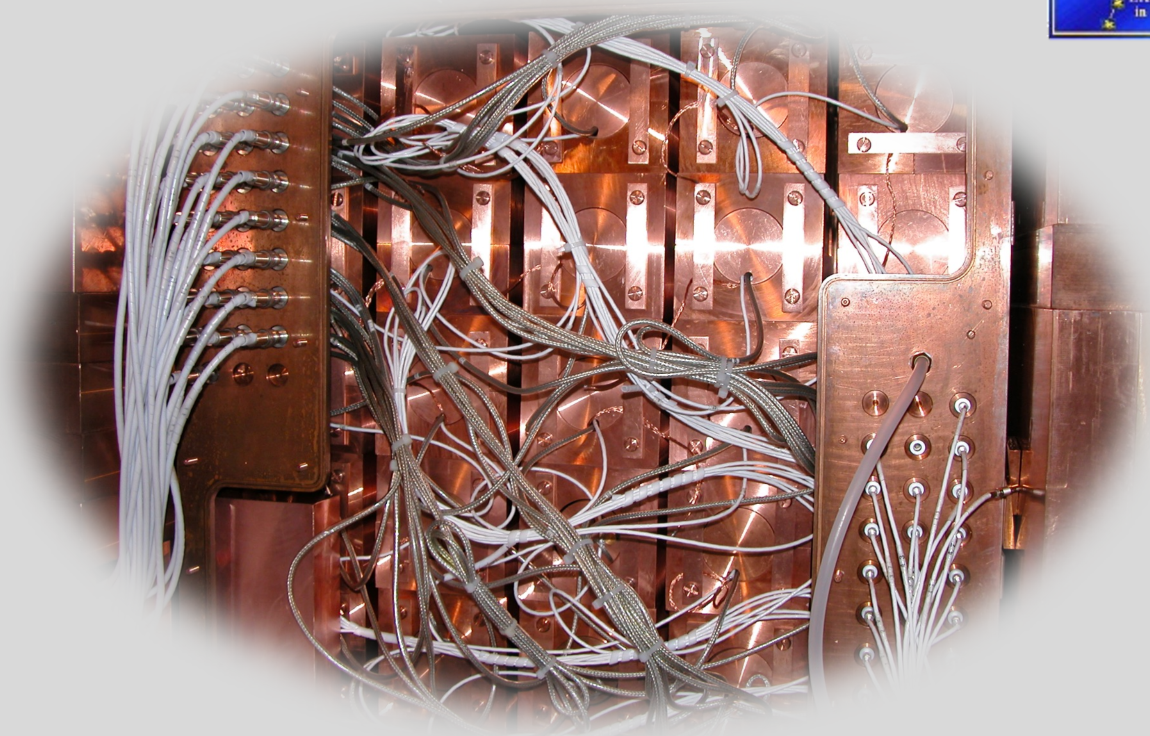
Status of DAMA/LIBRA-phase2 and its empowered stage



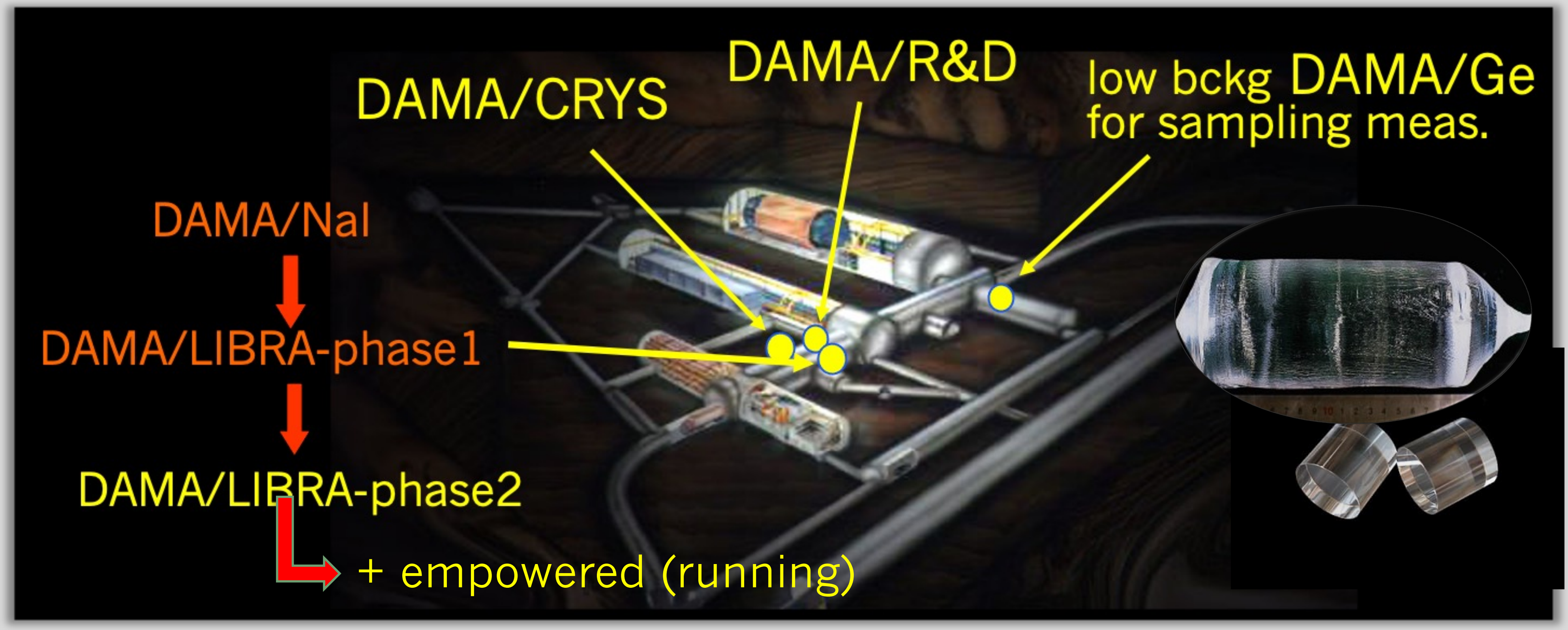
27th Int. workshop ''What comes beyond the standard models'', July 2024

R. BERNABEI
UNIVERSITA' AND INFN – Roma Tor Vergata

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

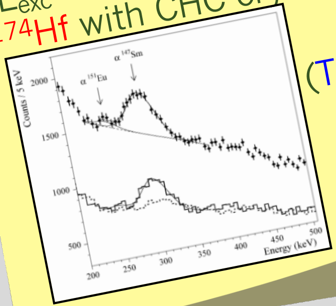
+ by-products and small scale expts.: INR-Kiev + other institutions
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia
+ in some studies, on ββ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

The experimental activities of DAMA will gradually cease at the end of 2024/Spring-2025, according to plans fixed by the coll. since years

Main results obtained by DAMA in the search for rare processes

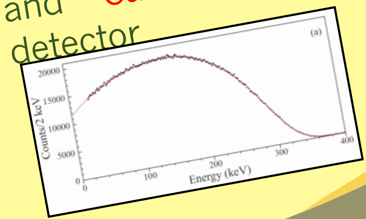
- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{144}Sm, ^{154}Sm, ^{150}Nd, ^{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 PEP violating processes in Sodium and in Iodine

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

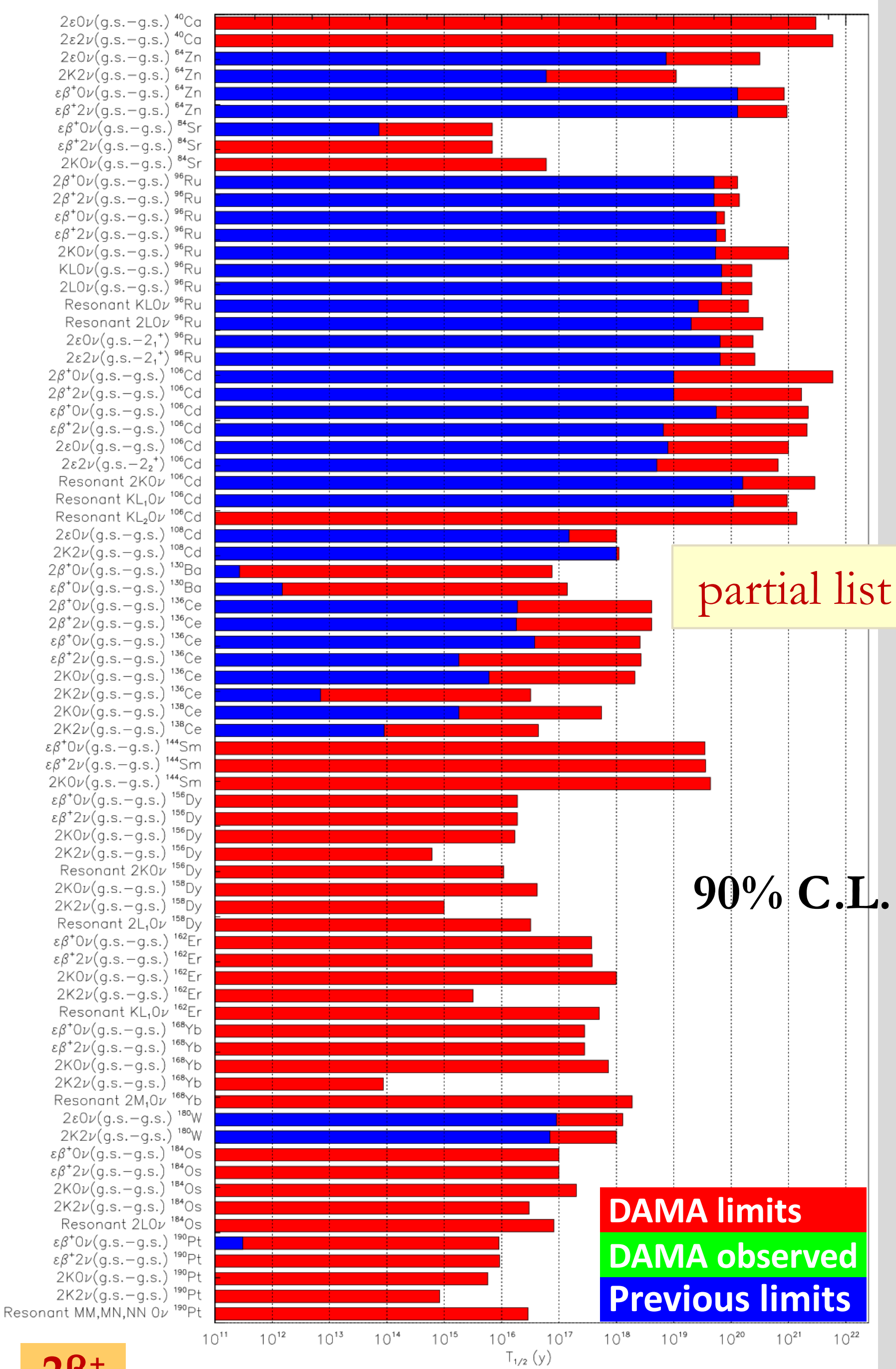
Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

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

Dark Matter investigation

... many others

Search for ββ decay modes in various isotopes at DAMA and STELLA set-ups



partial list

90% C.L.

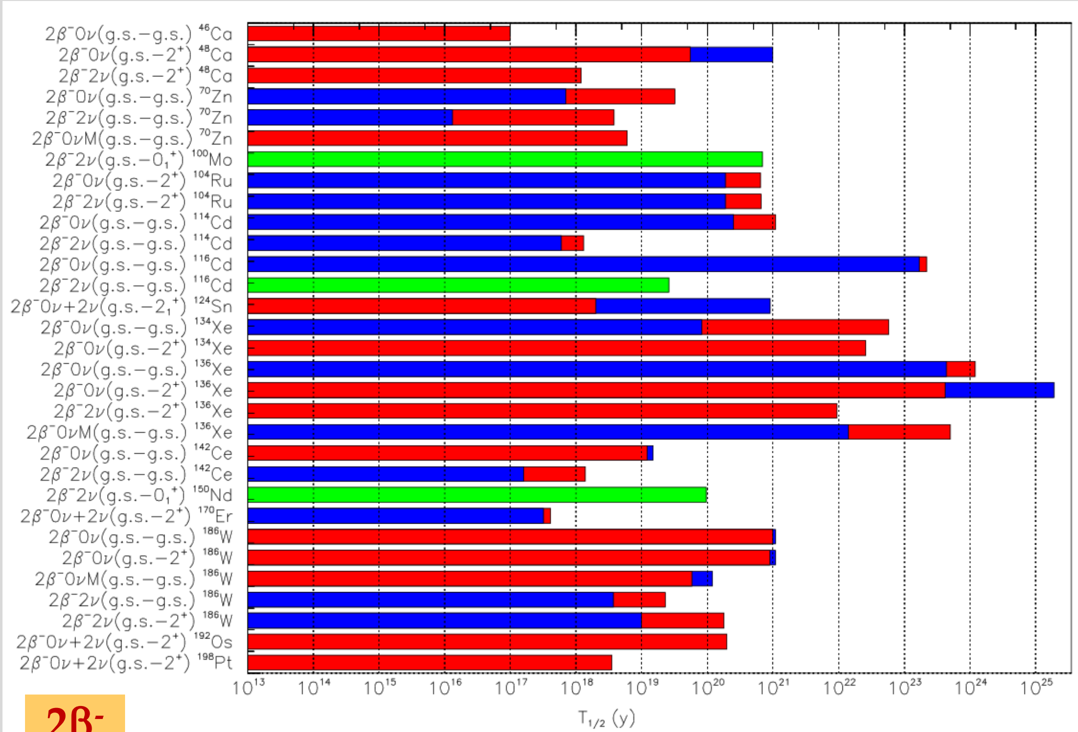
2β+

DAMA and DAMA/Kiev

- Many competitive limits obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes
- First searches for resonant $0\nu 2\varepsilon$ decays in some isotopes

New observations:

ARMONIA:	$2\nu 2\beta^-$ decay	$^{100}Mo \rightarrow {}^{100}Ru(0_1^+)$	NPA846(2010)143
AURORA:	$2\nu 2\beta^-$ decay	$^{116}Cd \rightarrow {}^{116}Sn$	PRD98(2018)092007
Nd_2O_3-HPGe:	$2\nu 2\beta^-$ decay	$^{150}Nd \rightarrow {}^{150}Sm(0_1^+)$	NPAE19(2018)95 Phys.Scr.96(2021)085302 (+ final result: submitted)



2β-

Relic DM particles from primordial Universe

- SUSY (as neutralino or sneutrino in various scenarios)
- the sneutrino in the Smith and Weiner scenario
- sterile ν
- electron interacting dark matter
- a heavy ν of the 4-th family
- even a suitable particle not yet foreseen by theories
- etc…
- axion-like (light pseudoscalar and scalar candidate)
- self-interacting dark matter
- mirror dark matter
- Kaluza-Klein particles (LKK)
- heavy exotic canditates, as "4th family atoms", ...
- Elementary Black holes, Planckian objects, Daemons
- invisible axions, ν's

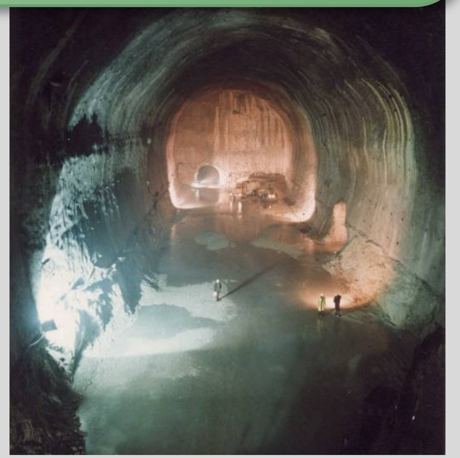
multi-component non-baryonic DM?

What accelerators can do:
to demostrate the existence of some of the possible DM candidates

What accelerators cannot do:
to credit that a certain particle is the Dark Matter solution or the "single" Dark Matter particle solution…

+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

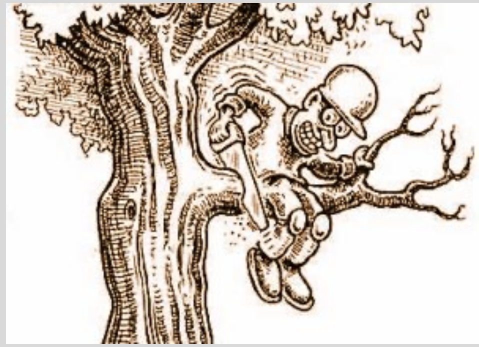
→ DM direct detection method using a model independent approach sensitive both to nuclear and/or to e.m. signals, and a low-background widely-sensitive target material and suitable procedures



Direct detection experiments

The detection experiments can be classified in **two classes**, depending direct on what they are based:

1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a **DM *model-independent* signature**



2. on the use of several uncertain techniques of statistical **subtractions** including subtraction of a hypothesized modellisation of backg in the counting rate (adding systematical effects and/or lost of some DM candidates)

Direct comparison of sensitivities are linked to realistic considerations on many technical, experimental and methodological aspects in the many possible scenarios + different observables

REMARK: It does not exist any approach to investigate the nature of the candidate in the direct and indirect DM searches, which can offer this latter information independently on assumed astrophysical, nuclear and particle Physics scenarios…

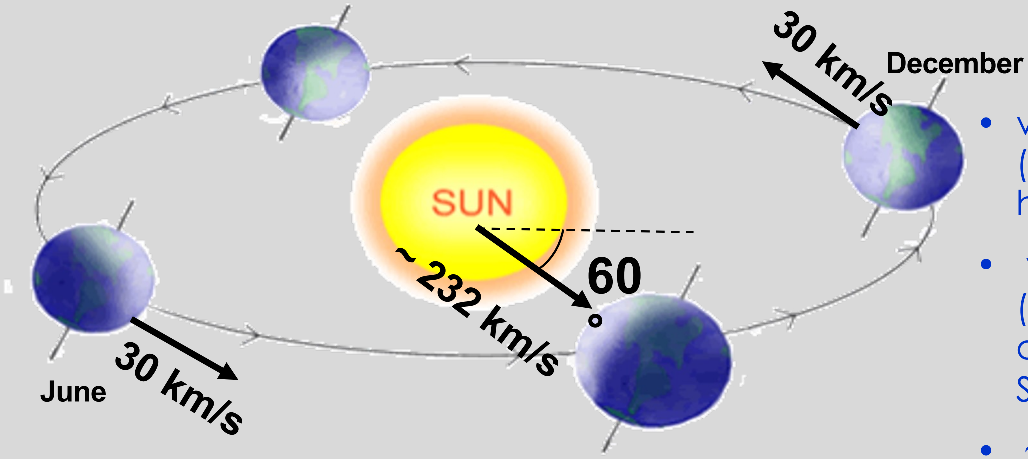
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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

Merit of ULB NaI(Tl) as target-material

- Well known technology
- High duty cycle
- Large mass possible
- "Ecological clean" set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- λ of the NaI(Tl) scintillation light well directly match PMTs sensitivity
- Uniform response in the realized detectors
- High light response (5.5 - 7.5 ph.e./keV phase1 and typically 6-10 phe/keV in phase2)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios on the contrary of other proposed target-materials and approaches
- Sensitive to both high (mainly by Iodine target) and low mass (mainly by Na target) candidates and to candidates also inducing e.m. radiation
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up
- etc.

ULB NaI(Tl) also allows the study of several rare processes

→ **High benefits/cost**

To develop ULB NaI(Tl): many years of work, specific experience in the specific detector, suitable raw materials availability/selections, developments of purification strategies, additives, growing/handling protocols, selective cuts, abrasives, etc. etc. → long dedicated time and efforts.

→ The developments themselves are difficult and uncertain experiments.
ULB NaI(Tl) – as whatever ULB detector - cannot be simply bought or made by another researcher for you ….. features depend on specific realization

road sign or labyrinth?

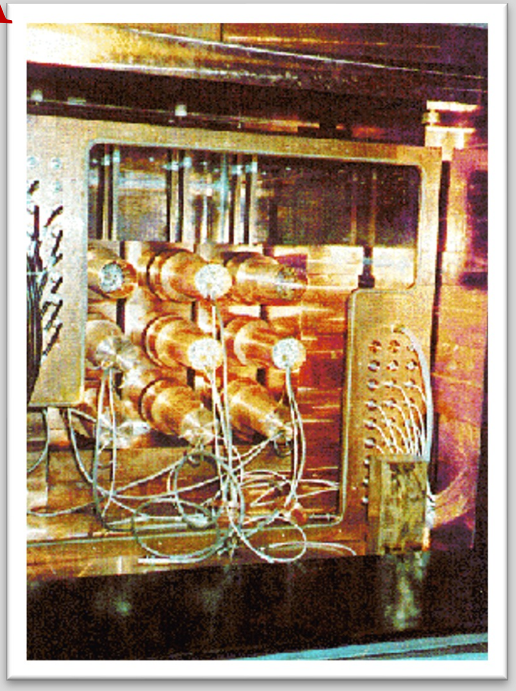
The presence of DM particles in the galactic halo:

- in the DAMA approach is NOT based – as other cases - on the tentative extraction of the constant part of the signal (S_0) from the measured rate (S_0+bckg) with many subtraction procedures including also that of an hypothesized (uncertain) bckg model extrapolated at low energy ⟷ this latter results are model-dependent.

- in the DAMA approach it is based on the study of the presence of a modulated part (amplitude S_m), which should satisfy many specific peculiarities. An evidence is largely model-independent.

Remark: DAMA results account both for DM candidates inducing nuclear recoils and/or e.m. signals since it does not exploit PSD on the modulation data.

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

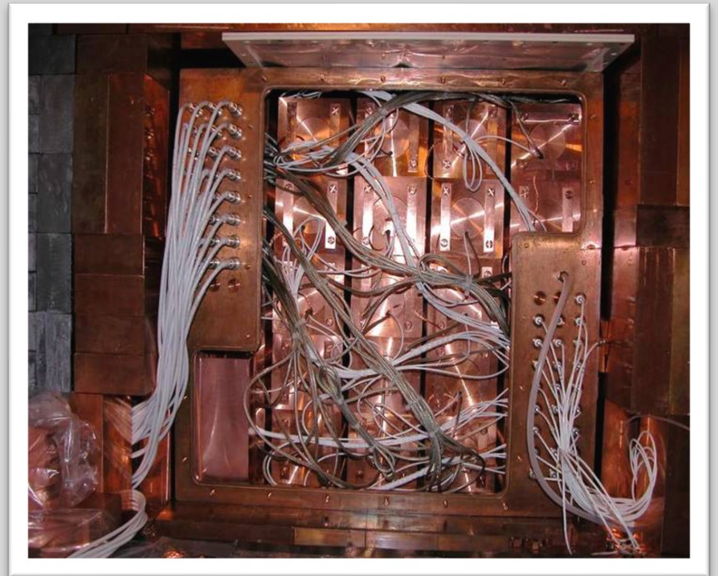
Results on rare processes: PLB408(1997)439, PRC60(1999)065501, PLB460(1999)235, PLB515(2001)6, EPJdirect C14(2002)1, EPJA23(2005)7, EPJA24(2005)51

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

The sensitivity of the DM annual modulation signature depends – apart from the counting rate – on the product:

Model-independent DM annual modulation signature

$$\varepsilon \times \Delta E \times M \times T \times (\alpha-\beta^2)$$

ε: increased in DAMA/LIBRA-phase2

ΔE: increased in DAMA/LIBRA-phase2

T: increased with DAMA/LIBRA-phase2

DAMA/LIBRA-phase2 & now the -empowered equivalent to have somehow instead enlarged the exposed mass

+

Lowering software energy threshold → better discrimination among corollary model-dependent interpretations

&: DM annual modulation signature acts itself as a strong bckg reduction strategy as already pointed out in the original paper by Freese et al.

&: No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

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.

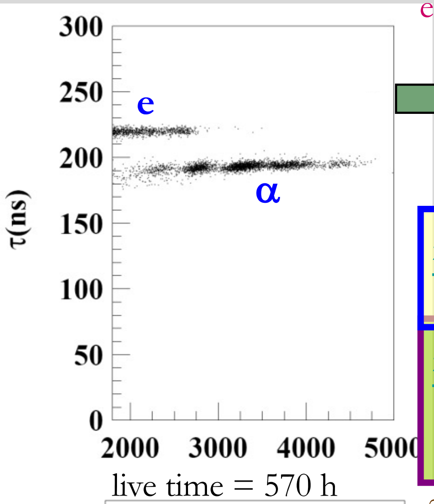
Goal: software energy threshold at 1 keV – accomplished

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

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

Residual contaminants in the ULB NaI(Tl) detectors

α/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 α/kg/day

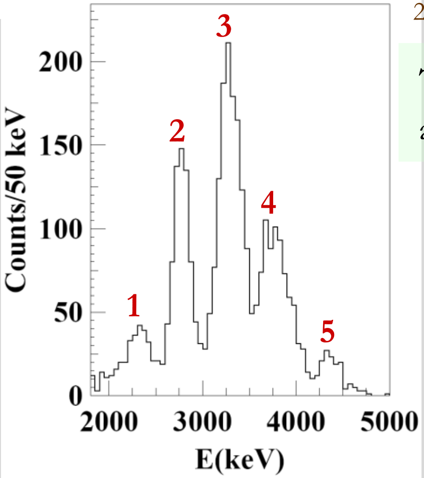
Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling

^{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 α 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



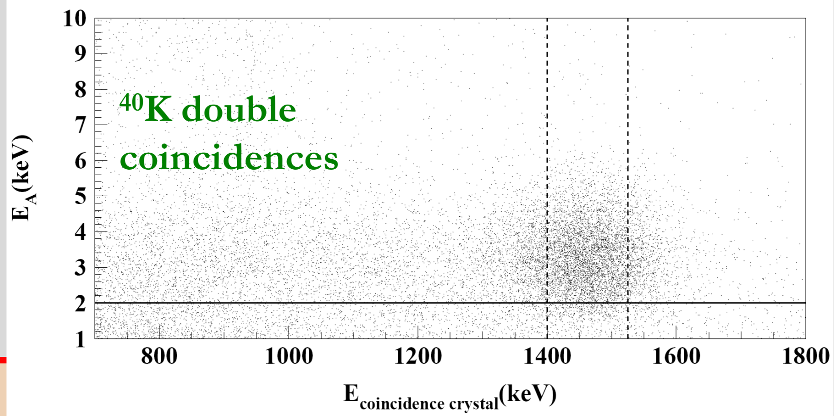
^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow ^{234}U \rightarrow ^{230}Th \rightarrow ^{226}Ra \rightarrow ^{210}Pb \rightarrow ^{206}Pb$

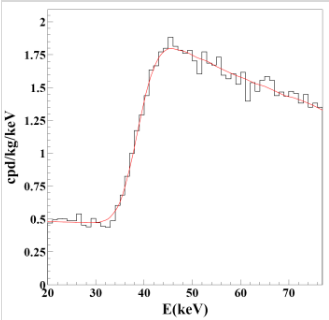
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

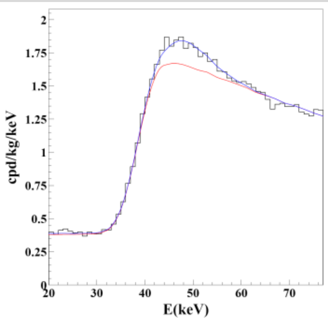
and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{nat}K residual contamination

The analysis has given for the ^{nat}K content in the crystals values not exceeding about 20 ppb (for ^{40}K multiply by 10^{-4})







^{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

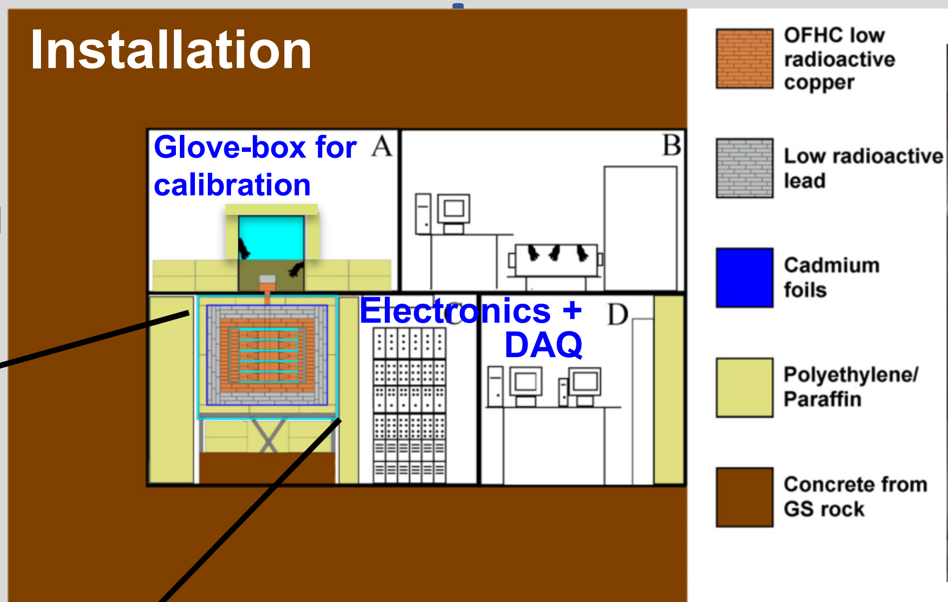
... more on NIMA592(2008)297

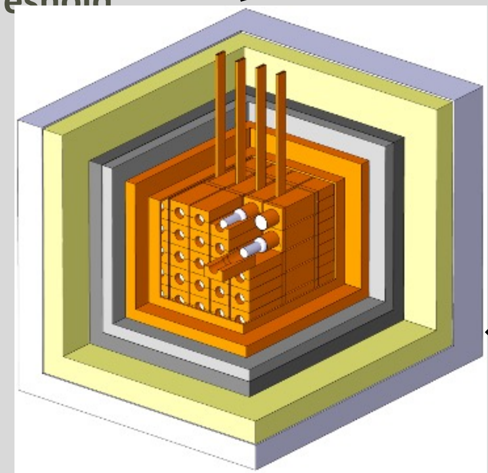
Set-up materials & detectors deep **underground since decades**

The DAMA/LIBRA–phase2

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

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix; grown with Kyropoulos method and dedicated selections/purify-cations/protocols
- two Suprasil-B light guides directly coupled to each bare crystal
- two new high Q.E. PMTs for each crystal working in coincidence at the single ph. el. threshold
- 6-10 phe/keV; 1 keV software energy threshold



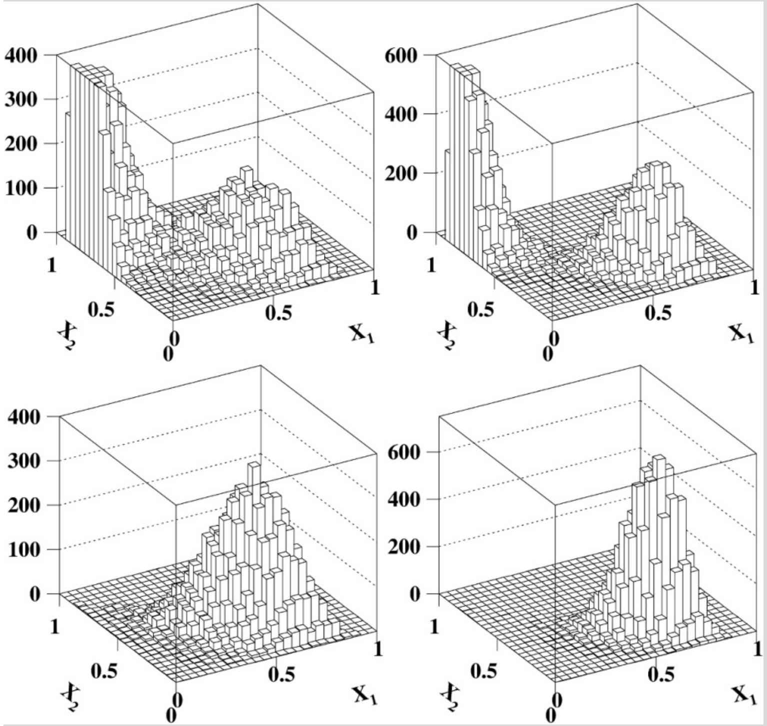


- Whole setup decoupled from ground
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- Dismounting/Installing protocol in HP N$_2$
- All the materials selected for low radioactivity
- Multiton-multicomponent passive shield (>10 cm of OFHC Cu, 15 cm of boliden Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as prod runs
- Never neutron source in DAMA installations
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data

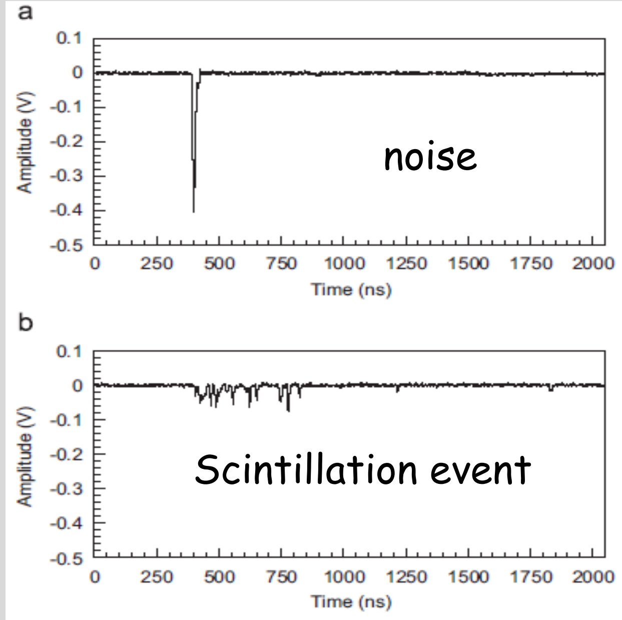
All materials deeply selected for ULB and underground since more than 20 yr

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

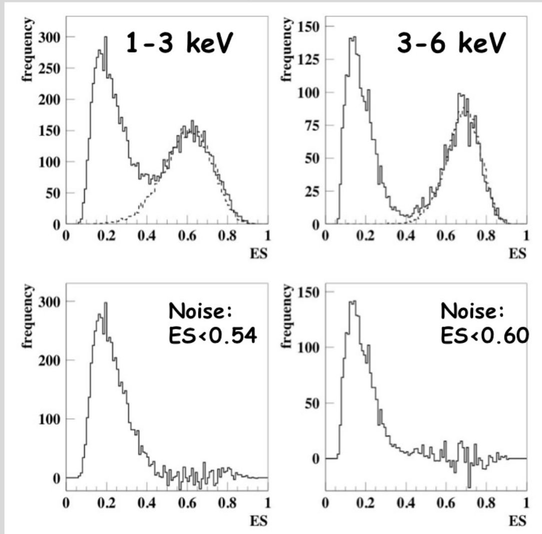
Noise rejection in phase2: only procedure applied to analysed data



- Comparison of the noise and the scintillation pulses distributions in 1-3 keV and 3-6 keV
- production data vs γ source
- scintillation events well separated from noise

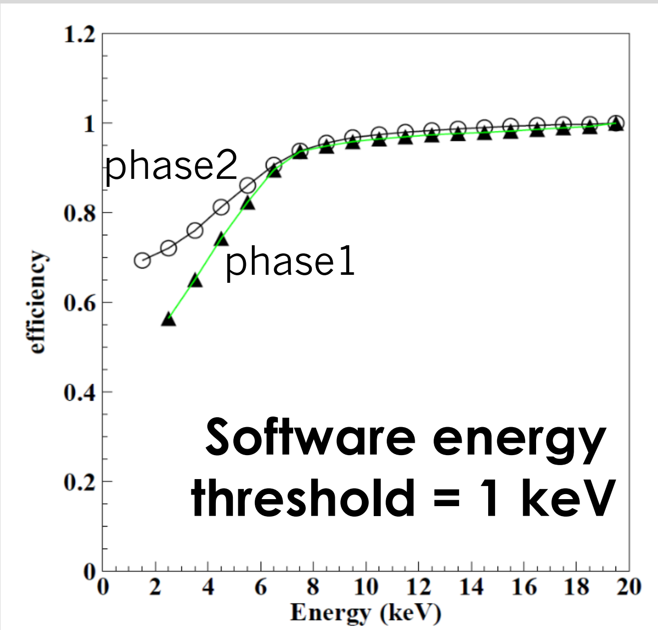


X_1=Area(from 100 to 600 ns)/Area from 0 to 600 ns)
X_2=Area(from 0 to 50 ns)/Area from 0 to 600 ns)



$$ES = \frac{1-(X_2 - X_1)}{2}$$

Residual noise events:
(15±62) (<120)
-(18±41) (<51)

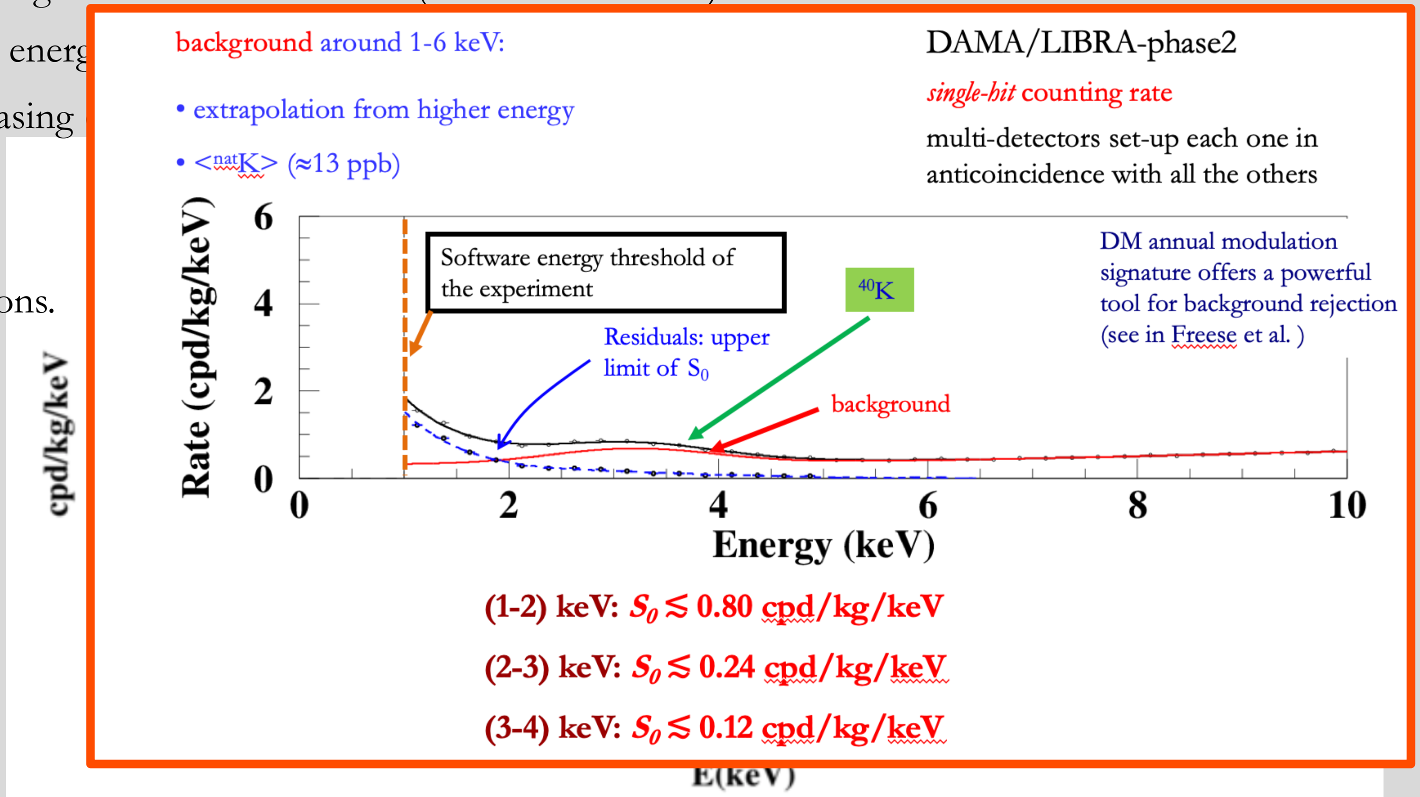


→ possible noise contamination, *f*, in the selected events <3% @ software energy threshold

JINST 7(2012)03009

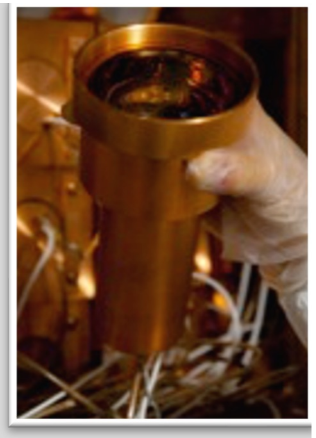
For a prior in corollary model dependent analysis: DAMA/LIBRA-phase2 energy spectrum

- 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 × 10^8 events from sources
- ✓ Acceptance window eff. 8 a.c.: ≈ 4.2 × 10^6 events (≈ 1.7 × 10^5 events/keV)

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

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

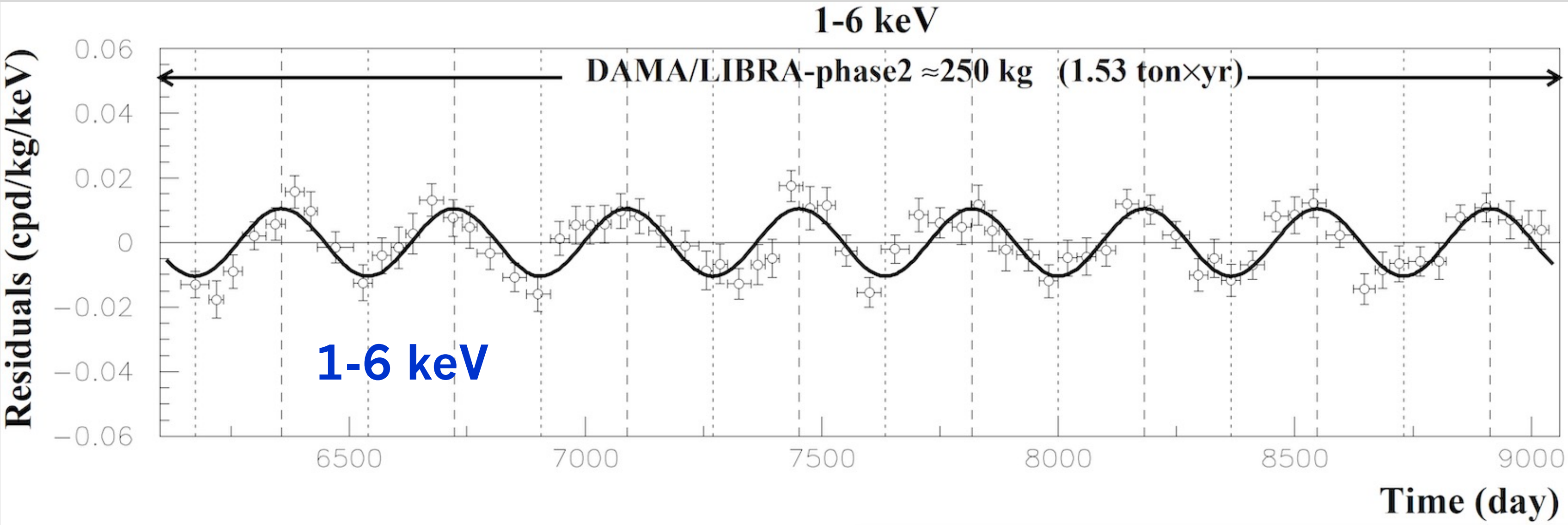
Exposure of DAMA/LIBRA-phase2 with the annual cycles released so far: **1.53 ton × yr**

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

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.**

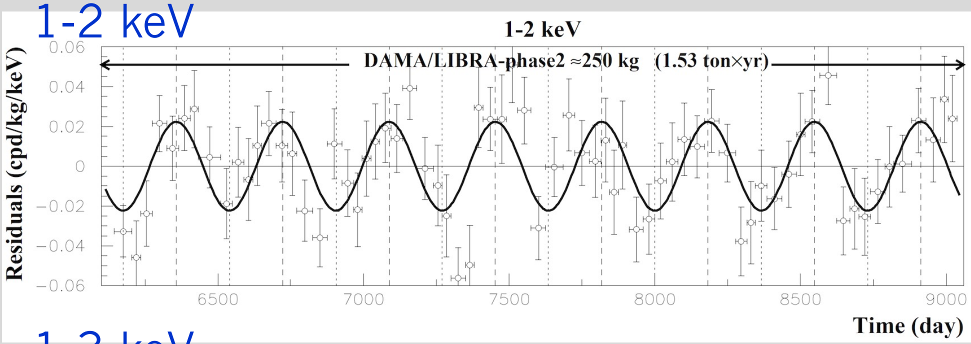
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6σ C.L.

DM model-independent Annual Modulation Result

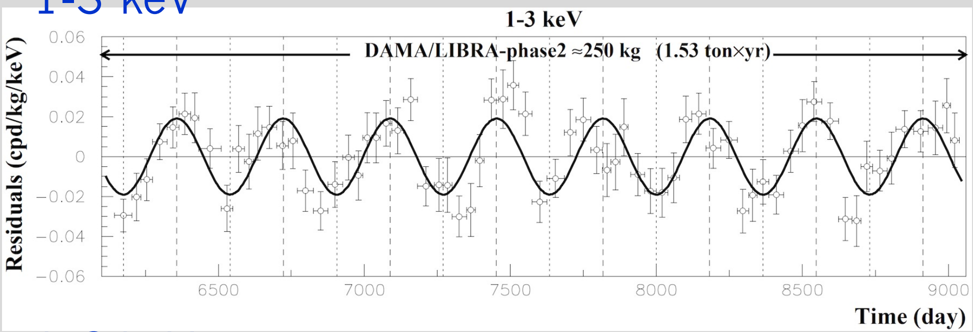
DAMA/LIBRA-phase2 (1.53 ton × yr)

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

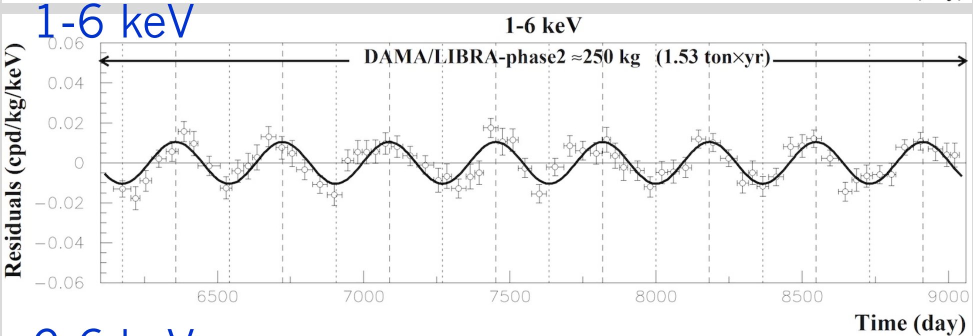
1-2 keV



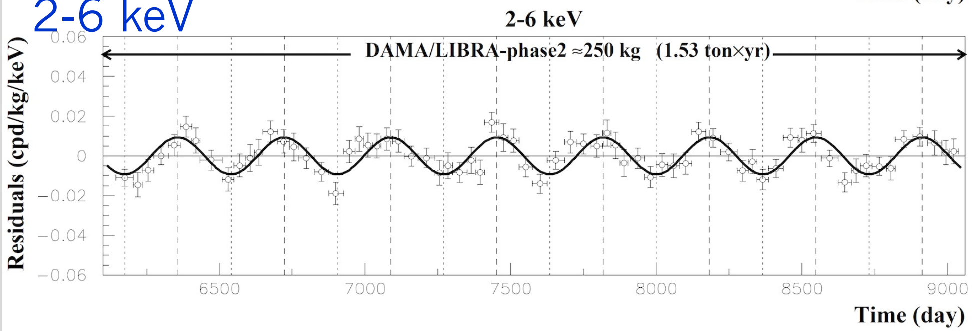
1-3 keV



1-6 keV



2-6 keV



Absence of modulation? No

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

Fit on DAMA/LIBRA-phase2

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

1-2 keV

A=(0.0224±0.0030) cpd/kg/keV

χ^2/dof = 75.8/68 **7.4 σ C.L.**

1-3 keV

A=(0.0191±0.0020) cpd/kg/keV

χ^2/dof = 81.6/68 **9.7 σ C.L.**

1-6 keV

A=(0.01048±0.00090) cpd/kg/keV

χ^2/dof = 66.2/68 **11.6 σ C.L.**

2-6 keV

A=(0.00933±0.00094) cpd/kg/keV

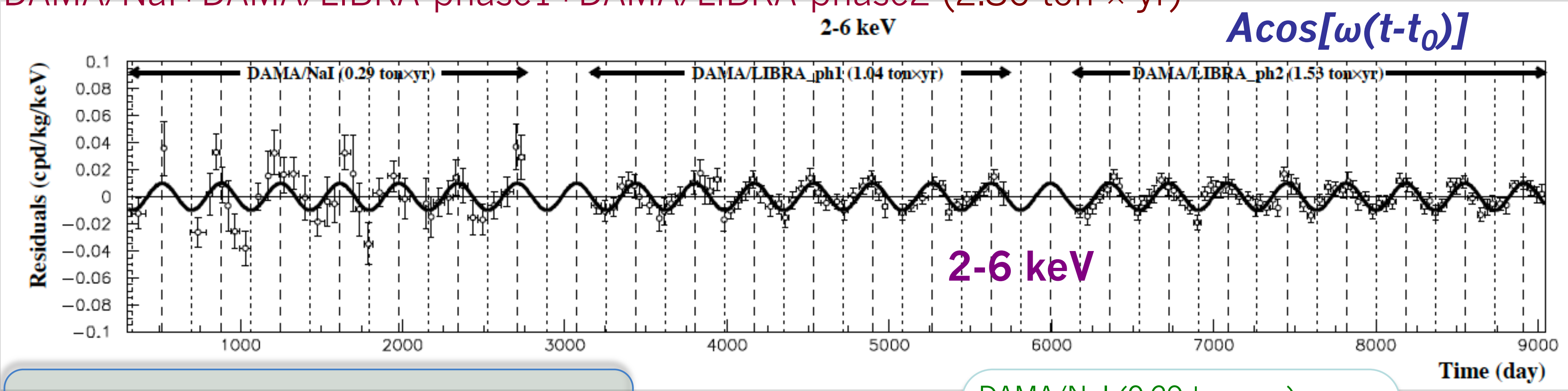
χ^2/dof = 58.2/68 **9.9 σ C.L.**

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

DM model-independent Annual Modulation Result

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

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



Absence of modulation? No

χ^2/dof=311/156 ⇒ 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.**

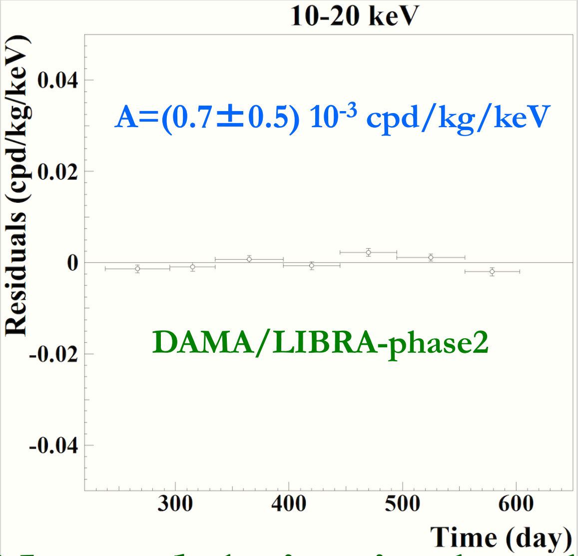
Releasing period (*T*) and phase (t_0) in the fit

	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.

Examples of consistency: Rate behaviour above 6 keV

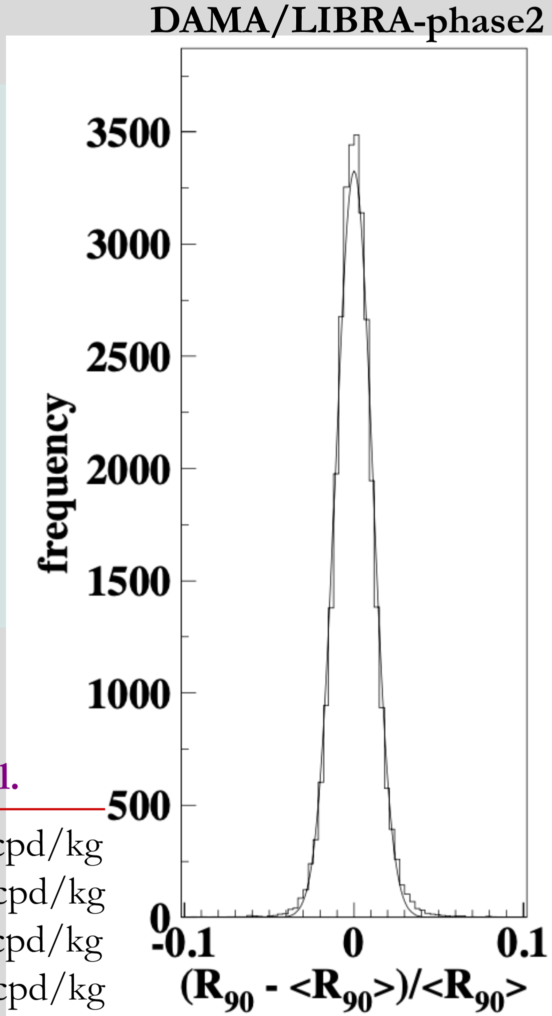
- **No Modulation above 6 keV**



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

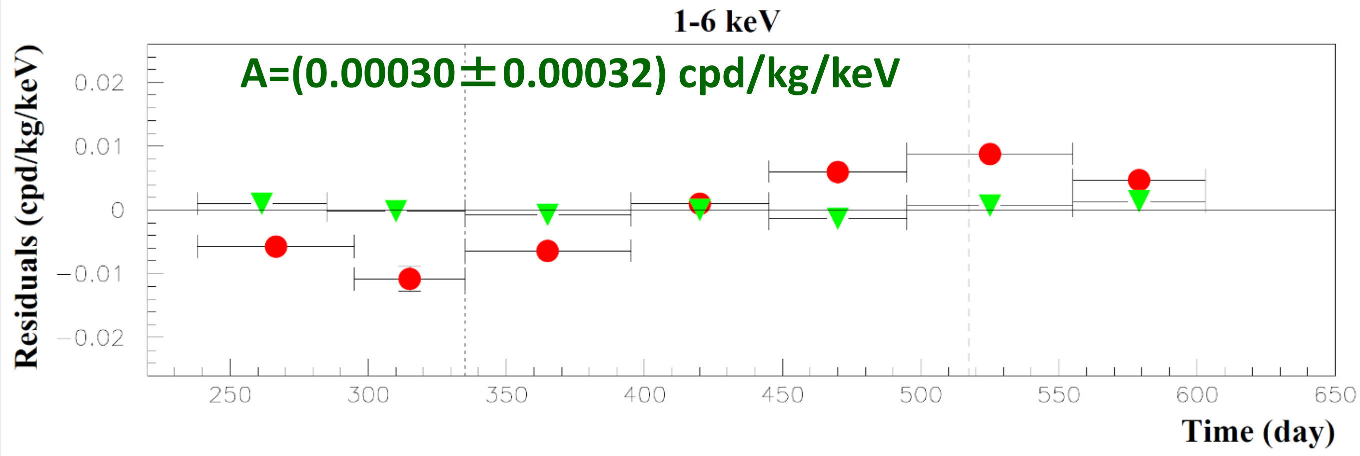
Period	Mod. Ampl.
DAMA/LIBRA-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg
DAMA/LIBRA-ph2_8	-(0.18±0.13) cpd/kg
DAMA/LIBRA-ph2_9	(0.08±0.14)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

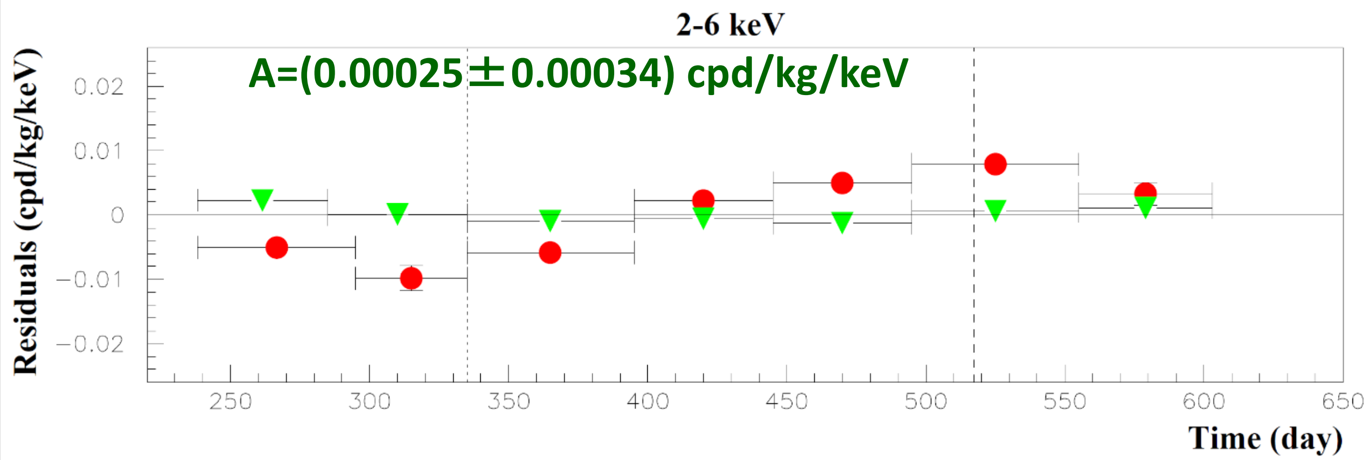
No modulation above 6 keV
This accounts for all sources of bckg and is consistent with the studies on the various components

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

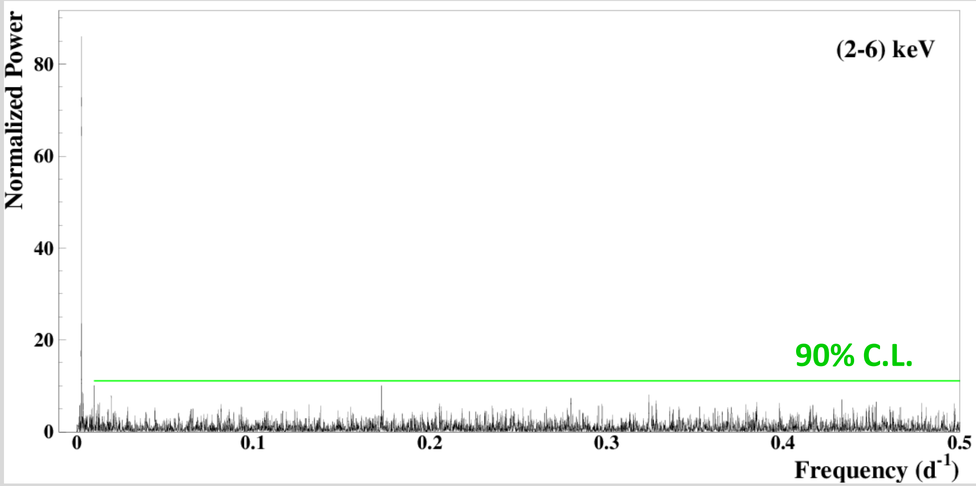
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

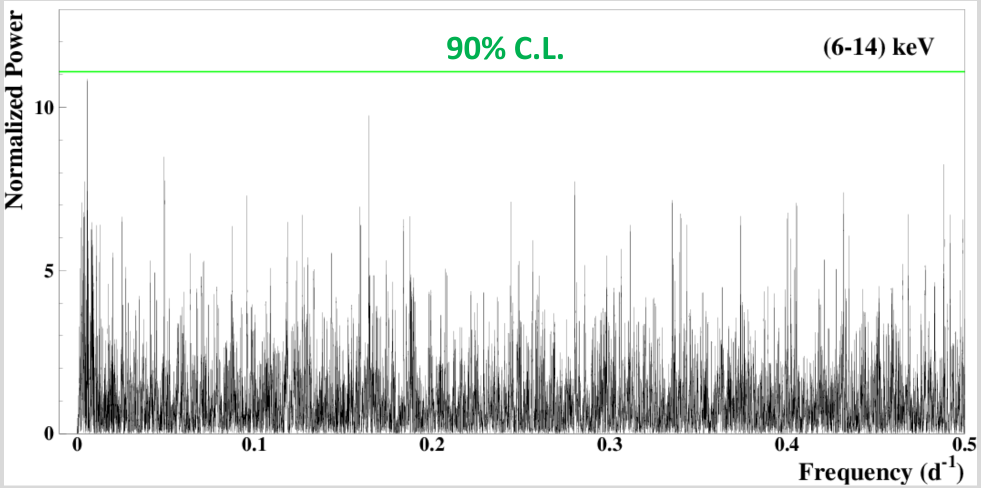
The analysis in frequency

(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

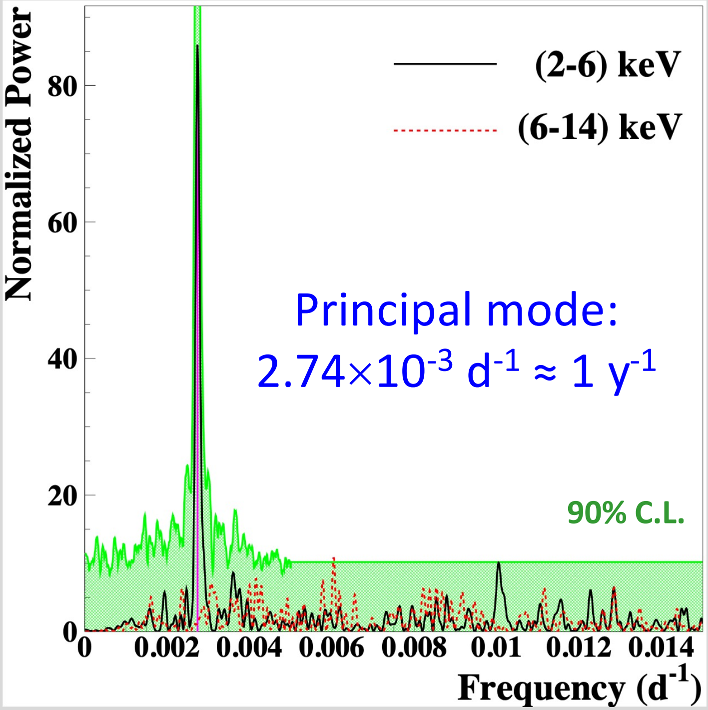
The whole power spectra up to the Nyquist frequency





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

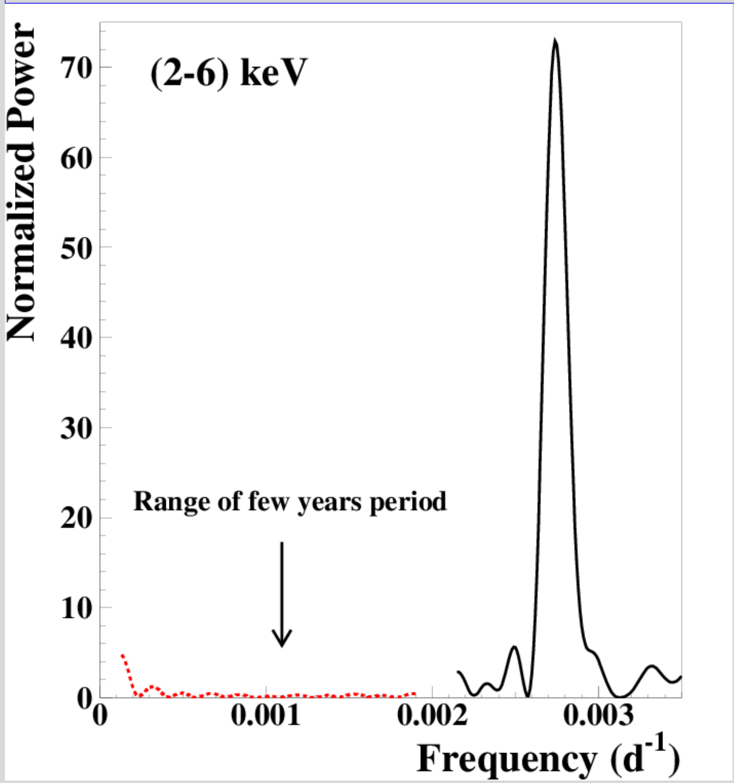
Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region

Investigating the possible presence of long term modulation in the counting rate

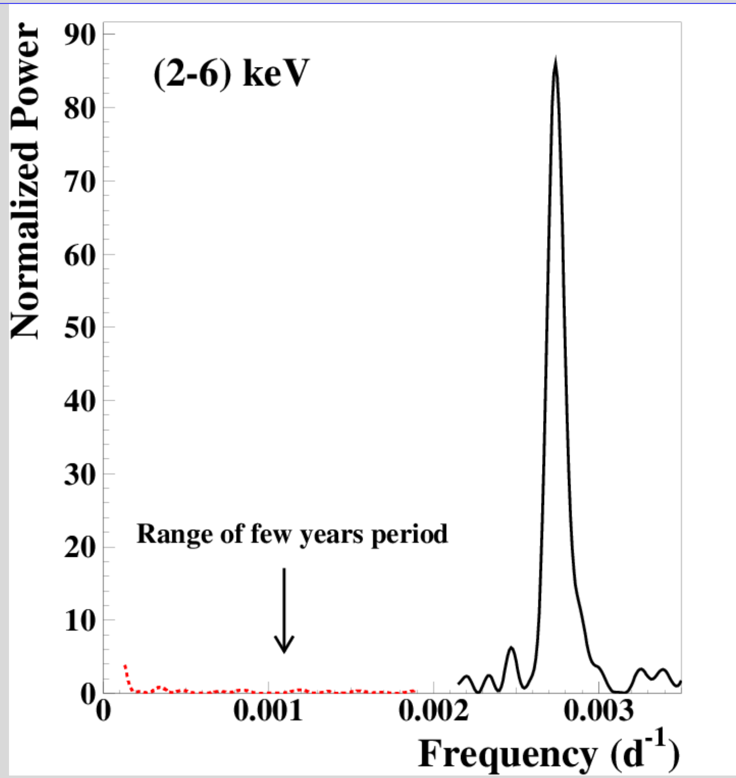
We calculated annual baseline counting rates – that is the averages on all the detectors (j index) of $flat_j$ (i.e. the single-hit scintillation rate of the j-th detector averaged over the annual cycle)

For comparison the power spectra for the measured single-hit residuals in (2–6) keV are also shown: Principal modes @ 2.74×10^{-3} d^{-1} ≈ 1 y^{-1}

DAMA/LIBRA-ph1+ph2(8 a.c.)



DAMA/NaI + DAMA/LIBRA-ph1+ph2(8a.c.)



No statistically significant peak at lower frequency

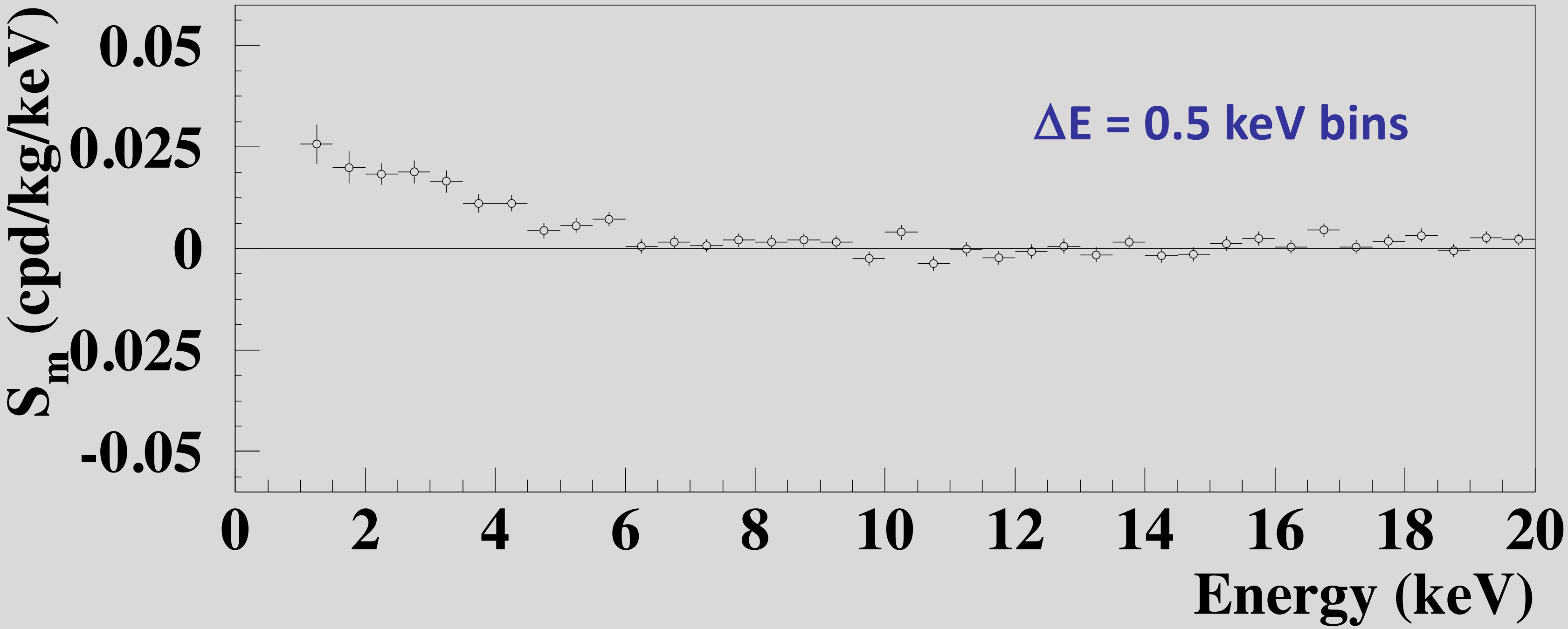
Energy distribution of the modulation amplitudes

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

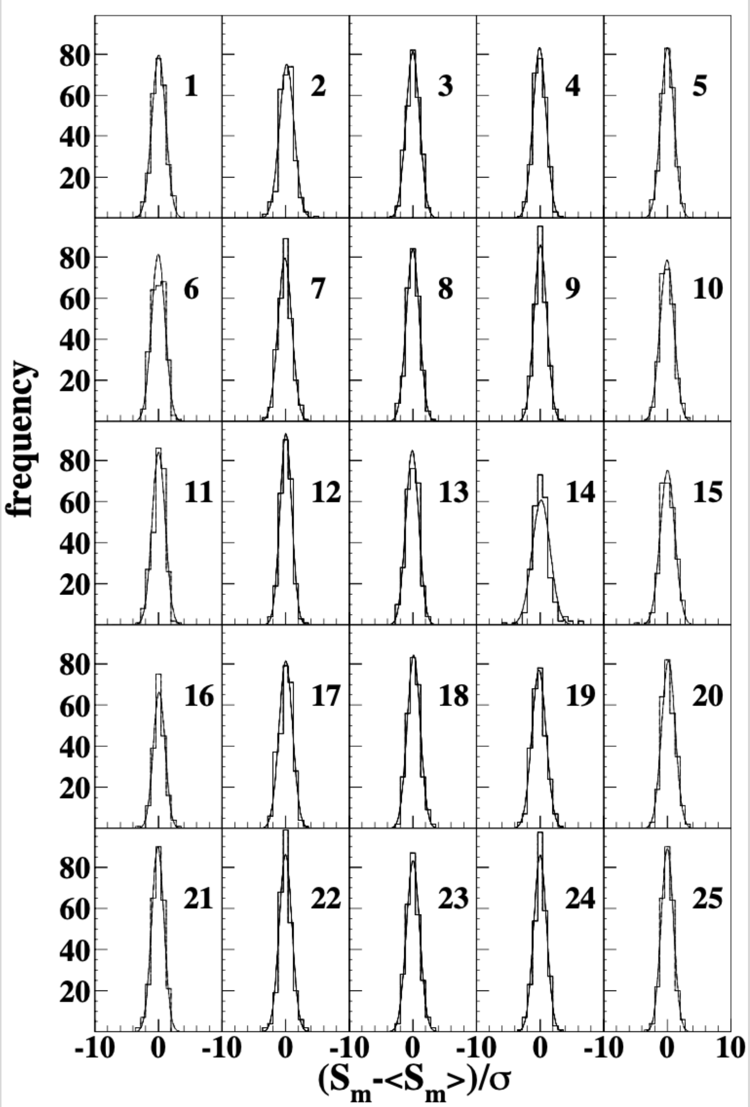
- The S_m values in the (6–14) keV energy interval have random fluctuations around zero with χ^2 equal to 20.3 for 16 degrees of freedom (upper tail probability 21%).
- In (6–20) keV χ^2/dof = 42.2/28 (upper tail probability 4%). The obtained χ^2 value is rather large due mainly to two data points, whose 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%.

Statistical distributions of the modulation amplitudes (S_m)

a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)

b) <S_m> = mean values over the detectors and the annual cycles for each energy bin; σ = error on S_m

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



Each panel refers to each detector separately; 272 entries (the 16 energy bins in the (2–6) keV energy interval of the 7 DAMA/LIBRA–phase1 annual cycles and the 20 energy bins in the (1–6) keV energy interval of the 8 DAMA/LIBRA–phase2 annual cycles)**, but 192 for the 16th detector** (only 2 annual cycles of DAMA/LIBRA-phase1)

2–6 keV phase1 + 1-6 keV phase2

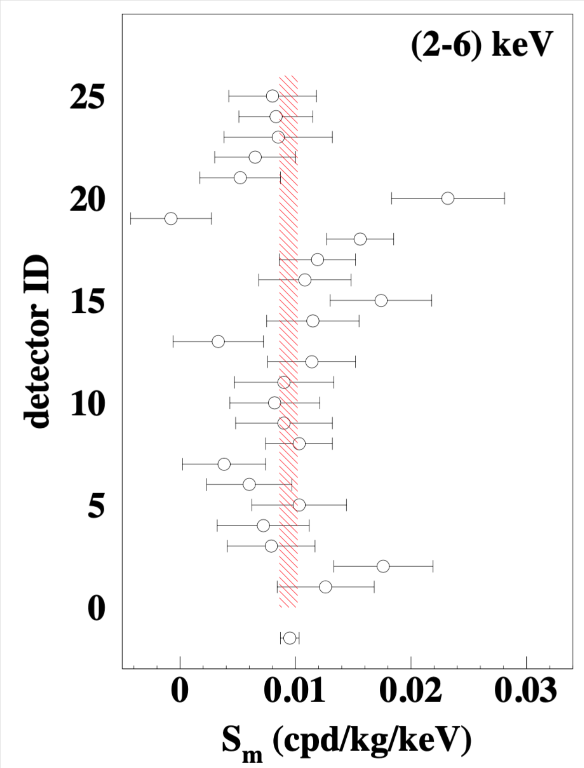
$$x=(S_m-\langle S_m\rangle)/\sigma, \qquad \chi^2=\Sigma x^2$$

Individual S_m values follow a normal distribution since ***x*** is distributed as a Gaussian with a unitary standard deviation

S_m statistically well distributed in all the detectors, energy bin and annual cycles

The $\chi^2/d.o.f.$ values range from 0.8 to 2.0 for all the 25 detectors

- The mean value of the 25 χ^2 is 1.092, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematic.
- In this case, one would have an additional error of $\leq 2.4 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 3.6 \times 10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude below 6 keV.
- This possible additional error ($\leq$2.4% or $\leq$0.4%, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects



S_m for each detector in

DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2

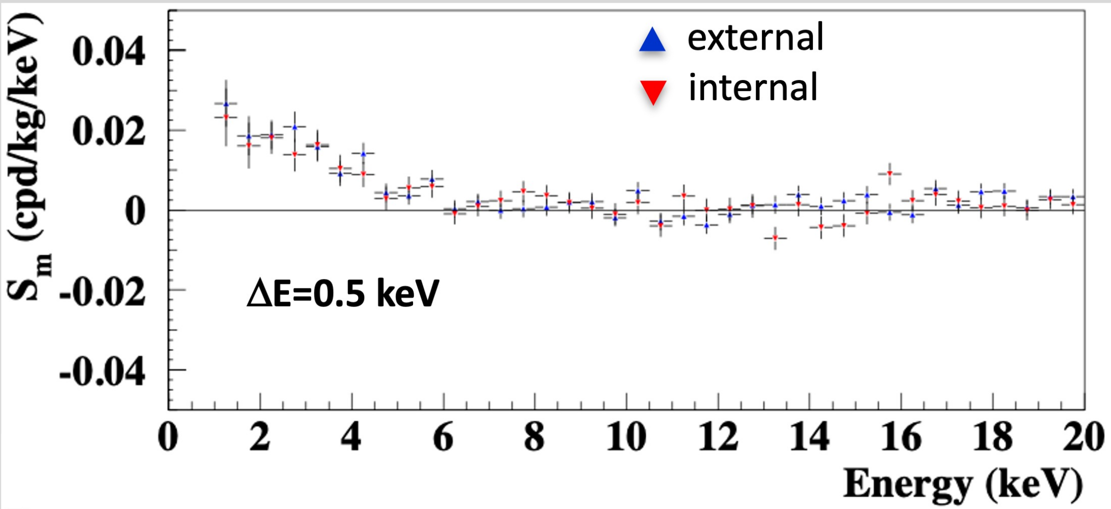
total exposure: 2.57 ton×yr

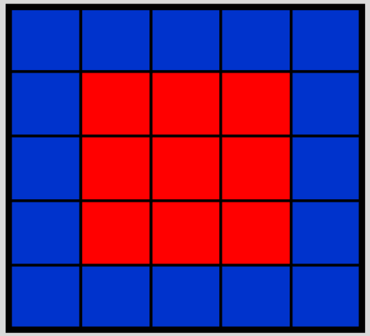
S_m in (2 - 6) keV for each of the 25 detectors (1σ error)

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

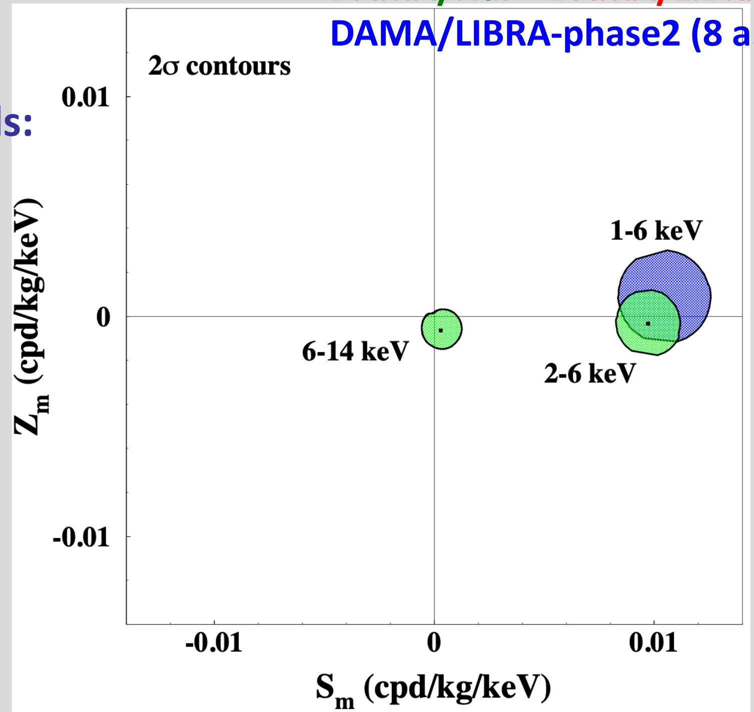
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

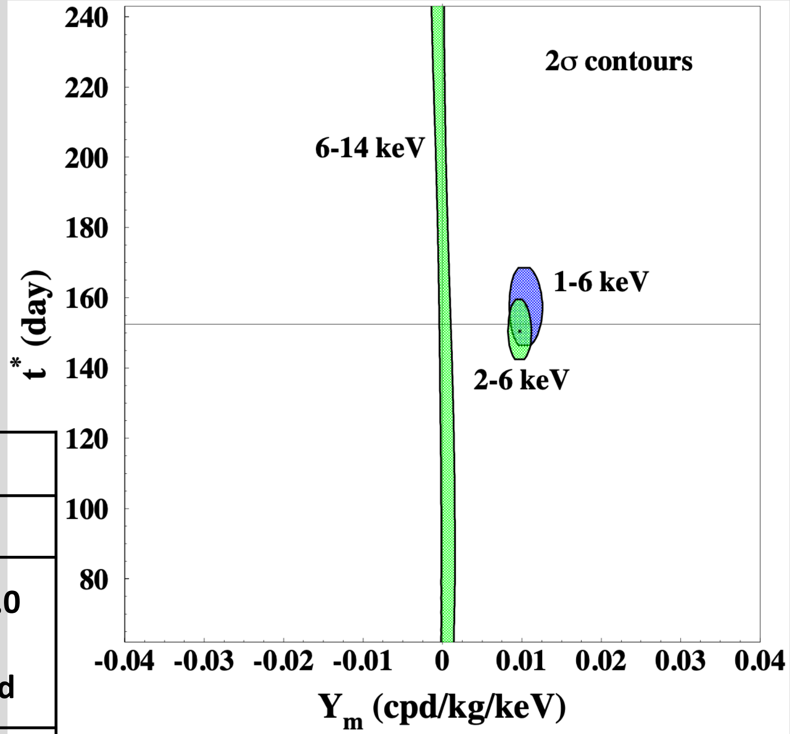
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]

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

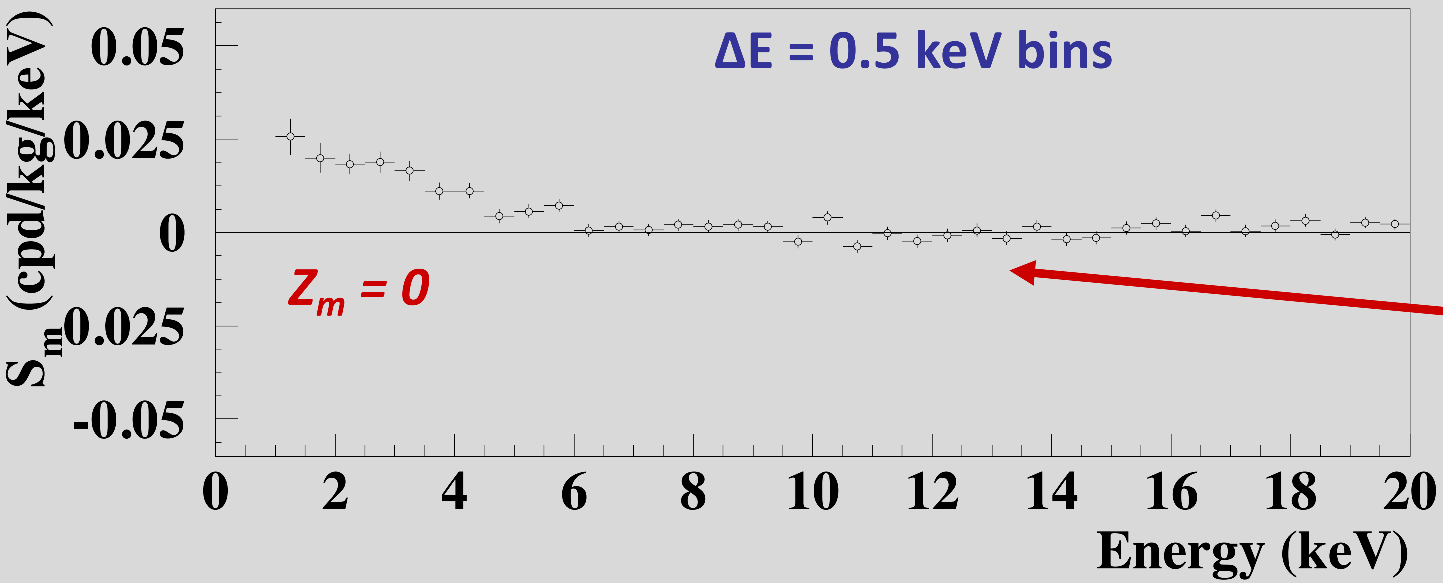


E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0097 ± 0.0007	- 0.0003 ± 0.0007	0.0097 ± 0.0007	150.5 ± 4.0
6-14	0.0003 ± 0.0005	-0.0006 ± 0.0005	0.0007 ± 0.0010	undefined
1-6	0.0104 ± 0.0007	0.0002 ± 0.0007	0.0104 ± 0.0007	153.5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

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

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

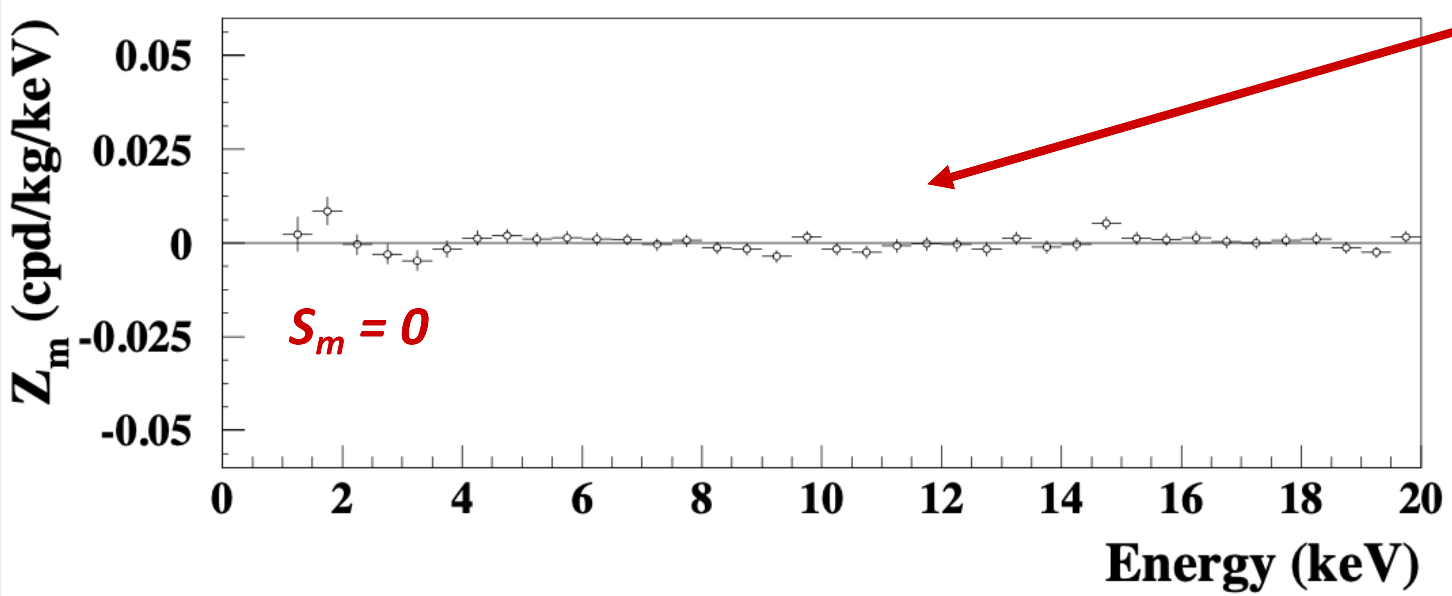
t_0 = 152.5 day (2nd June)



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

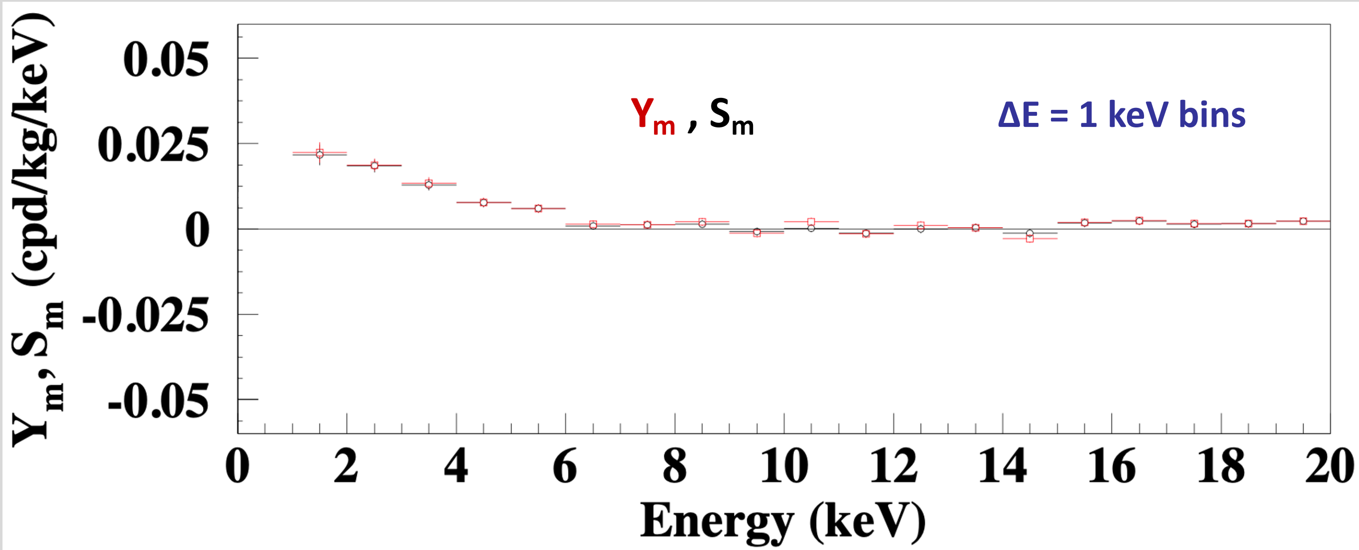


The χ^2 test in (1-20) keV energy region (χ^2/dof = 40.6/38 probability of 36%) supports the hypothesis that the Z_m values are simply fluctuating around zero.

Phase vs energy

$$R(t) = S_0 + Y_m \cos\left[\omega\left(t - t^*\right)\right]$$

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

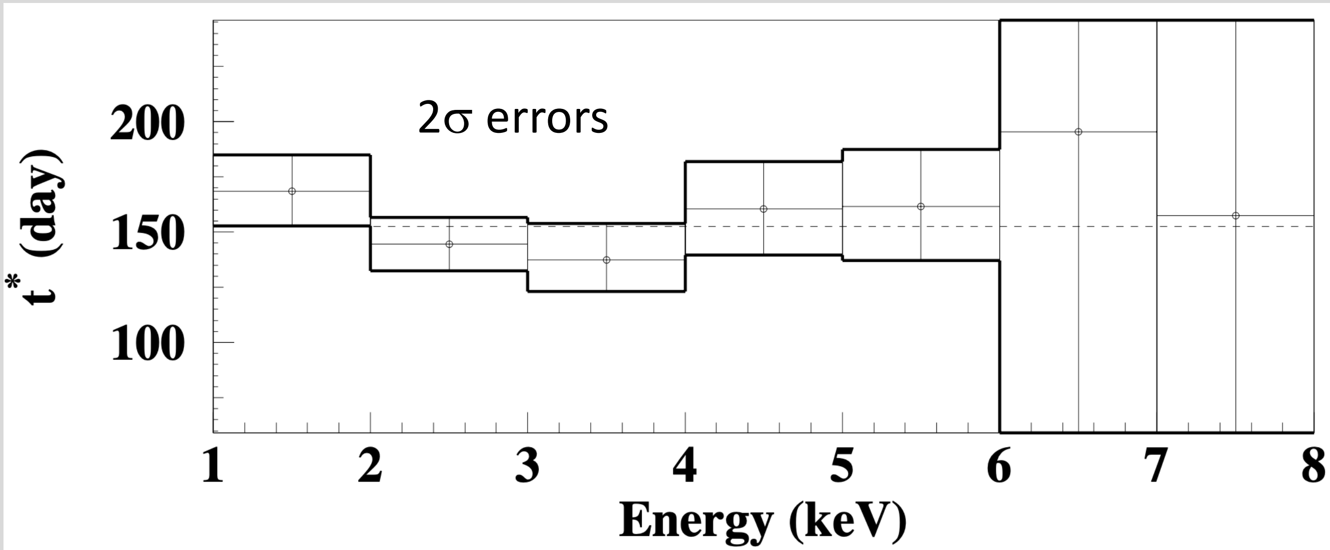


For DM signals:

$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

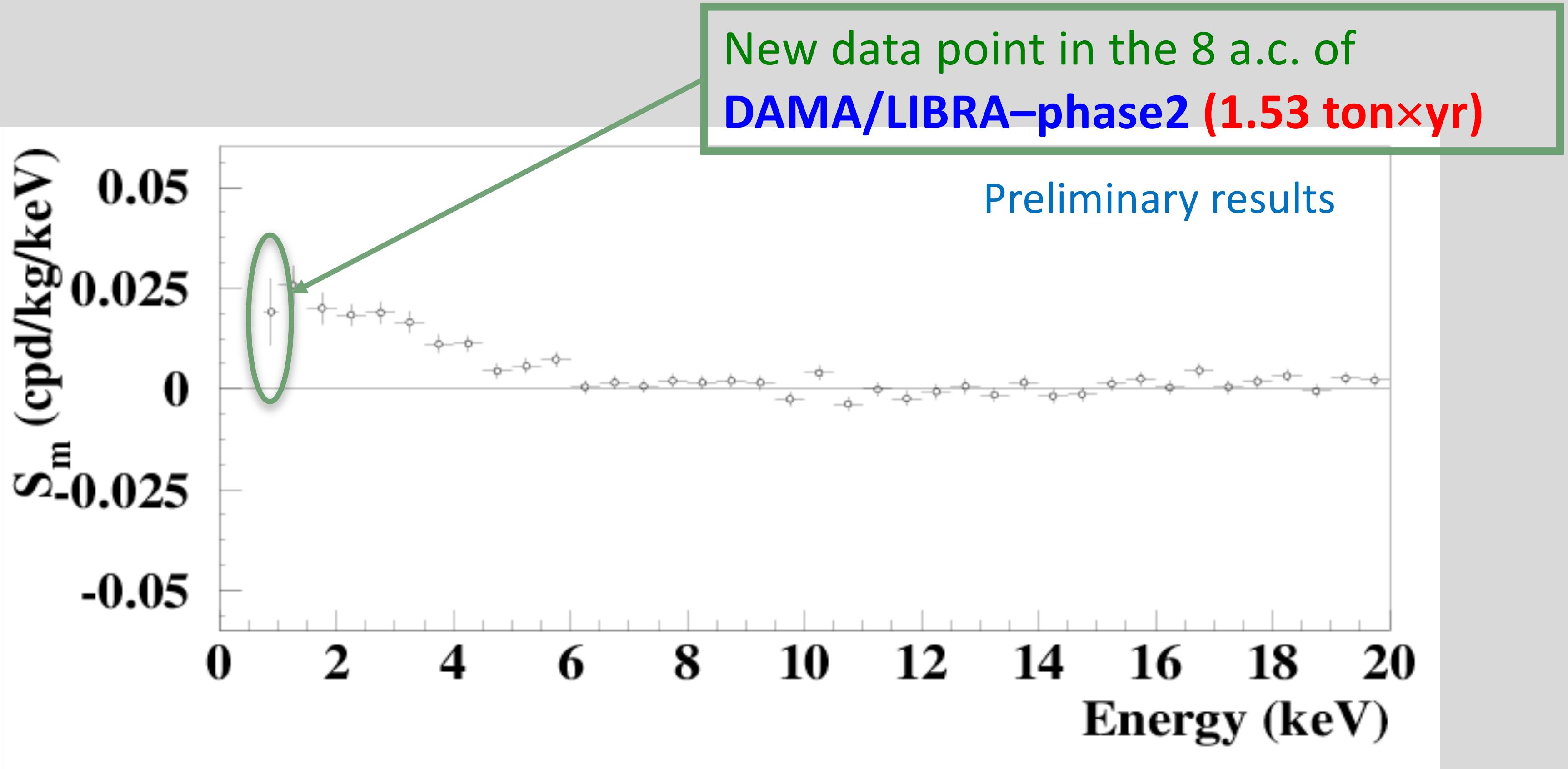
$\omega = 2\pi/T$; $T = 1$ year



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

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



- 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

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

- 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:
  - ✓ 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)

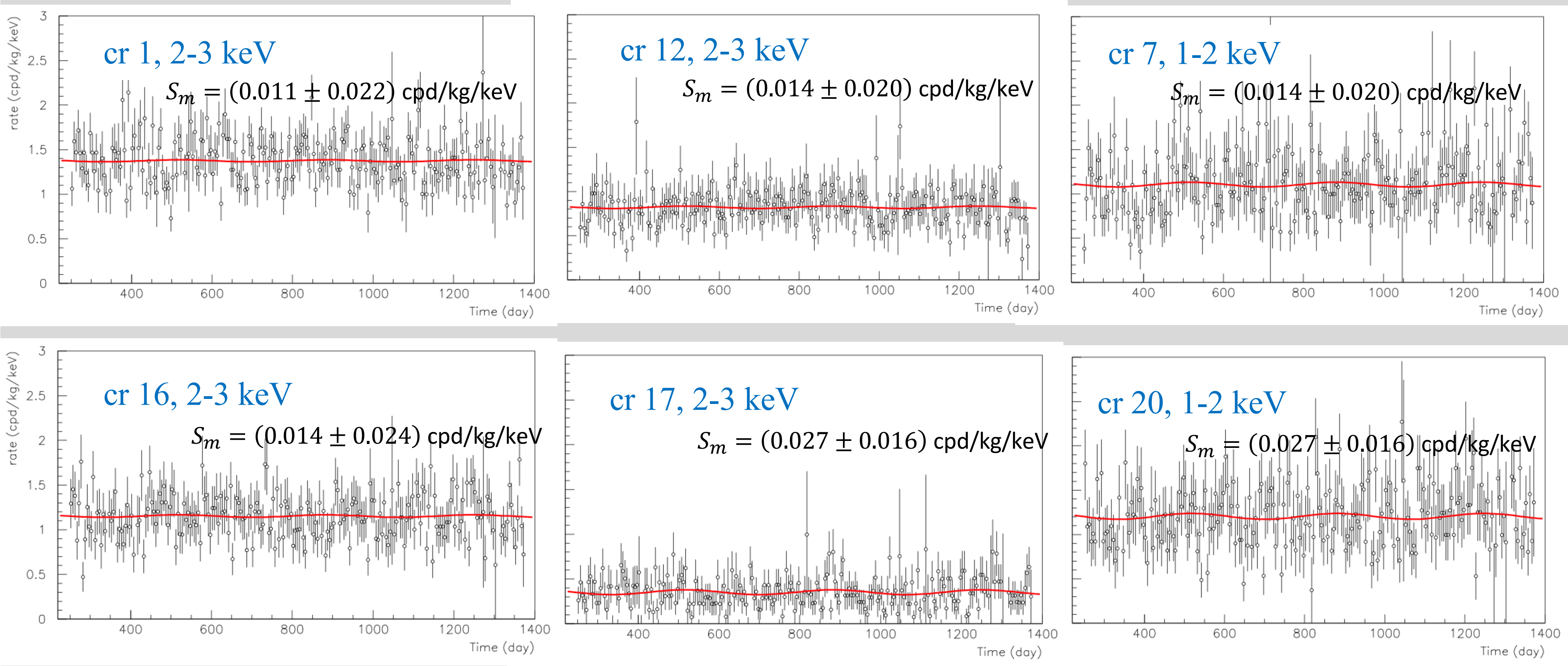
- The **last three published years** of DAMA/LIBRA–phase2 (in which there was continuity between one year and the next) analysed considering the same bckg (w/ and w/o any slope)

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

Investigation on the rate time dependence

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



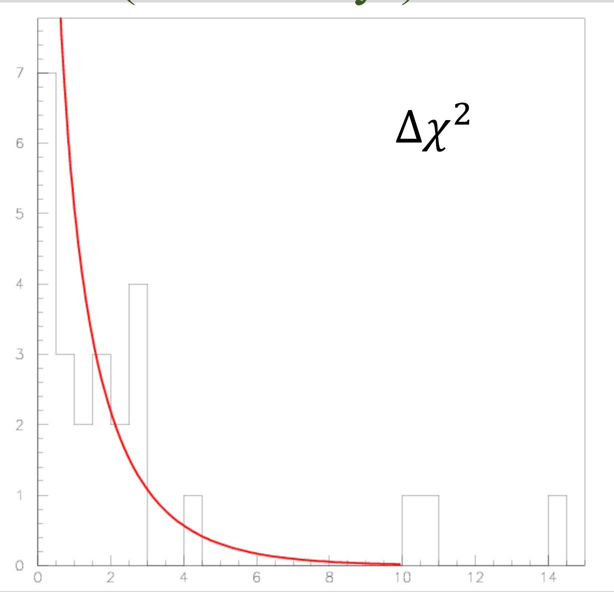
$$\sigma_{Sm}(1\text{ crystal}) \simeq 0.02 \rightarrow \sigma_{Sm}(25\text{ crystals}) \simeq \frac{0.02}{\sqrt{25}} \simeq 0.004\text{ cpd/kg/keV}$$

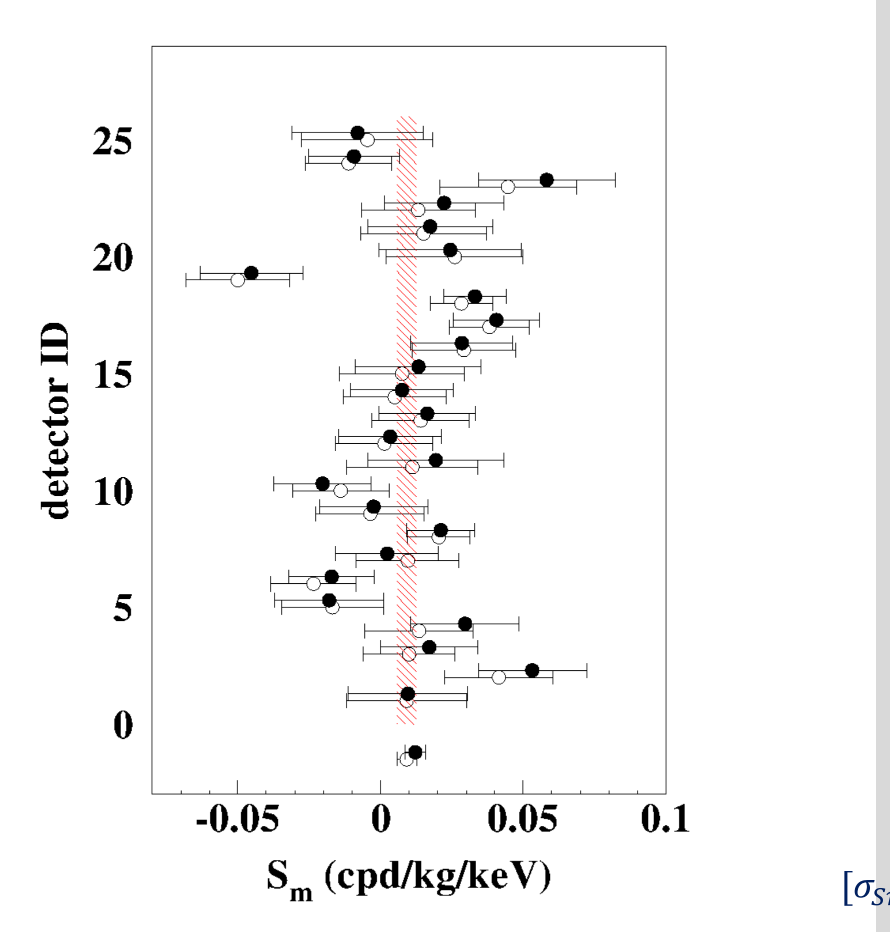
- Time bin: 5 days
- Red: maxlik analysis on single crystal with common (constant) background

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

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: $\Delta\chi^2 = \chi_A^2 - \chi_B^2$ with dof=1





- Plot of $\Delta\chi^2$ for each detector
- It follows a χ^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 $\simeq 0.26\sigma$

(For each detector data see e.g in https://pbelli.users.roma2.infn.it/pdf/belli_ECT2024.pdf)

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

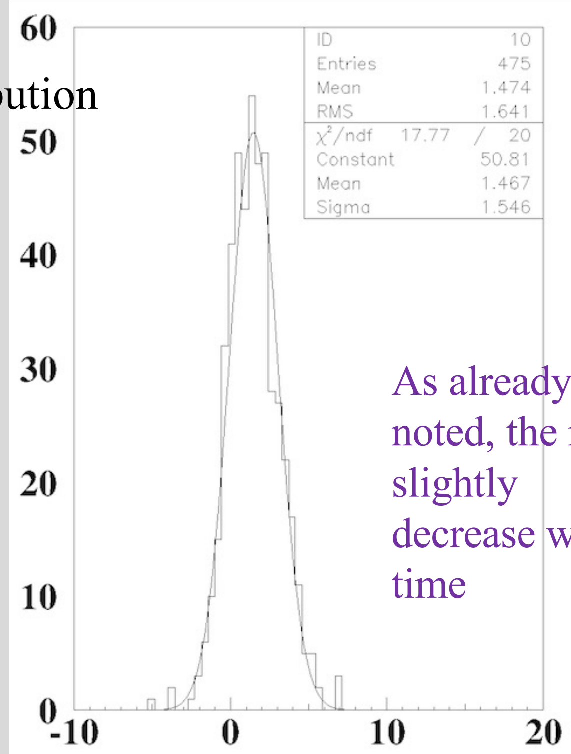
- S_m over all: (0.0092±0.0034) cpd/kg/keV

Investigation on the rate time dependence

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

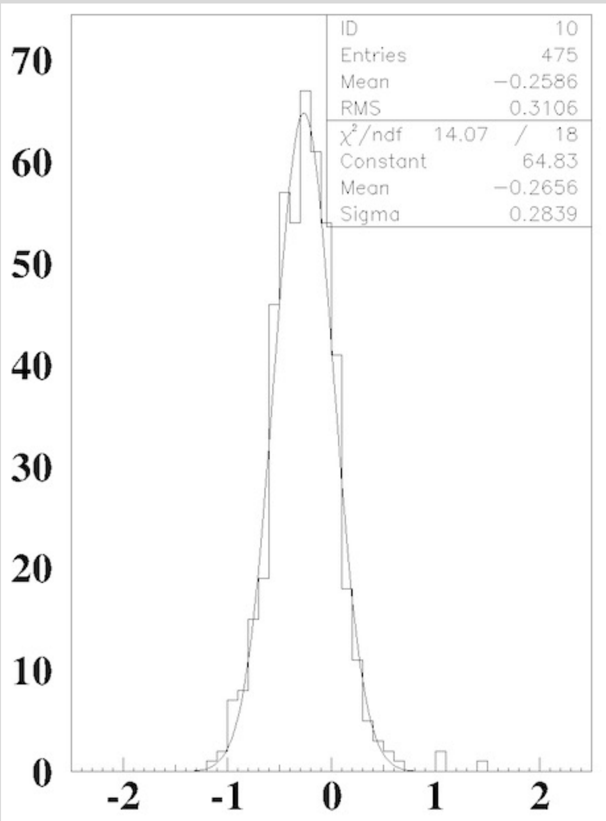
- For each detector the rates are fitted by MaxLik
  by case **A**: $b + S_m^{flat} cos$
- and by case **B**: $b - a \times time + S_m^{slope} cos$
- 475 entries = 25 detectors × 19 energy bins

Slopes distribution



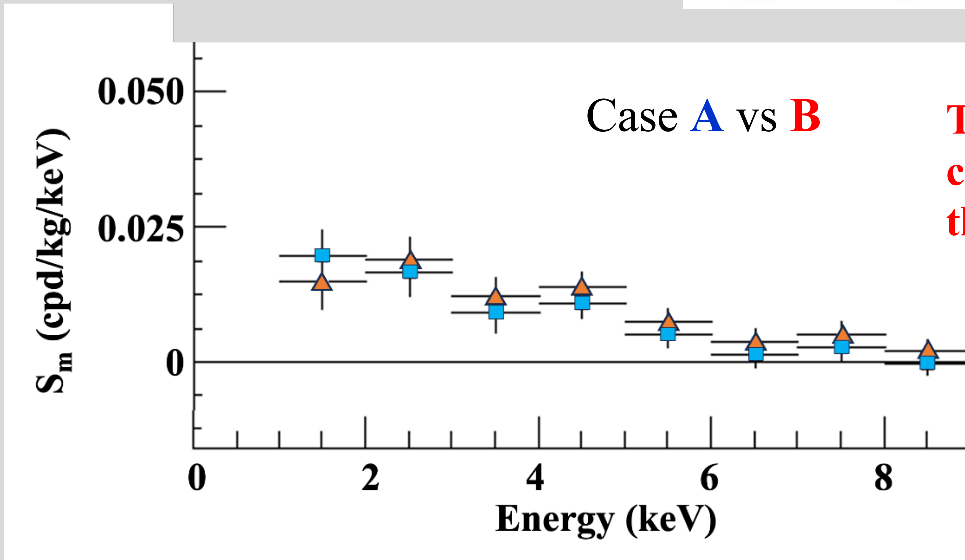
a/σ

As already noted, the rate slightly decrease with time



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

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



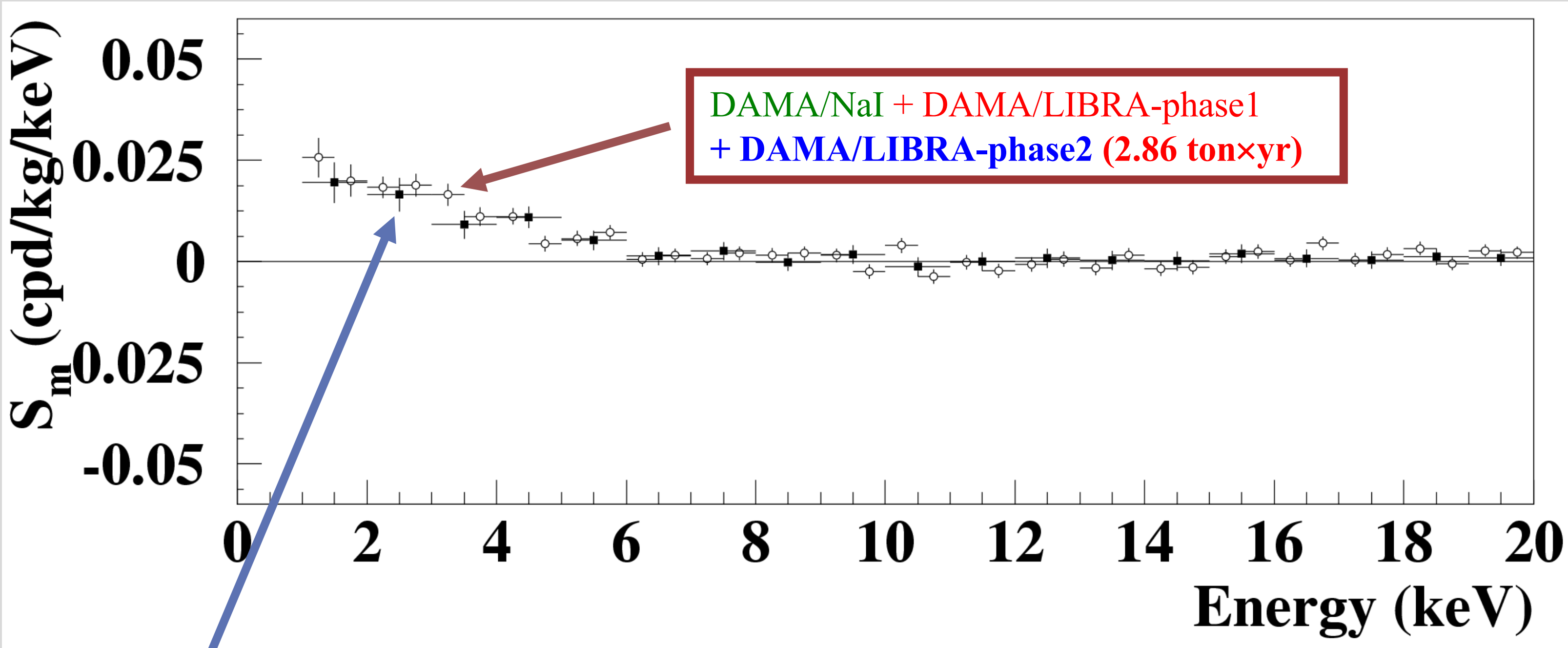
The two cases well compatible within the errors

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

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

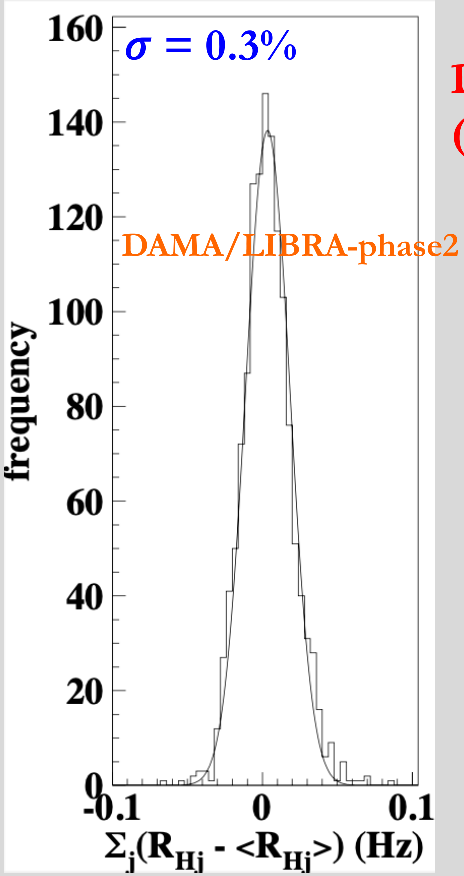
Stability parameters of DAMA/LIBRA–phase2

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 ± 0.0051)	$-(0.0002 \pm 0.0049)$	$-(0.0003 \pm 0.0031)$	(0.0009 ± 0.0050)	(0.0018 ± 0.0036)	$-(0.0006 \pm 0.0035)$	$-(0.0029 \pm 0.0039)$	(0.0014 ± 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 ± 0.25)	(0.014 ± 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 ± 0.034)	$-(0.002 \pm 0.050)$	$-(0.009 \pm 0.028)$	$-(0.044 \pm 0.050)$	(0.082 ± 0.086)	(0.06 ± 0.11)	$-(0.046 \pm 0.076)$	(0.002 ± 0.035)
Hardware rate above single ph.e. (Hz)	$-(0.12 \pm 0.16) \times 10^{-2}$	$(0.00 \pm 0.12) \times 10^{-2}$	$-(0.14 \pm 0.22) \times 10^{-2}$	$-(0.05 \pm 0.22) \times 10^{-2}$	$-(0.06 \pm 0.16) \times 10^{-2}$	$-(0.08 \pm 0.17) \times 10^{-2}$	$(0.04 \pm 0.20) \times 10^{-2}$	$-(0.19 \pm 0.18) \times 10^{-2}$

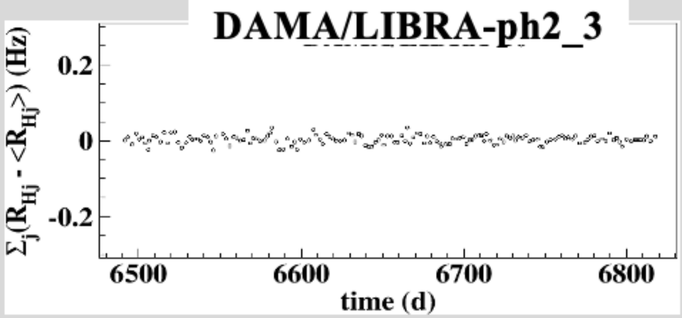
All the measured amplitudes well compatible with zero
+ none can account for the observed effect
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)



Distribution of total hardware rates above the single ph.el. threshold (that is from noise to "infinity")

R_{Hj} = hardware rate of j-th detector above single photoelectron

$<R_{Hj}>$ = mean of R_{Hj} in the corresponding annual cycle



Can a noise tail account for the observed modulation effect?

Amplitudes for annual modulation well compatible with zero:

	Hardware rate (Hz)
DAMA/LIBRA-ph2_2	$-(0.12 \pm 0.16) \times 10^{-2}$
DAMA/LIBRA-ph2_3	$(0.00 \pm 0.12) \times 10^{-2}$
DAMA/LIBRA-ph2_4	$-(0.14 \pm 0.22) \times 10^{-2}$
DAMA/LIBRA-ph2_5	$-(0.05 \pm 0.22) \times 10^{-2}$
DAMA/LIBRA-ph2_6	$-(0.06 \pm 0.16) \times 10^{-2}$
DAMA/LIBRA-ph2_7	$-(0.08 \pm 0.17) \times 10^{-2}$
DAMA/LIBRA-ph2_8	$(0.04 \pm 0.20) \times 10^{-2}$
DAMA/LIBRA-ph2_9	$-(0.19 \pm 0.18) \times 10^{-2}$

The modulation amplitude of the "Hardware Rate" (period and phase as for DM particles) is compatible with zero:

$-(0.067 \pm 0.060) \times 10^{-2}$ Hz → $< 0.5 \times 10^{-3}$ Hz (90% CL)

Hardware Rate = noise +bckg [up to ≈MeV]+signal [up to ≈6keV]

- noise/crystal ≈ 0.10 Hz
- relative modulation amplitude from noise $< 0.5\ 10^{-3}$ Hz/2.5 Hz ≈ 2×10^{-4} (90%CL)

see also in PPNP114(2020)103810

even in the *worst hypothetical* case of 10% residual tail of noise in the data → relative modulation amplitude from noise at low energy $< 2\times10^{-5}$ → $<10^{-4}$ cpd/kg/keV

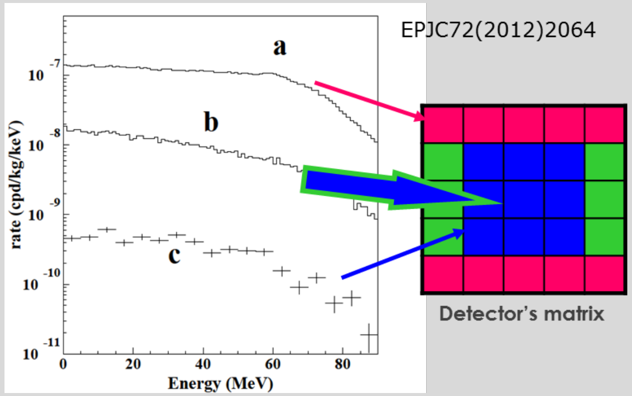
NO

No role for μ in DAMA annual modulation result

✓ **Direct μ interaction in DAMA/LIBRA set-up:**

DAMA/LIBRA surface ≈0.13 m^2
μ flux @ DAMA/LIBRA ≈2.5 μ/day

It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.



MonteCarlo simulation

✓ **Rate, R_n, of fast neutrons produced by μ:**

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Annual modulation amplitude at low energy due to μ **modulation**:

$$S_m^{(\mu)} = R_n \, g \, \varepsilon \, f_{\Delta E} \, f_{single} \, 2\% / (M_{setup} \, \Delta E)$$

$S_m^{(\mu)} < (0.3\text{-}2.4) \times 10^{-5}$ cpd/kg/keV

Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events

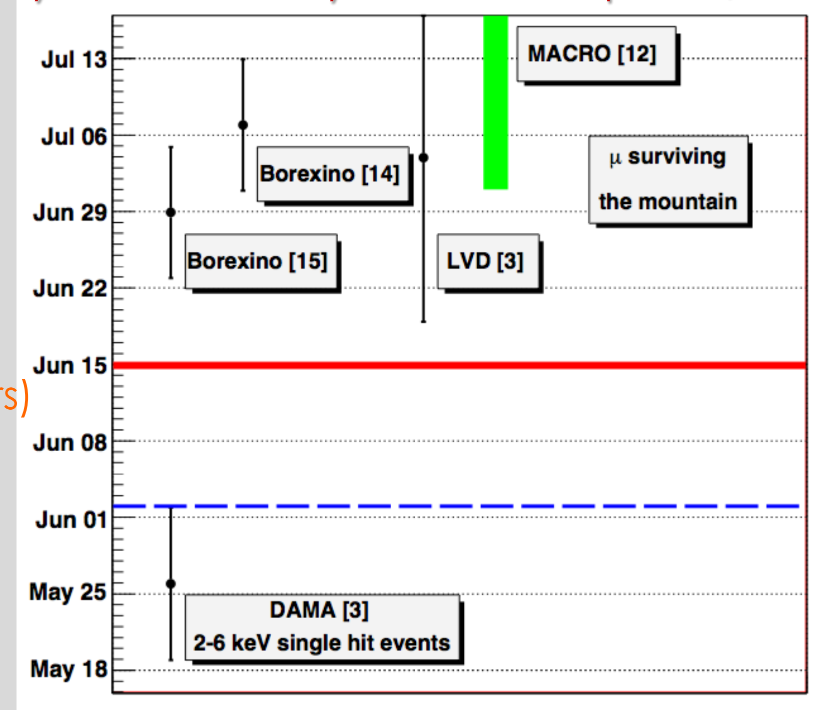
It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.

✓ **Inconsistency of the phase between DAMA signal and μ modulation**

μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈3·10^{-4} $m^{-2}s^{-1}$; modulation amplitude 1.5%; **phase**: July 7 ± 6 d, June 29 ± 6 d (Borexino)

The DAMA phase: May 26 ± 7 days (stable over 13 years)

The DAMA phase is 5.7σ far from the LVD/BOREXINO phases of muons (7.1 σ far from MACRO measured phase)



... many others arguments EPJC72(2012)2064, EPJC74(2014)3196

- Contributions to the total neutron flux at LNGS; → $\Phi_k = \Phi_{0,k}\left(1+\eta_k cos\omega\left(t-t_k\right)\right)$
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by: → $R_k = R_{0,k}\left(1+\eta_k cos\omega\left(t-t_k\right)\right)$
  - neutrons,
  - muons,
  - solar neutrinos.

EPJC 74 (2014) 3196 (also EPJC 56 (2008) 333, EPJC 72 (2012) 2064,IJMPA 28 (2013) 1330022)

Modulation amplitudes

	Source	$\Phi^{(n)}_{0,k}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)		$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2}-10^{-1}$ eV)	1.08×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8\times10^{-6}$	[2, 7, 8]	$\ll 8\times10^{-7}$	$\ll 7\times10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3\times10^{-3}$	[2, 7, 8]	$\ll 3\times10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha,n)\to$ n (1-10 MeV)	$\simeq 0.9\times10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6\times10^{-4}$	[2, 7, 8]	$\ll 6\times10^{-5}$	$\ll 5\times10^{-3}$
	$\mu\to$ n from rock (> 10 MeV)	$\simeq 3\times10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7\times10^{-4}$	(see text and [2, 7, 8])	$\ll 9\times10^{-6}$	$\ll 8\times10^{-4}$
	$\mu\to$ n from Pb shield (> 10 MeV)	$\simeq 6\times10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4\times10^{-3}$	(see text and footnote 3)	$\ll 2\times10^{-5}$	$\ll 1.6\times10^{-3}$
	$\nu\to$ n (few MeV)	$\simeq 3\times10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7\times10^{-5}$	(see text)	$\ll 2\times10^{-6}$	$\ll 2\times10^{-4}$
	direct μ	$\Phi_0^{(\mu)} \simeq 20\ \mu$ m^{-2}d^{-1} [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi_0^{(\nu)} \simeq 6\times10^{10}\ \nu$ cm^{-2}s^{-1} [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

All are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude.

+ In no case neutrons (of whatever origin) can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail, such as the neutrons would induce e.g. variations in all the energy spectrum, variation in the multiple hit events,… which were not observed.

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 result
DAMA/NaI+DAMA/LIBRA-phase1+phase2 so far

- Presence of modulation over 22 annual cycles at 13.7 σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 22 independent experiments of 1 year each one
- The total exposure by former DAMA/NaI, DAMA/LIBRA-phase1 and phase2 is 2.86 ton × yr

Summarizing:

1) **The *single-hit* events show a clear cosine-like modulation, as expected for the DM signal**

2) **Measured period is equal to (0.998±0.001)* yr, well compatible with the 1 yr period, as expected for the DM signal**

3) **Measured phase (142±4)* days is well compatible with the roughly about 152.5 days as expected for the DM signal**

4) **The modulation is present only in the low energy (2—6) keV energy interval and not in other higher energy regions, consistently with expectation for the DM signal**

5) **The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal**

6) **The measured modulation amplitude in NaI(Tl) of the *single-hit* events is: (0.0101 ± 0.0007)* cpd/kg/keV (13.7 σ C.L.).**

* Here 2-6 keV energy interval

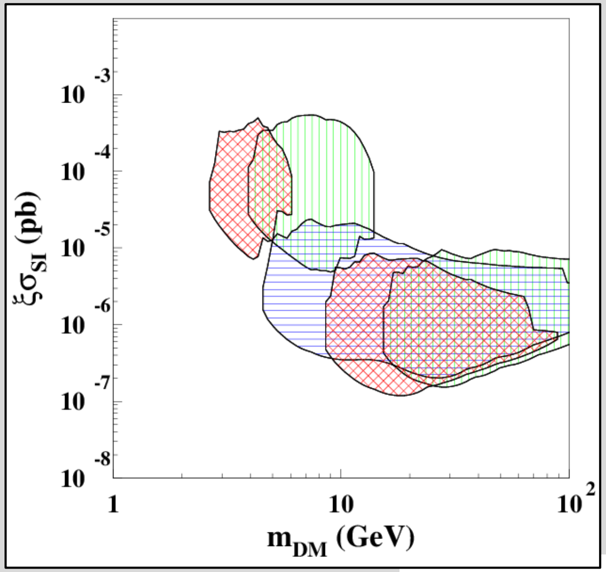
No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

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

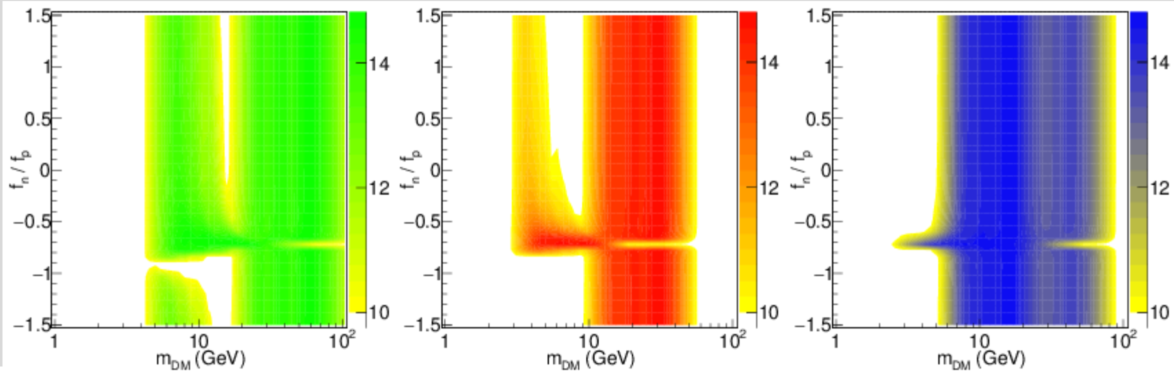


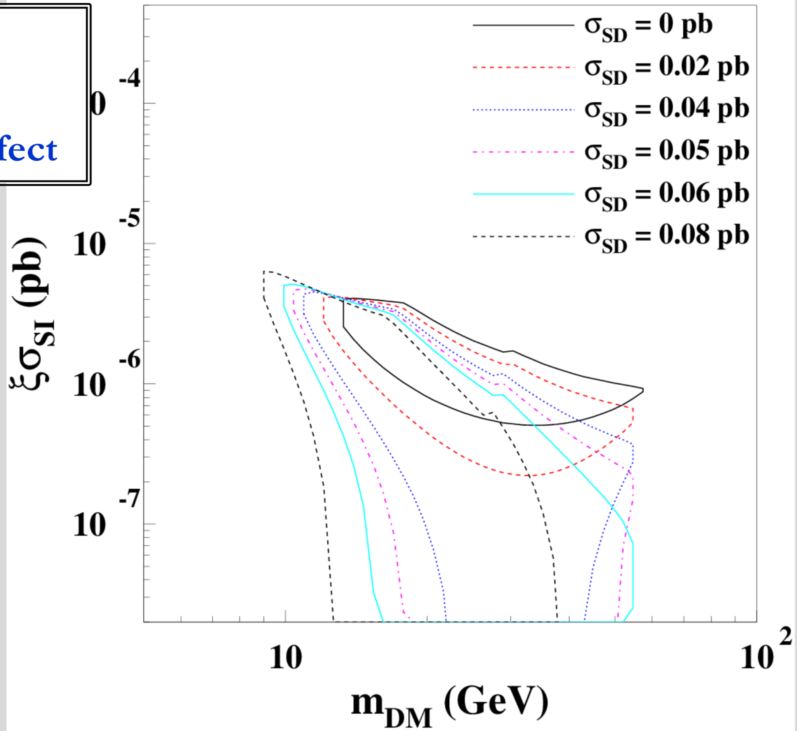
1. Constants q.f.
2. Varying q.f.(E_R)
3. With channeling effect

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.

Other examples

Scratching Below the Surface of the Most General Parameter Space
(S. Scopel arXiv:1505.01926)

Most general approach: consider ALL possible NR couplings, including those depending on velocity and momentum

- A much wider parameter space opens up
- First explorations show that indeed large rooms for compatibility can be achieved

$$\mathcal{O}_1 = 1_\chi 1_N,$$
$$\mathcal{O}_2 = (v^\perp)^2,$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N,$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp,$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N},$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}.$$

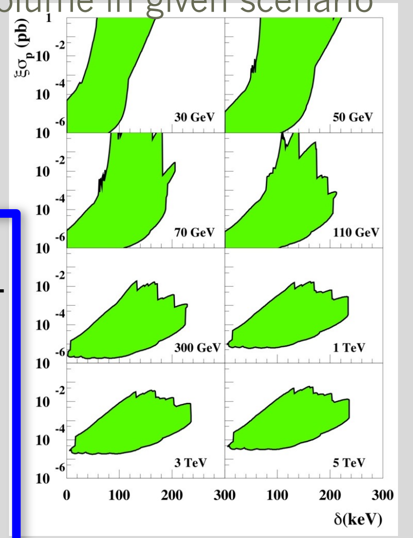
… and much more considering experimental and theoretical uncertainties

DMp with preferred inelastic interaction: $\chi^- + N \rightarrow \chi^+ + N$

- iDM mass states χ^+, χ^- with δ mass splitting
- Kinematic constraint for iDM:

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

DAMA/NaI+DAMA/LIBRA
Slices from the 3d allowed volume in given scenario



Fund. Phys. 40(2010)900

iDM interaction on Tl nuclei of the NaI(Tl) dopant?
PRL106(2011)011301

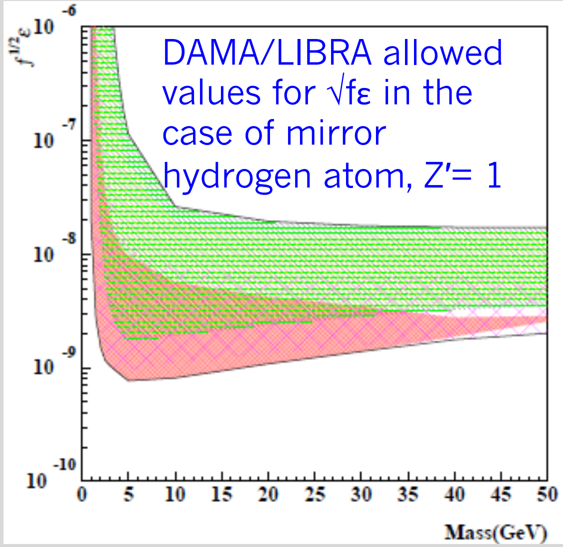
- For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with A~205, which are present as a dopant at the 10^{-3} level in NaI(Tl) crystals.
- large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

Mirror Dark Matter

Asymmetric mirror matter: mirror parity spontaneously broken $\Rightarrow$ mirror sector becomes a heavier and deformed copy of ordinary sector
(**See EPJC75(2015)400**)

- Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$
- mirror atom scattering of the ordinary target nuclei in the NaI(Tl) detectors of DAMA/LIBRA set-up with the Rutherford-like cross sections.

$\sqrt{f} \cdot \epsilon$ coupling const. and fraction of mirror atom



Other DAMA investigations which involve also low mass candidates

- ✓ **Migdal effect** [IJMPA22(2007)3155]:

Ionization and excitation of bound atomic e^- induced by the recoiling atomic nucleus, in the case of DM particle-nucleus elastic scattering

- recoiling nucleus can "shake off" some of the atomic e
- recoil signal + e.m. contribution (escaping electron, X-rays, Auger e^- arising from rearrangement of atomic shells)
- e.m. radiation fully contained in the detector

can give an appreciable impact at low masses

- ✓ **electron interacting DM** [PRD77(2008)023506]

The electron in the atom is not at rest → there is a very-small but not-zero probability to have electrons with momenta of ≈ MeV/c.

Candidates expected, e.g.:
- in theories that foreseen leptonic colour interactions: $SU(3)_l \times SU(3)_c \times SU(2)_L \times U(1)$ broken at low energy.
- in models where they interact through a neutral current light (MeV scale) U boson.
- domains in general SUSY parameter space where LSP-electron interaction can dominate on LSP-quark one.

- ✓ **direct detection of LDM** [MPLA23(2008)2125]

in the interaction with electron or nucleus a lighter particle is produced and the target (either nucleus or electrons) recoils with an energy which can be detectable.

LDM can be either a boson or a fermion.

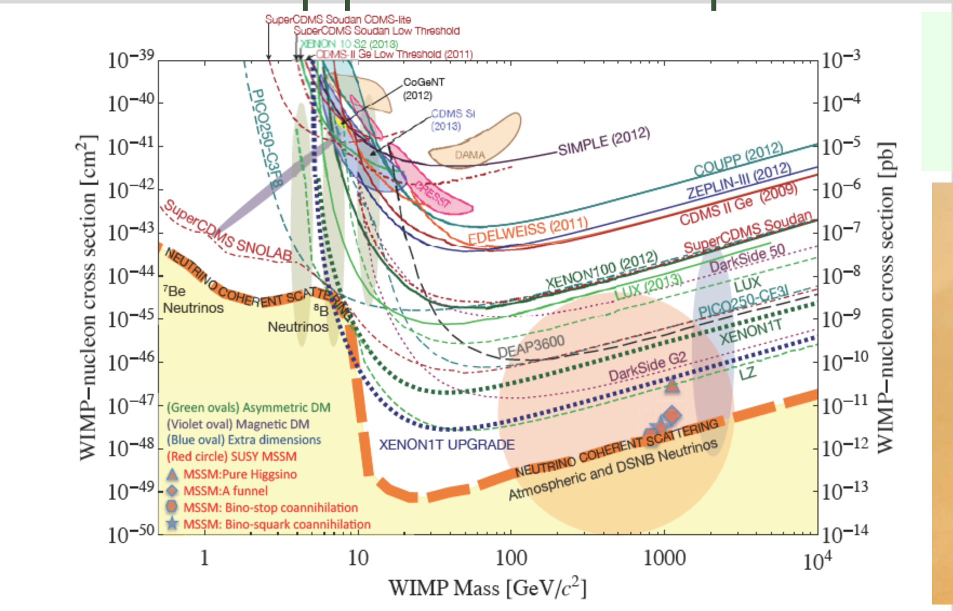
- DM candidates with sub-GeV mass can contribute to the Warm Dark Matter (such as e.g. keV-scale sterile ν, axino or gravitino)
- MeV-scale DM particles (e.g. axino, gravitino, heavy neutrinos, moduli fields from string theories,…) proposed as source of 511 keV γ's from the GC
- SUSY models exist where the LSP naturally has a MeV-scale mass and other properties required to generate the 511 keV γ's in the galactic bulge

- ✓ **light bosonic particles (Axion-like)** [IJMPA21(2006)1445]

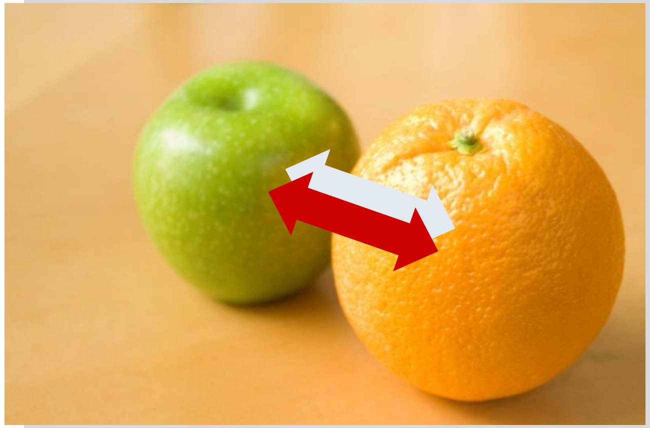
detection is based on the total conversion of the absorbed bosonic mass into electromagnetic radiation

- Hypothesis: ~ keV axion-like (K.K. axion) trapped in the Sun neighborhood and γγ decay
- Astrophysical hints: solar corona problem; X-ray from dark side of the Moon; soft X-ray background radiation; "diffuse" soft X-ray excess

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

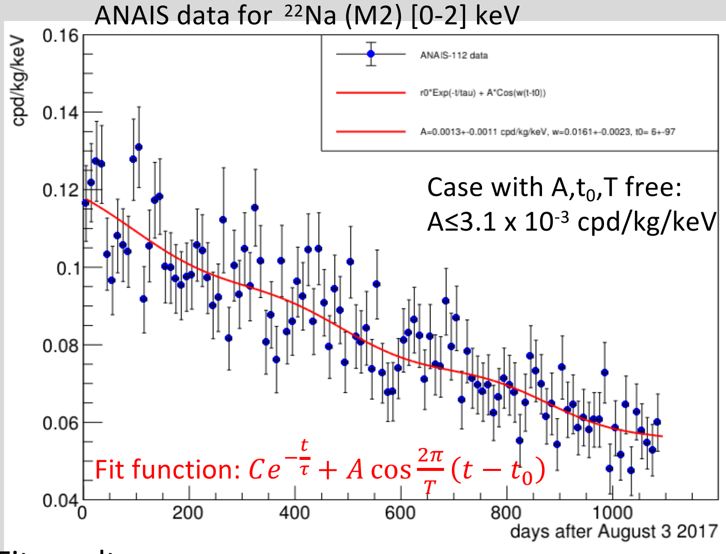
Stability of the running conditions in ANAIS

A detailed evaluation: the stability of the counting rate in [1-2] keV region

- ❑ The needed stability can be calculated taking into account:
  - The measured counting rate in prod runs: ≈ 5 cpd/kg/keV;
  - The effect searched for: 0.02 cpd/kg/keV (from DAMA/LIBRA-phase2)

⇒ Needed a stability of the experimental conditions much better than 0.4% (=0.02/5)

- ❑ A check on the stability of the noise removal procedures is performed analysing the events induced in [0-2] keV window by the ^{22}Na contaminations, requiring a double coincidence with another detector (M=2)
- ❑ But the statistics is very low; in DAMA/LIBRA the cut efficiencies are periodically evaluated with dedicated calibrations collecting 50000 ev/detector at low energy
- ❑ A fit of these data including a modulated components shows that they cannot exclude an effect at the level of 2-3%, much higher than the needed stability
- ❑ Similar result can be obtained for the [2-5] keV region (studying ^{40}K double) the sensitivity is ≈ 1% (needed: <0.4%)

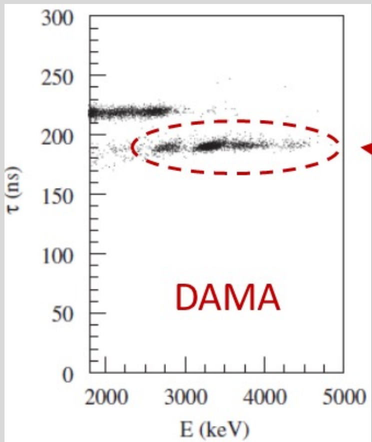


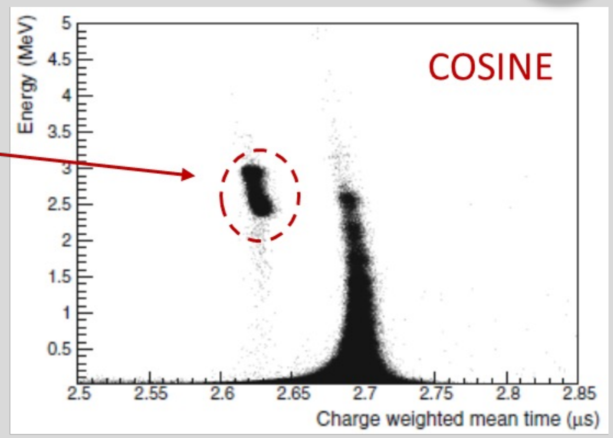
Fit results:

T [d]	t_0 [d]	A [cpd/kg/keV]	A(%)
365 fix	152 fix	-0.0002(11) → <0.0016	< 2%
390(56)	6(97)	0.0013(11) → <0.0031	< 3%

About nuclear quenching factors

- Different quenching factors are expected and measured for different NaI(Tl) crystals (they depends, e.g., on the used growing technique, on the different thallium doping concentration, …)
- A clear evidence is offered by the different α/β light ratio measured with DAMA and COSINE crystals
- As mentioned also in the ANAIS paper, this effect introduce a systematic uncertainty in the comparison with DAMA/LIBRA





α events from ^{238}U and ^{232}Th chains in DAMA crystal span from 2.6 to 4.5 MeVee, while for the COSINE crystal they span from 2.3 to 3.0 MeVee

The importance of studying second order effects and the annual modulation phase

Higher exposure and lower threshold can allow further investigation on:

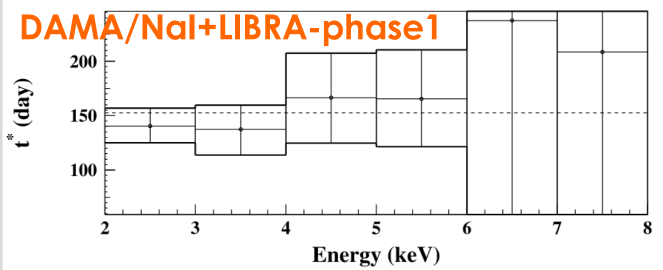
- **the nature of the DMp**
  - ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, form factors, spin-factors …)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DMp halo?

possible diurnal effects in sidereal time

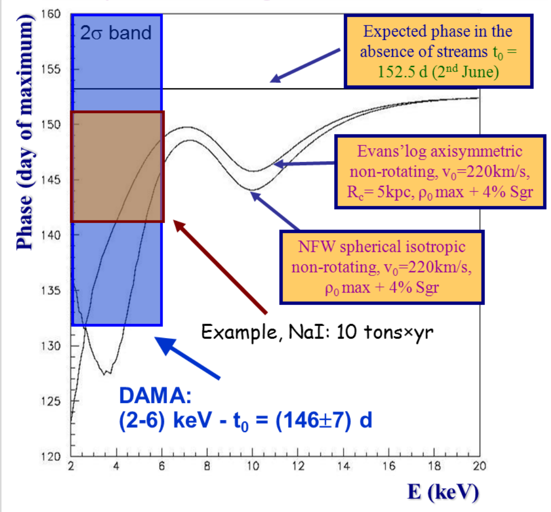
- ✓ expected in case of high cross section DM candidates (shadow of the Earth)
- ✓ due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates)
- ✓ due to the channeling in case of DM candidates inducing nuclear recoils.

- **astrophysical models**
  - ✓ velocity and position distribution of DMp in the galactic halo, possibly due to:
    - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";
    - caustics in the halo;
    - gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");
    - possible structures as clumpiness with small scale size
    - Effects of gravitational focusing of the Sun

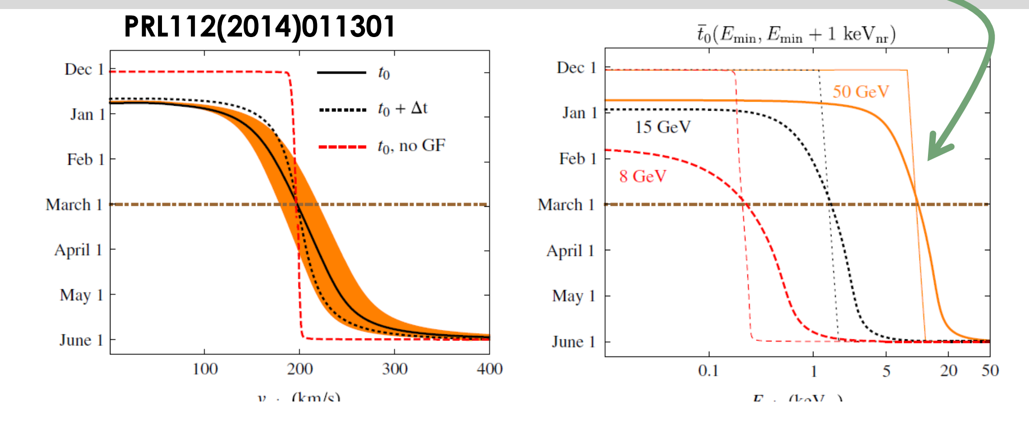
A step towards such investigations:
➔DAMA/LIBRA-phase2 running with lower energy threshold



The effect of the streams on the phase depends on the galactic halo model

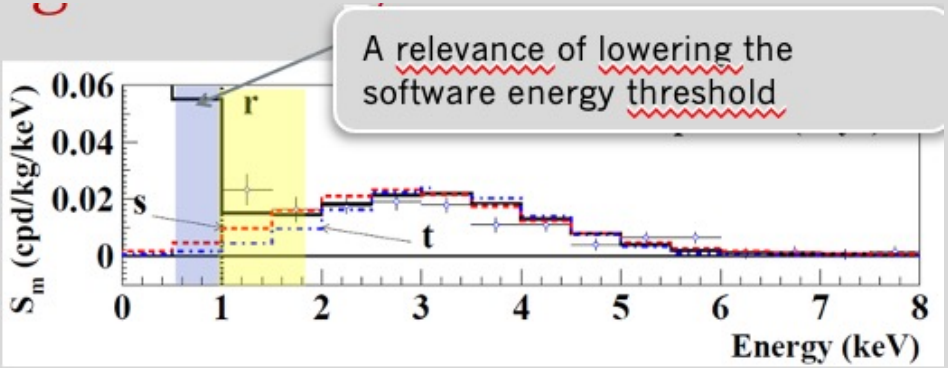


The annual modulation phase depends on :
- Presence of streams (as SagDEG and Canis Major) in the Galaxy
- Presence of caustics
- Effects of gravitational focusing of the Sun



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)

Higher resolution of TDs makes appreciable the improvements coming from the new voltage-dividers-plus-preamps on the same board

3) The data taking in this new configuration started on Dec, 1 2021

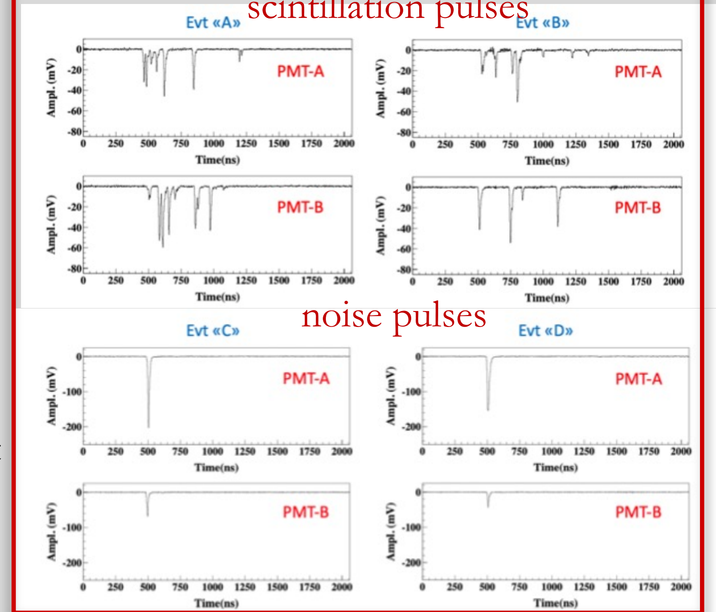
The features of the voltage divider+preamp system:
- S/N improvement ≈3.0-9.0;
- discrimination of the single ph.el. from electronic noise: 3 - 8;
- the Peak/Valley ratio: 4.7 - 11.6;
- residual radioactivity lower than that of single PMT

- 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 analysi

The software energy threshold is 0.5 keV with suitable efficiency

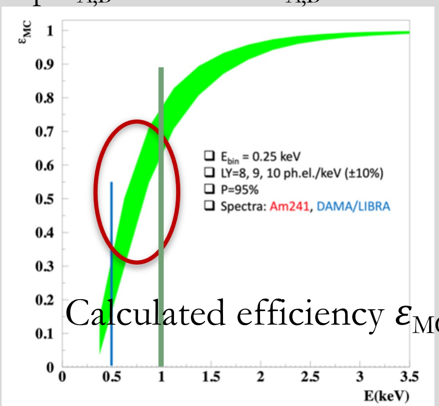
- Higher resolution (0.122 mV/digit) of the 14-bit TDs makes appreciable the improvements coming from the new voltage-dividers-plus-preamps on the same board in terms of baseline noise
- The distributions of the baselines show a very stable operational feature
- The baseline fluctuations are more than a factor two lower than those of the previous configuration; this improvement is appreciable thanks to the "new" 14-bit TDs. The RMS of the baseline distributions of all the fifty PMT lines is around 150 μV, ranging between 110 and 190 μV
- This allows us **to decrease the** Software Trigger Level (**STL)** in the offline analysis of the recorded waveforms
- 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

Examples of few-keV pulses



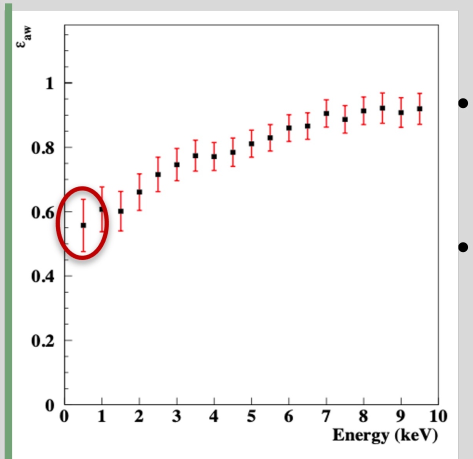
$(\#p.e._A>1)$ .AND. $(\#p.e._B>1)$

$\#p.e._{A,B}>1 \rightarrow tm600_{A,B}> \sim 25$ ns



Calculated efficiency ε_{MC}

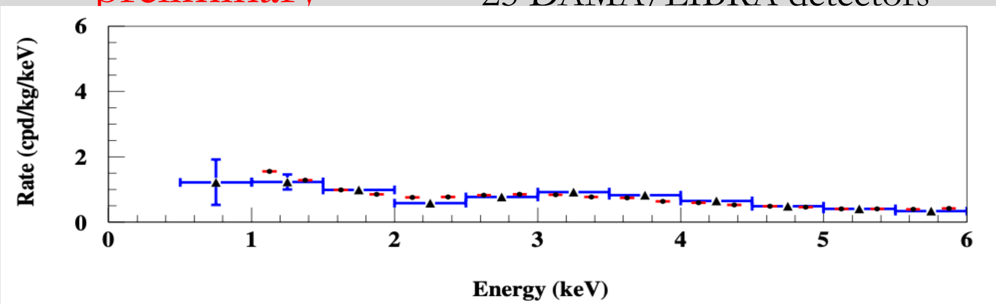
preliminary



- ε_{aw} efficiencies for the used acceptance windows, measured by applying the same acceptance windows to events by ^{241}Am in the same experimental conditions as the production data.
- Very stringent acceptance windows, which assure the absence of any noise tail, can be considered and related efficiencies can be properly evaluated and used.

A suitable efficiency below 1 keV is possible in the new configuration

25 DAMA/LIBRA detectors



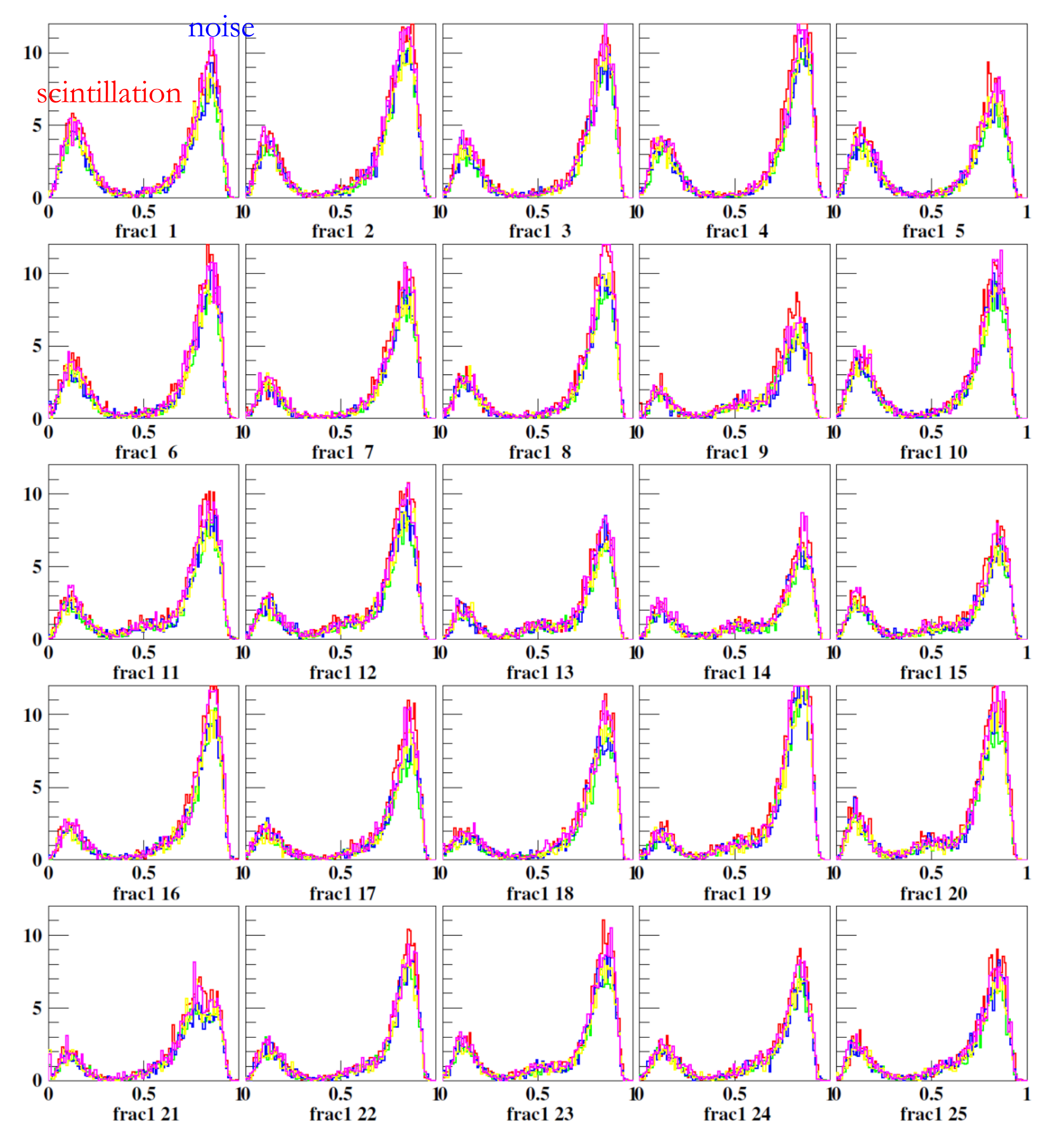
Energy spectrum of the *single-hit* scintillation events – already corrected for the efficiencies – in the new configuration (blue, exposure about 70265 kg × d) and in DAMA/LIBRA–phase2 (red, the energy threshold was 1 keV, 1.53 ton×yr).

$frac3$ = Area(from 100 to 600 ns)/Area(from 0 to 600 ns)

$frac1$ = Area(from 0 to 50 ns)/Area(from 0 to 600 ns)

Distributions of the *frac1* variable in the 0.5-5 keV energy range

- *frac3* is distributed around 0 for noise events and around 0.63 for scintillation pulses (assuming a pure exponential behaviour);
- *frac1* is distributed around 1 for noise and around 0.20 for scintillation events (assuming a pure exponential behaviour).



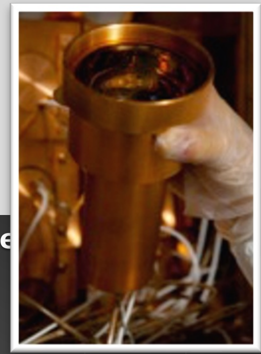
- Stability along the 2022 (colours correspond to five different periods of the considered data set:

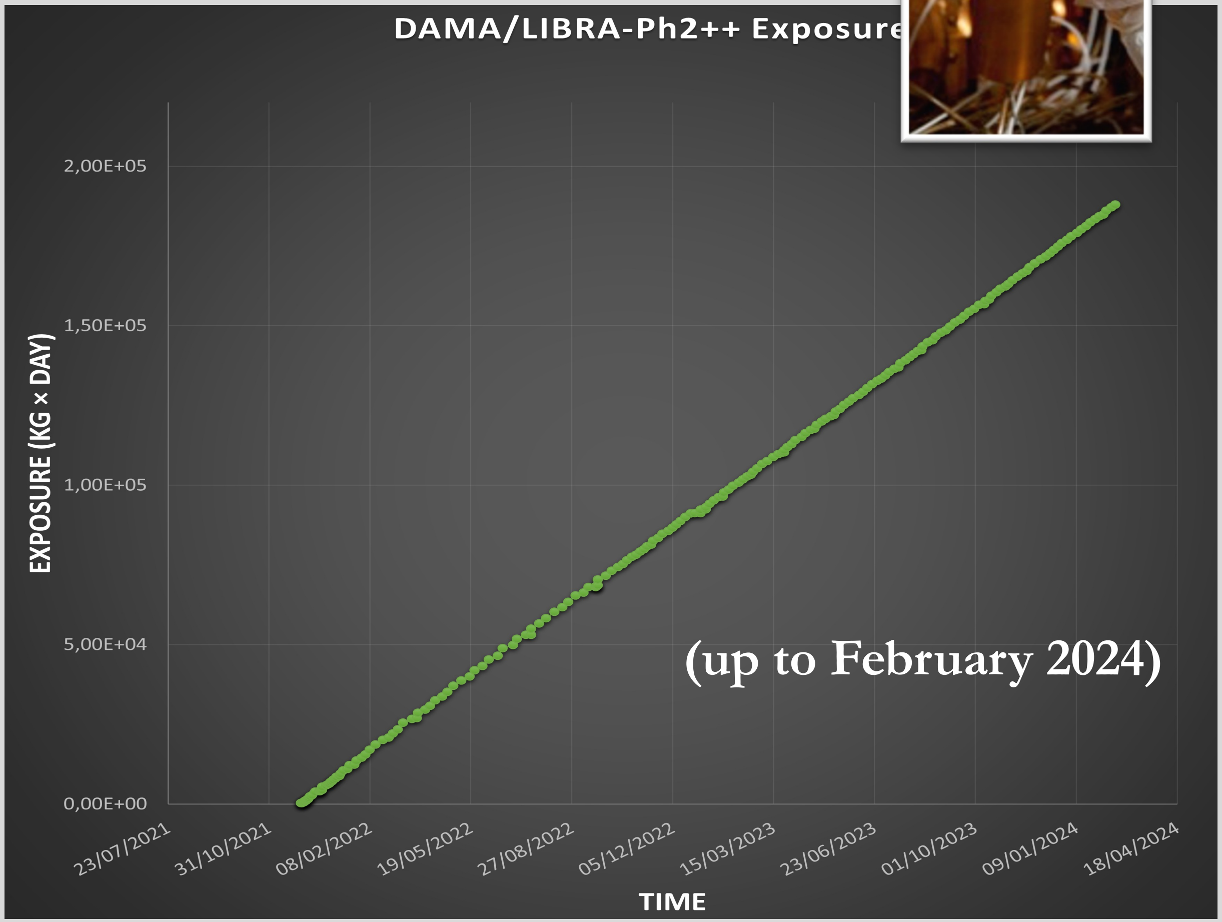
  Dec 2021 – Feb 2023

see also arguments in JINST 7 (2012) P03009

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

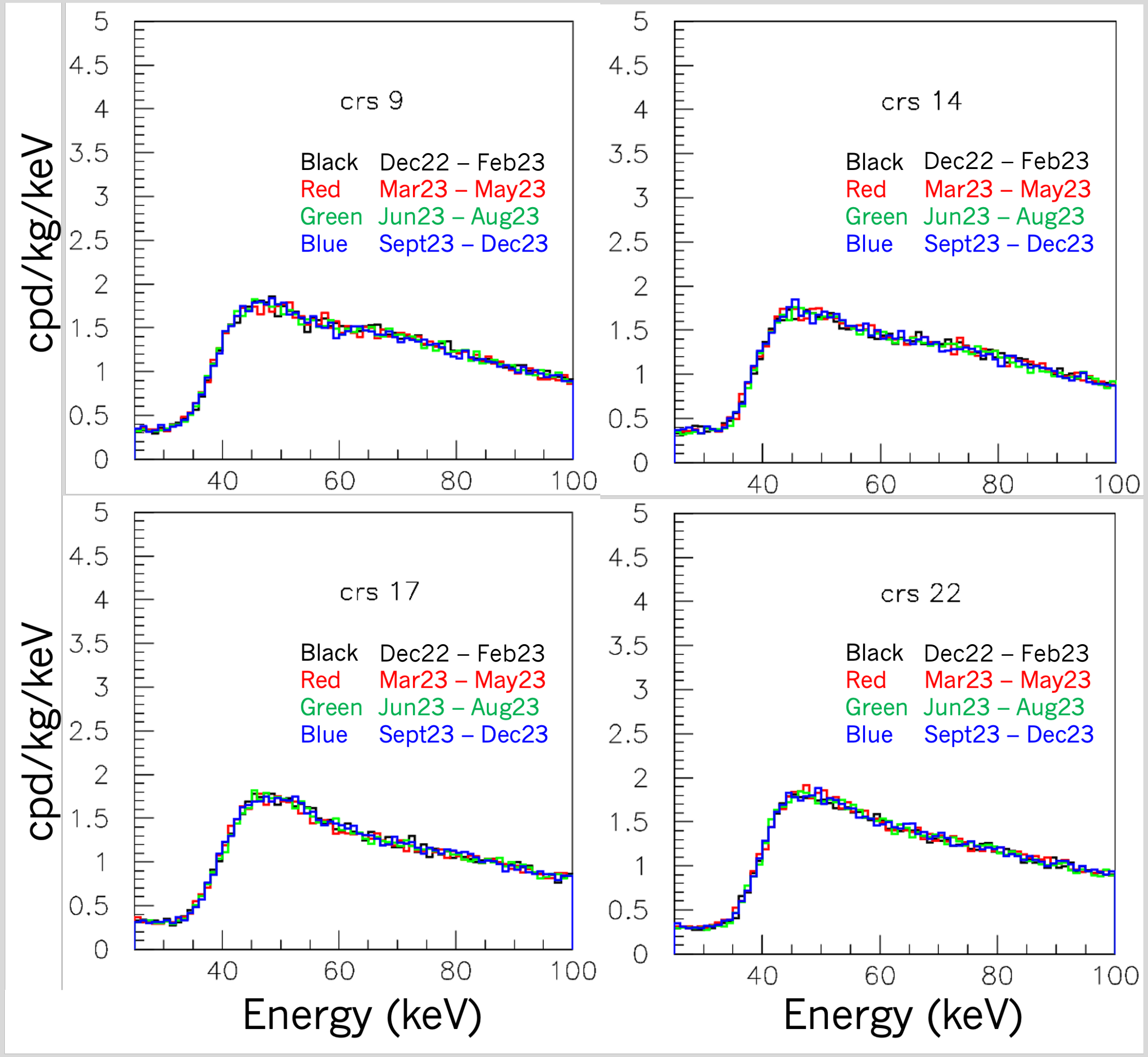
✓Acceptance window eff. per all crystals: $\approx 3.60 \times 10^7$ events ($\approx 1.4 \times 10^6$ events/keV)

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

Stability of the energy scale

- Distribution of the percentage variations (ε_{tdcal}) of each energy scale factor ($tdcal_k$) with respect to the value measured in the previous calibration ($tdcal_{k-1}$)
- From Dec 1, 2021 to Feb 23, 2023
- Gaussian behaviour

$$\varepsilon_{tdcal} = \frac{tdcal_k - tdcal_{k-1}}{tdcal_{k-1}}$$

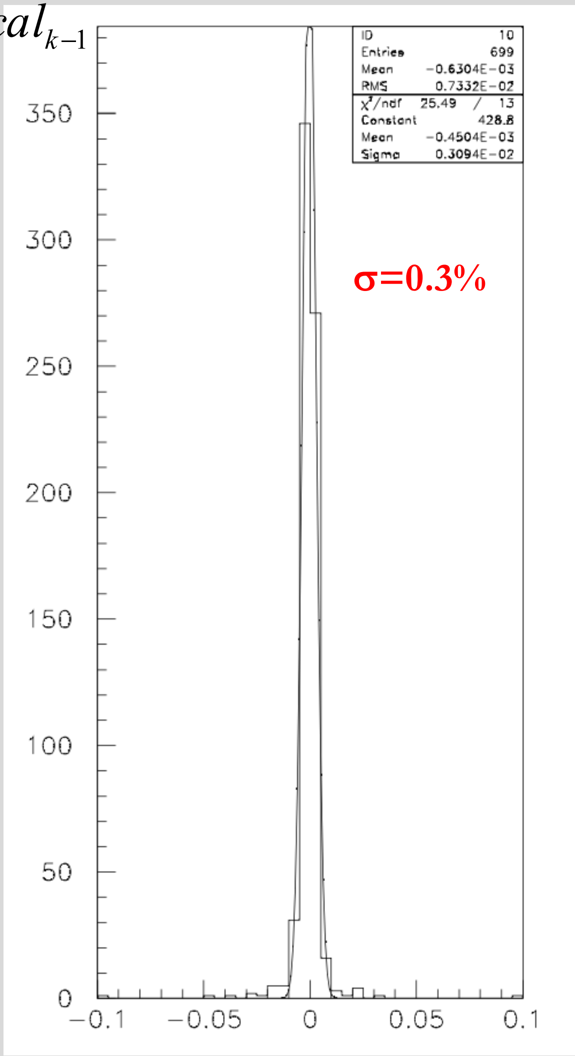
→ the low energy calibration factor for each detector is known with an uncertainty ≪1% during the data taking periods: **additional energy spread σ_{cal}**

$$\sigma = \sqrt{\sigma_{res}^2 + \sigma_{cal}^2} \approx \sigma_{res} \cdot \left[1 + \frac{1}{2}\left(\frac{\sigma_{cal}}{\sigma_{res}}\right)^2\right]; \frac{1}{2}\left(\frac{\sigma_{cal}/E}{\sigma_{res}/E}\right)^2 \leq 7.5 \cdot 10^{-4} \frac{E}{20keV}$$

Negligible effect considering routine calibrations and energy resolution at low energy

Confirmation from MC: maximum relative contribution to annual modulation amplitude $< 1 - 2\times10^{-4}$ cpd/kg/keV

No modulation in the energy scale + cannot mimic the signature



Low-Energy calibration factors (ε_{tdcal})

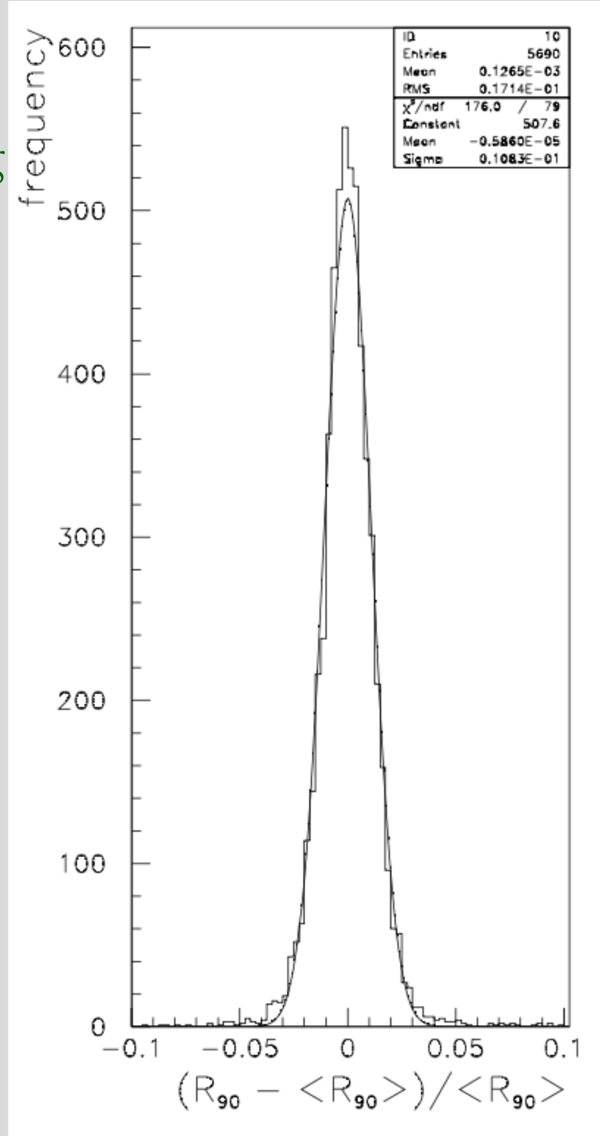
Stability of the background

- **No modulation in the whole energy spectrum:** studying integral rate at higher energy (above 90 keV), R_{90}

- R_{90} percentage variations with respect to their mean values for single crystal in the empowered DAMA/LIBRA-phase2 from Dec 1, 2021 to Feb 23, 2023

- Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:

A_{mod} = (0.04±0.11) cpd/kg consistent with zero

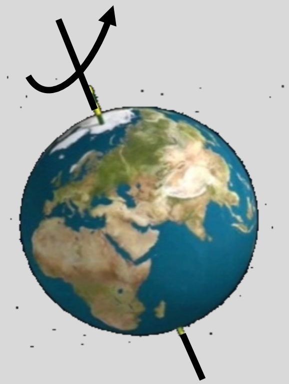


σ ≈ 1%, fully accounted by statistical considerations

+ 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

Other signatures? Second order effects?

- Diurnal effects
- Shadow effects
- Directionality
- ...



Investigated by DAMA in the past at some extention (see below)

New analyses with full exposure and lower software energy threshold can significantly increase the sensitivity

Investigating diurnal modulation in DAMA/LIBRA-phase1

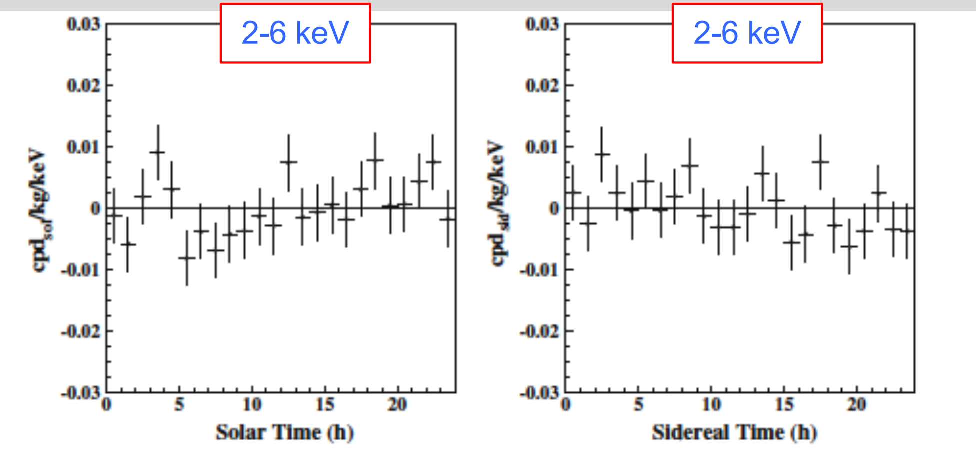
EPJC74(2014)2827

A diurnal modulation with sidereal time is expected because of Earth rotation

$$\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t),$$

Model Independent result on Diurnal Modulation

- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.



Energy	Solar χ^2/d.o.f (P)	Sideral χ^2/d.o.f (P)
2-4 keV	35.2/24 (7%)	28.7/24 (23%)
2-5 keV	35.5/24 (6%)	24.0/24 (46%)
2-6 keV	25.8/24 (36%)	21.2/24 (63%)
6-14 keV	25.5/24 (38%)	35.9/24 (6%)

Diurnal variation (sidereal and solar) excluded at 95% C.L. at the reached level of sensitivity

The ratio R_{dy} of the diurnal over annual modulation amplitudes (sideral time) is a model independent constant at give latitude

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$

@ LNGS

- Annual modulation amplitude in DAMA/LIBRA-phase1 in the (2-6) keV: (0.0097 ± 0.0013) cpd/kg/keV
- Expected value of diurnal modulation amplitude:

$\simeq 1.5 \times 10^{-4}$ cpd/kg/keV.

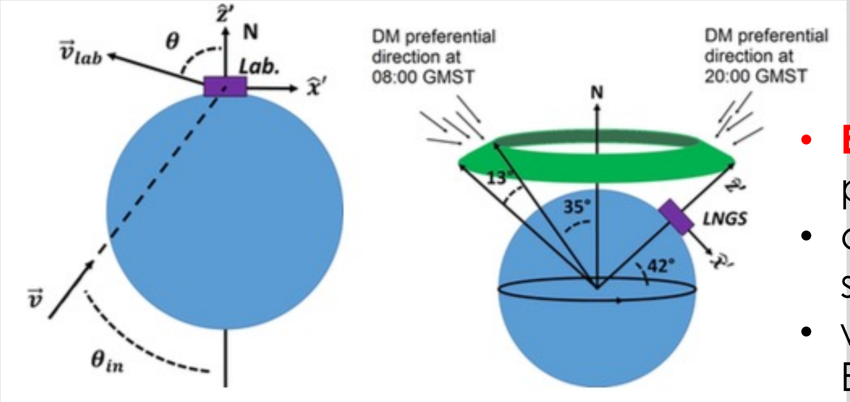
- Fitting the *single-hit* residuals with a cosine function with amplitude A_d as free parameter, period 24 h and phase 14 h

$A_d^{(2\text{-}6\ kev)} < 1.2 \times 10^{-3}$ cpd/kg/keV (90%CL)

Present experimental sensitivity lower than the diurnal modulation amplitude expected from the DAMA/LIBRA-phase1 observed effect.

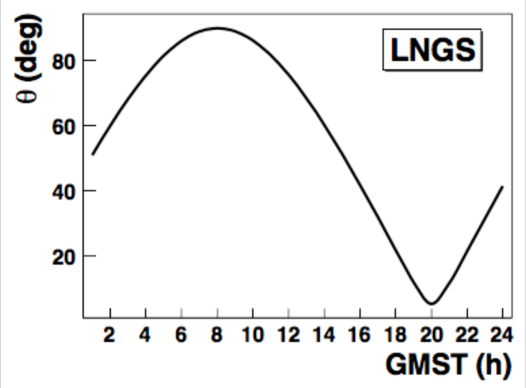
DAMA/LIBRA-phase2 + -empowered can offer increased sensitivity

Earth shadowing effect with DAMA/LIBRA–phase1

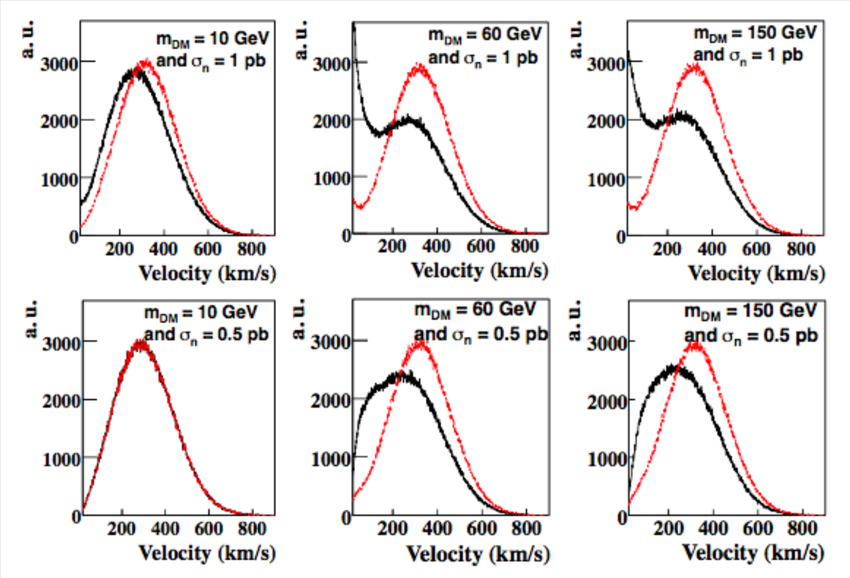


EPJC75 (2015) 239

- **Earth Shadow Effect** could be expected for DM candidate particles inducing just nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM particle in order to reach the experimental set-up



- DM particles crossing Earth lose their energy
- DM velocity distribution observed in the laboratory frame is modified as function of time (**GMST 8:00 black**; **GMST 20:00 red**)



Study of the *Earth Shadow Effect* in DAMA/LIBRA-phase1

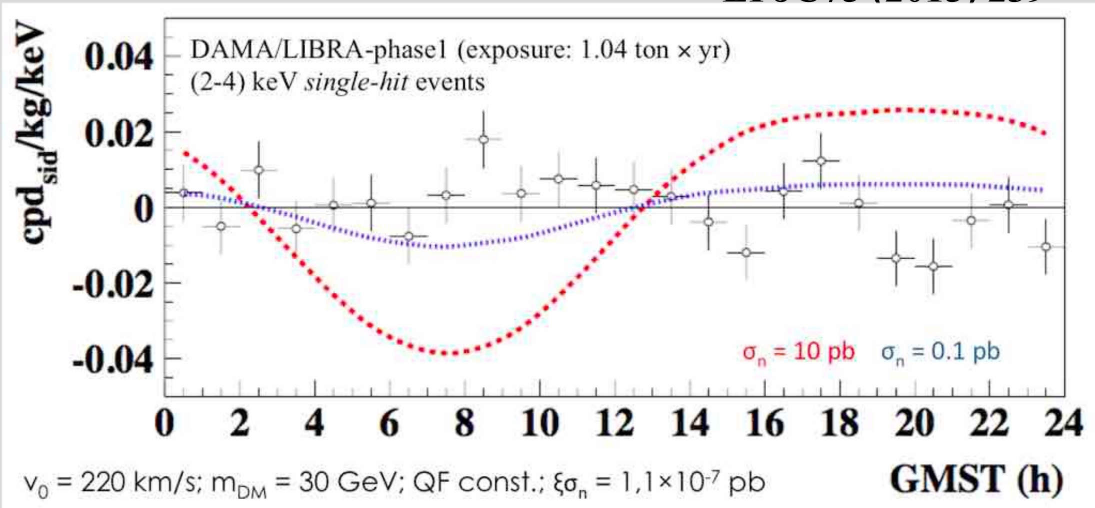
EPJC75 (2015) 239

By MC code, the expected counting rate for a given mass, cross section and scenario has been estimated:

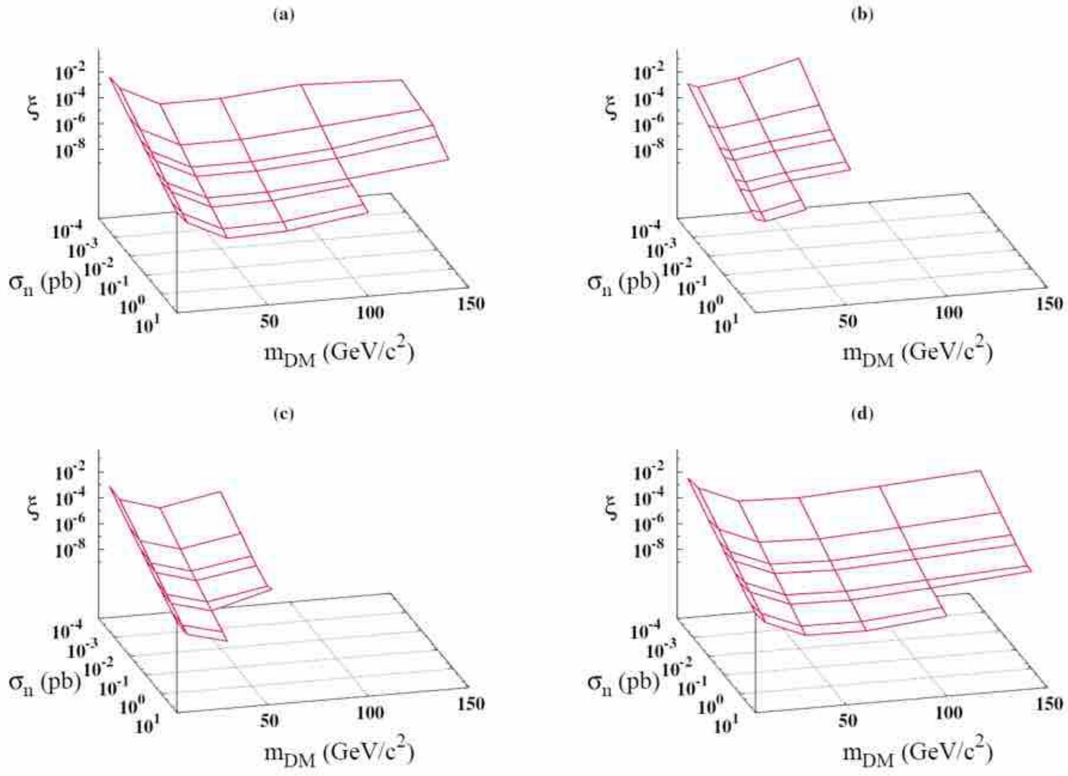
$$S_{d,sh}(t) = \xi\sigma_n S'_{d,sh}(t)$$

Expectations are compared with the experimental diurnal residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA-phase1 in the (2-4) keV energy interval

Minimizing χ^2, upper limits on ξ can be evaluated



v_0 = 220 km/s; m_{DM} = 30 GeV; QF const.; $\xi\sigma_n = 1{,}1\times10^{-7}$ pb



Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the ξ vs σ_n plane for each m_{DM}.

In these examples:
Isothermal halo model with v_0 = 220 km/s and v_{esc} = 650 km/s

a) QF const. without channeling
b) QF const. including channeling
c) QF depending on energy
d) QF depending on energy renormalized to DAMA/LIBRA values

Red surface: 95% C.L. allowed mean value (uncertanties ± 30%)

Directionality technique with anisotropic scintillator

- Identification of the presence of DM candidates inducing just nuclear recoils by exploiting the non-isotropic nuclear recoil distribution correlated to the Earth motion in the galactic frame

N.Cim.C15(1992)475; EPJC28(2003)203; EPJC73(2013)2276, ...

$ZnWO_4$ anisotropic scintillators well suitable

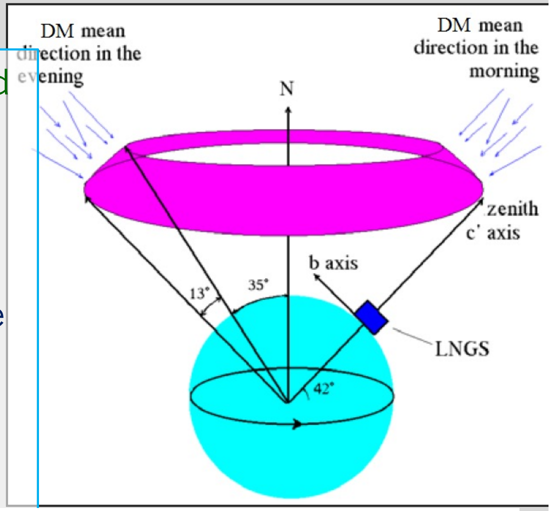
Light output and pulse shape of $ZnWO_4$ for highly ionizing particles (as nuclear recoils) depend on the direction with respect to the crystal axes

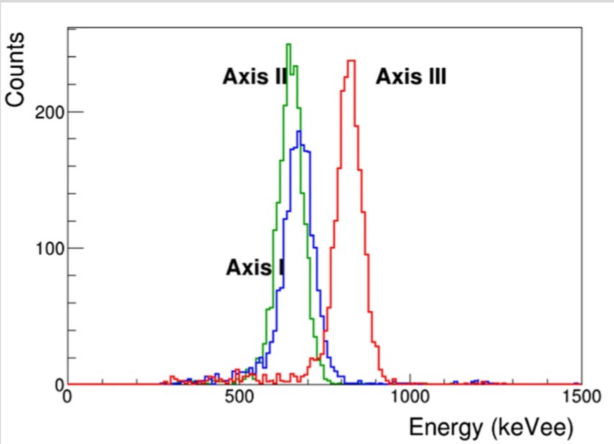
Both anisotropic features can provide two independent ways to exploit the directionality approach

No anisotropy for e.m. signals

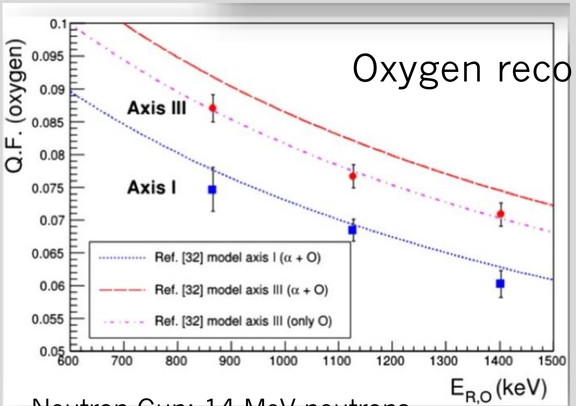
Nuclear recoils are expected to be strongly correlated with impinging direction of those DM candidates

This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day



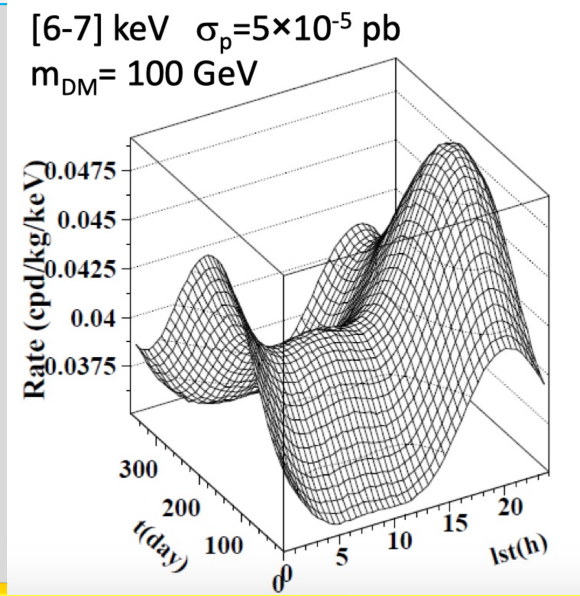


Energy spectra of 4.63 MeV α particles impinging along the three axes of the crystal. The crystal was irradiated in the directions along the crystal axes I (blue on-line), II (green on-line), and III (red on-line), respectively



Neutron Gun: 14 MeV neutrons coincidence between a scattered neutron at a fixed angle and scintillation event in $ZnWO_4$ occurred in a well defined time window

Eur.Phys.J.A 56 (2020) 83



Example for a given model framework of expected counting rate vs function of the days during the year (annual modulation) and of hours during the day (directionality)

An example: the DM annual modulation on Mars

PPNP114(2020)103810

MARS:

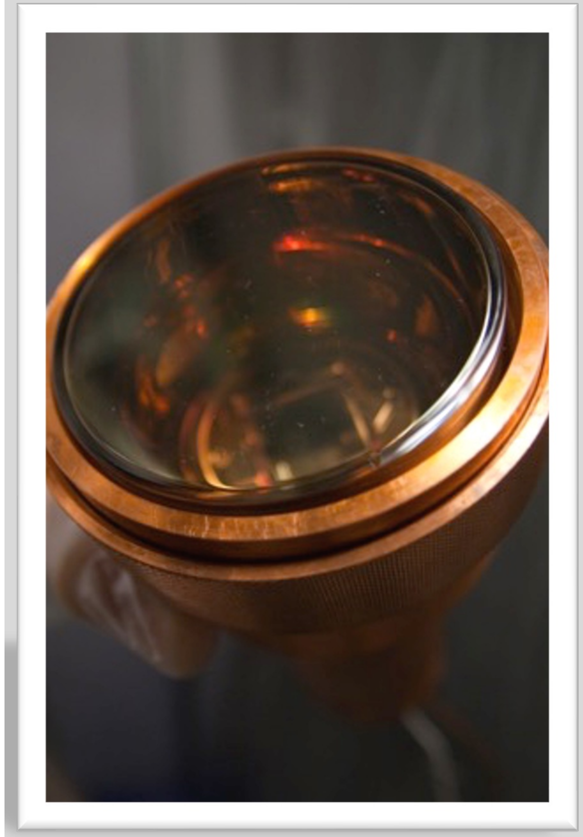
- semi-major axis of 1.524 A.U.
- average orbital speed of 24.1 km/s (26.5 km/s max and 22.0 km/s min).
- eccentricity of the orbit: difference between the aphelion and perihelion distances is 0.285 U.A.
- orbit inclined of 1.85^0 with respect to the ecliptic.
- tilted axis, inclined 25.19^0 to its orbital plane (Earth's axial tilt of approx. 23.44^0)
- period T_M = 668.6 Sols.

Expected DM annual modulation with period T_M, phase ≃ 354 Sols in the Mars calendar and an amplitude ≃ 5% (i.e. the S_m/S_0 value) for usually adopted halo distributions.
(Mars parameters evaluated by Starlink Project)

The measurement of DM modulation signature both on Earth and on Mars would strongly improve our knowledge on astrophysical parameters and therefore on corollary data analyses, once the experimental parameters and the other uncertainties were fully under control, on both the planets, with the needed sensitivity.

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**.
- Completing 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 have been investigated