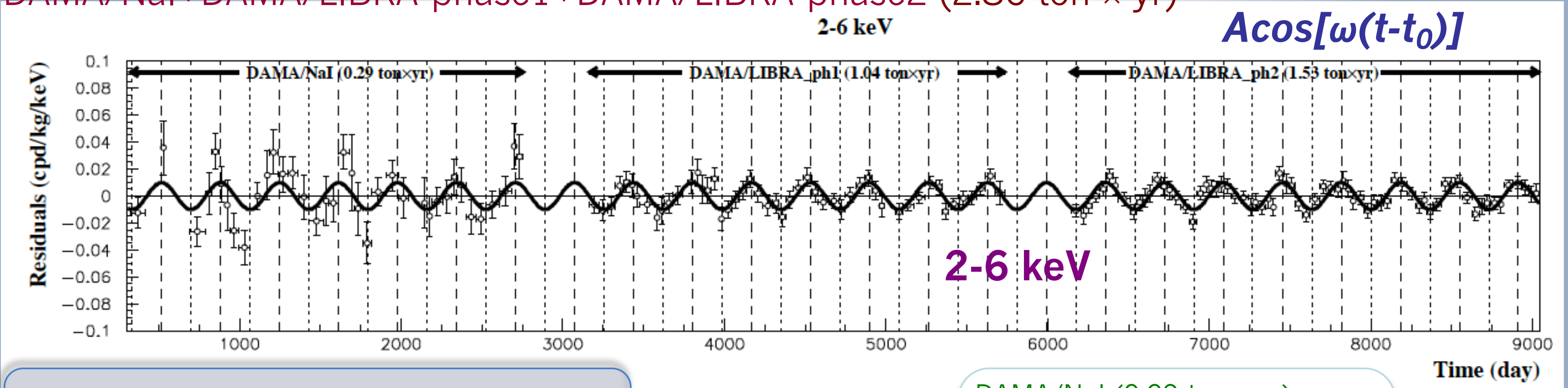
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6σ C.L.

# 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)

$A\cos[\omega(t-t_0)]$




Absence of modulation? No

$\chi^2$/dof=311/156 ⇒ P(A=0) =$2.3\times10^{-12}$

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.**

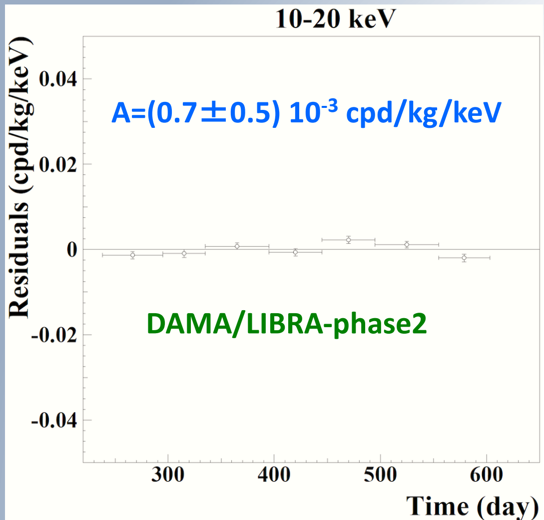
Releasing period (*T*) and phase (*$t_0$*) in the fit

| | 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.

# Rate behaviour above 6 keV

- **No Modulation above 6 keV**



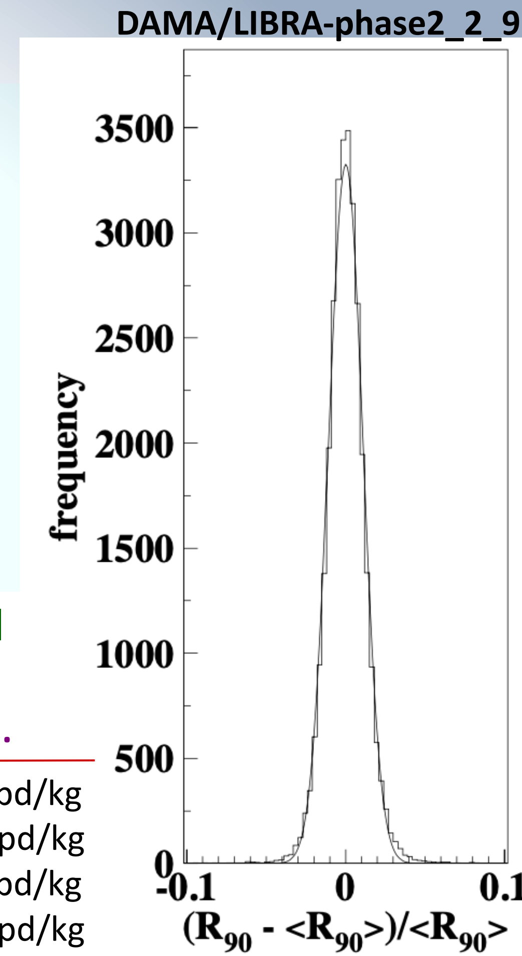

Mod. Ampl. (6-14 keV): cpd/kg/keV
(0.0032 ± 0.0017) DAMA/LIBRA-ph2_2
(0.0016 ± 0.0017) DAMA/LIBRA-ph2_3
(0.0024 ± 0.0015) DAMA/LIBRA-ph2_4
-(0.0004 ± 0.0015) DAMA/LIBRA-ph2_5
(0.0001 ± 0.0015) DAMA/LIBRA-ph2_6
(0.0015 ± 0.0014) DAMA/LIBRA-ph2_7
-(0.0005 ± 0.0013) DAMA/LIBRA-ph2_8
-(0.0003 ± 0.0014) DAMA/LIBRA-ph2_9
→ 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 |



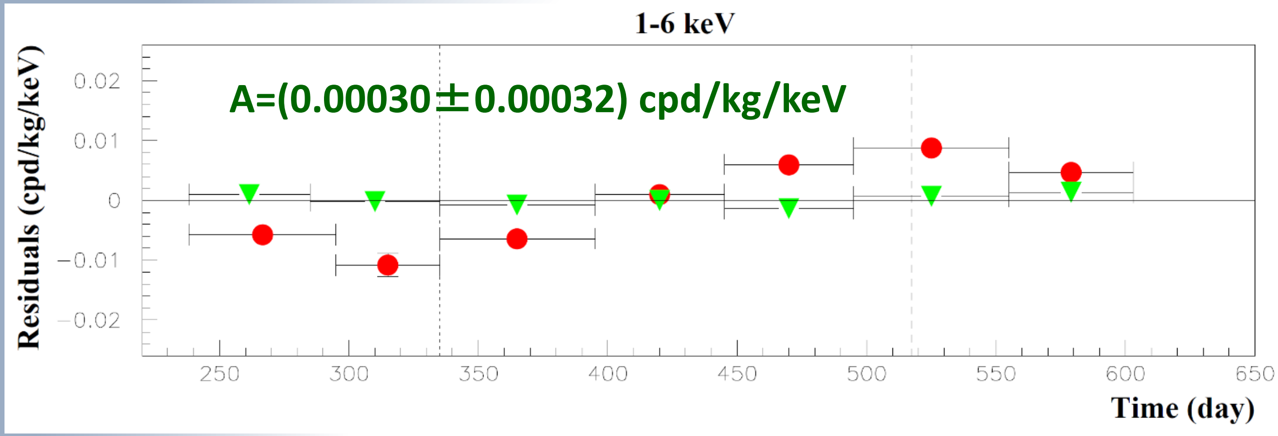

**σ ≈ 1%, fully accounted by statistical considerations**

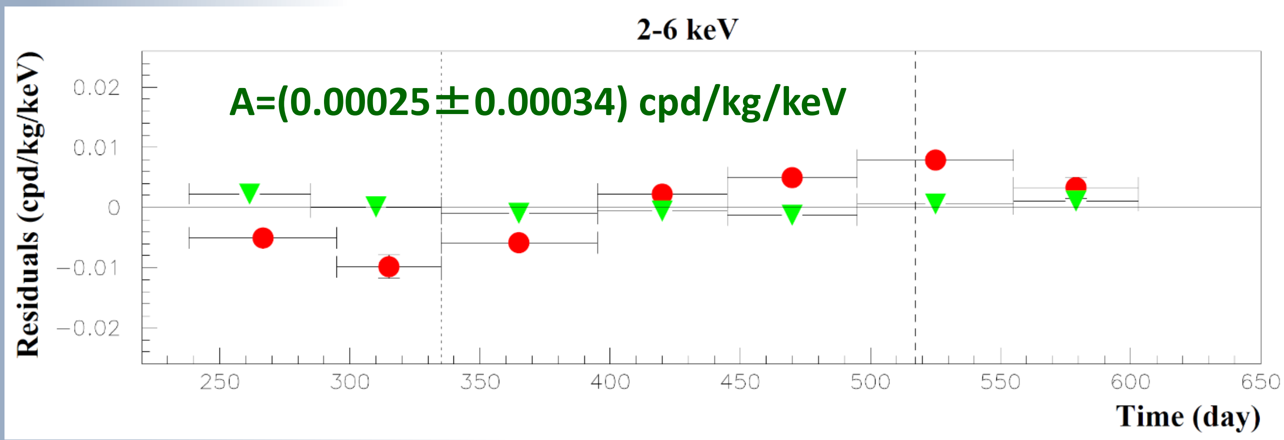
**No modulation above 6 keV**
**This accounts for all sources of bckg and is consistent with the studies on the various components**

# 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

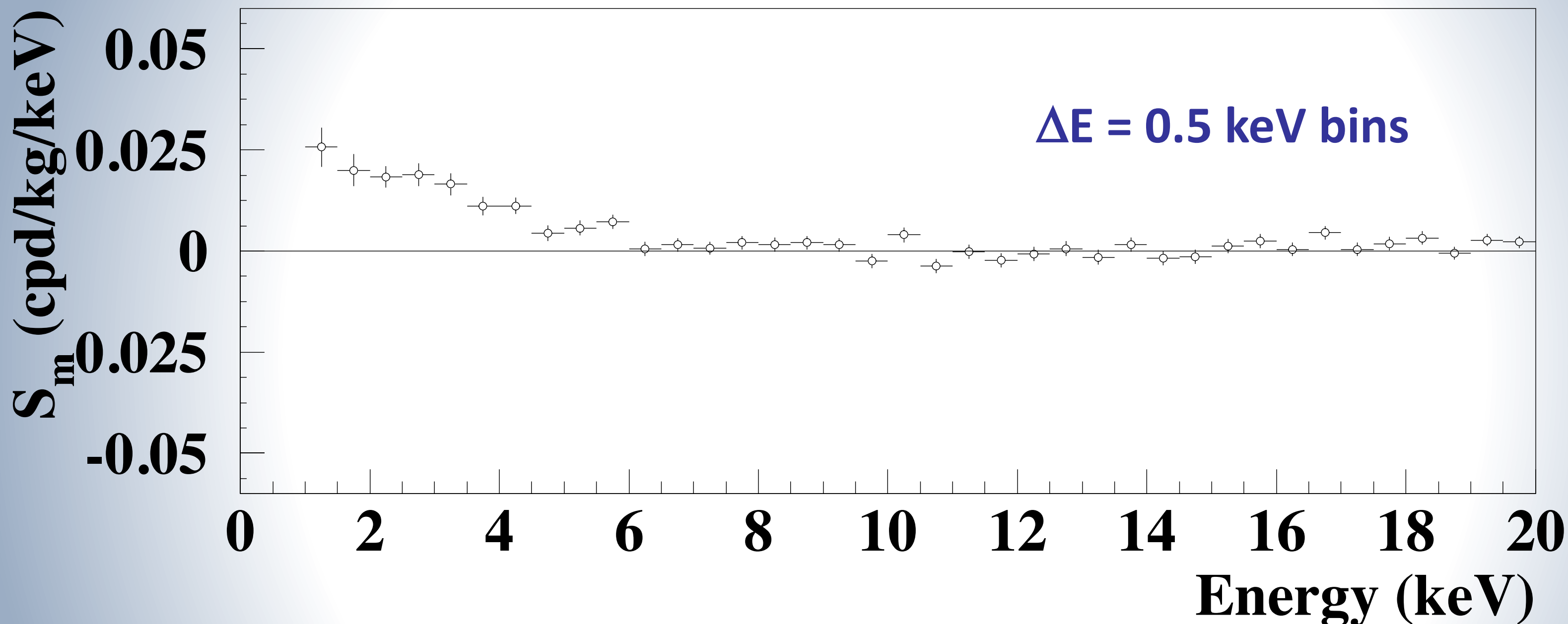
# Energy distribution of the modulation amplitudes

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

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

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

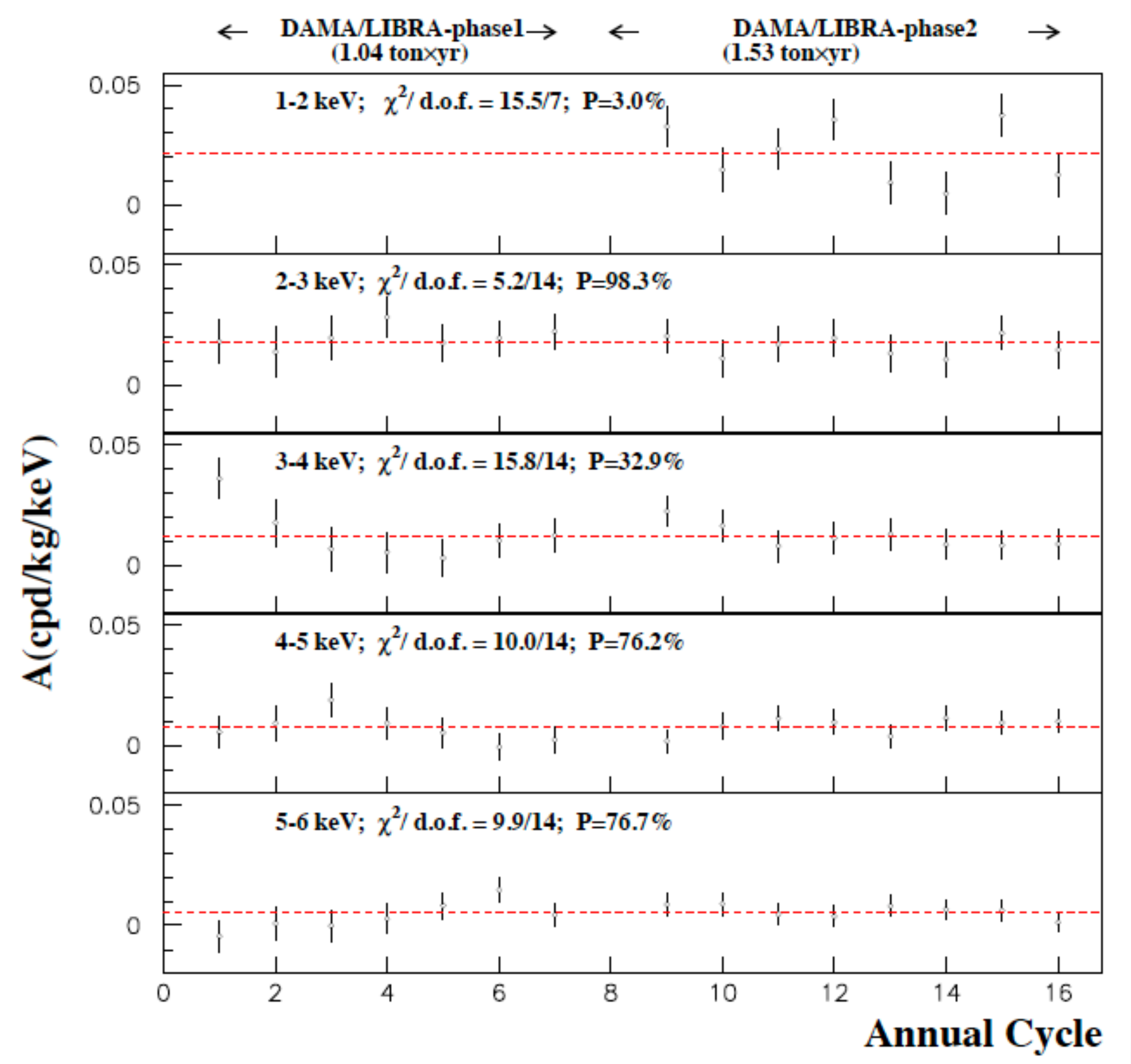
max-likelihood analysis of the single hit scintillation events




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

- 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%.

# $S_m$ for each annual cycle




**DAMA/LIBRA-phase1 +**
**DAMA/LIBRA-phase2**
total exposure: **2.57 ton×yr**

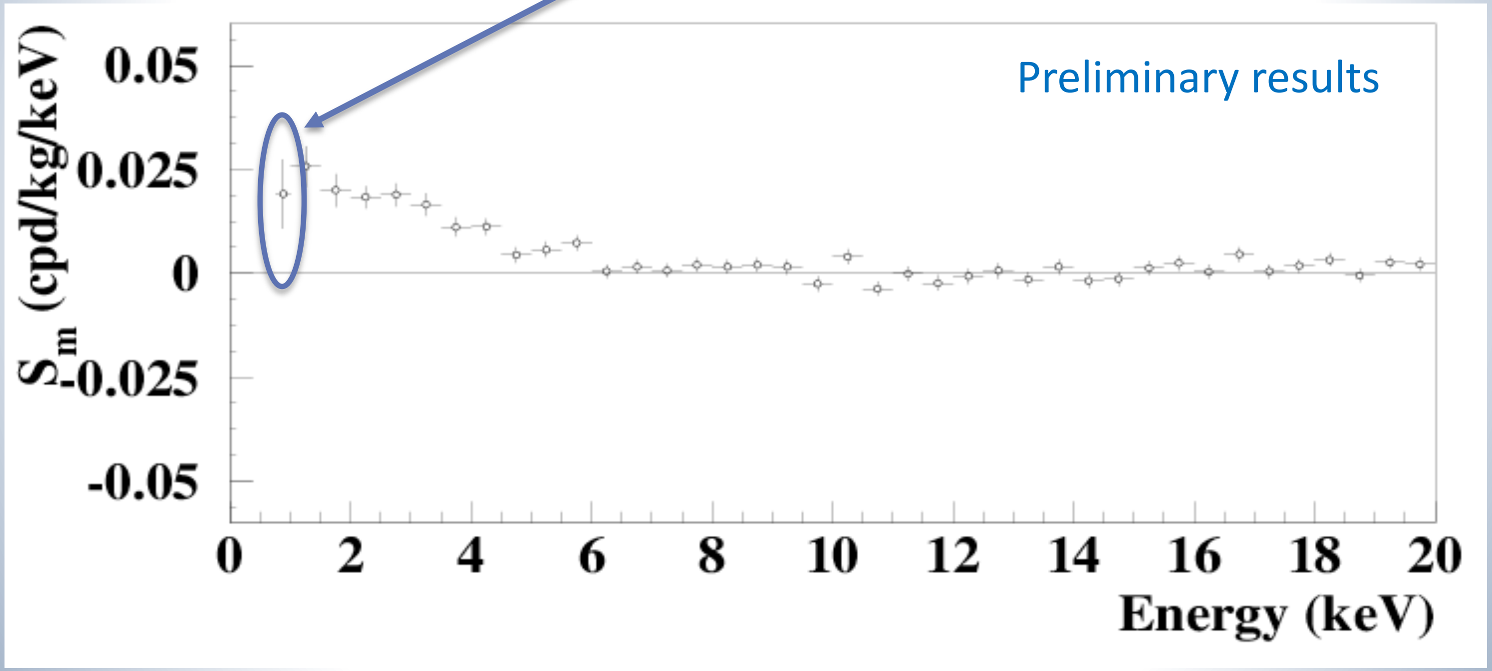
| Energy bin (keV) | run test probability | |
|---|---|---|
| | Lower | Upper |
| 1-2 | 89% | 37% |
| 2-3 | 87% | 30% |
| 3-4 | 17% | 94% |
| 4-5 | 17% | 94% |
| 5-6 | 30% | 85% |

**The signal is well distributed over all the annual cycles in each energy bin**

# Efforts towards lower software energy threshold

- decreasing the software energy threshold down to 0.75 keV
- using the same technique to remove the noise pulses
- evaluating the efficiency by dedicated studies

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

# Few comments on analysis procedure in DAMA/LIBRA

**arXiv:2209.00882, Prog. Part. Nucl. Phys. 114, 103810 (2020)**

- Data taking of each annual cycle starts before the expected **minimum** (Dec) of the DM signal and ends after its expected **maximum** (June)
- Thus, assuming a **constant background** within each annual cycle:
  - ✓ any possible decay of **long–term–living isotopes** cannot mimic a 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 (JHEP2020,137, arXiv:2208.05158) that the DAMA annual modulation signal may be biased by a slow variation only in the low-energy *single-hit* rate, possibly due to *some background* with odd behaviour increasing with time ⇨ already **confuted** quantitatively (see e.g. Prog. Part. Nucl. Phys. 114, 103810, 2020 and here)

- arXiv:2208.05158 claims that an annual modulation in the **COSINE–100** data can appear if they use an analysis method somehow similar to DAMA/LIBRA. However, they get a modulation with reverse phase (**NEGATIVE modulation amplitude if phase = 2 June**) ⇒ **NO SURPRISE!!**
  - → This is expected by the elementary consideration that their rate is very–decreasing with time.

- COSINE-100: **different** NaI(TI) crystal manufacturing wrt DAMA, different starting powders, different purification, different growing procedures and protocols; different electronics and experimental set-up, all stored underground since decades. Different quenching factor for alpha's and nuclear recoils

- Odd idea that low-energy rate might increase with time due to spill out of noise ⇒ deeply **investigated**:
  - ✓ the stability with time of noise and rate
  - ✓ remaining noise tail after the noise rejection procedure <1%

**Any effect of long–term time–varying background or low-energy rate increasing with time ➔ negligible in DAMA/LIBRA**

# Excluding any effect of long-term decay or odd low-energy rate increasing with time in DAMA/LIBRA

arXiv:2209.00882, Prog. Part. Nucl. Phys. 114, 103810 (2020)

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

- We recalculate the (2–6) keV *single-hit* residual rates considering a possible time–varying background. They provide modulation amplitude, fitted period and phase well **compatible** with those obtained in the *original* analysis, showing that the effect of long–term time–varying background – if any – is marginal

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

- Any possible long–term time–varying background would also induce a (either positive or negative) **fake modulation amplitudes (Σ)** on the tail of the $S_m$ distribution above the energy region where the signal has been observed.
- The analysis shows that $|\Sigma| < 1.5\times10^{-3}$ cpd/kg/keV.
- Observed *single-hit* annual modulation amplitude at low energy is order of $10^{-2}$ cpd/kg/keV
- Thus, the effect – if any – is marginal.

**3) The maximum likelihood analysis.**

- The maximum likelihood analysis has been repeated including a **linear term decreasing with time**.
- The obtained $S_m$ averaged over the low energy interval are **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, strongly **disfavours** the hypothesis that the counting rate has significant long–term time–varying contributions.

Any effect of long–term time–varying background or odd low-energy rate increasing with time ➔ **negligible** in DAMA/LIBRA

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

# Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA

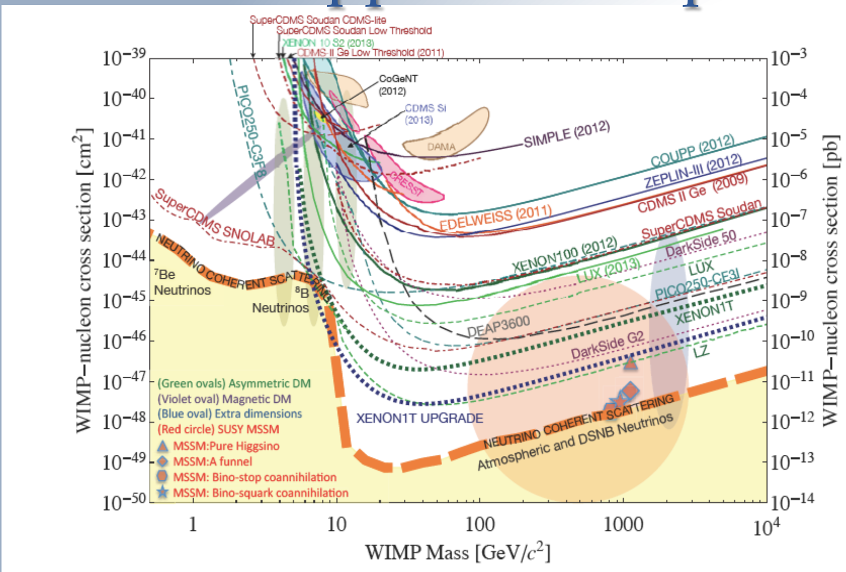
NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196, IJMPA31(2017)issue31, Universe4(2018)116, Bled19(2018)27, NPAE19(2018)307, PPNP114(2020)103810

| Source | Main comment | Cautious upper limit (90%C.L.) |
|---|---|---|
| **RADON** | Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc. | **<$2.5\times10^{-6}$ 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 | **<1-2 $\times10^{-4}$ 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** |

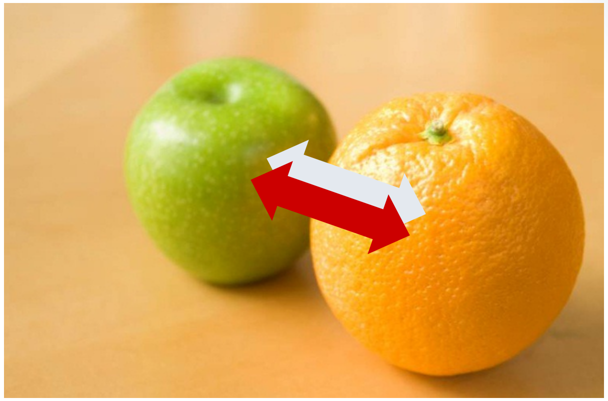
**+ they cannot satisfy all the requirements of annual modulation signature**

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

# About Interpretation: is an “universal” and “correct” way to approach the problem of DM and comparisons?




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



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?
- …

**…and experimental aspects…**

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

**Uncertainty** in experimental parameters, and necessary **assumptions** on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with **a fixed set** of assumptions and parameters’ values **are intrinsically strongly uncertain**.

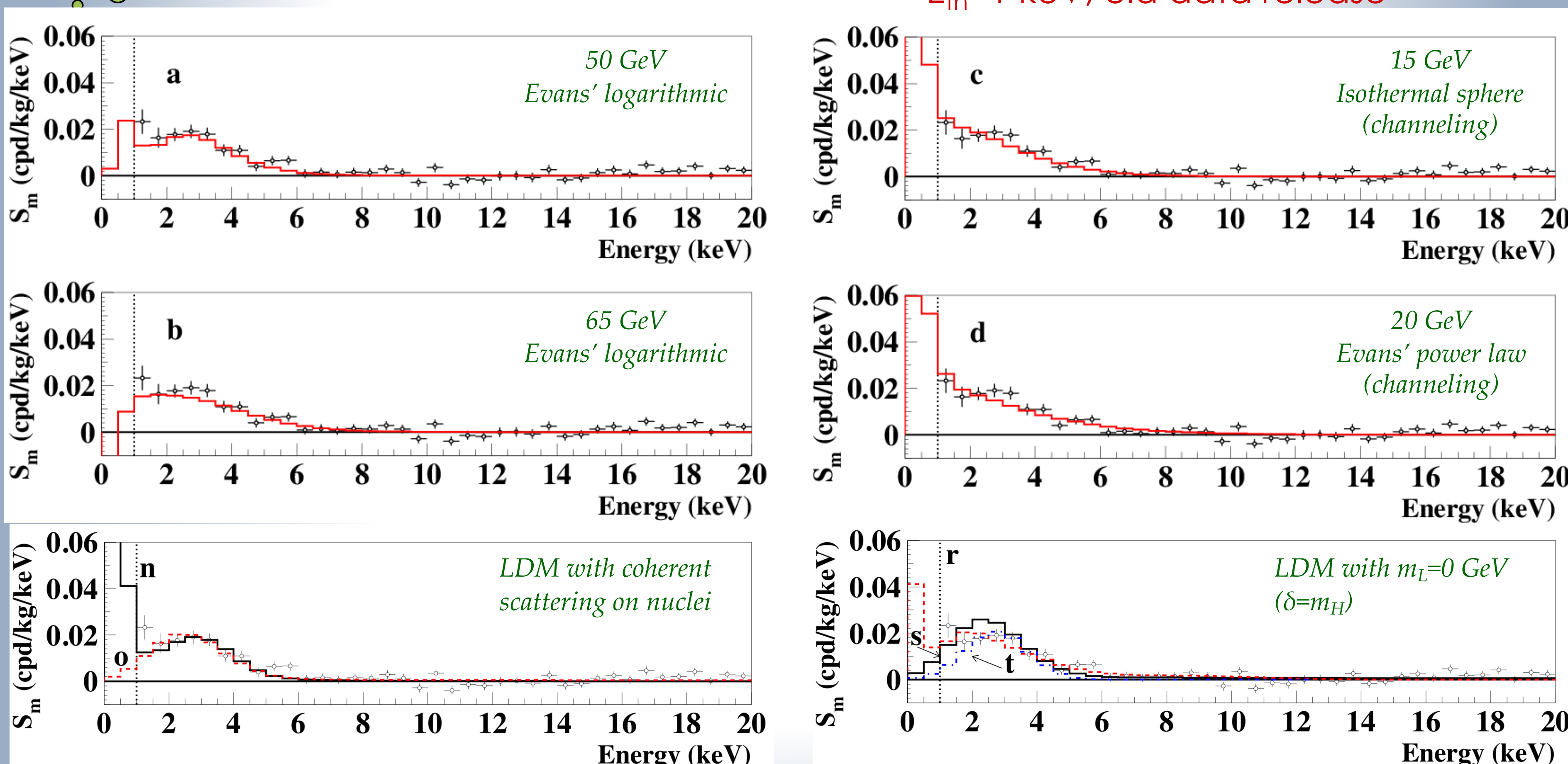
No direct model-independent comparison among expts with different target-detectors and different approaches

# Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

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

- Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

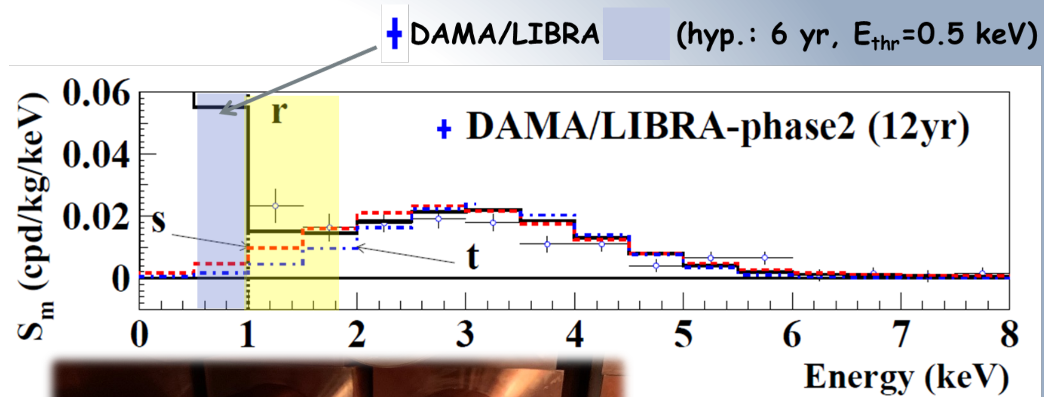
- $E_{th}$=1 keV; old data release

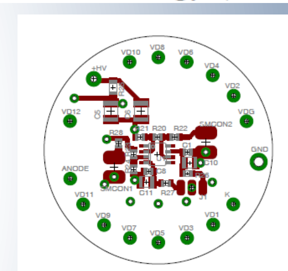


# Running phase2-empowered with lower software energy threshold below 1 keV with high efficiency

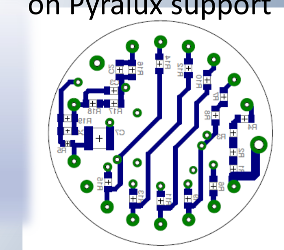
Enhancing experimental sensitivities and improving DM corollary aspects, other DM features, second order effects and other rare processes

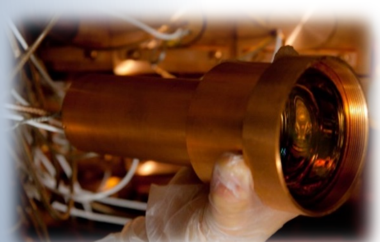
1) In fall 2021 DAMA/LIBRA–phase2 heavily upgraded:
    a. equipping all the PMTs with new low-background voltage dividers with pre-amps on the same board
    b. the use of Transient Digitizers with higher vertical resolution (14 bits).
2) After a dedicated R&D and data taking, the chosen implementation was demonstrated to be effective → very low values of the software trigger level on each PMT
3) The data taking in this new configuration started on Dec, 1 2021



Voltage divider + preamp on Pyralux support



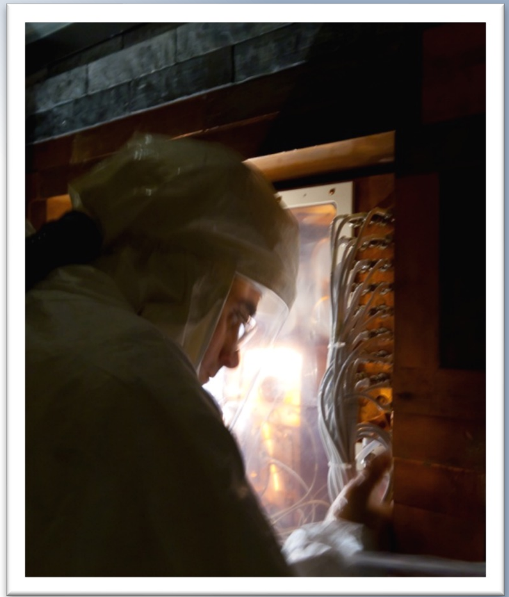


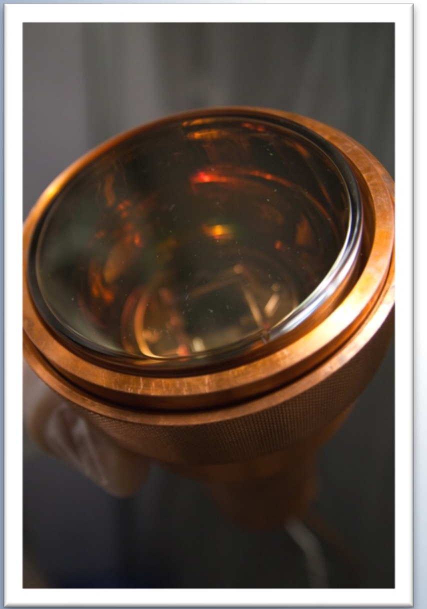
The features of the voltage divider+preamp system:
- S/N improvement ≈3.0-9.0;
- discrimination of the single ph.el. from electronic noise: 3 - 8;
- the Peak/Valley ratio: 4.7 - 11.6;
- residual radioactivity lower than that of single PMT

Shortly, 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; the daq acquires three traces for each detector (the two PMTs and the high-energy sum of them). The read-out is made by a daisy-chain of optical fibers directly connected to the daq pc

# Conclusion

- 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
- Preliminary efforts towards 0.75 keV software energy threshold done
- DAMA/LIBRA–phase2-empowered: lower software energy threshold of 0.5 keV with suitable efficiency. New divider/amp systems and new 14bit digitizers installed.
- DAMA/LIBRA–phase2-empowered running
- Continuing investigations of rare processes other than DM
- Other pursued ideas: $ZnWO_4$ anisotropic scintillator for DM directionality. Response to nuclear recoils measured.

# Additional Slides

• • •

# 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

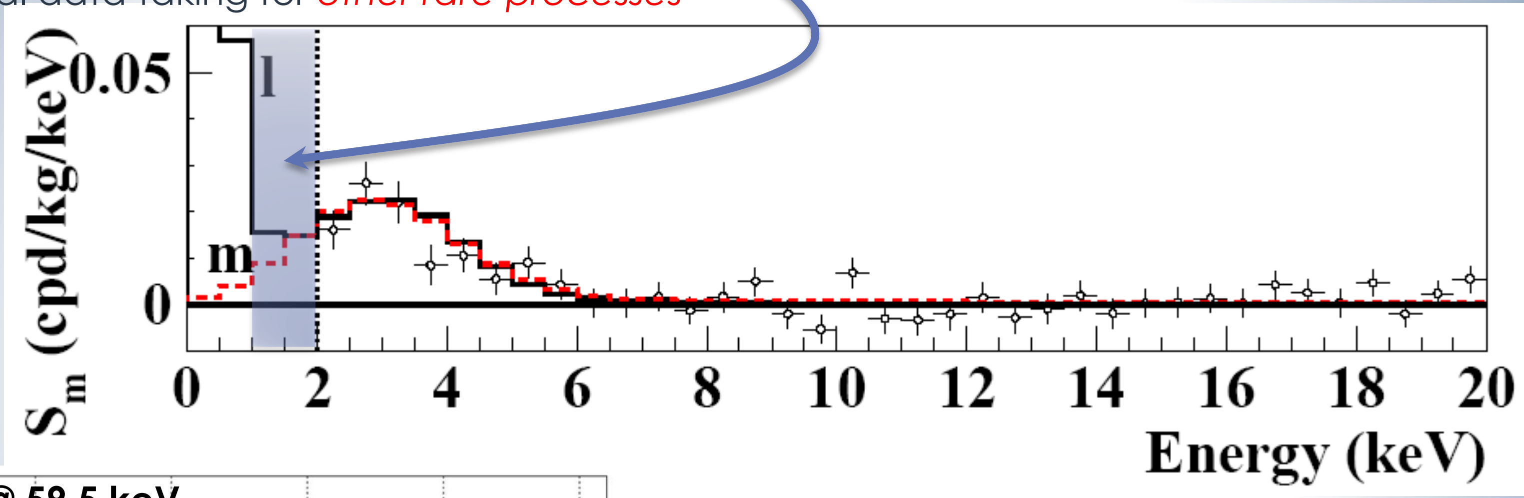
**DAMA/LIBRA–phase1 (7 annual cycles, 1.04 ton×yr) confirmed the model-independent evidence of DM: reaching 9.3σ C.L.**

# DAMA/LIBRA–phase2

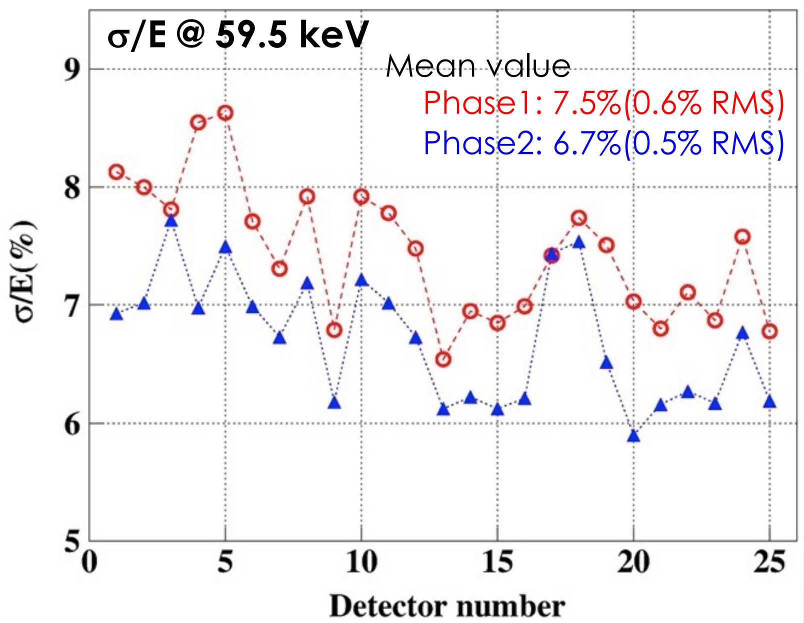
JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4) (2019) 317
PPNP114(2020)103810
NPAE 22(2021) 329

Lowering software energy threshold below 2 keV:

- to study the nature of the particles and features of astrophysical, nuclear and particle physics aspects, and to investigate 2nd order effects
- special data taking for *other rare processes*




The resolution:




The contaminations:

| | $^{226}$Ra (Bq/kg) | $^{235}$U (mBq/kg) | $^{228}$Ra (Bq/kg) | $^{228}$Th (mBq/kg) | $^{40}$K (Bq/kg) |
|---|---|---|---|---|---|
| Mean Contamination | 0.43 | 47 | 0.12 | 83 | 0.54 |
| Standard Deviation | 0.06 | 10 | 0.02 | 17 | 0.16 |

The light responses:

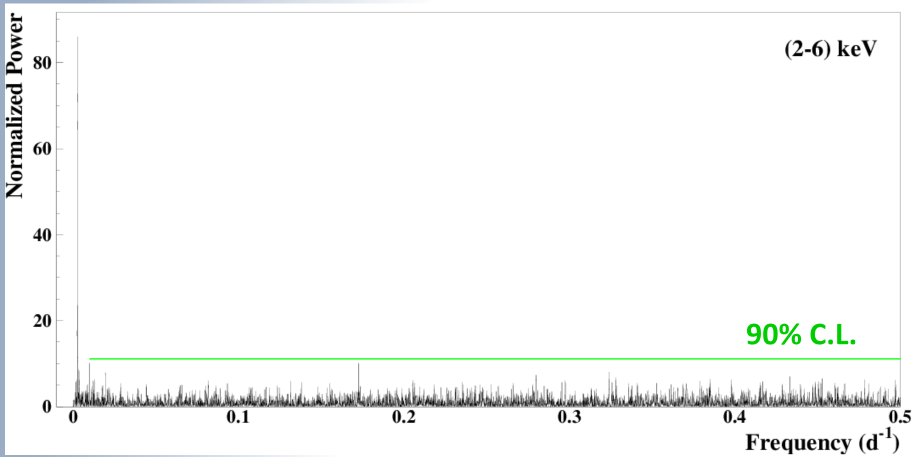
DAMA/LIBRA-phase1: 5.5 – 7.5 ph.e./keV
DAMA/LIBRA-phase2: 6-10 ph.e./keV

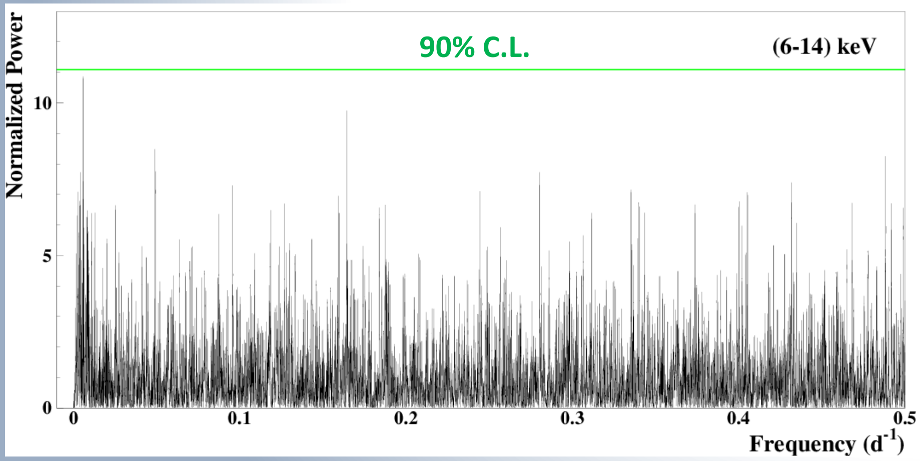
# The analysis in frequency

(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

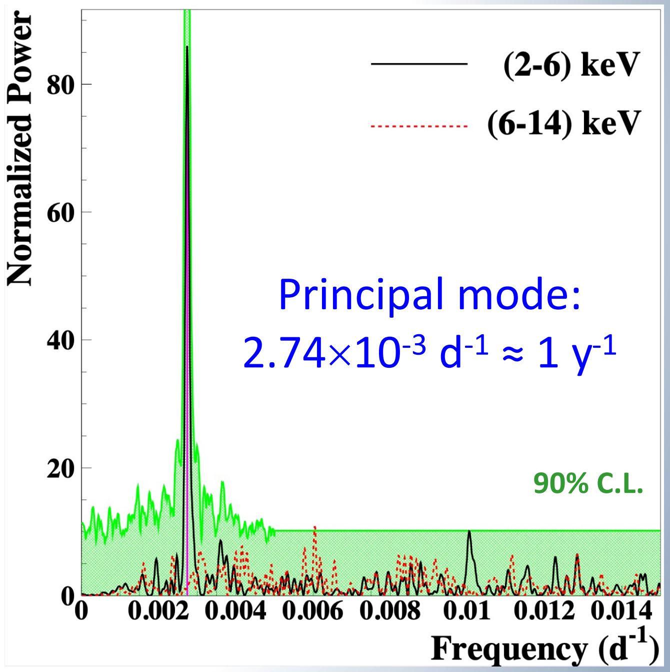
The whole power spectra up to the Nyquist frequency




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

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



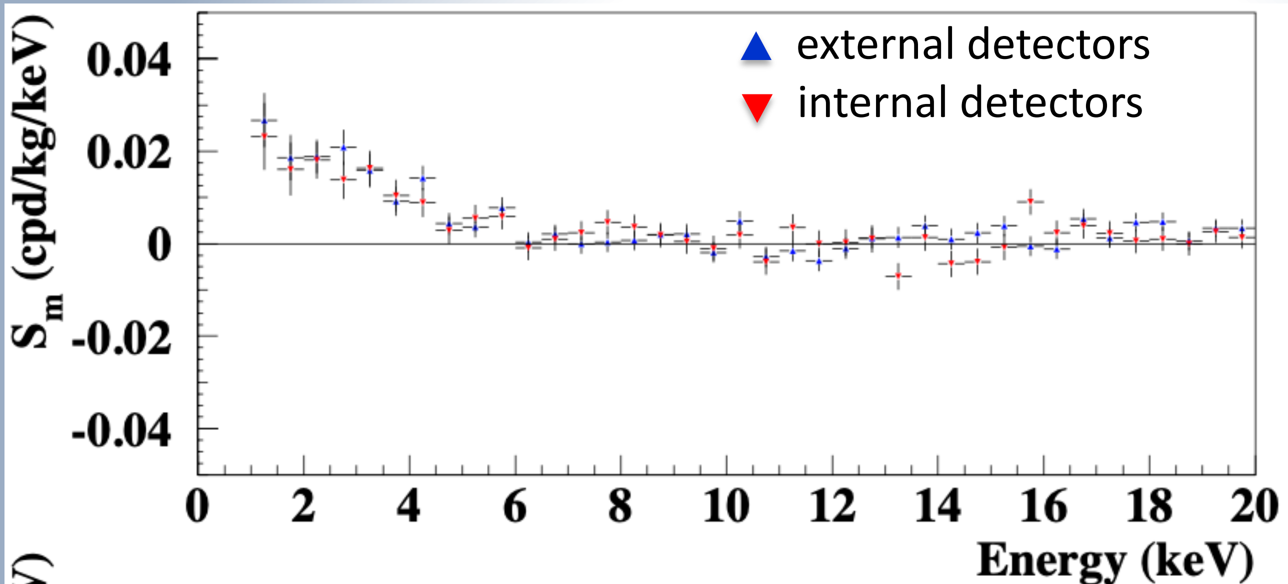

Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

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

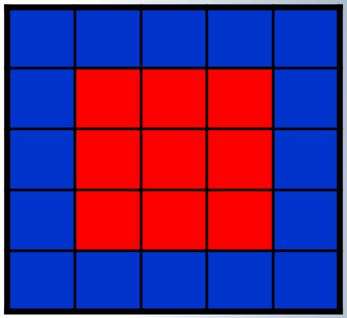
# $S_m$ analysis: external vs internal detectors

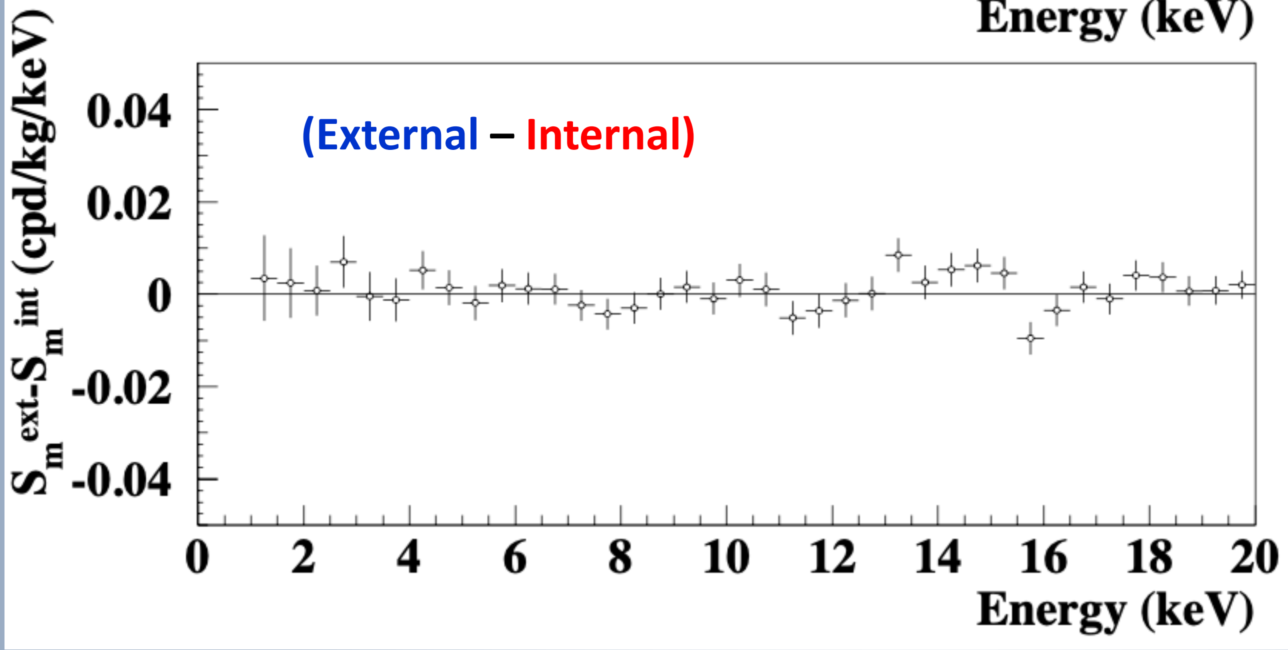
## DAMA/LIBRA-phase1, -phase2 (8.a.c.)

ΔE=0.5 keV




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

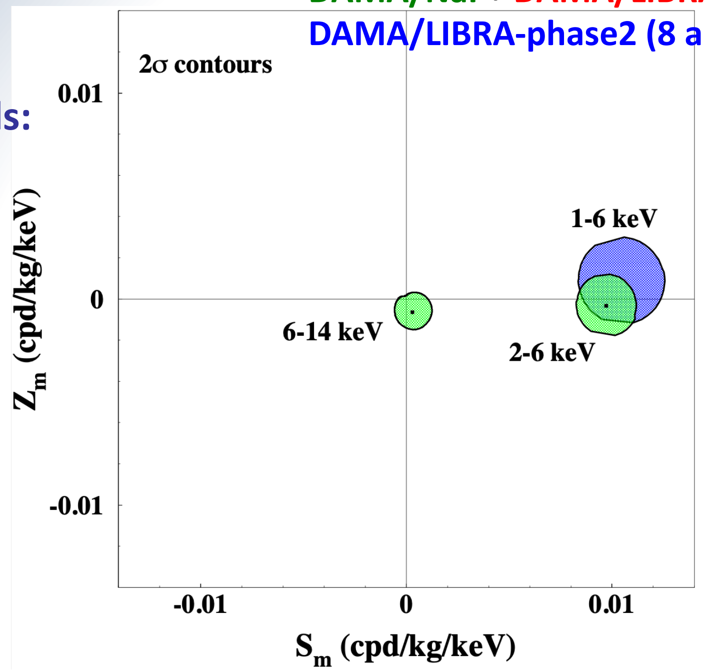
# A sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

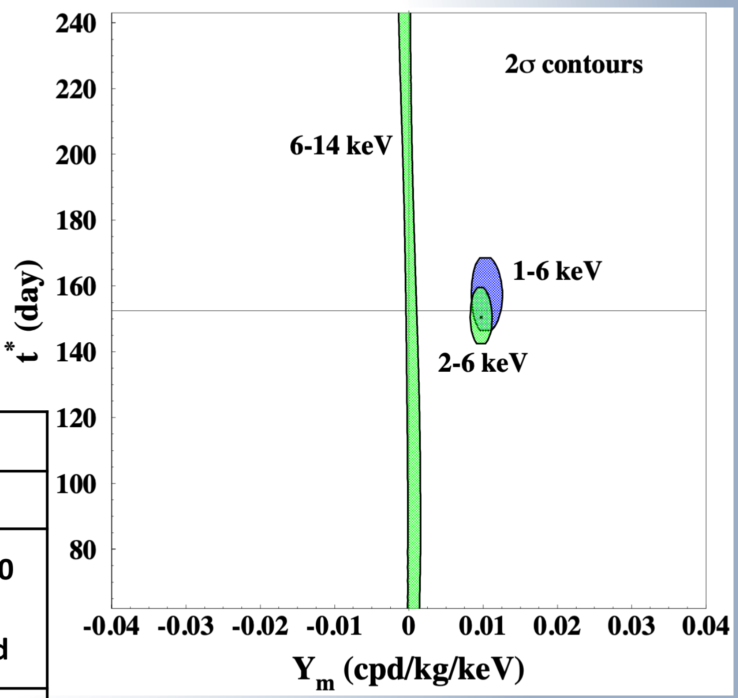
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]

**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 |

# Stability parameters of DAMA/LIBRA–phase2

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation

Running conditions stable at a level better than 1% also in the new running periods

| | DAMA/LIBRA-phase2_2 | DAMA/LIBRA-phase2_3 | DAMA/LIBRA-phase2_4 | DAMA/LIBRA-phase2_5 | DAMA/LIBRA-phase2_6 | DAMA/LIBRA-phase2_7 | DAMA/LIBRA-phase2_8 | DAMA/LIBRA-phase2_9 |
|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | $(0.0012 \pm 0.0051)$ | $-(0.0002 \pm 0.0049)$ | $-(0.0003 \pm 0.0031)$ | $(0.0009 \pm 0.0050)$ | $(0.0018 \pm 0.0036)$ | $-(0.0006 \pm 0.0035)$ | $-(0.0029 \pm 0.0039)$ | $(0.0014 \pm 0.0033)$ |
| Flux $N_2$ (l/h) | $-(0.15 \pm 0.18)$ | $-(0.02 \pm 0.22)$ | $-(0.02 \pm 0.12)$ | $-(0.02 \pm 0.14)$ | $-(0.01 \pm 0.10)$ | $-(0.01 \pm 0.16)$ | $(0.05 \pm 0.25)$ | $(0.014 \pm 0.092)$ |
| Pressure (mbar) | $(1.1 \pm 0.9) \times 10^{-3}$ | $(0.2 \pm 1.1)) \times 10^{-3}$ | $(2.4 \pm 5.4) \times 10^{-3}$ | $(0.6 \pm 6.2) \times 10^{-3}$ | $(1.5 \pm 6.3) \times 10^{-3}$ | $(7.2 \pm 8.6) \times 10^{-3}$ | $(3 \pm 12) \times 10^{-3}$ | $(3.5 \pm 4.9) \times 10^{-3}$ |
| Radon (Bq/m$^3$) | $(0.015 \pm 0.034)$ | $-(0.002 \pm 0.050)$ | $-(0.009 \pm 0.028)$ | $-(0.044 \pm 0.050)$ | $(0.082 \pm 0.086)$ | $(0.06 \pm 0.11)$ | $-(0.046 \pm 0.076)$ | $(0.002 \pm 0.035)$ |
| Hardware rate above single ph.e. (Hz) | $-(0.12 \pm 0.16) \times 10^{-2}$ | $(0.00 \pm 0.12) \times 10^{-2}$ | $-(0.14 \pm 0.22) \times 10^{-2}$ | $-(0.05 \pm 0.22) \times 10^{-2}$ | $-(0.06 \pm 0.16) \times 10^{-2}$ | $-(0.08 \pm 0.17) \times 10^{-2}$ | $(0.04 \pm 0.20) \times 10^{-2}$ | $-(0.19 \pm 0.18) \times 10^{-2}$ |

All the measured amplitudes well compatible with zero

+ none can account for the observed effect

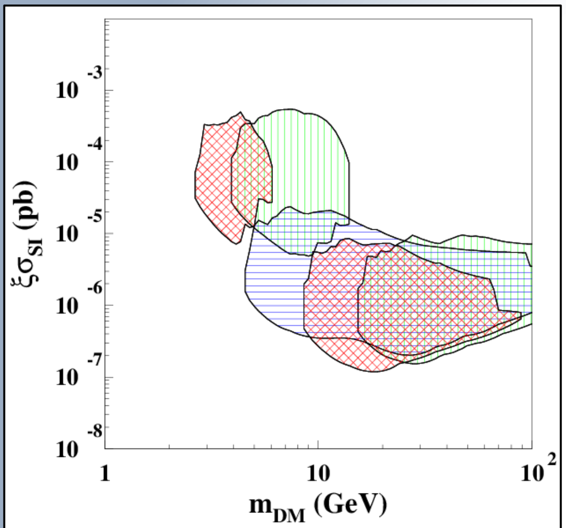
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

# Examples of model-dependent analyses

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

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

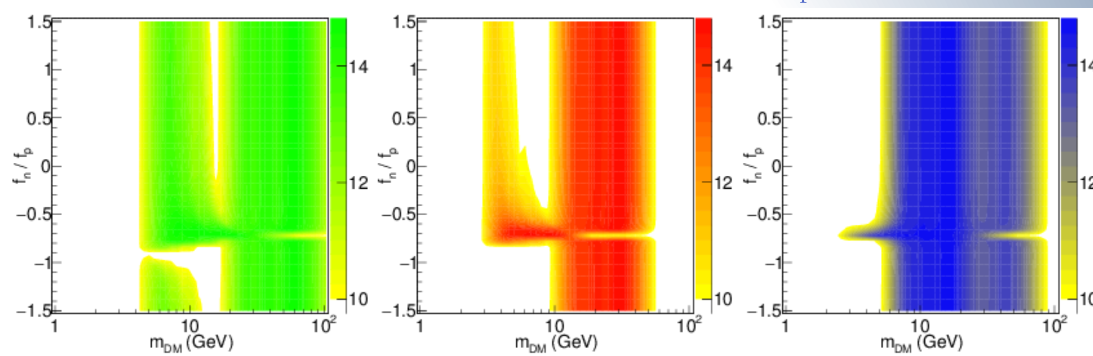
$E_{th}$=1 keV; old data release



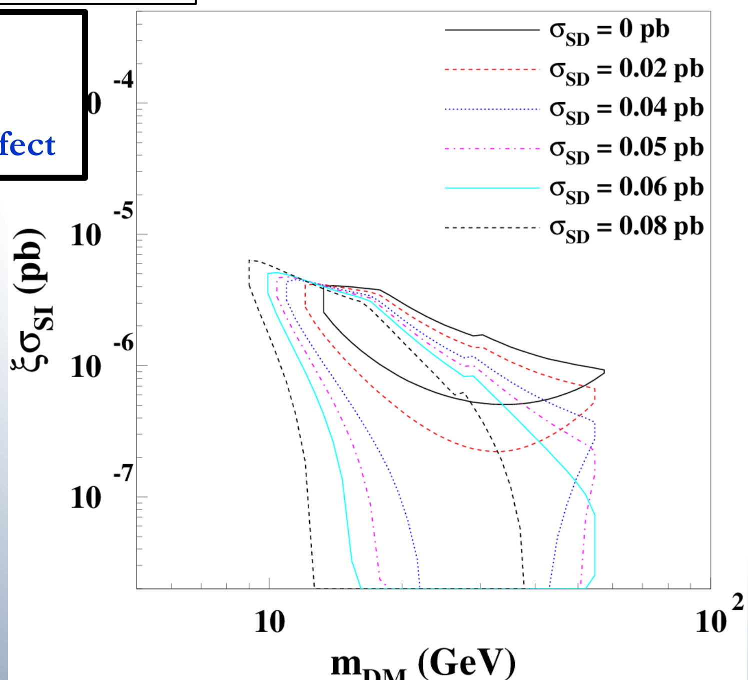

DM particles elastically scattering off target nuclei – SI interaction

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

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




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.