Stato e prospettive di DAMA/LIBRA-fase2 migliorata

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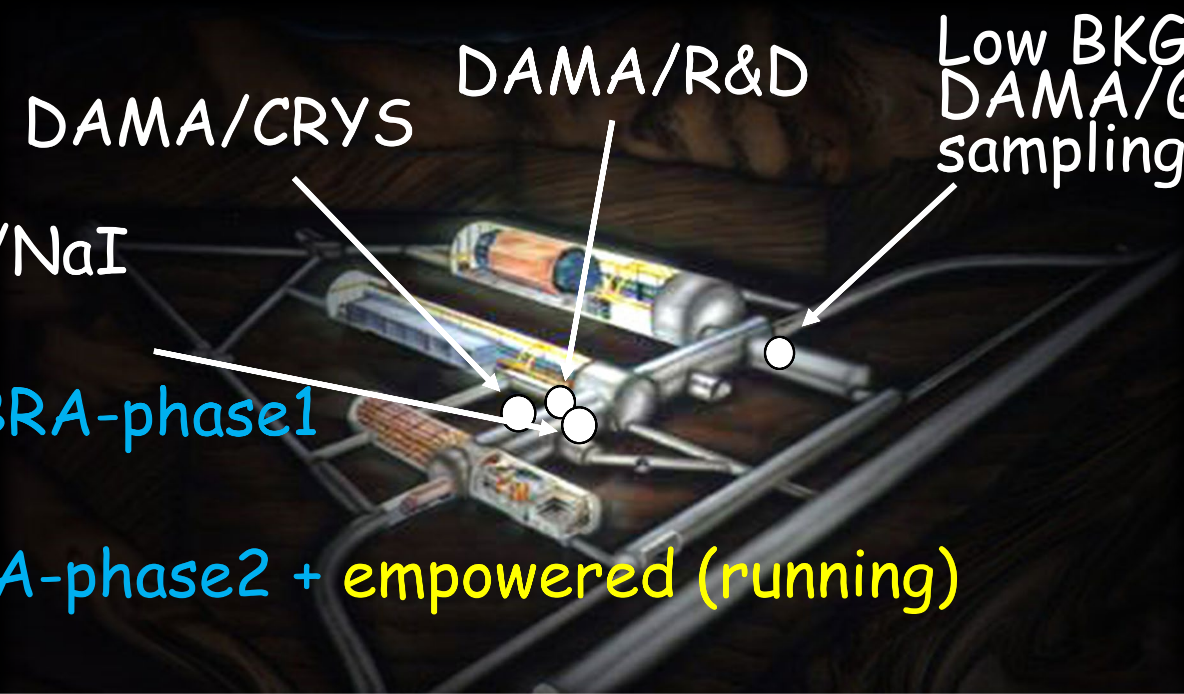
DAMA Experimental Activities

DAMA Collaboration:

Roma2, Roma1, LNGS-INFN, IHEP/Beijing

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

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

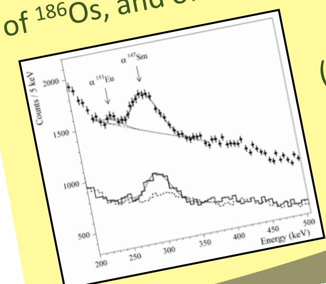


DAMA: an observatory for rare processes @LNGS

Main results obtained by DAMA in the search for rare processes

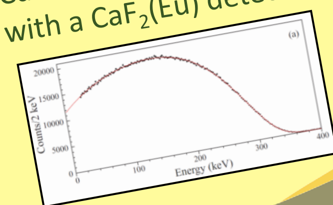
- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{144}Sm, ^{154}Sm, ^{150}Nd, ^{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 spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state

Search for PEP violating processes in Sodium and in Iodine

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

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

Dark Matter investigation

See A. Leoncini talk on 15/09/22

… many others are in progress

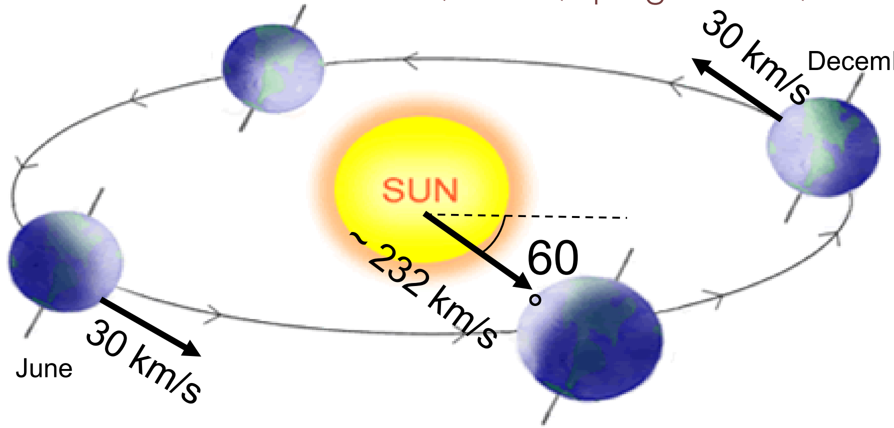
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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.

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

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



- 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)

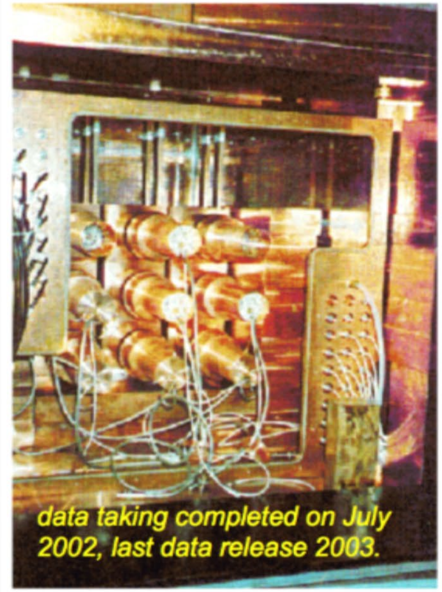
$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

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

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

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



Performances:

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

Results on rare processes:

- Possible Pauli exclusion principle violation — PLB408(1997)439
- CNC processes — PRC60(1999)065501
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) — PLB460(1999)235
- Search for solar axions — PLB515(2001)6
- Exotic Matter search — EPJdirect C14(2002)1
- Search for superdense nuclear matter — EPJA23(2005)7
- Search for heavy clusters decays — EPJA24(2005)51

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- **Annual Modulation Signature** — PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

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

total exposure (7 annual cycles) 0.29 ton×yr

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

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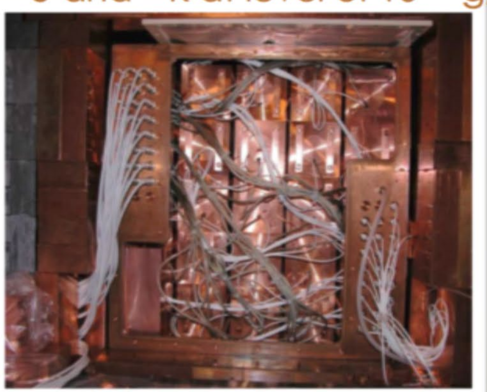
The DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques
(all operations involving - including photos - in HP Nitrogen atmosphere)

- 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

Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g



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

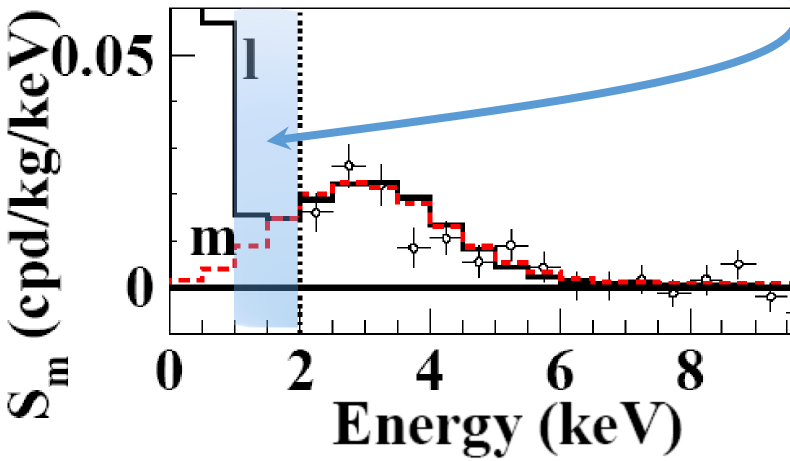
DAMA/LIBRA–phase2

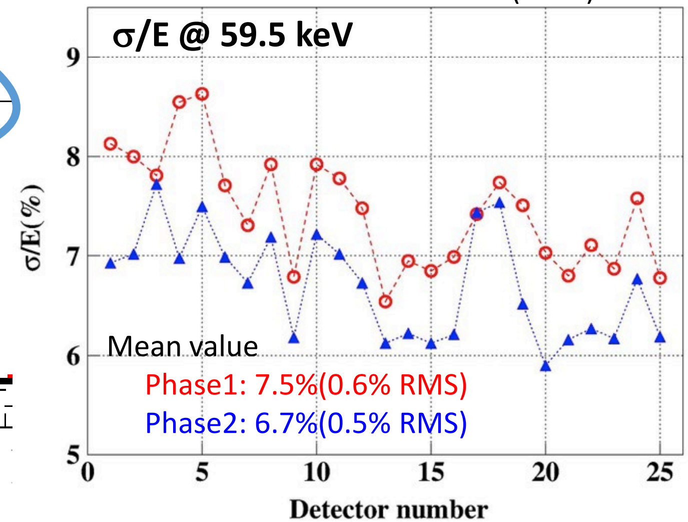
JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4) (2019) 317
PPNP114(2020)103810
NPAE 22(2021) 329

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

- 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*

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





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

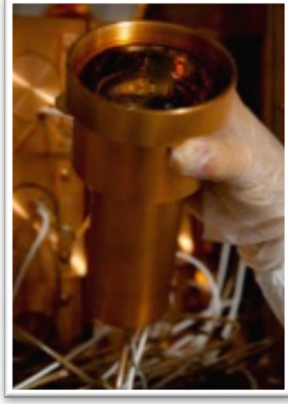
The light responses:

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

Goal: software energy threshold at 1 keV – accomplished

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**

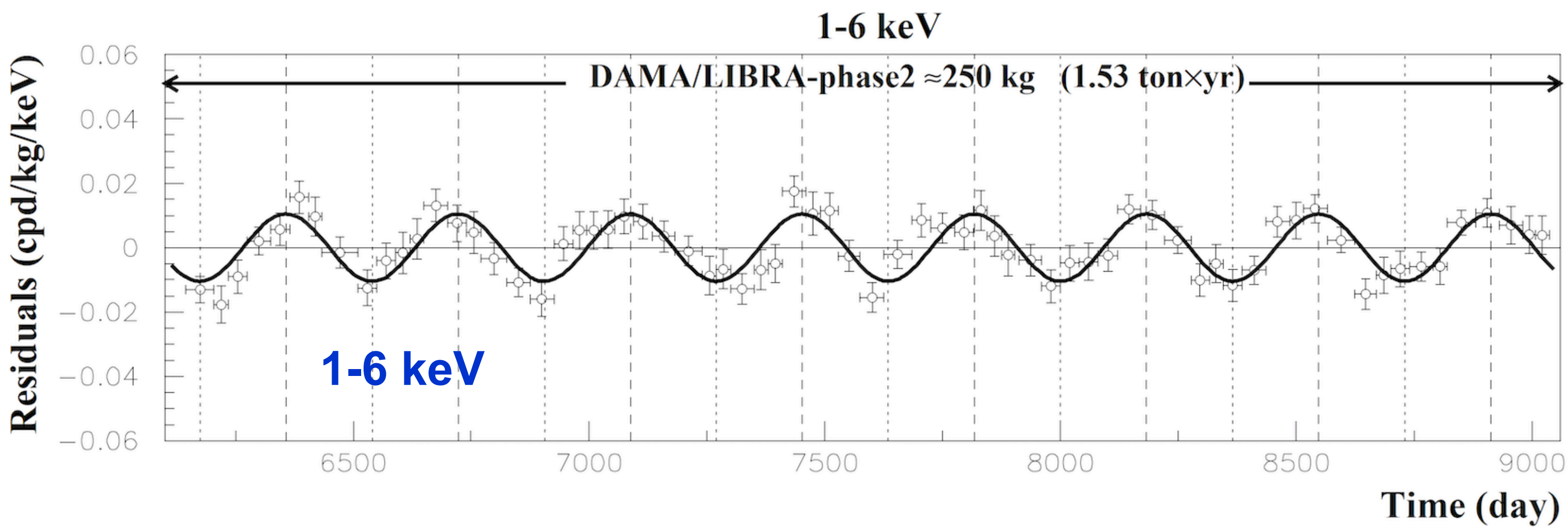
Exposure with this data release of DAMA/LIBRA-phase2: **1.53 ton × yr**

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

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

χ^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

χ^2/dof = 66.2/68 **11.6 σ C.L.**

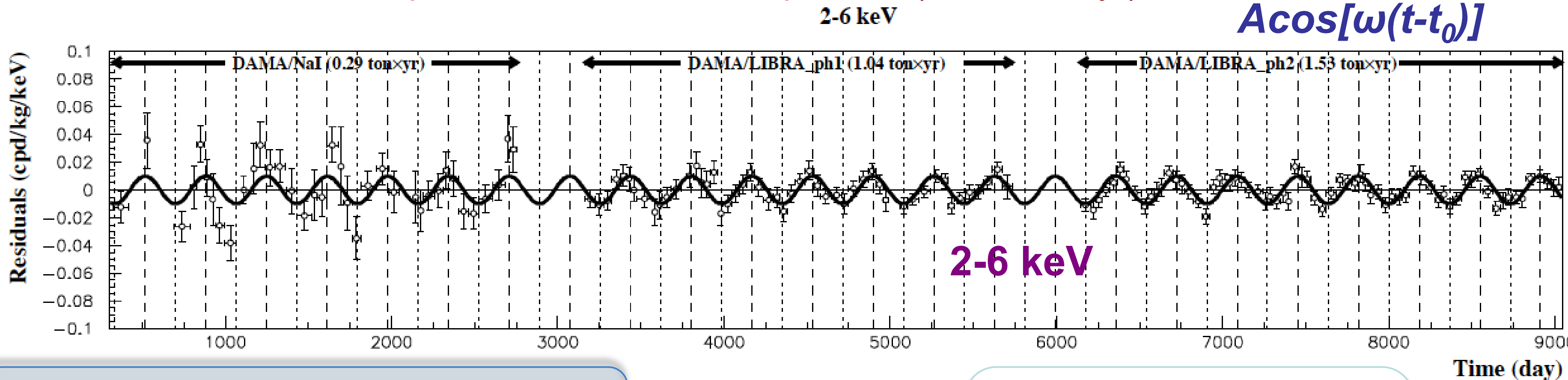
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6σ C.L.

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)

$Acos[\omega(t-t_0)]$



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.**

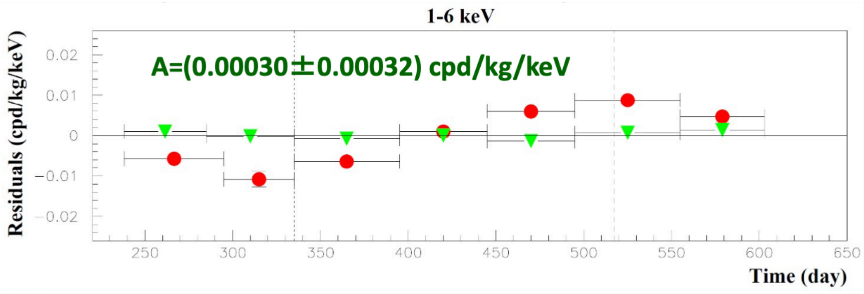
Releasing period (*T*) and phase (t_0) in the fit

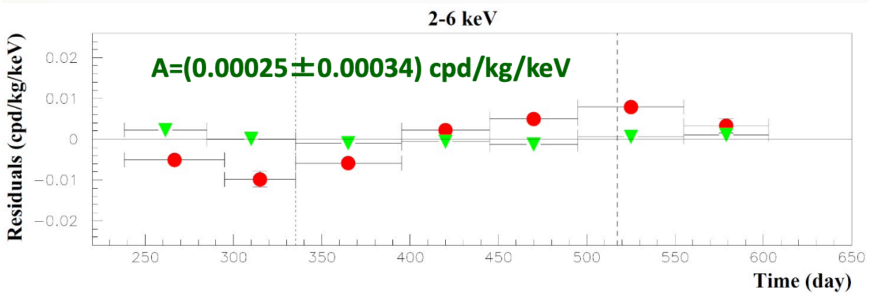
	ΔE	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0191±0.0020	0.99952±0.00080	149.6±5.9	9.6σ
	(1-6) keV	0.01058±0.00090	0.99882±0.00065	144.5±5.1	11.8σ
	(2-6) keV	0.00954±0.00076	0.99836±0.00075	141.1±5.9	12.6σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.00959±0.00076	0.99835±0.00069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

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

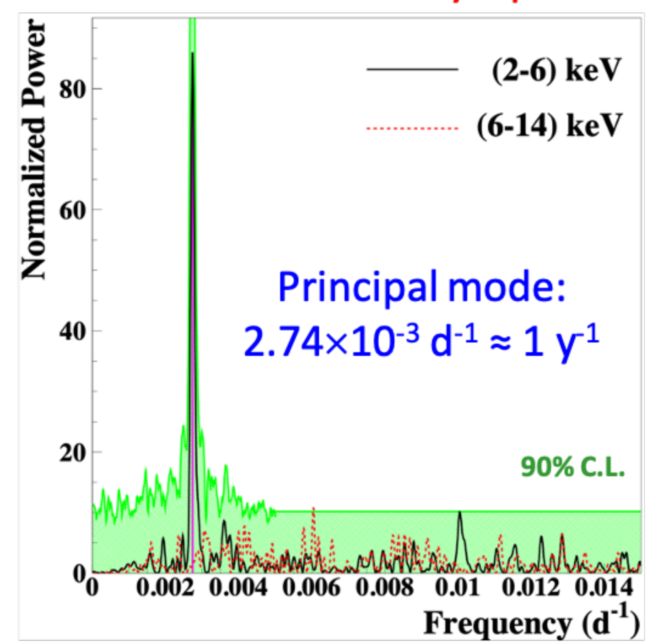
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The analysis in frequency

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

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

Zoom around the 1 y^{-1} peak



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

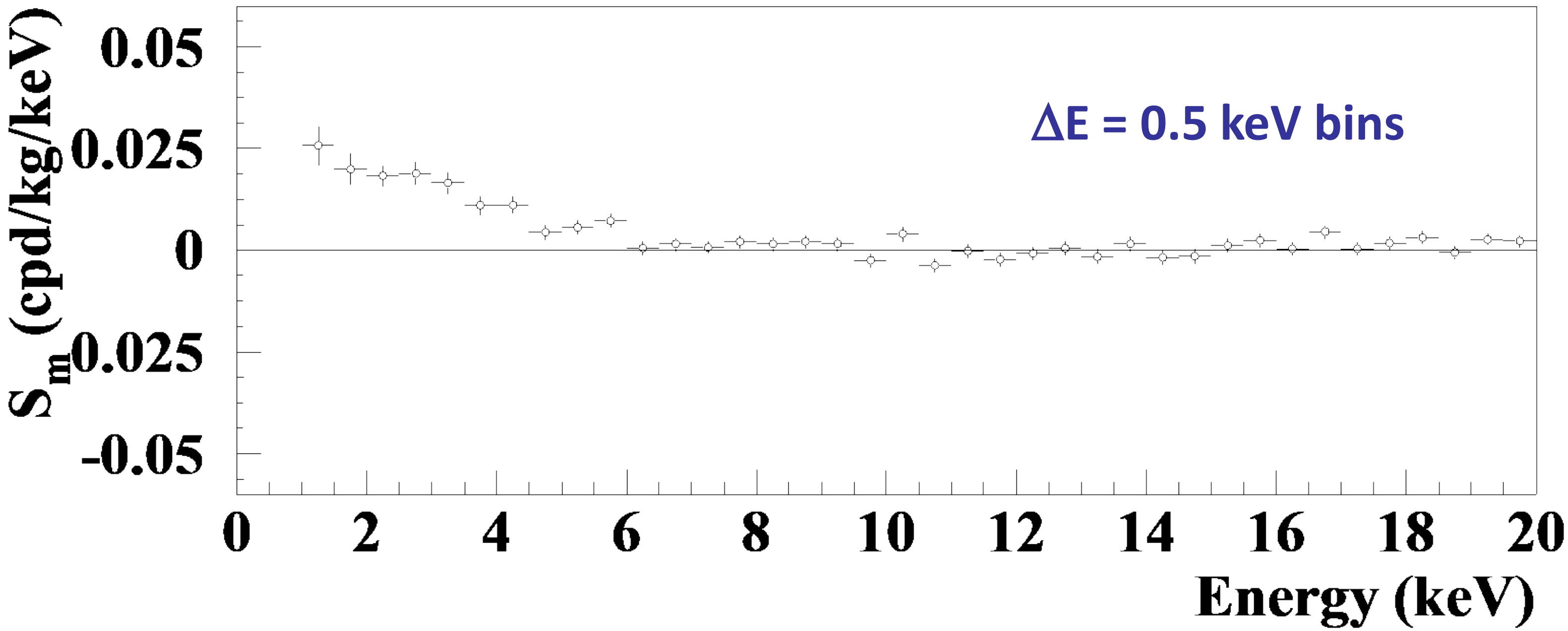
Energy distribution of the modulation amplitudes

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

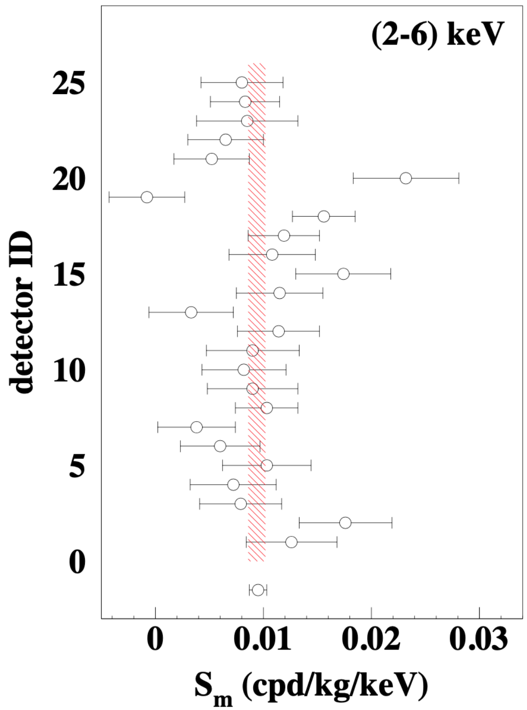
DAMA/NaI + DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2 (2.86 ton×yr)



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 χ^2 equal to 20.3 for 16 degrees of freedom (upper tail probability 21%).
- In (6–20) keV χ^2/dof = 42.2/28 (upper tail probability 4%). The obtained χ^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 detector



DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2

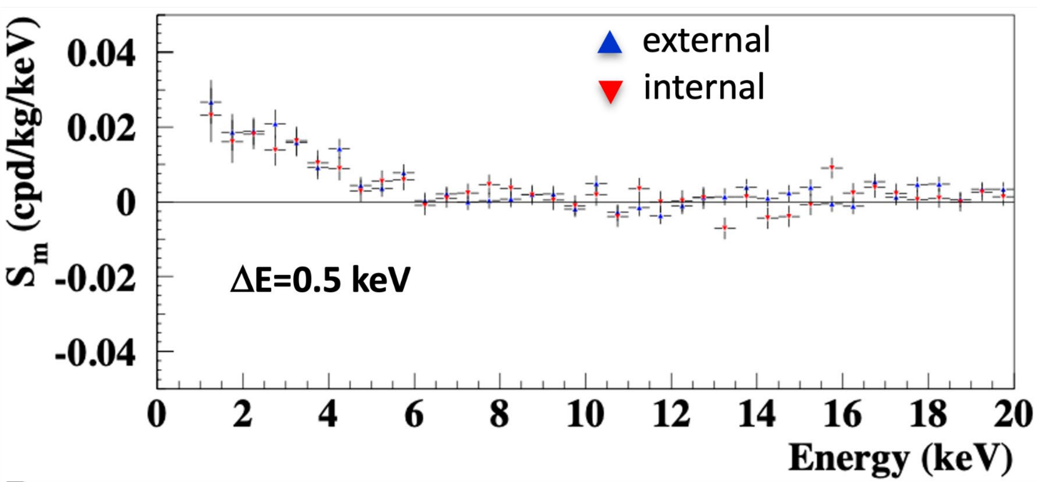
total exposure: 2.57 ton×yr

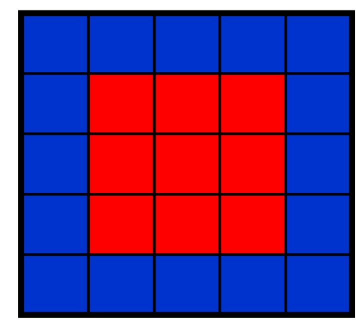
S_m in (2 - 6) keV for each of the 25 detectors (1σ error)

Shaded band = weighted averaged S_m ± 1σ

- χ^2/dof = 38.2/24 d.o.f. (P=3.3%)
- removing C19 and C20: χ^2/dof = 22.1/22 d.o.f.

External vs internal detectors:





1-4 keV χ^2/dof =1.9/6

1-10 keV χ^2/dof =7.6/18

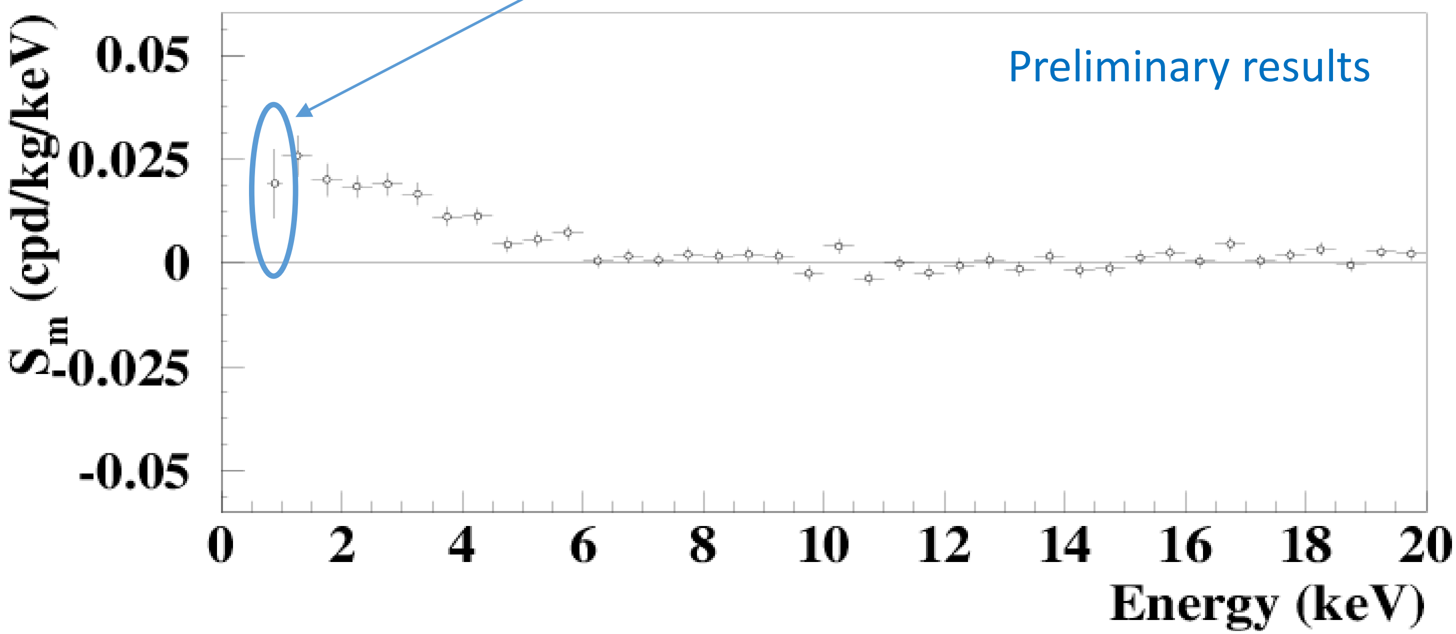
1-20 keV χ^2/dof =36.1/38

- The signal is rather well distributed over all the 25 detectors
- No difference between ext and int detectors

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

- 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 **arXiv: 2209.00882 (2022)**)

- 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(Tl) 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

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	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

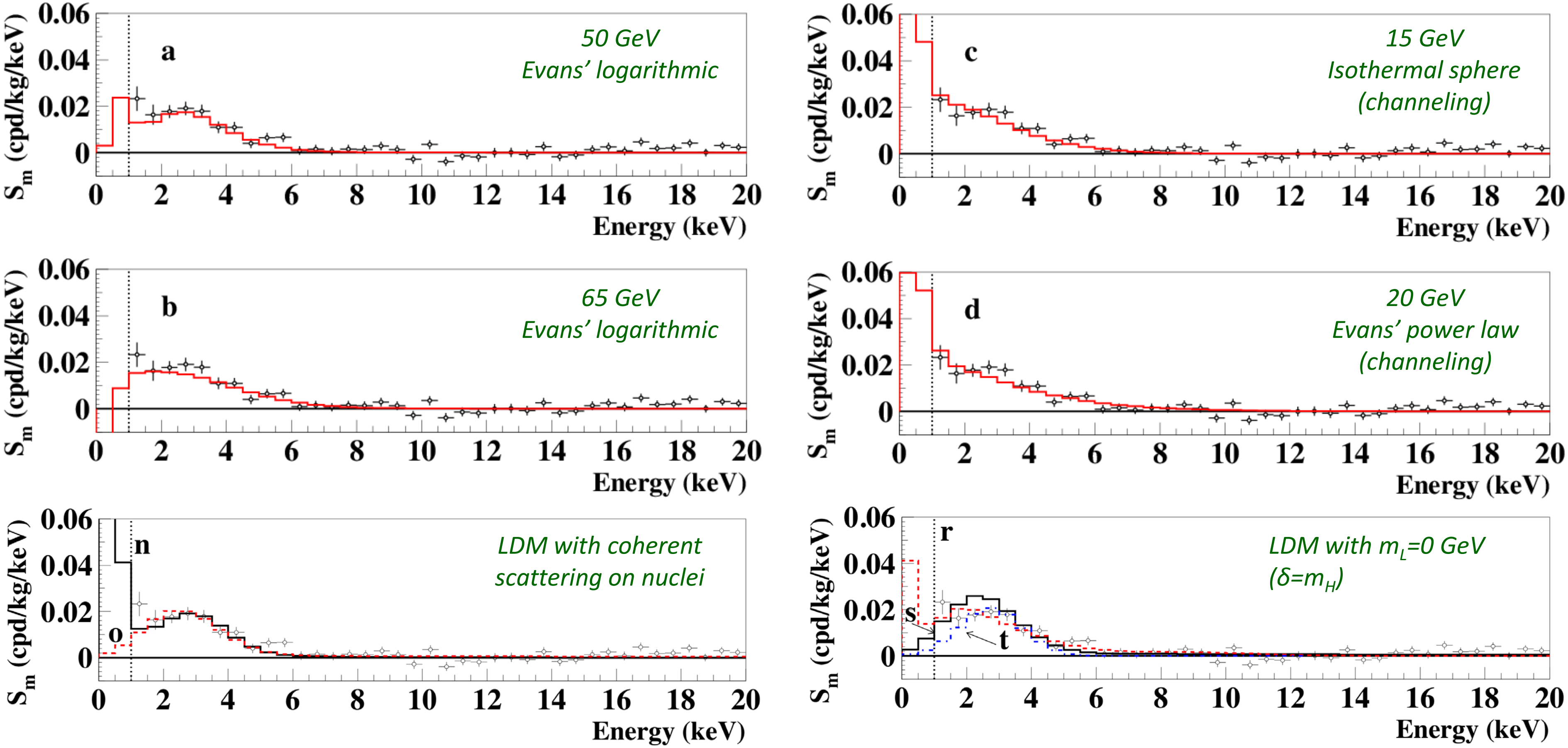
+ they cannot satisfy all the requirements of annual modulation signature

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

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

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

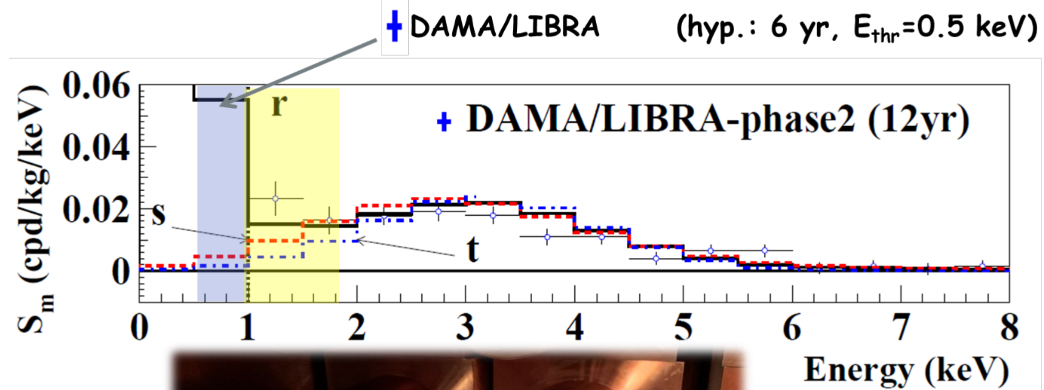
- Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios
- E_{th}=1 keV; old data release

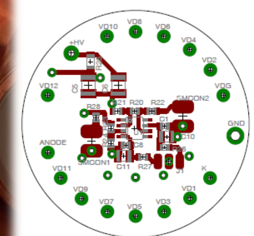


Running phase2-empowered with lower software energy threshold below 1 keV with suitable high efficiency

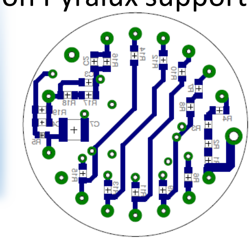
Enhancing experimental sensitivities and improving DM corollary aspects, other DM features, second order effects and other rare processes

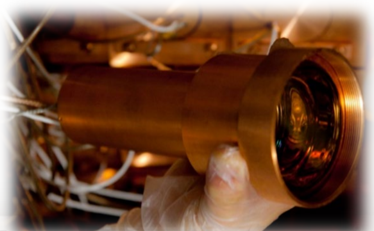
1) During fall 2021, DAMA/LIBRA–phase2 set-up was heavily upgraded
2) The upgrade basically consisted on:
   a. equipping all the PMTs with new low-background voltage dividers with pre-amps on the same board
   b. the use of Transient Digitizers with higher vertical resolution (14 bits).
3) After a dedicated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

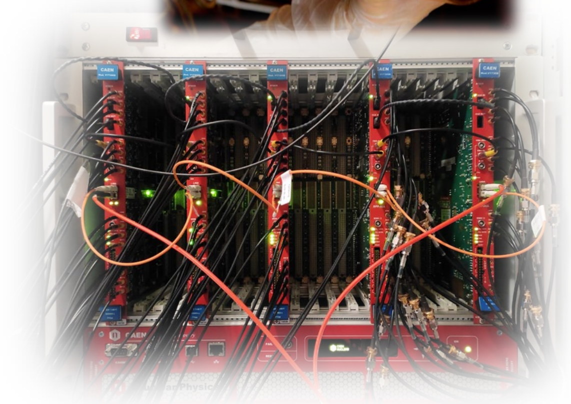




Voltage divider + preamp on Pyralux support







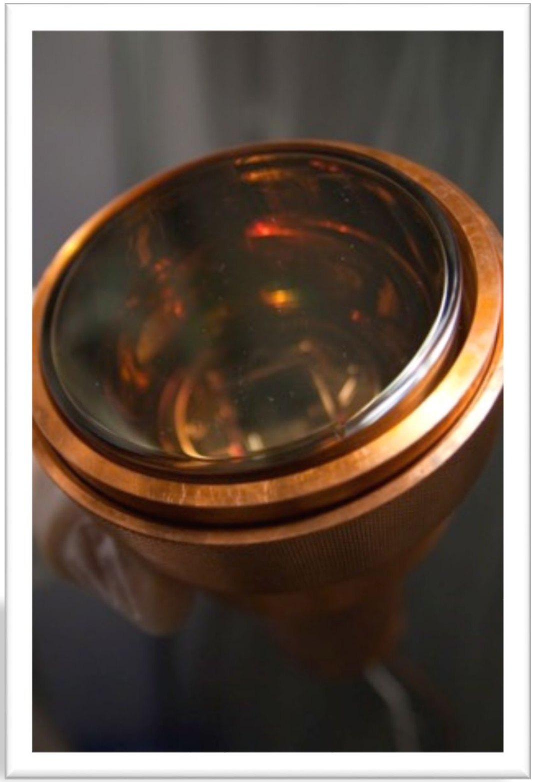
The features of the voltage divider+preamp system:

- 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 fibres directly connected to the daq pc

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
- 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.