Università di Roma
Tor Vergata

INFN
ROMA TOR VERGATA

Status of the DAMA project

R. Bernabei

26th (real and virtual) workshop "What Comes Beyond the Standard Models?», July 10 - 19, 2023 - Bled

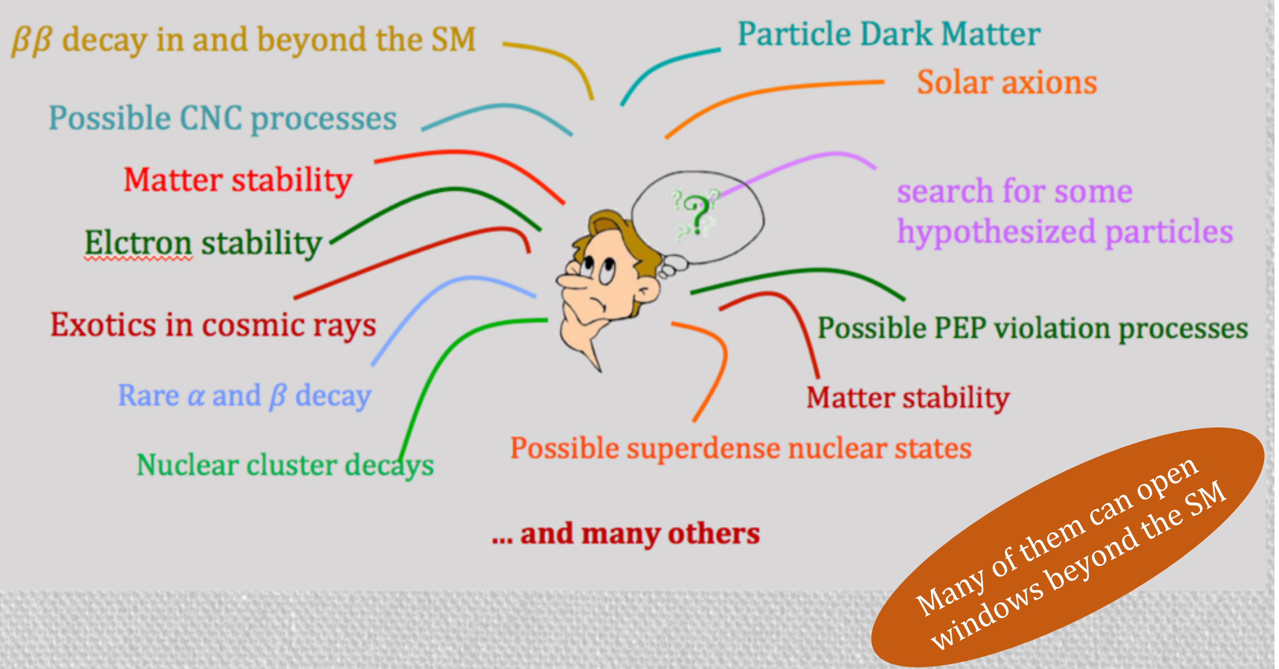
High benefits/cost

- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- Absence of microphonic noise
- Effective routine calibrations feasible in the same conditions as production runs
- Possibility of high light response in many cases
- Possibility of application both in passive and active source approaches as well as coincidence/anticoincidence techniques in multi-detectors set-up
- Relatively small underground space needed and no safety problems
- Use of enriched materials in some cases
- Many isotopes and decay modes can be explored
- ...

note: mass NOT the only key parameters to increase sensitivity + larger mass detectors may show poorer performances than smaller ones, in production

Old and new crystal scintillators @ non-cryogenic temperature

in studying rare processes, involving several fields of Nuclear, sub-Nuclear and Astroparticle Physics:
a leading role



Main requirements

- ✓ Suitable radio-purity, exposure (mass × running time), enrichment in some cases (at least in perspective), ...
- ✓ Suitable detector performances
- ✓ high duty-cycle and suitable control of all the running conditions
- ✓ Well known technology, acceptable cost, safety

Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products, small scale expts. and several detectors developments with INR-Kiev/leader companies/ Queens Univ. (Canada)/… + neutron meas.: ENEA-Frascati, ENEA-Casaccia

An observatory for rare processes @ LNGS

DAMA set-ups

Many low background crystal scintillators developed and used

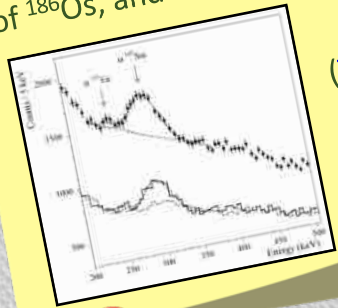
Main DAMA results in searches for rare processes

- 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)

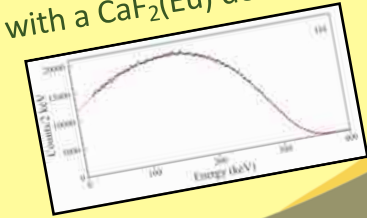
… many others also in progress

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



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

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

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

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 PEP violating processes in Sodium and in Iodine

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

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

Dark Matter investigation

In addition to ULB NaI(Tl): developments/measurements of low-bckg scintillators in the low background DAMA set-ups

$ZnWO_4$	Ukraine	NIMA1029(2022)166400, J. of Lumin. 249 (2022) 119028, EPJA56(2020)83, NIMA935(2019)89, NIMA833(2016)77, PS90(2015)085301, EPJC73(2013)2276, JPG:NPP38(2011)115107, NIMA626-627(2011)31, NPA826(2009)256, PLB658(2008)193, + R&D ongoing
$CdWO_4$	Ukraine	EPJA36(2008)167, PRC76(2007)064603
$^{106}CdWO_4$	Ukraine	Univ.6(2020)182, PRC93(2016)045502, PRC85(2012)044610, NIMA615(2010)301, AstroPhys10(1999)115 & running
$^{116}CdWO_4$	Ukraine	PS97(2022)085302, PRD98(2018)092007, NIMA833(2016)77, JINST6(2011)08011 & running
Cs_2HfCl_6	Canada	NPA1002(2020)121941 & running
Cs_2ZrCl_6	Canada	in publication & running
SrI_2	Ukraine, USA	NIMA670(2012)10, testing
$CaF_2(Eu)$	Bicron/Crismatec(Saint Gobain)	NPA789(2007)15, NPA705(2002)29, NPB563(1999)97
CeF_3	Crystal Clear coll. or China	NIMA498(2003)352, NCIM 110A (1997) 189
BaF_2	China or Bicron/Saint Gobain	EPJA50(2014) 134, NIMA525(2004)535
LiF(W)	Ukraine	NPA806(2008)388
$^{7}LiI(Eu)$	Ukraine	NIM704(2013)40
$LaCl_3(Ce)$	Saint Gobain	Ukr. J. of Phys.51(2006)1037, NIMA555(2005)270
$CeCl_3$	Iltis/Saint Gobain	JPG:NPP38(2011)015103, NPA824 (2009)101
Li_2MoO_4	Ukraine	NIMA607(2009)573
$Li_6Eu(BO_3)_3$	Ukraine	NIMA572(2007)734
$BaWO_4$	Canada	NIMA901(2018)150

and also polycrystalline powder:

ZnS(Ag)	Saint-Gobain	MPLA27, No. 8 (2012)1250031

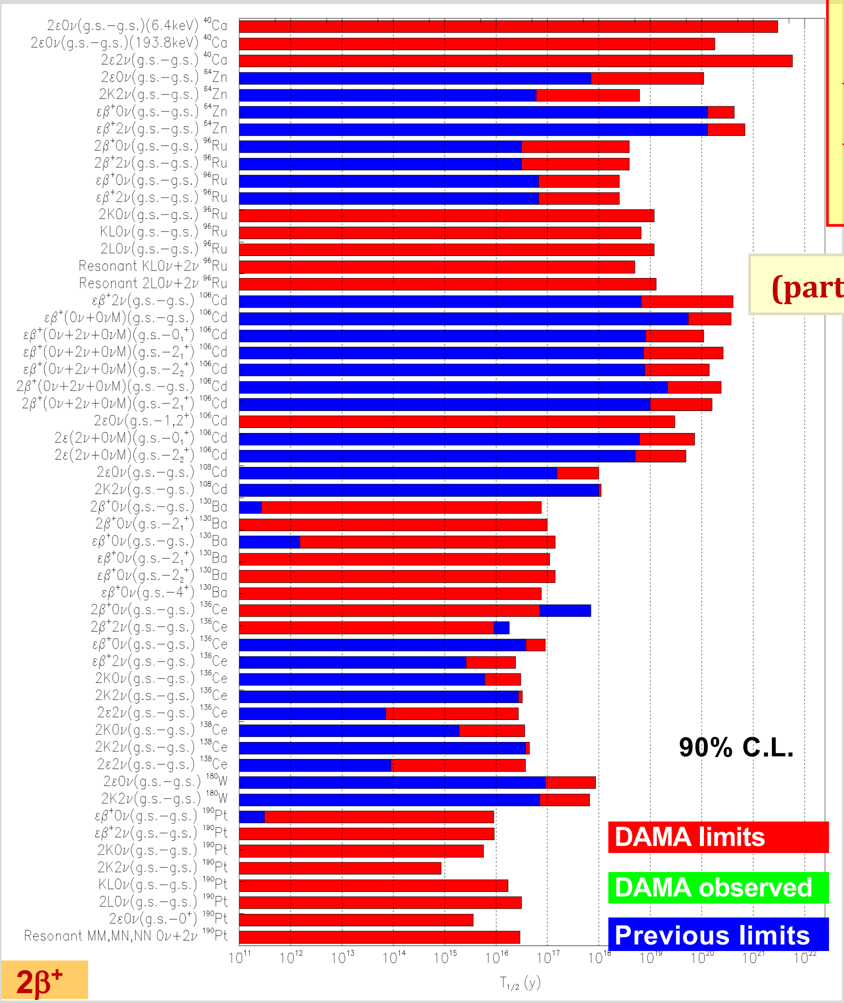
Searches for **2β decay** modes in various **isotopes** at **DAMA** set-ups and in **STELLA** HPGe facility

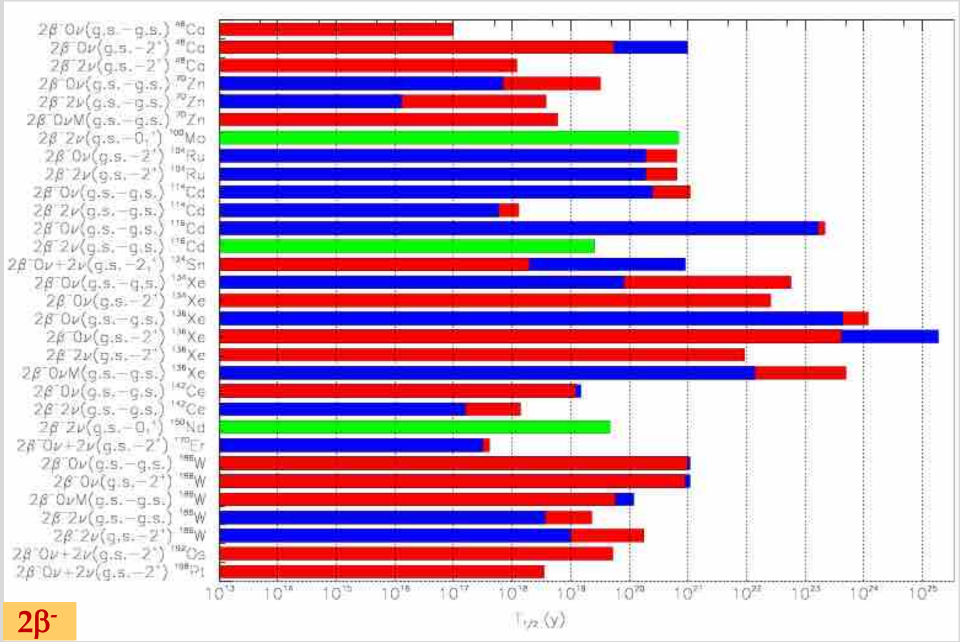
New observations: DAMA and DAMA-Kiev

ARMONIA:	$2\nu2\beta^-$ decay $^{100}Mo \rightarrow ^{100}Ru(0_1^+)$	NPA846(2010)143
AURORA:	$2\nu2\beta^-$ decay $^{116}Cd \rightarrow ^{116}Sn$	PRD98(2018)092007
Nd_2O_3-HPGe:	$2\nu2\beta^-$ decay $^{150}Nd \rightarrow ^{150}Sm(0_1^+)$	NPAE19(2018)95

(partial list)

(^{40}Ca, ^{64}Zn, ^{96}Ru, ^{106}Cd, ^{108}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{180}W, ^{190}Pt, ^{184}Os, ^{156}Dy, ^{158}Dy, ...).





Thanks to the developments on **crystal scintillators**, **competitive results** obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes; **first searches** for **resonant $0\nu2\varepsilon$** decays in some isotopes

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

What accelerators cannot do:
to credit that a certain particle is a DM solution or the "only" DM particle solution…

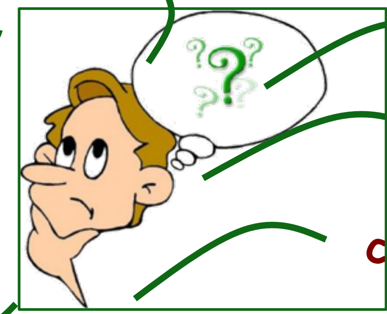
+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

Nucler recoils and/or e.m. radiation

MULTI-MESSENGER? ONLY FOR SOME PARTICULAR CASES

Right halo model and parameters?

- **DM multicomponent also in the particle part?**
- **Right related nuclear and particle physics?**



Non thermalized components?

Caustics?

clumpiness?

etc

Direct detection experiments can be classified in 2 classes, depending on what they are based:

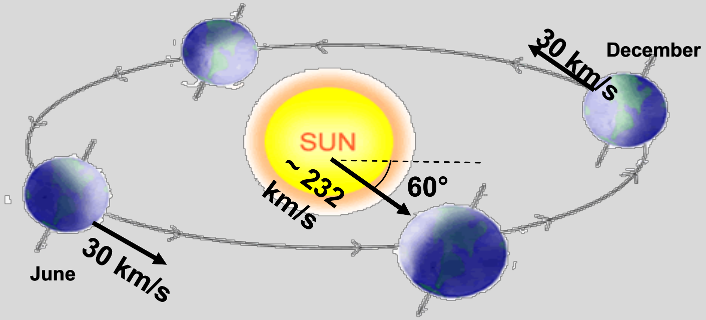
1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a peculiar *model-independent* signature and a suitable set-up and procedures

2. on the use of uncertain techniques of several statistical subtractions from the originally measured counting rate and/or of an hypothesized background model (adding systematical effects, additional uncertainties and often lost of candidates)

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

Signatures for direct detection experiments

In direct detection experiments to provide a Dark Matter signal identification with respect to the background a model independent signature is needed



- Model independent annual modulation: annual variation of the interaction rate due to Earth motion around the Sun which is moving in the Galaxy

  at present the only feasible one, sensitive to many DM candidates and scenarios

  (**successfully exploited by DAMA**)

- Model independent diurnal modulation: due to the Earth revolution around its axis

  2nd order effect

- Diurnal variation: daily variation of the interaction rate due to the different Earth depth crossed by the Dark Matter particles

  only for high cross sections

- Directionality: correlation of Dark Matter impinging direction with Earth's galactic motion

  only for DM candidate particle inducing nuclear recoils

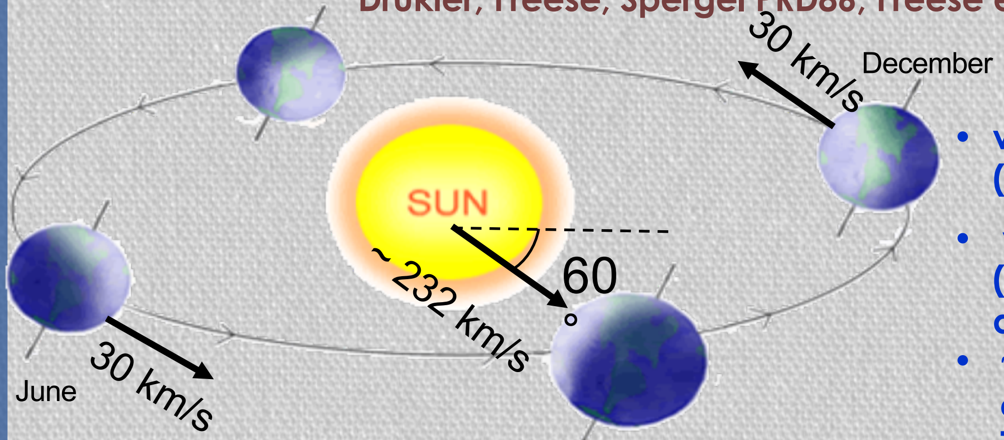
The DM annual modulation: a model independent signature to investigate DM particles component in the galactic halo

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 halo)
- v_{orb} = 30 km/s (Earth vel around 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 relevance 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.

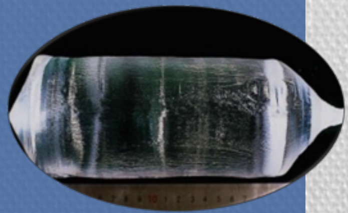
ULB NaI(Tl) also allows the study of several rare processes

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



But never forget:

- Crystals just 1 of components of low-bckg expt.
- Each ULB production cannot exactly be reproduced e.g. because of:
  - ❑ change of sources of materials
  - ❑ unavoidability of all needed materials from the same selections
  - ❑ possible activation/pollution in (long) storage at sea level
  - ❑ different additives, seeds, wrapping materials, housing, glues, …
  - ❑ different procedures due to time modification of the production
  - ❑ protocols for cutting, handling, surface cleaning, etc.
  - ❑ equipment, change in safety rules
  - ❑ loss of some competences in the periodical change of involved people

In low background experiments even a screw (or used tool) can make the difference

Performances of (ULB) crystal scintillators depend on many specific parameters as e.g.:

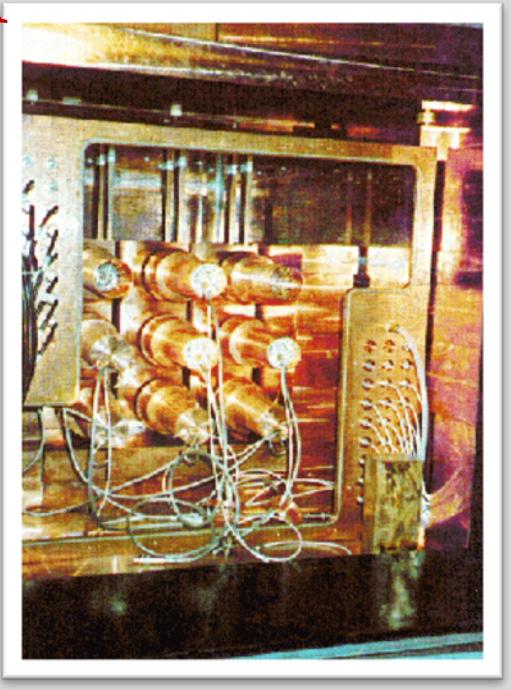
- ✓ purity of the components, purity of the additives, of the dopants and of the seeds, time and environment of storing materials, adopted physical/chemical purification procedures, etc.
- ✓ Used growing method and related parameters and procedures
- ✓ Initial and final concentration of the dopant in the crystal, if any; its uniform distribution in the crystal
- ✓ For detectors cutted from large ingot: which part of the ingot is used, depending on growth technique
- ✓ Non-stoichiometry, i.e. deviation from congruent melting composition.
- ✓ The crystal machining, the surface preparation, the environment, the housing when necessary, reflector/diffuser, glues, …

& important parameters for optical properties e.g.: form and size of the crystal and crystal surface treatment,… + impurities often have a significant impact on the crystal-growth processes and on optical properties.

& then, particular care in the selection of optical read-outs, of structural and shielding materials

To pursue the highest radiopurity in all the components of a detector/set-up always necessary as well as to pursue as much as possible model-independent signatures for rare processes. However, the higher is the initial radiopurity, the easier may be to lose it e.g. during handling in the company/lab, in the packing, in the transportation, in the assembling.

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

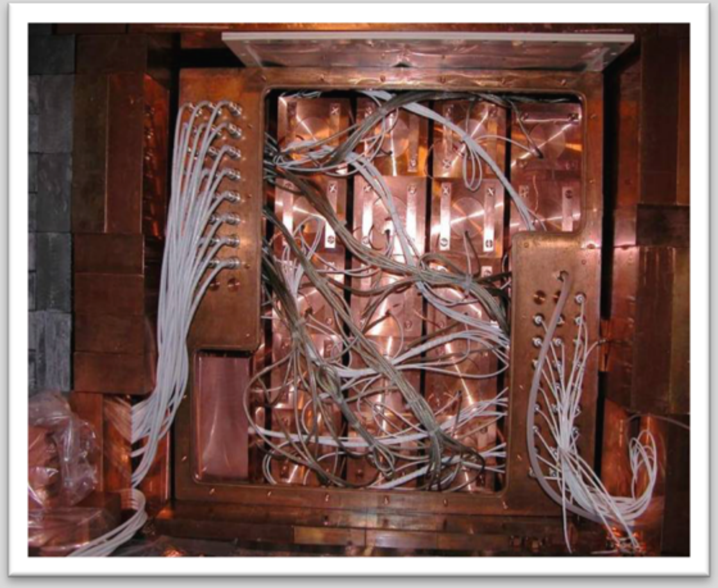
Results on rare processes: PLB408(1997)439, PRC60(1999)065501, PLB460(1999)235, PLB515(2001)6, EPJdirect C14(2002)1, EPJA23(2005)7, EPJA24(2005)51

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 radiopurer NaI(Tl) by new chemical/physical radio-purification techniques
- all operations involving - including photos - in HP Nitrogen atmosphere
- Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

- Performances: NIMA592(2008)297, JINST7(2012)03009

DAMA/LIBRA–phase1:

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

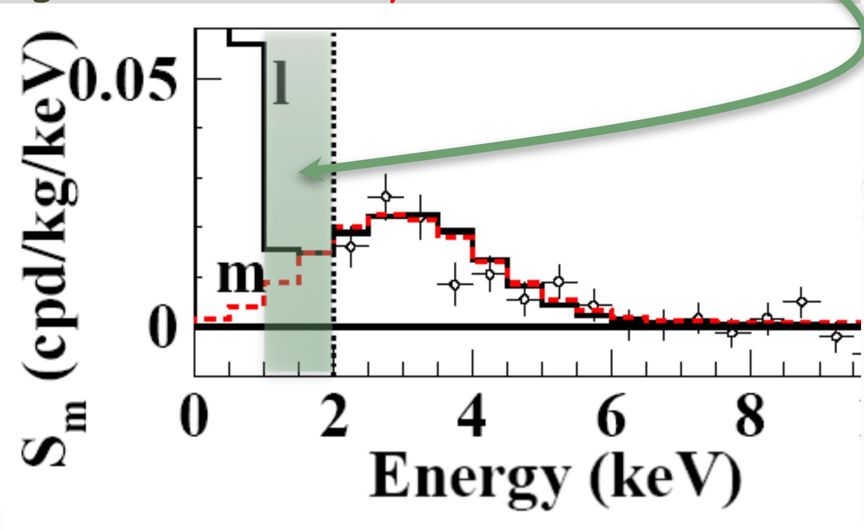
Data taking completed on July 2010

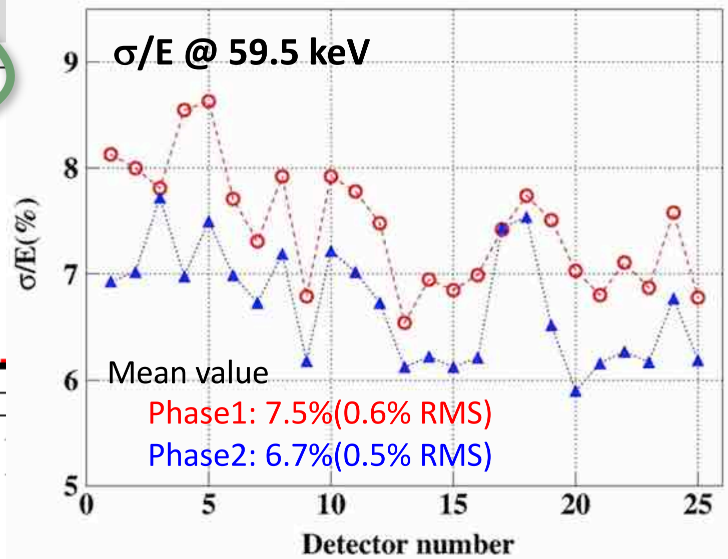
DAMA/LIBRA-phase2

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

Lowering software energy threshold below 2 keV:

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





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

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

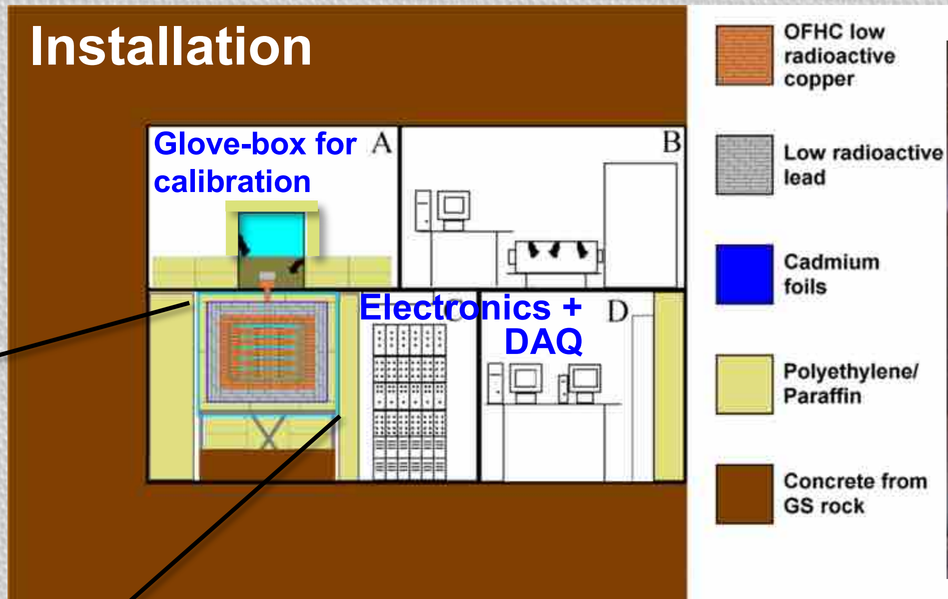
The light responses:

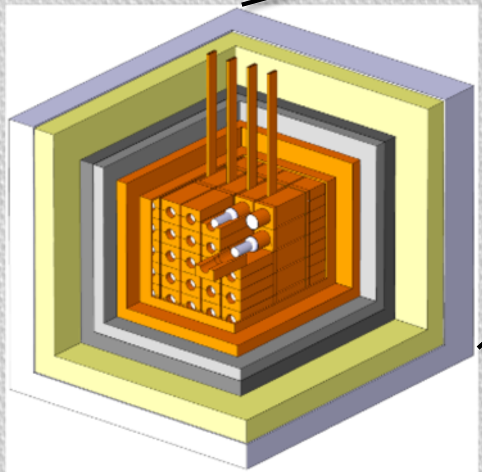
DAMA/LIBRA-phase1: 5.5 – 7.5 ph.e./keV
DAMA/LIBRA-phase2: 6-10 ph.e./keV

The DAMA/LIBRA–phase2 set-up

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

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- 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 HPN_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

- 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

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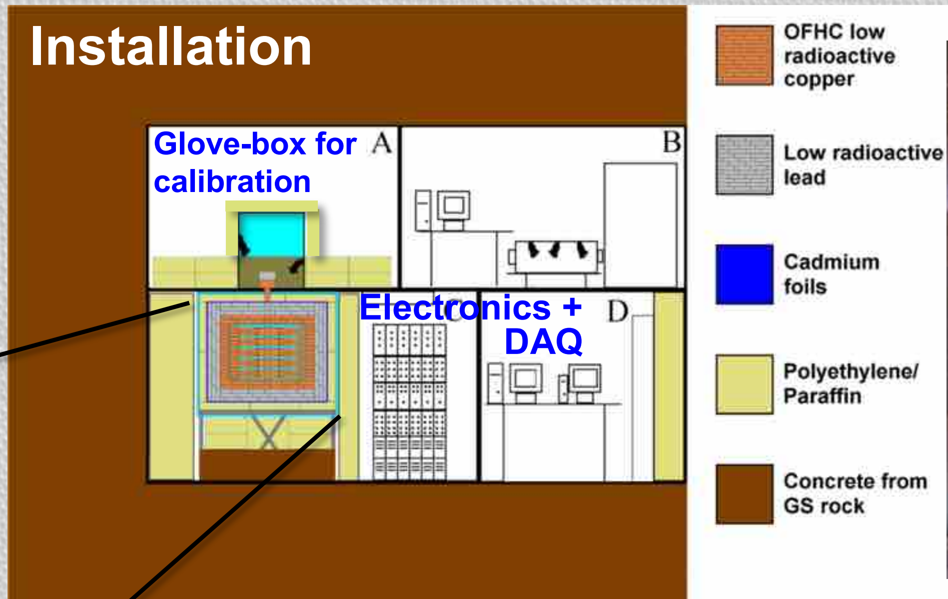

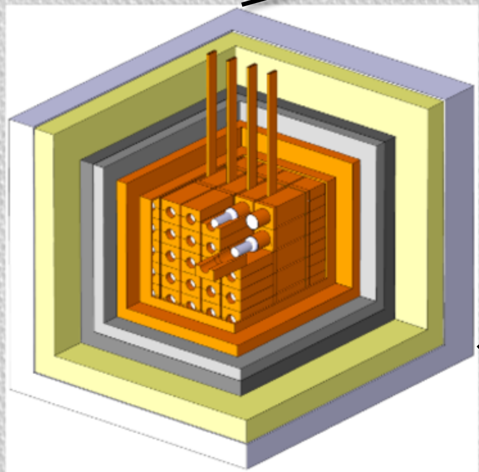

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- New electronic modules

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

DAMA/LIBRA–phase2

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Universe 4 (2018) 116
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arXiv:2209.00882

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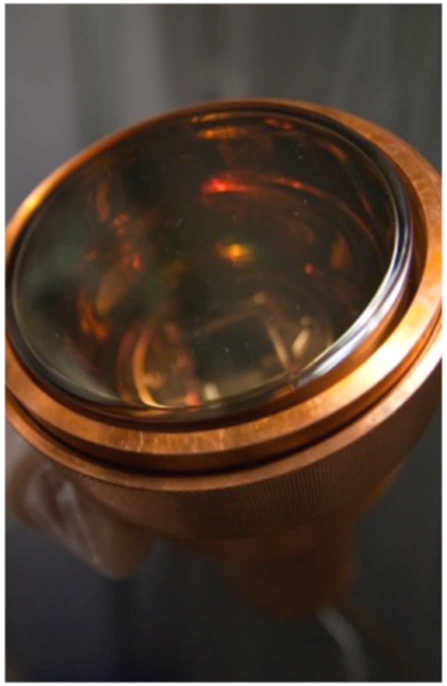

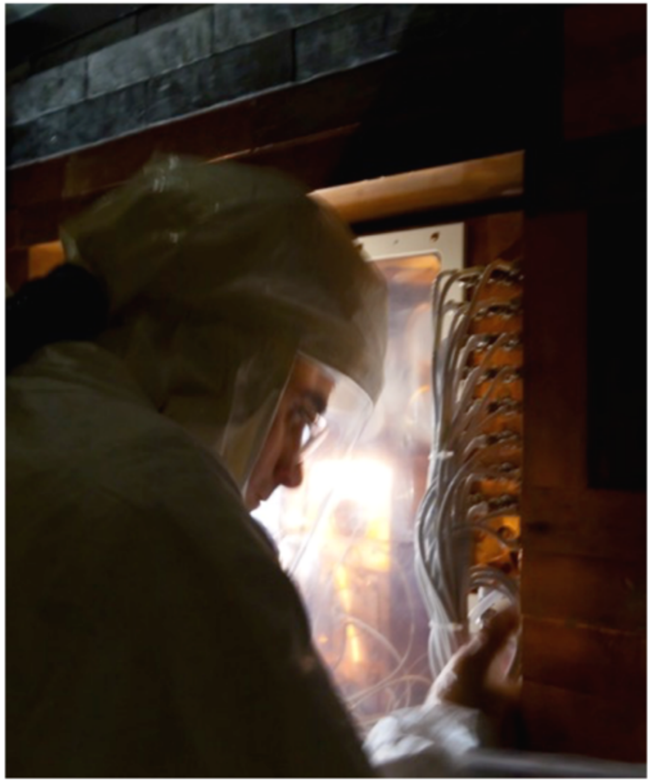

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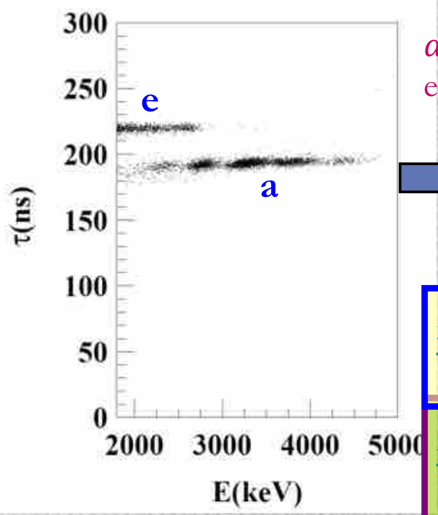
A new stage of the experiment: **Empowered DAMA/LIBRA-phase2** with 0.5 keV energy threshold running since Dec 1, 2021, see later

Goal: software energy threshold at 1 keV – accomplished

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

Residual contaminants in the ULB NaI(Tl) detectors



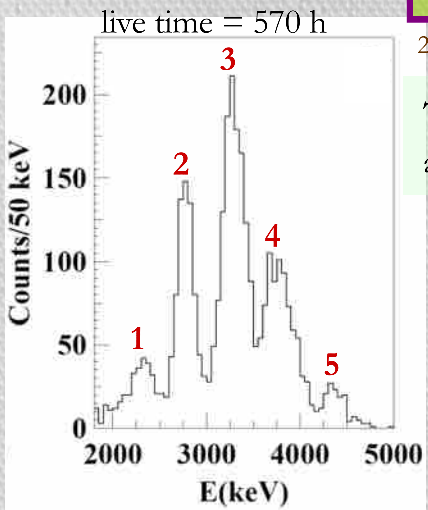
α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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



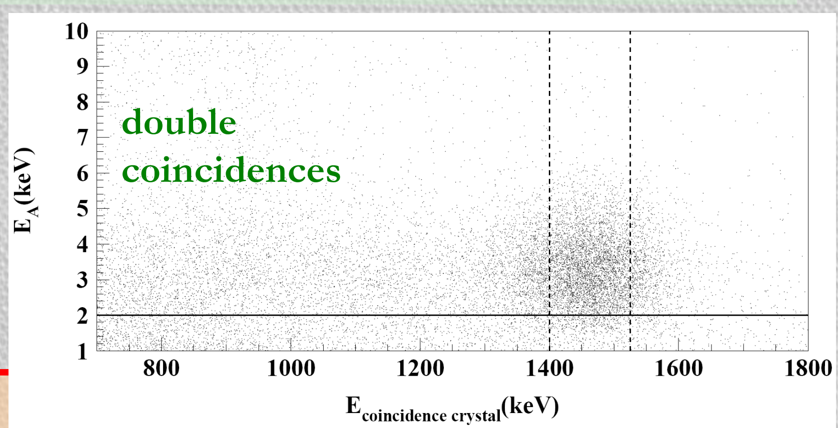
^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

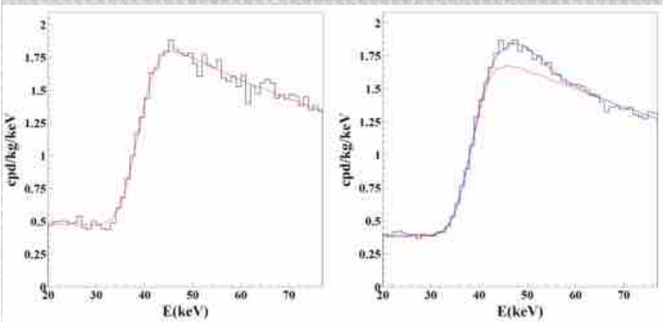
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

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





^{129}I and ^{210}Pb

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

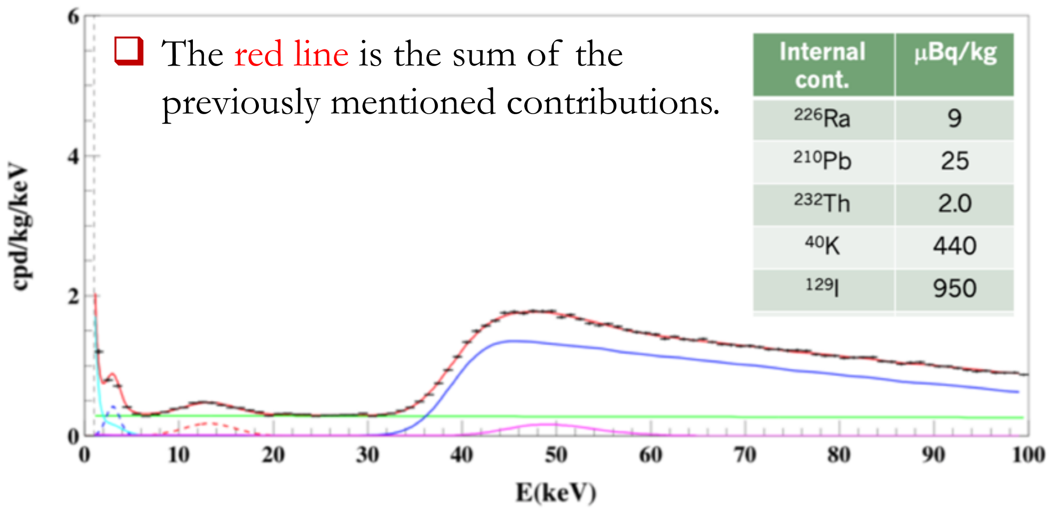
^{210}Pb in the new detectors: (5 − 30) μBq/kg.

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

... more on NIMA592(2008)297

Constrain on S_0 for corollary model-dependent analyses

- energy spectrum of the *single-hit* scintillation events collected by DAMA/LIBRA–phase2
- 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 (external) ^{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)
  - internal and external (Cu, PMTs, structural materials, etc) contributions of ^{238}U (mainly, internal ^{226}Ra: 9 μBq/kg), ^{232}Th (internal: 2.0 μBq/kg) and ^{40}K (internal: 450 μBq/kg) – light green line. Internal ^{40}K 15%, ^{238}U 10%, ^{232}Th 3%. External contributions are roughly equally shared among the three components: Cu, light guides, PMTs.
  - below 5 keV a sharp decreasing (cyan) curve represents the derived upper limit on S_0, the un-modulated term of the DM signal used just as *prior* in corollary *model-dependent analyses.*



- The red line is the sum of the previously mentioned contributions.

Internal cont.	μBq/kg
^{226}Ra	9
^{210}Pb	25
^{232}Th	2.0
^{40}K	440
^{129}I	950

Constrain on S_0 for corollary model-dependent analyses

- energy spectrum of the *single-hit* scintillation events collected by DAMA/LIBRA–phase2
- There are also represented the measured contributions of:
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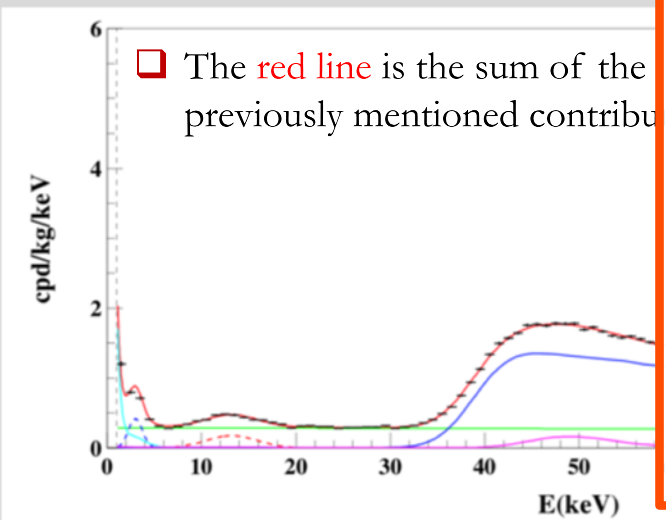
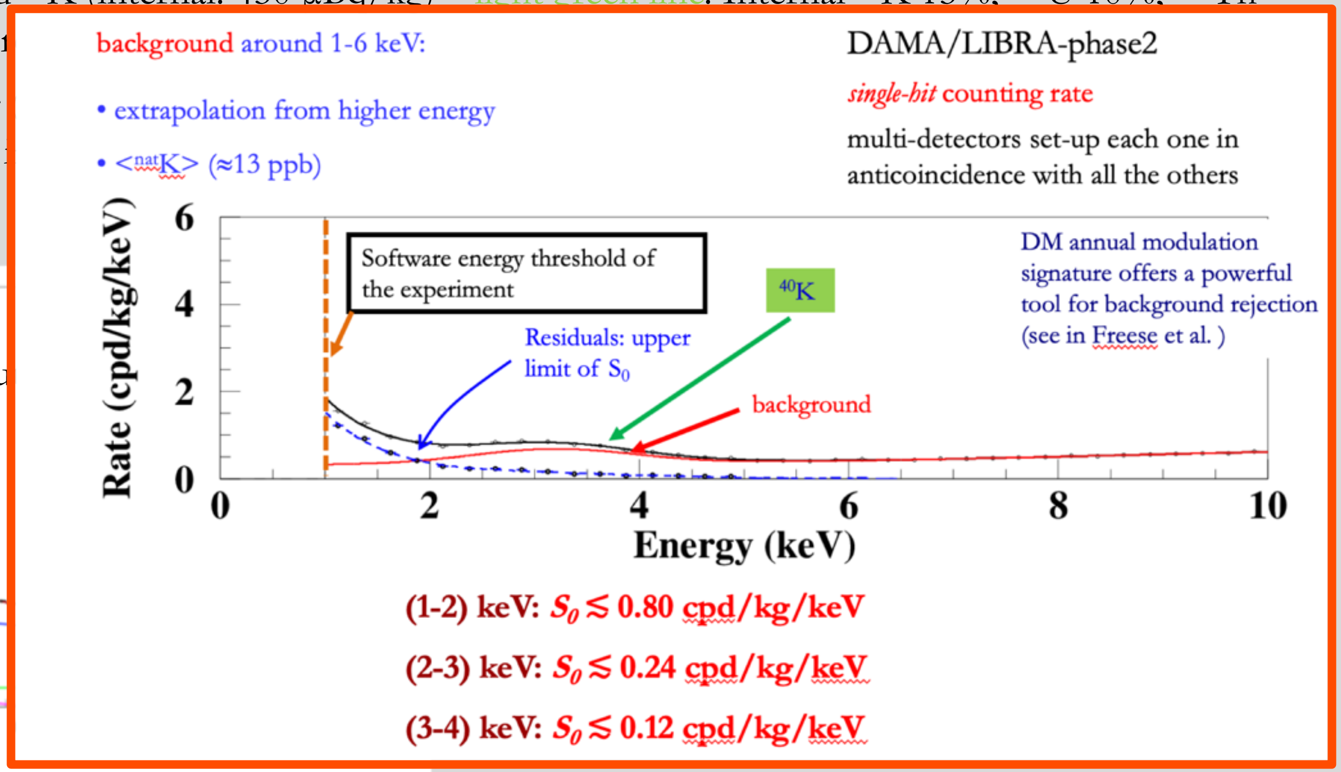
  - below 5 keV a sharp decreasing
    the DM signal used just as *prior* i

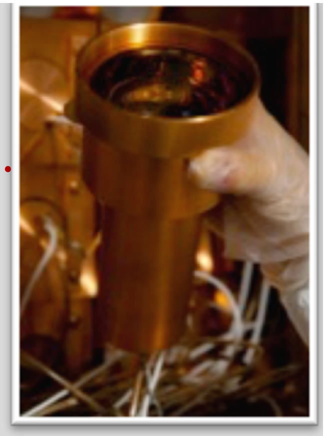
- The red line is the sum of the previously mentioned contribu





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

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

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**

- ✓ 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)

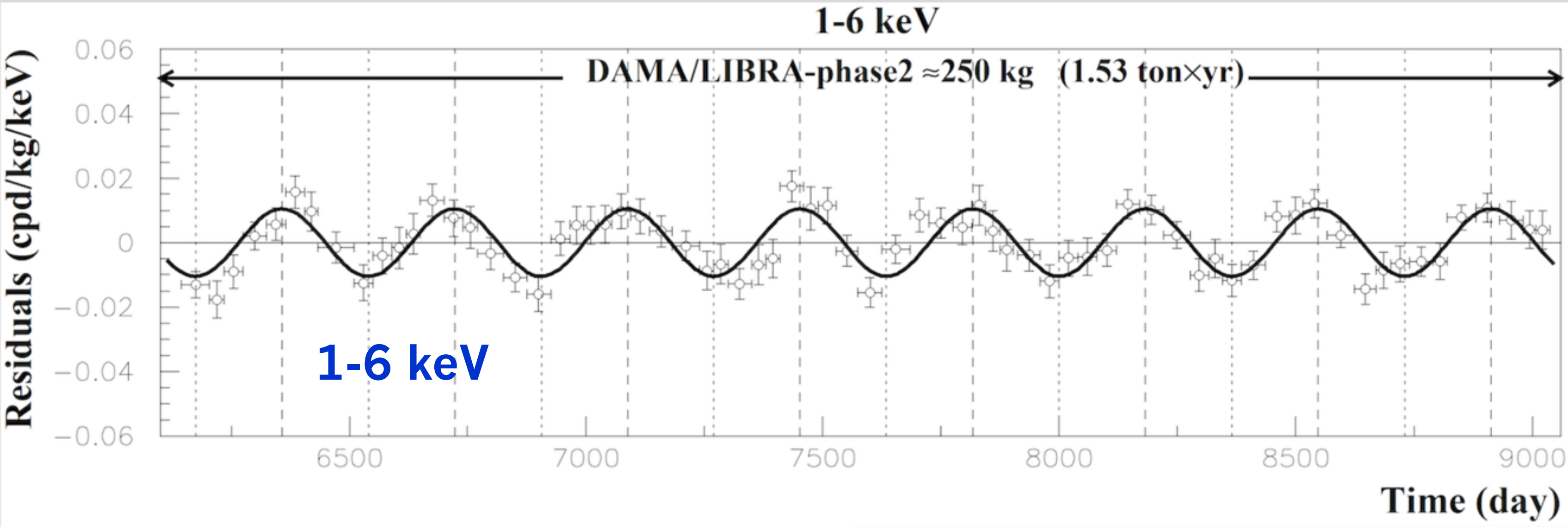
Exposure with this data release of DAMA/LIBRA-phase2: **1.53 ton × yr**

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

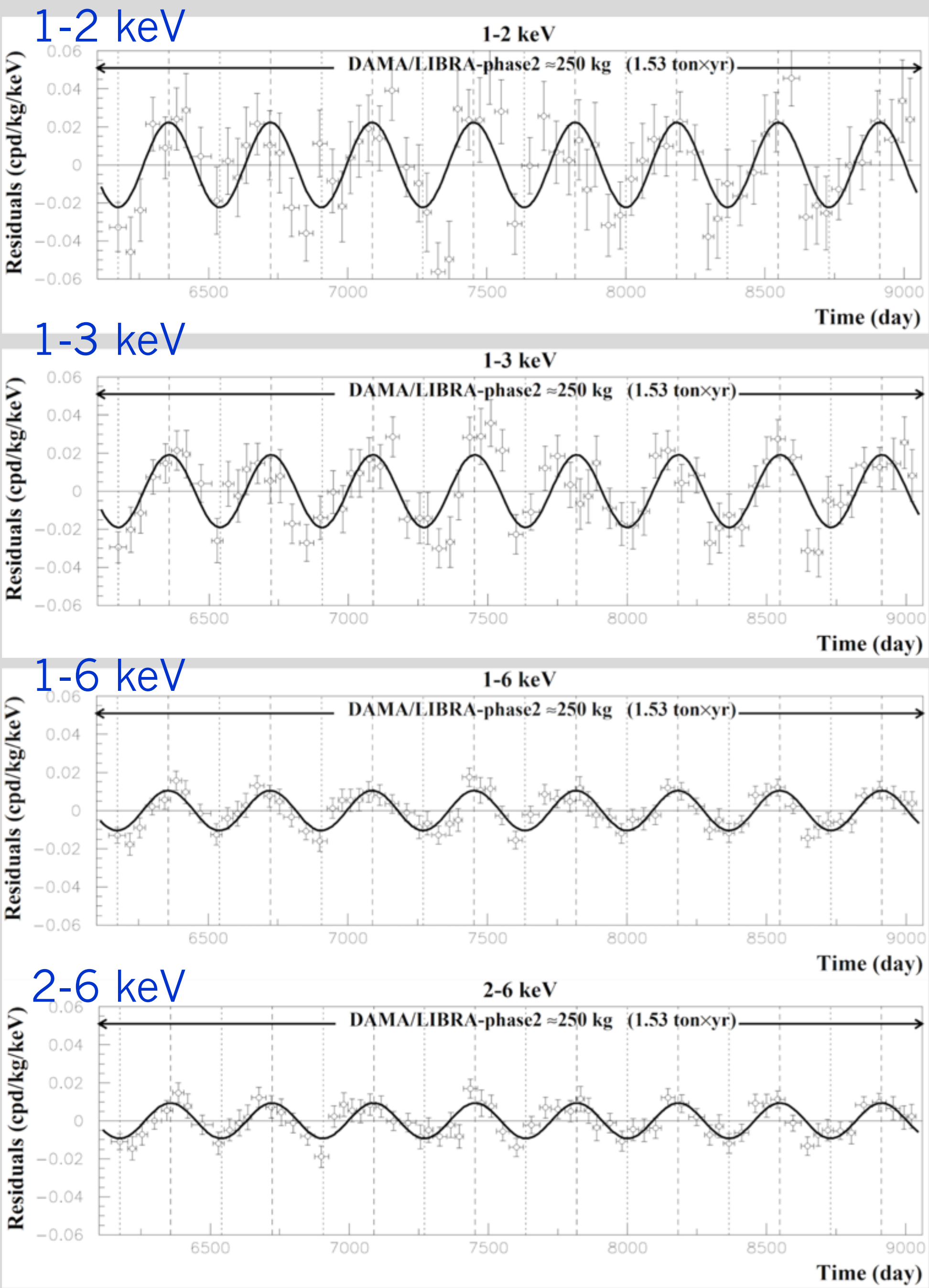
A=(0.01048±0.00090) cpd/kg/keV

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

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 = 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

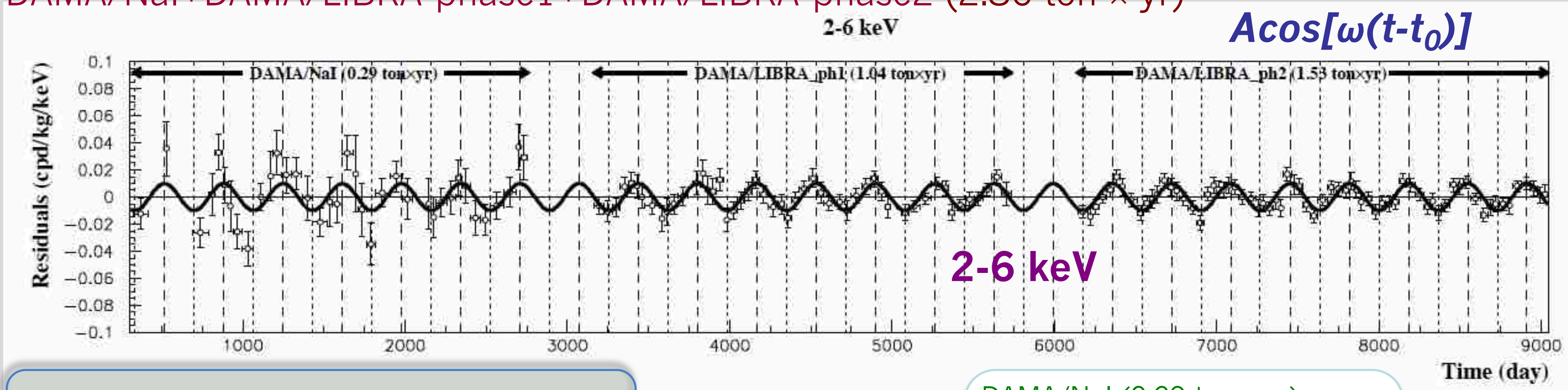
A=(0.00933±0.00094) cpd/kg/keV
χ^2/dof = 58.2/68 **9.9 σ C.L.**

The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6 σ 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 $\Rightarrow$ P(A=0) =2.3×10^{-12}

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.**

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

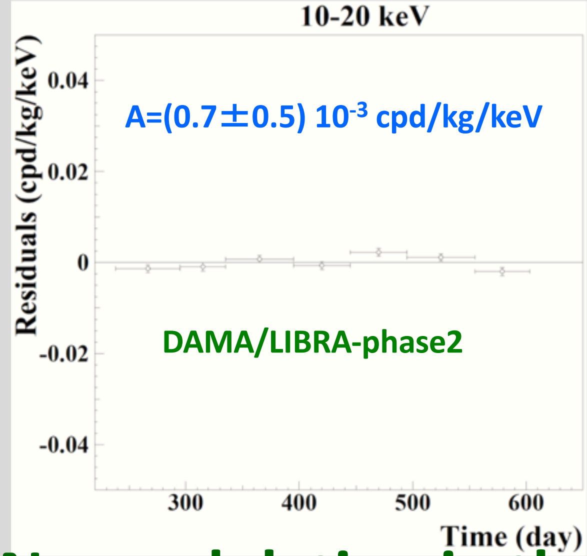
Releasing period (*T*) and phase (t_0) in the fit

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

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

Rate behaviour above 6 keV

• No Modulation above 6 keV



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

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

→ statistically consistent with zero

• No modulation in the whole energy spectrum:

studying integral rate at higher energy, R_{90}

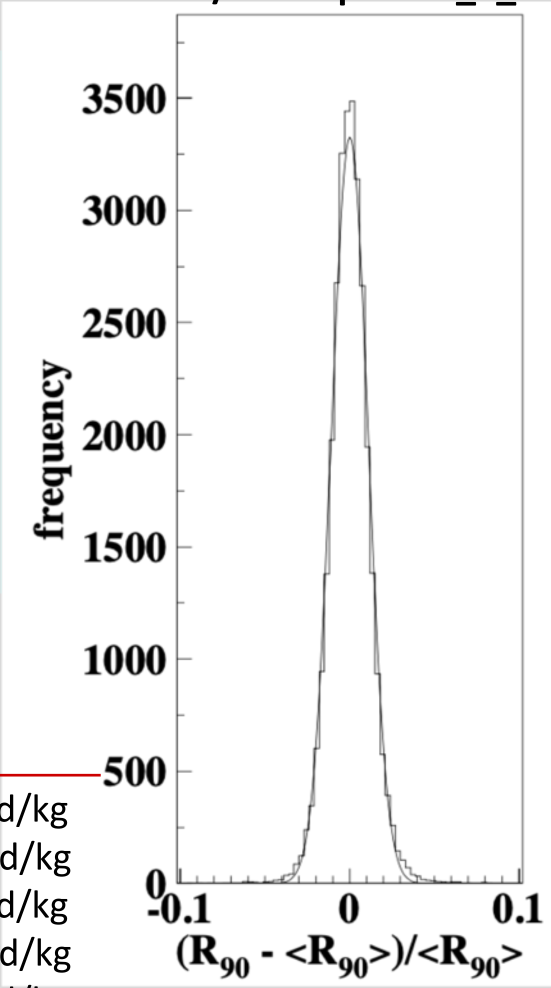
- R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods
- Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:

  consistent with zero

+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

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

DAMA/LIBRA-phase2_2_9



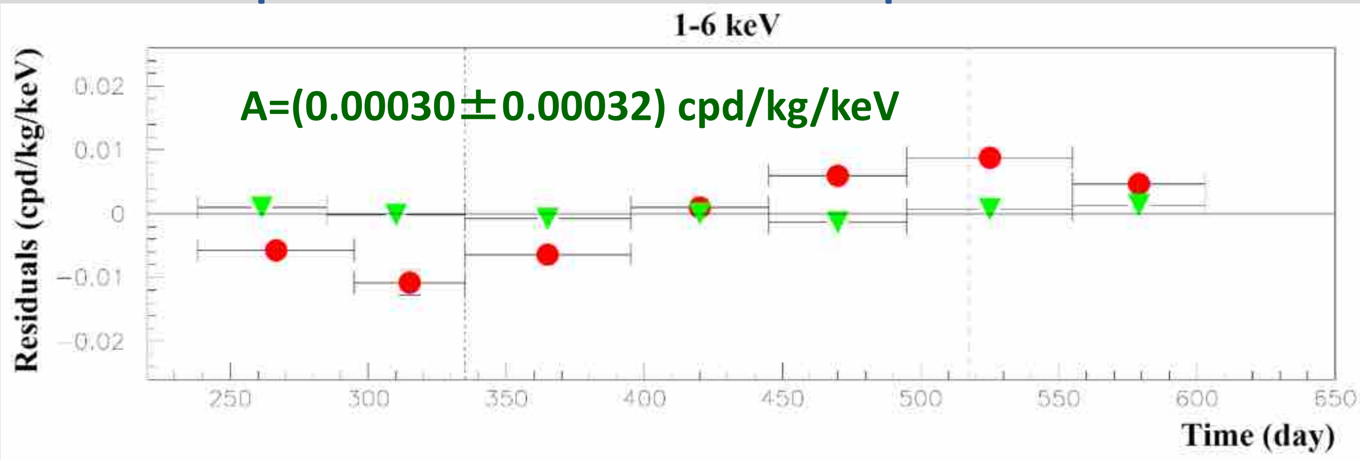
σ ≈ 1%, fully accounted by statistical considerations

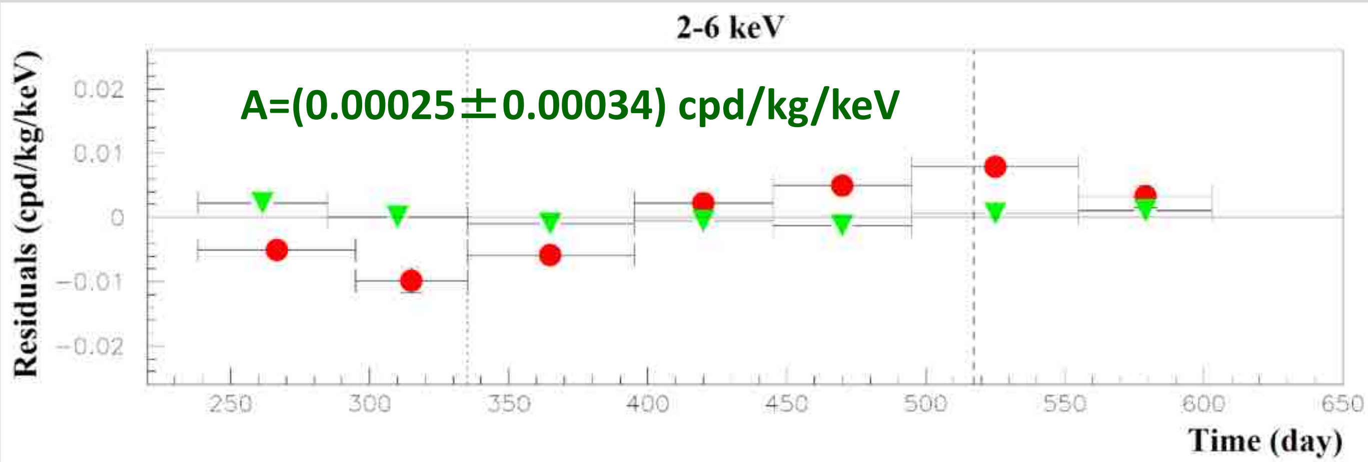
No modulation above 6 keV
This accounts for all sources of bckg and is consistent with the studies on the various components

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

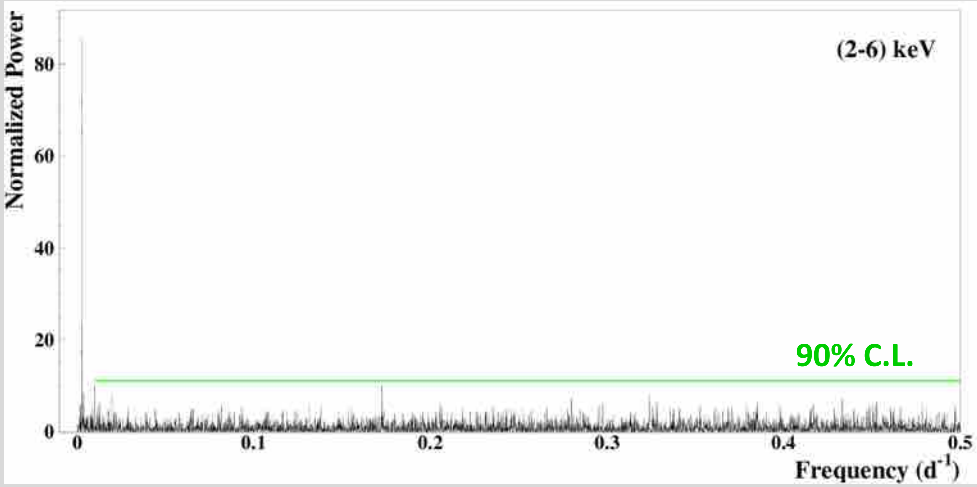
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

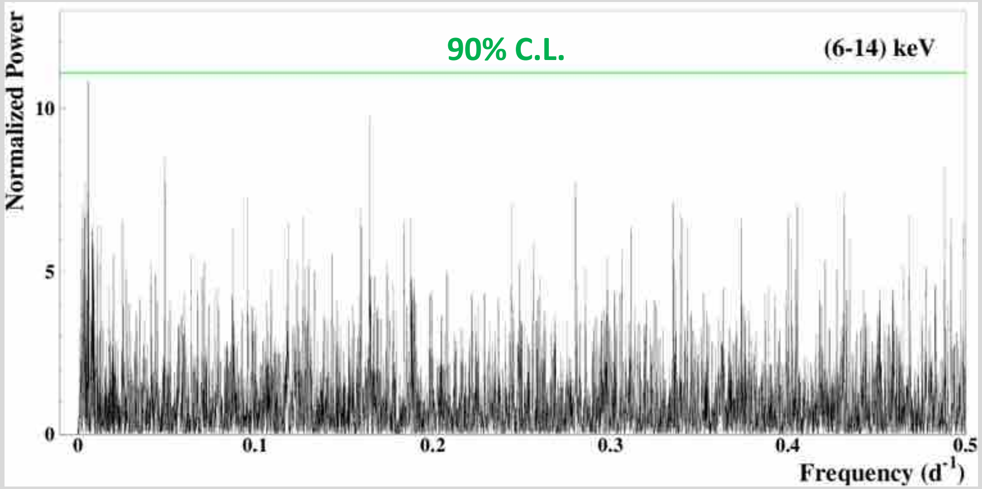
The analysis in frequency

(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

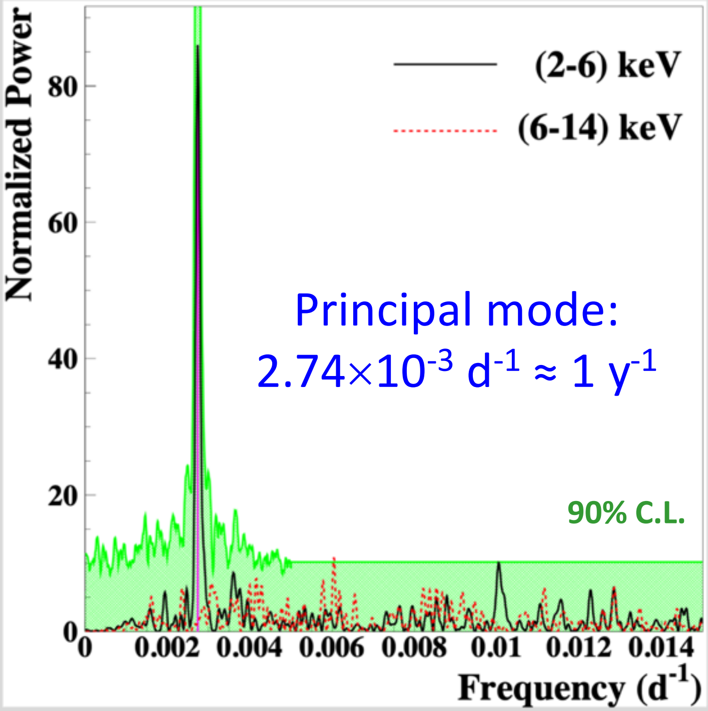
The whole power spectra up to the Nyquist frequency





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

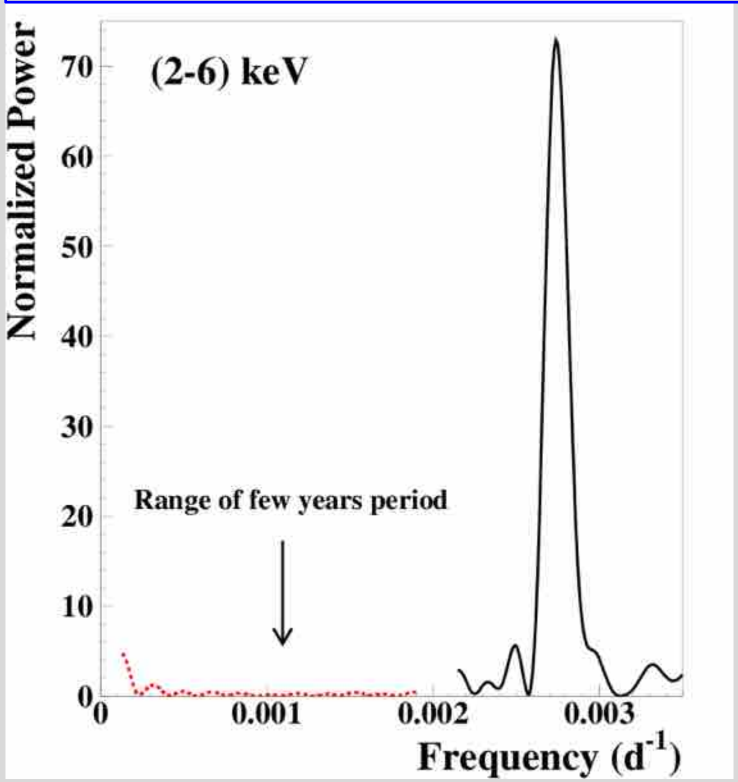
Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region

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

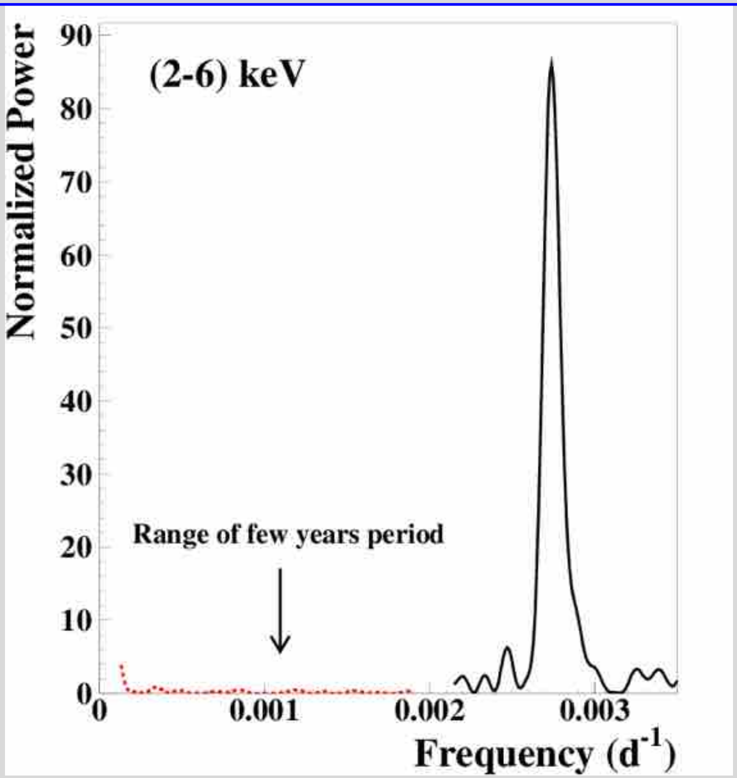
We calculated annual baseline counting rates – that is the averages on all the detectors (j index) of *flat*$_j$ (i.e. the single-hit scintillation rate of the j-th detector averaged over the annual cycle)

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

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



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



No statistically significant peak at lower frequency

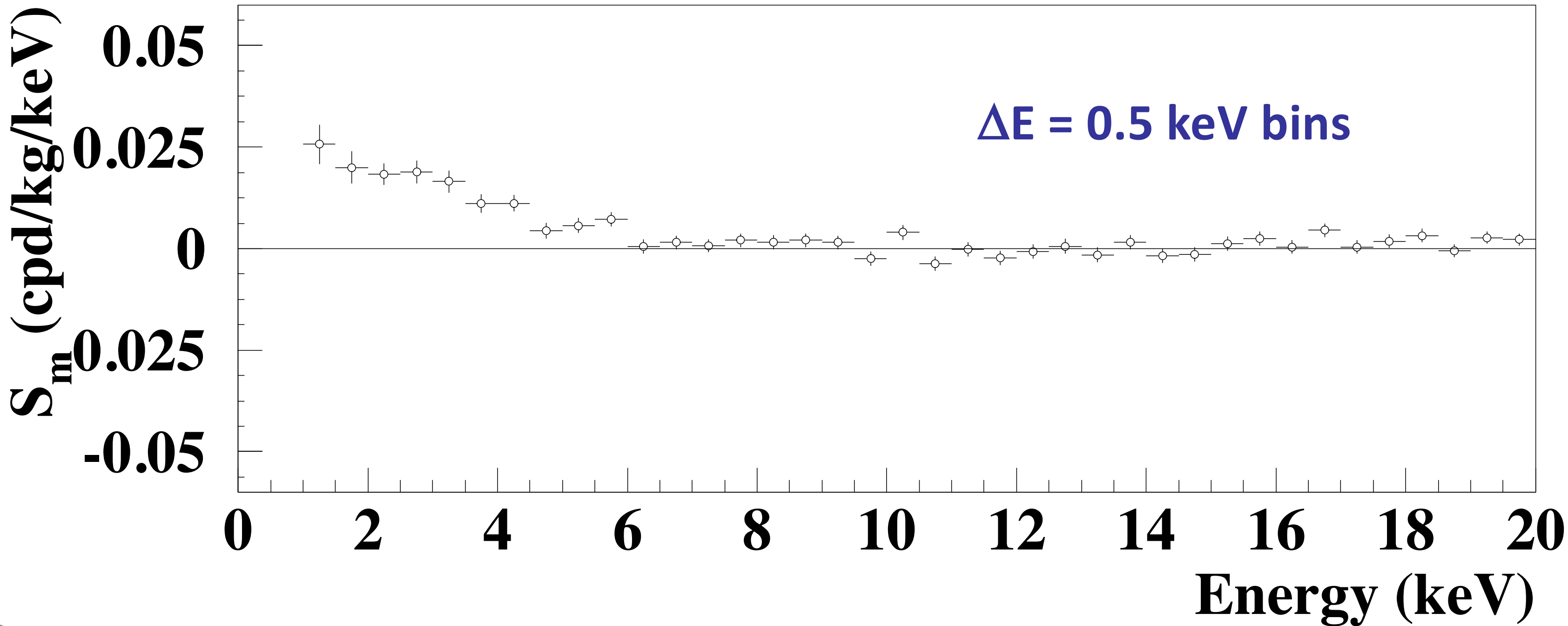
Energy distribution of the modulation amplitudes

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

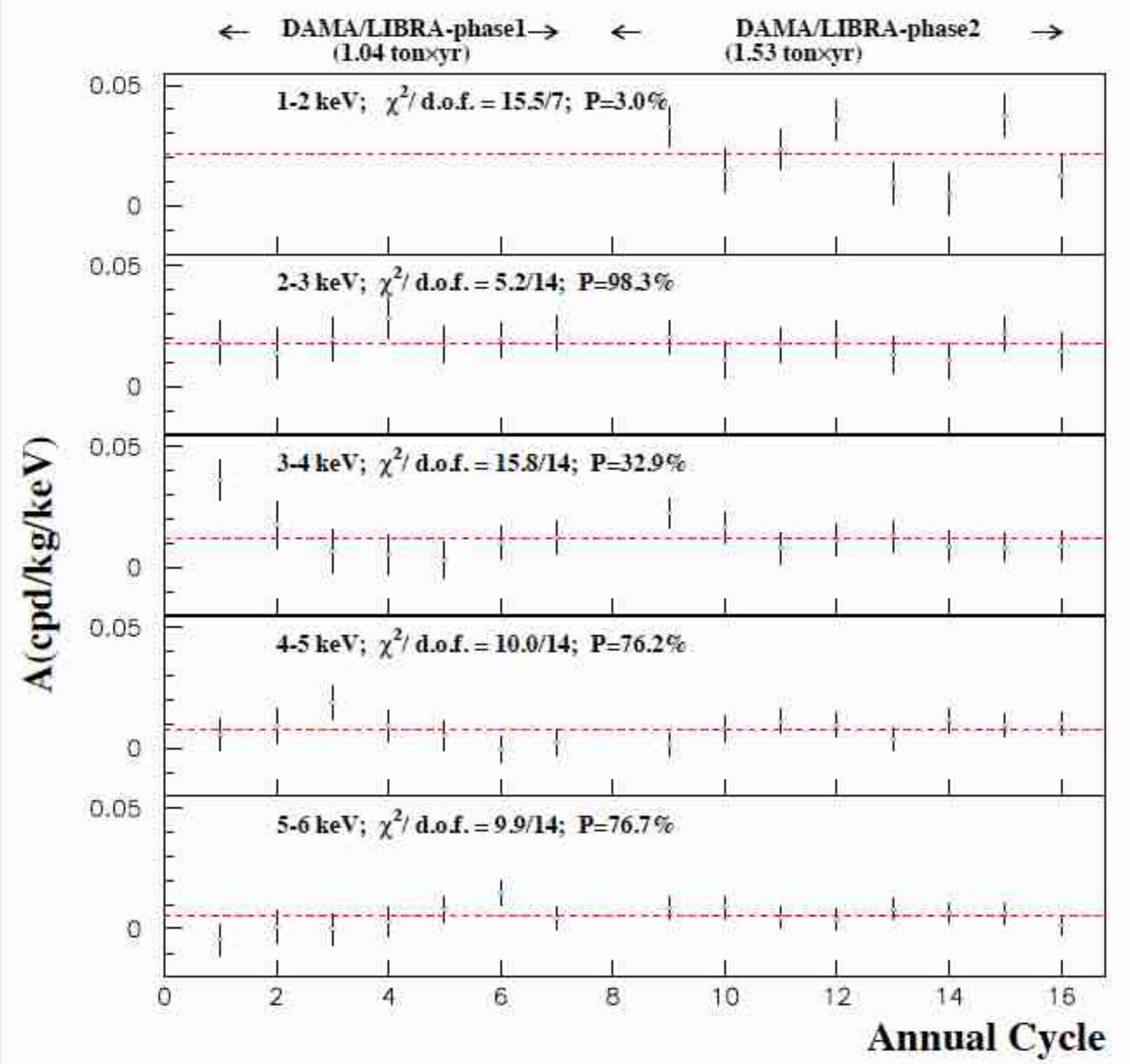
DAMA/NaI + DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2 (2.86 ton×yr)



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%.

S_m for each annual cycle



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

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

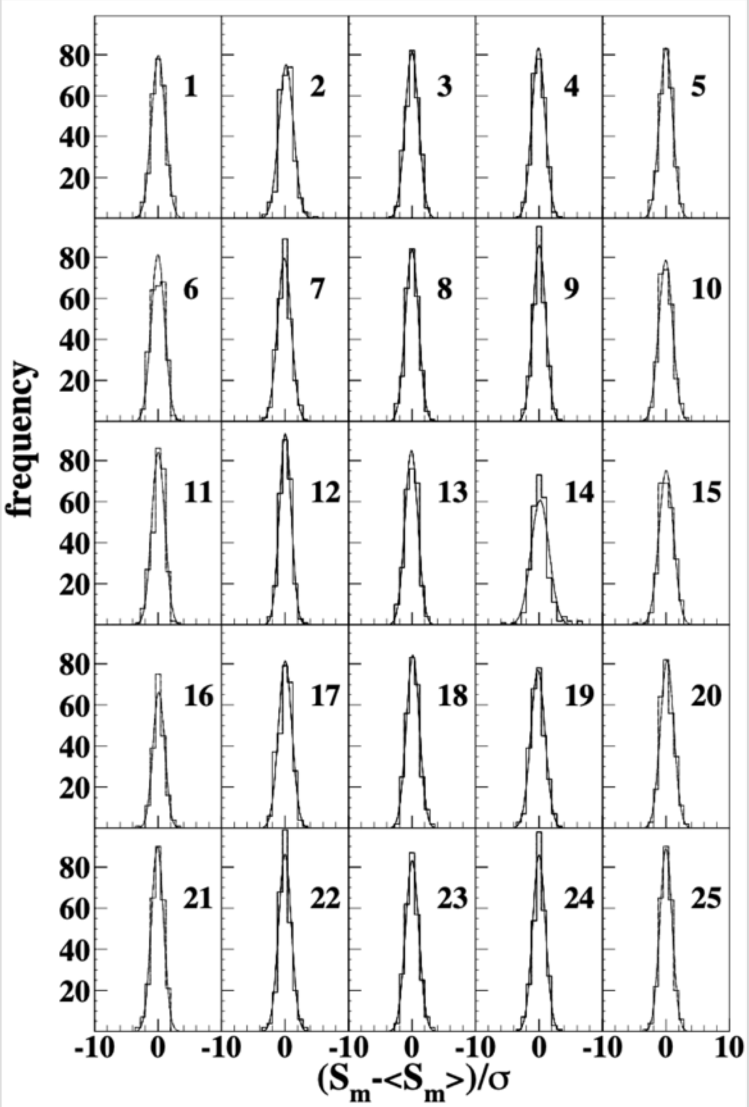
The signal is well distributed over all the annual cycles in each energy bin

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

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

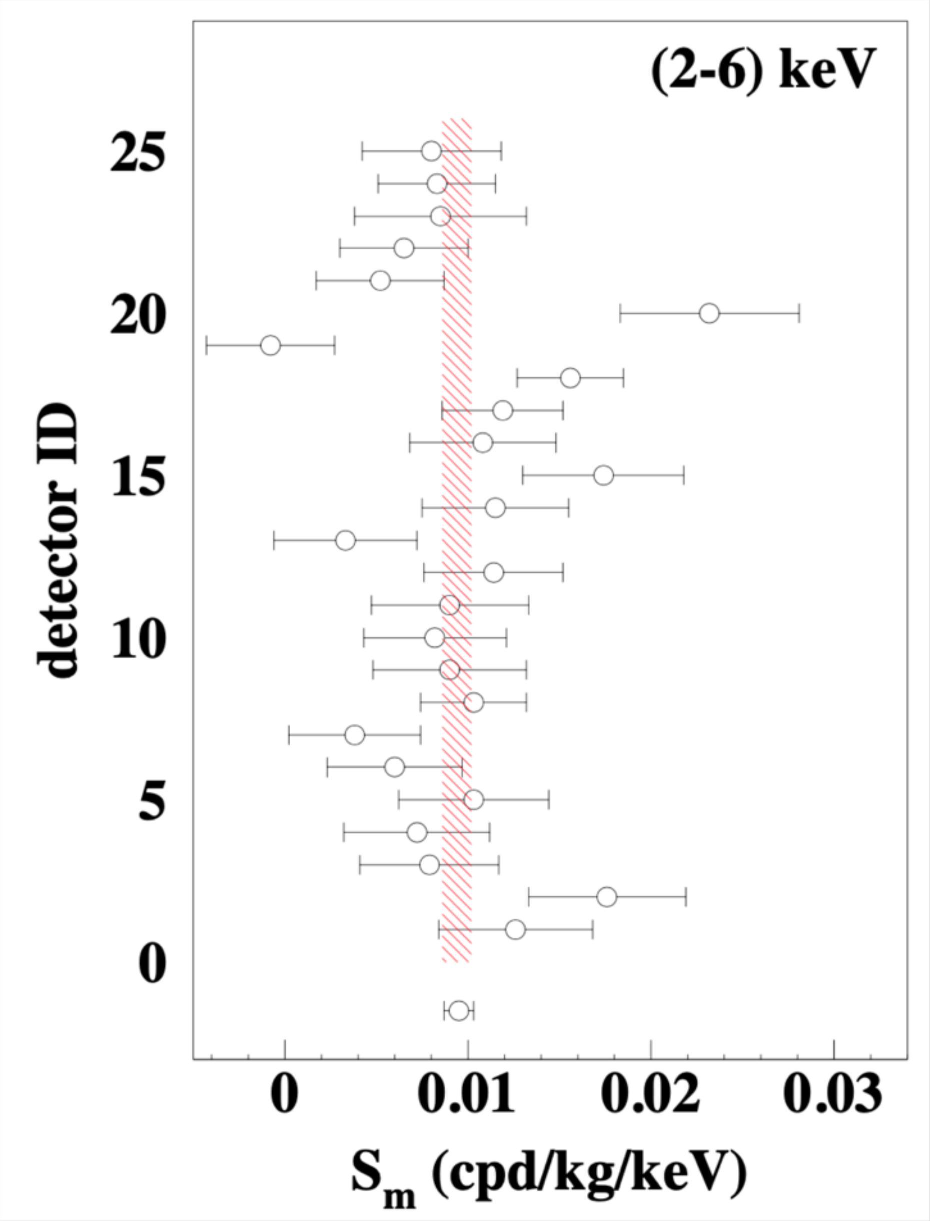
Individual S_m values follow a normal distribution since ***x*** is distributed as a Gaussian with a unitary standard deviation

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

The χ^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 systematics.
- In this case, one would have an additional error of ≤ 2.4 $\times 10^{-4}$ cpd/kg/keV, if quadratically combined, or ≤ 3.6 $\times 10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude below 6 keV.
- This possible additional error (≤2.4% or ≤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



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

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

Shaded band = weighted averaged S_m ± 1σ

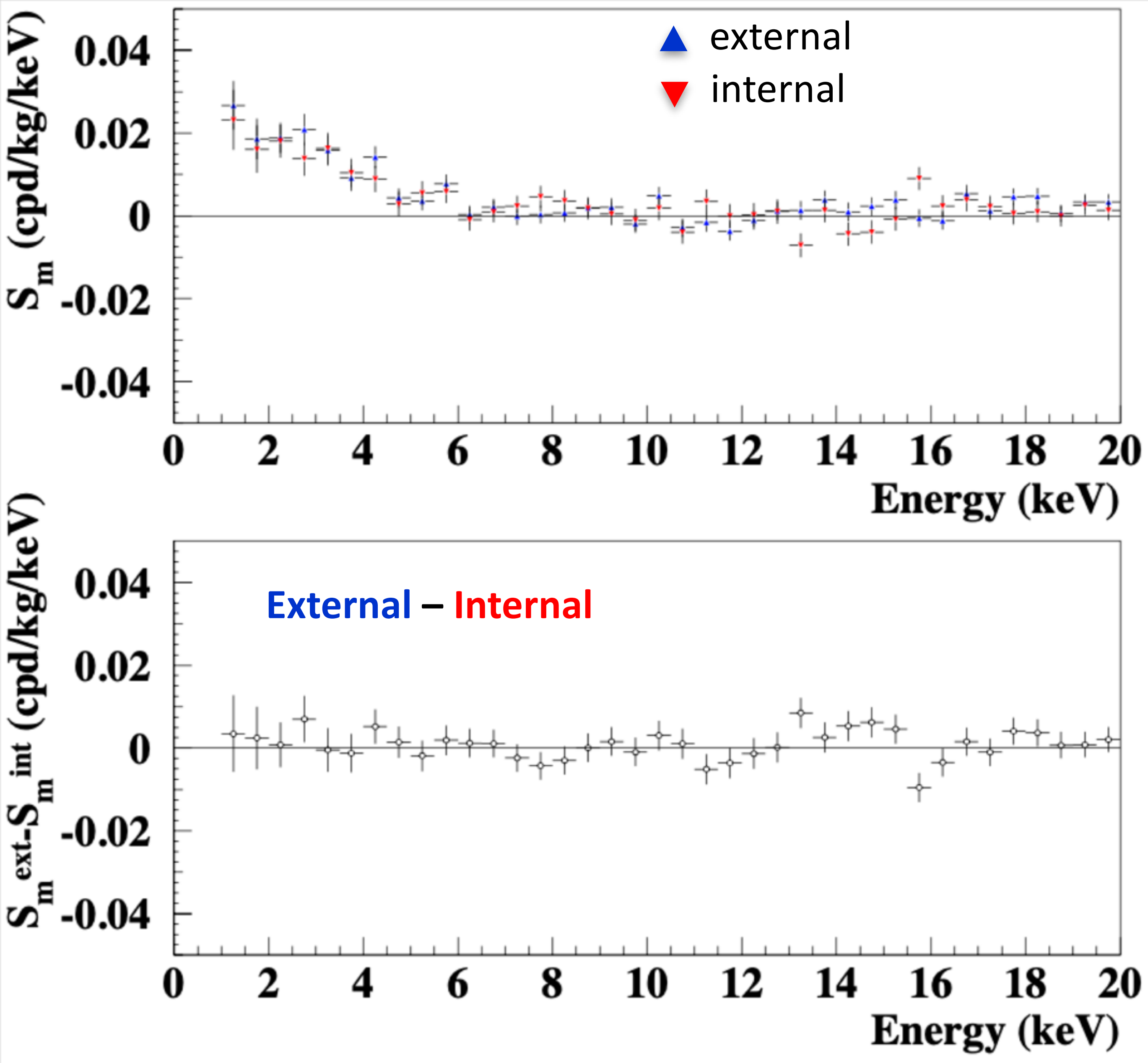
- χ^2/dof = 38.2/24 d.o.f. (P=3.3%)
- removing C19 and C20:
  χ^2/dof = 22.1/22 d.o.f.

The signal is rather well distributed over all the 25 detectors.

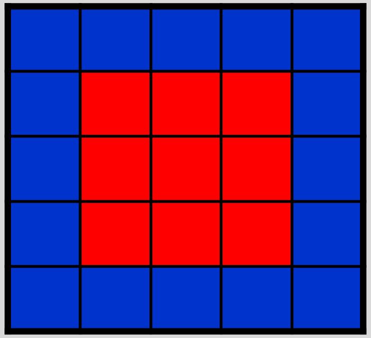
External vs internal detectors:

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

ΔE=0.5 keV



total exposure: **2.57 ton×yr**



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

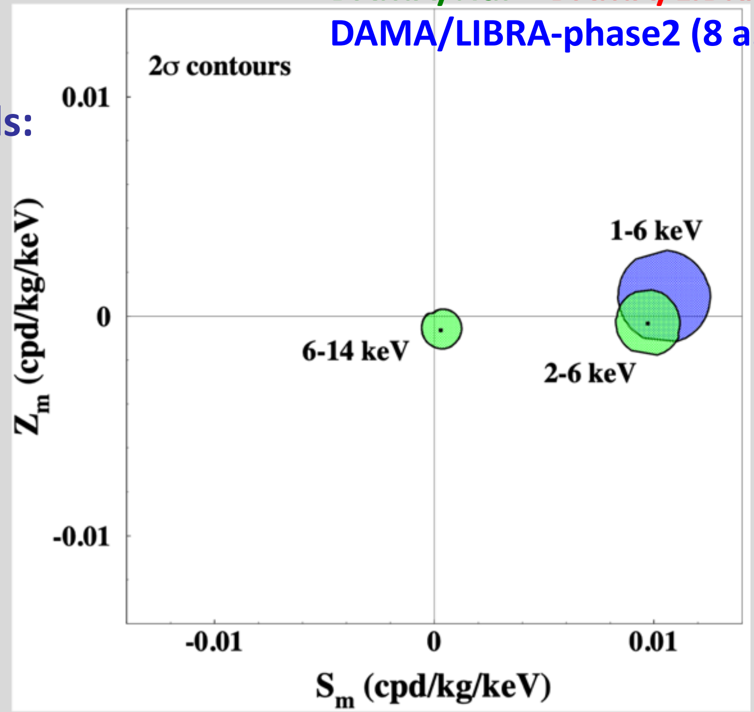
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

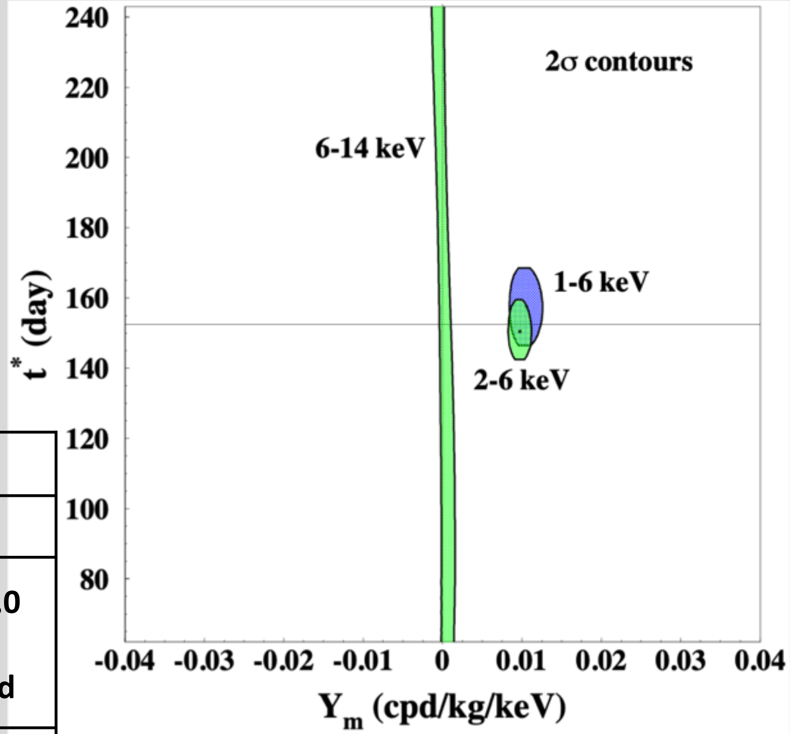
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]

For Dark Matter signals:

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



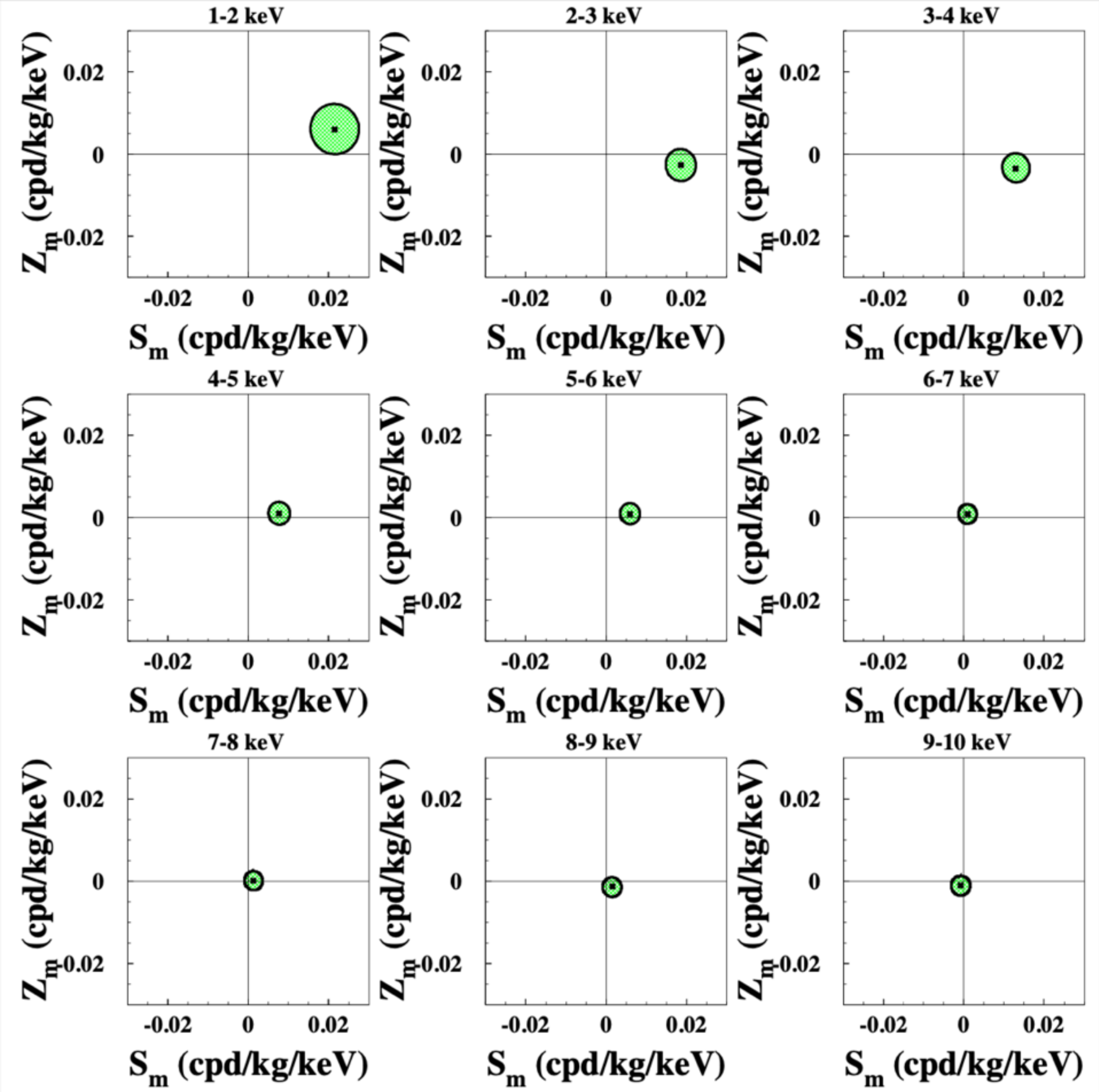
Slight differences from 2[nd] June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)



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

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

2σ contours



DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.)

total exposure: 2.86 ton × yr

For Dark Matter induced signals:

$|Z_m| \ll |Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

$\omega = 2\pi/T$

$T = 1$ year

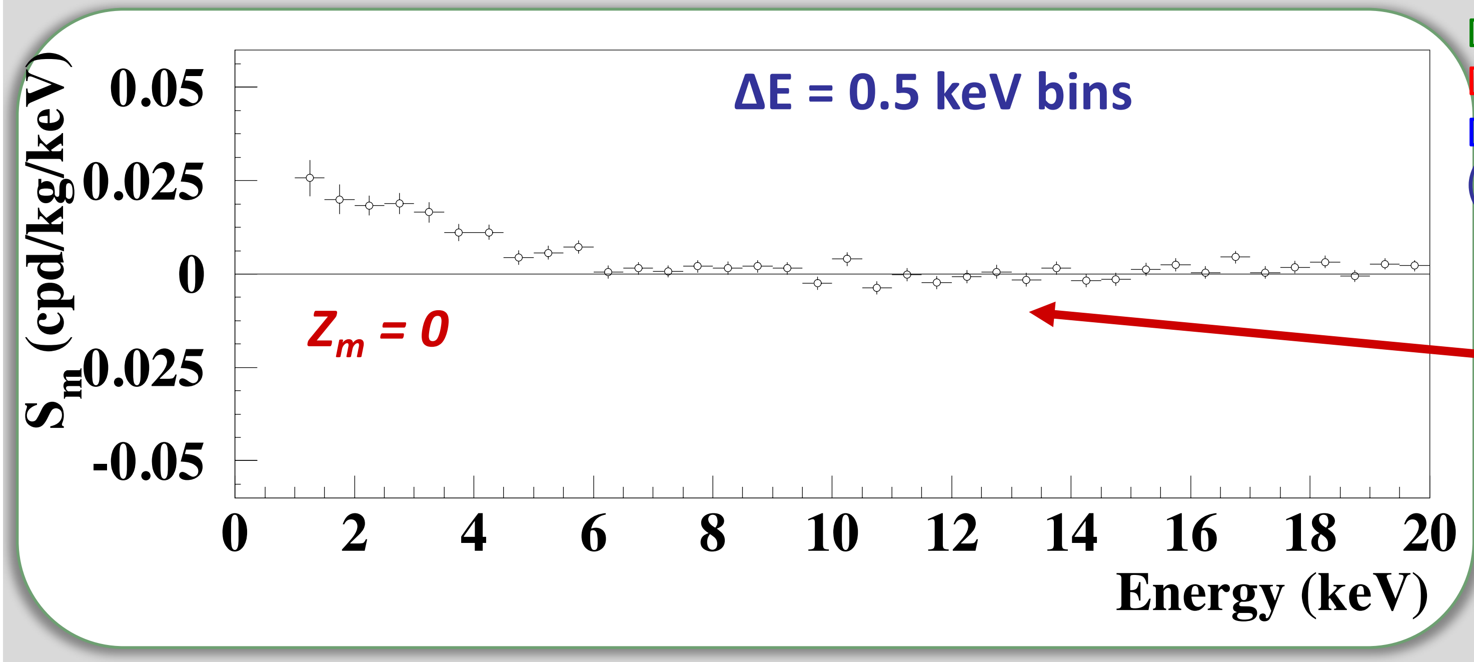
Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as the SagDEG stream)

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

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

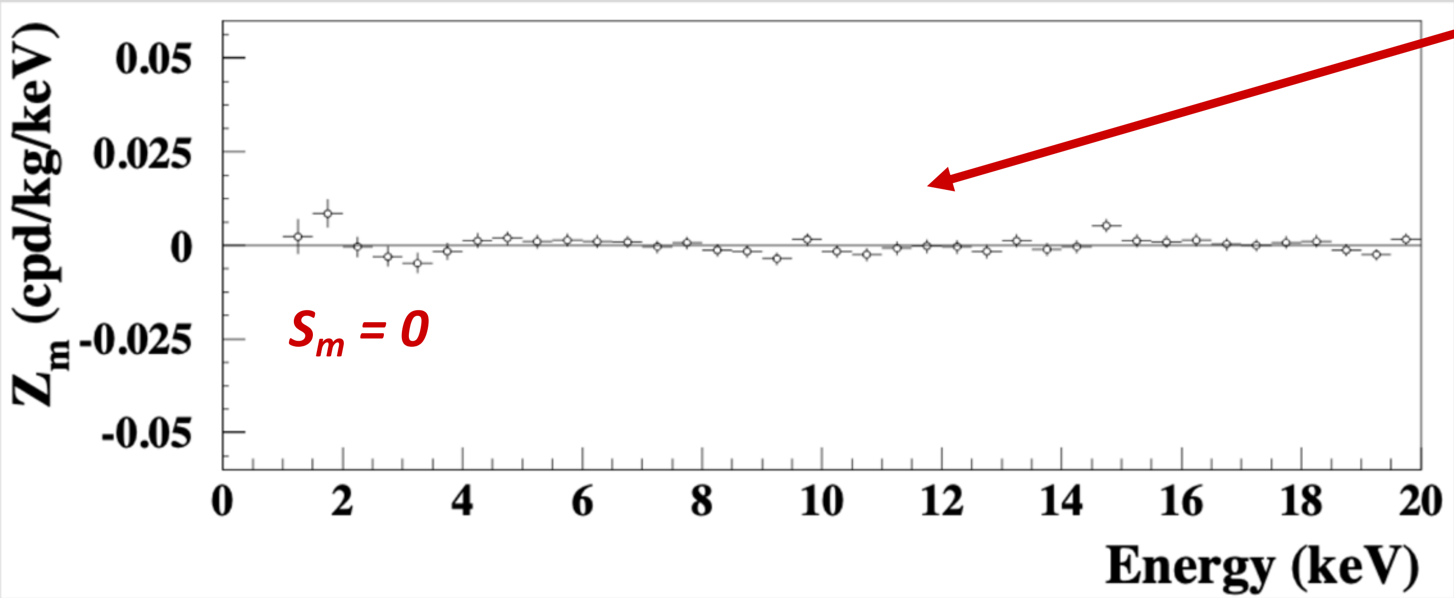
t_0 = *152.5 day* (2nd June)

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

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

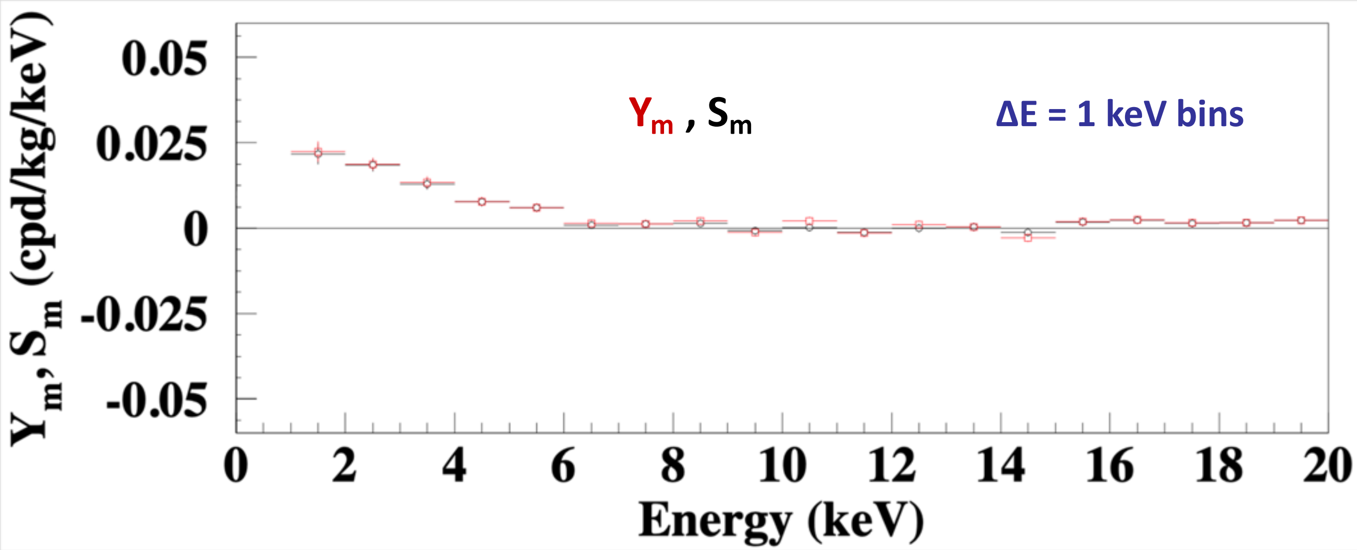
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.)
(**2.86 ton × yr**)

For DM signals:

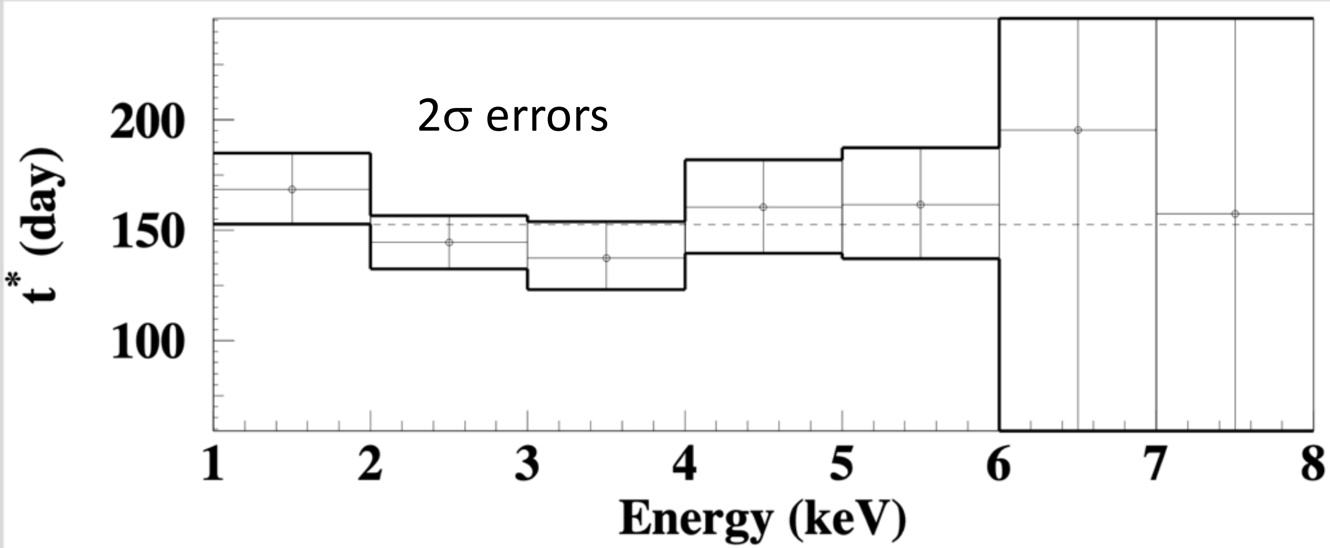
$|Y_m| \approx |S_m|$

$t^* \approx t_0$ = 152.5d

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



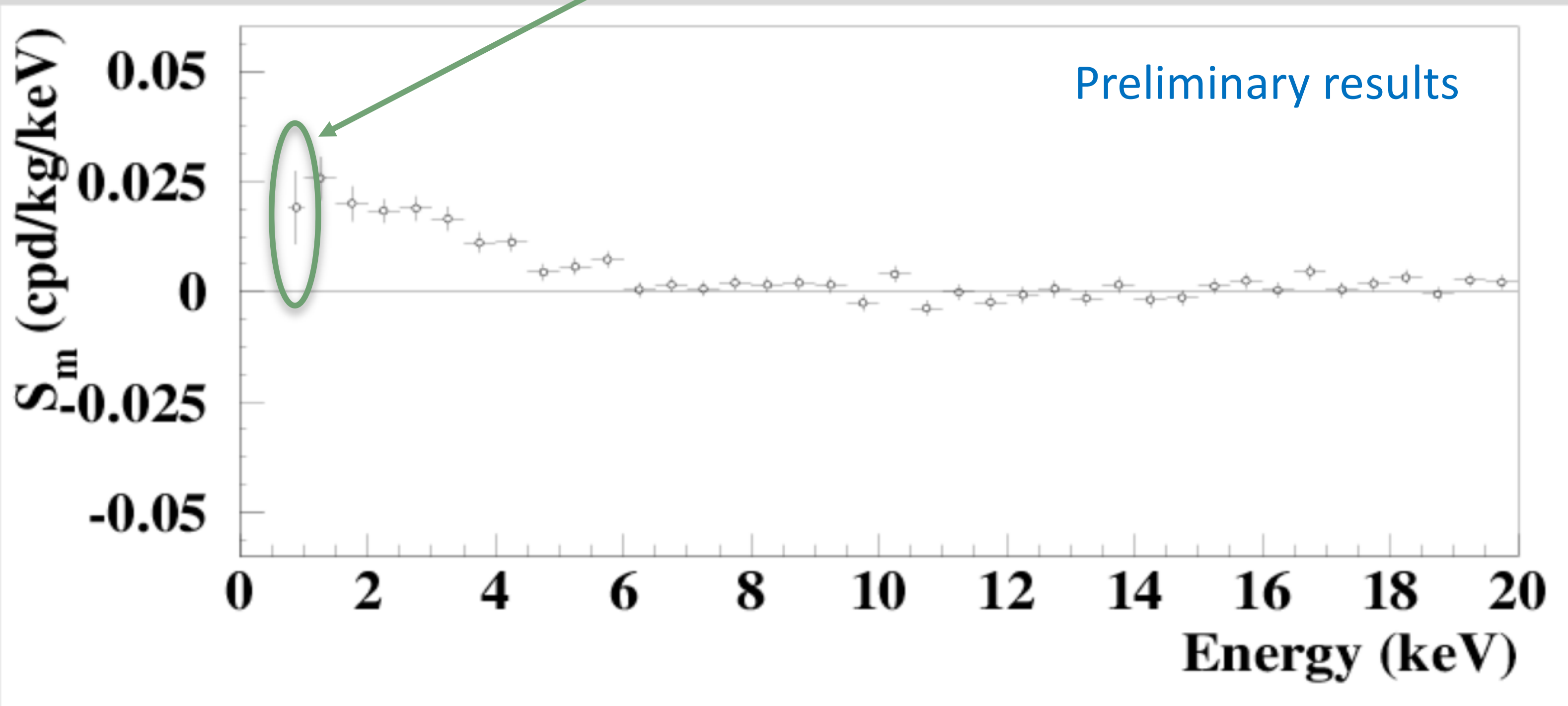
Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as the SagDEG stream)



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 near software energy threshold
- 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

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)	$-(0.12 \pm 0.16) \times 10^{-2}$	$(0.00 \pm 0.12) \times 10^{-2}$	$-(0.14 \pm 0.22) \times 10^{-2}$	$-(0.05 \pm 0.22) \times 10^{-2}$	$-(0.06 \pm 0.16) \times 10^{-2}$	$-(0.08 \pm 0.17) \times 10^{-2}$	$(0.04 \pm 0.20) \times 10^{-2}$	$-(0.19 \pm 0.18) \times 10^{-2}$

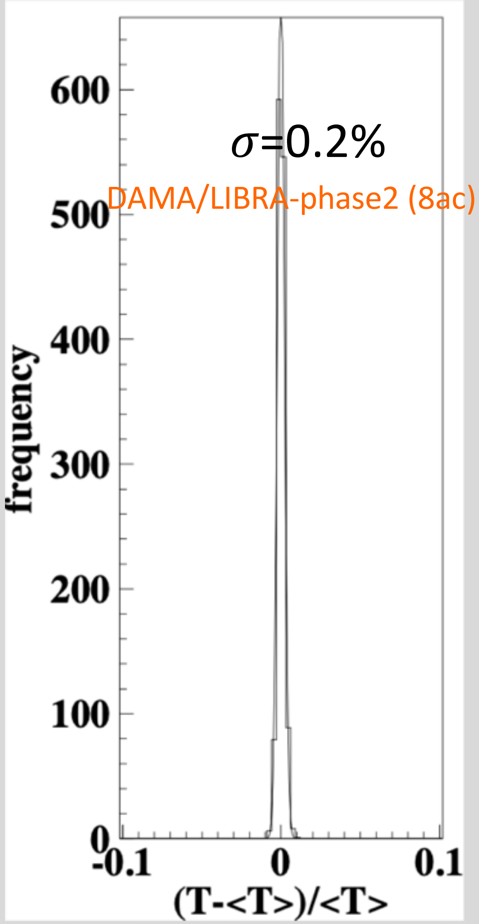
All the measured amplitudes well compatible with zero

+ 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)

Temperature

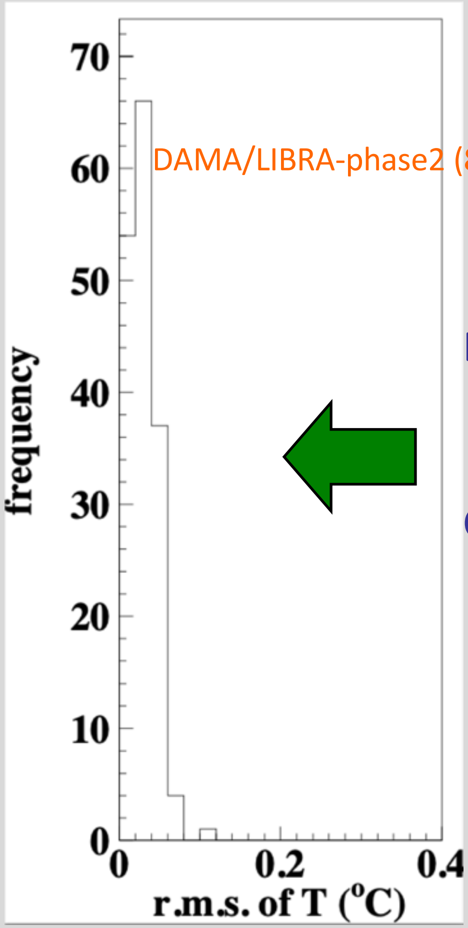
- Detectors in Cu housings directly in contact with multi-ton shield →huge heat capacity (≈10^6 cal/^{0}C)
- Experimental installation continuously air conditioned (2 independent systems for redundancy)
- Operating T of the detectors continuously controlled



Distribution of the relative variations of the operating T of the detectors

Amplitudes for annual modulation in the operating T of the detectors well compatible with zero

	T (^{0}C)
DAMA/LIBRA-ph2_2	(0.0012 ± 0.0051)
DAMA/LIBRA-ph2_3	$-(0.0002 \pm 0.0049)$
DAMA/LIBRA-ph2_4	$-(0.0003 \pm 0.0031)$
DAMA/LIBRA-ph2_5	(0.0009 ± 0.0050)
DAMA/LIBRA-ph2_6	(0.0018 ± 0.0036)
DAMA/LIBRA-ph2_7	$-(0.0006 \pm 0.0035)$
DAMA/LIBRA-ph2_8	$-(0.0029 \pm 0.0039)$
DAMA/LIBRA-ph2_9	(0.0014 ± 0.0033)



Distribution of the rms of the operating T within periods with the same calibration factors (typically ≈7days):

mean value ≈ 0.03 ^{0}C

Considering the slope of the light output ≈ -0.2%/^{0}C: relative light output variation < 10^{-4} :

<10^{-4} cpd/kg/keV (< 0.5% $S_m^{observed}$)

An effect from temperature can be excluded

+ Any possible modulation due to temperature would always fail some of the peculiarities of the signature

Can a possible thermal neutron modulation account for the observed effect?

NO

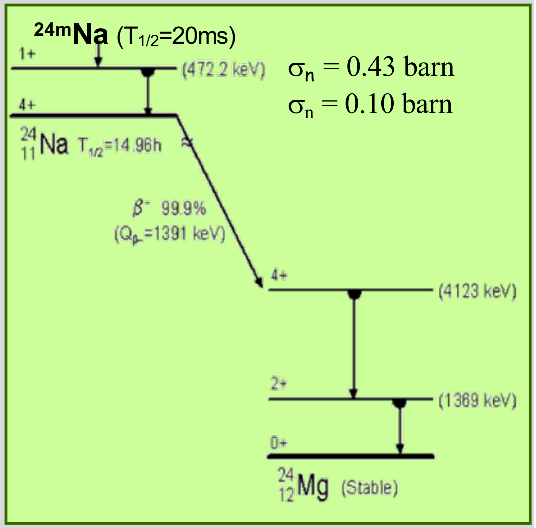
- **Thermal neutrons flux measured at LNGS :**

$\Phi_n = 1.08\ 10^{-6}$ n cm^{-2} s^{-1} (N.Cim.A101(1989)959)

- Experimental upper limit on the thermal neutrons flux "*surviving*" the neutron shield in DAMA/LIBRA:
  - studying triple coincidences able to give evidence for the possible presence of ^{24}Na from neutron activation:

$$\Phi_n < 1.2 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \text{ (90\%C.L.)}$$

- Two consistent upper limits on thermal neutron flux have been obtained with DAMA/NaI considering the same capture reactions and using different approaches.



Evaluation of the expected effect:

- Capture rate = $\Phi_n\ \sigma_n\ N_T < 0.022$ captures/day/kg

HYPOTHESIS: assuming very cautiously a 10% thermal neutron modulation:

$\Rightarrow S_m^{(\text{thermal n})} < 0.8 \times 10^{-6}$ cpd/kg/keV ($< 0.01\%\ S_m^{\text{observed}}$)

In all the cases of neutron captures (^{24}Na, ^{128}I, ...) a possible thermal n modulation induces a variation in all the energy spectrum

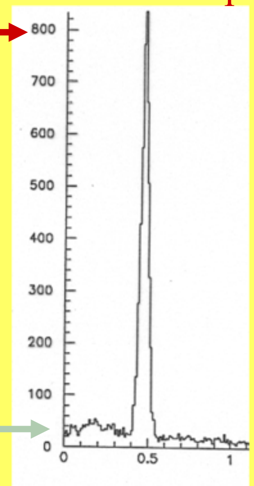
Already excluded also by R_{90} analysis

MC simulation of the process

When $\Phi_n = 10^{-6}$ n cm^{-2} s^{-1}:

$7 \cdot 10^{-5}$ cpd/kg/keV

$1.4 \cdot 10^{-3}$ cpd/kg/keV



E (MeV)

•Contributions to the total neutron flux at LNGS;

•Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by:

- neutrons,
- muons,
- solar neutrinos.

$$\Phi_k = \Phi_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$$

$$R_k = R_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$$

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]	–	$< 8 \times 10^{-6}$	[2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3 \times 10^{-3}$	[2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock ($>$ 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to$ n from Pb shield ($>$ 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi^{(\mu)}_0 \simeq 20$ μ $m^{-2}d^{-1}$ [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}$ ν $cm^{-2}s^{-1}$ [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.

Few comments on analysis procedure in DAMA/LIBRA

- Data taking of each annual cycle starts before the expected **minimum** (Dec) of the DM signal and ends after its expected **maximum** (June)

arXiv:2209.00882

- Thus, assuming a **constant background** within each annual cycle:
  - ✓ any possible decay of **long–term–living isotopes** cannot mimic a DM positive signal with all its peculiarities
  - ✓ it may only lead to **underestimate** the observed S_m, depending on the radio-purity of the set-up

Claims (JHEP2020,137, arXiv:2208.05158) that the DAMA annual modulation signal may be biased by a slow variation only in the low-energy *single-hit* rate, possibly due to *some background* with odd behaviour increasing with time

already **confuted** quantitatively (see e.g. Prog. Part. Nucl. Phys. 114, 103810, 2020 and here)

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

  → This is expected by the elementary consideration that their rate is very–decreasing with time.

- COSINE-100: **different** NaI(Tl) crystal manufacturing wrt DAMA, different starting powders, different purification, different growing procedures and protocols; different electronics and experimental set-up, our 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
thanks to the radiopurity and long-time underground of the ULB DAMA/LIBRA NaI(Tl)

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)
arXiv:2209.00882

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, NPAE 22(2021)329, arXiv:2209.00882, ...

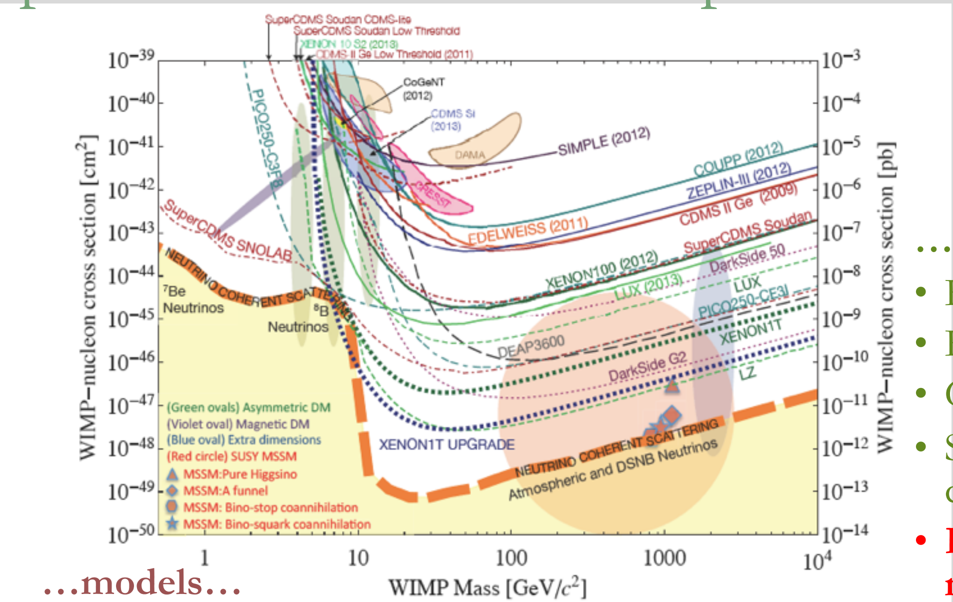
Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5\times10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously 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**

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

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



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

…models…

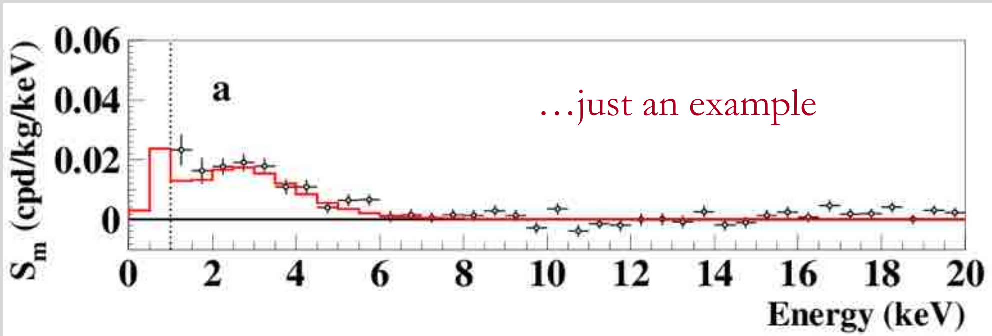
- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

…and experimental aspects…

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

No direct model-independent comparison is possible

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



…just an example

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

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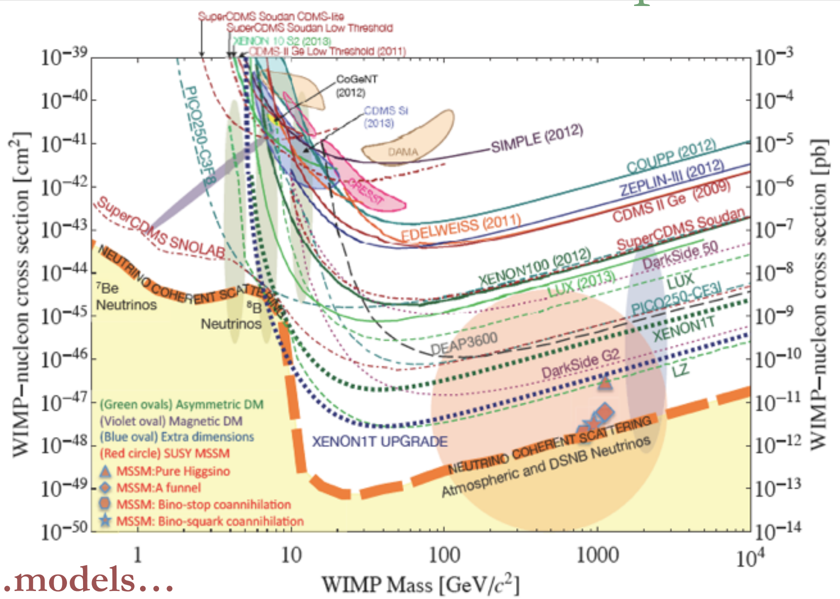

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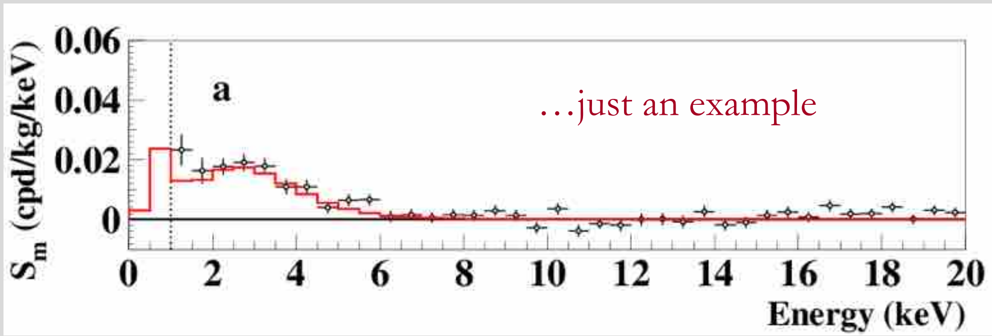
- Subtraction/rejection procedures and stability in time of all the selected windows
- **Quenching factors, channeling**
- …

Example: 2 keV(ee) of DAMA ≠2 keV(ee) of COSINE-100 for nuclear recoils

No direct model-independent comparison is possible

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

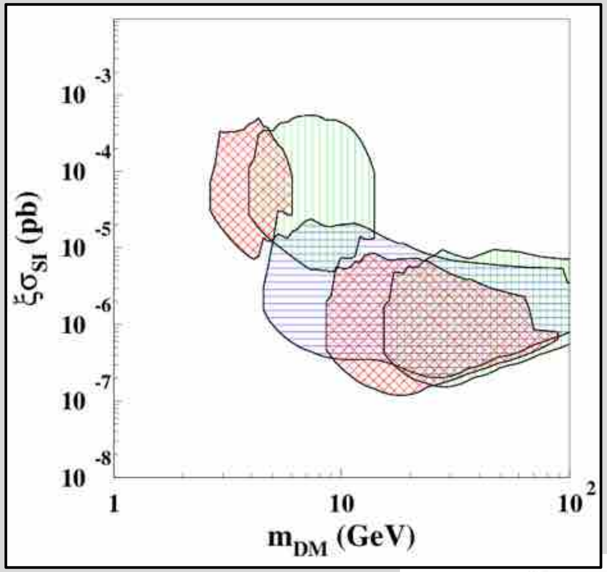


Few examples of model-dependent analyses

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

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

E_{th}=1 keV; old data release



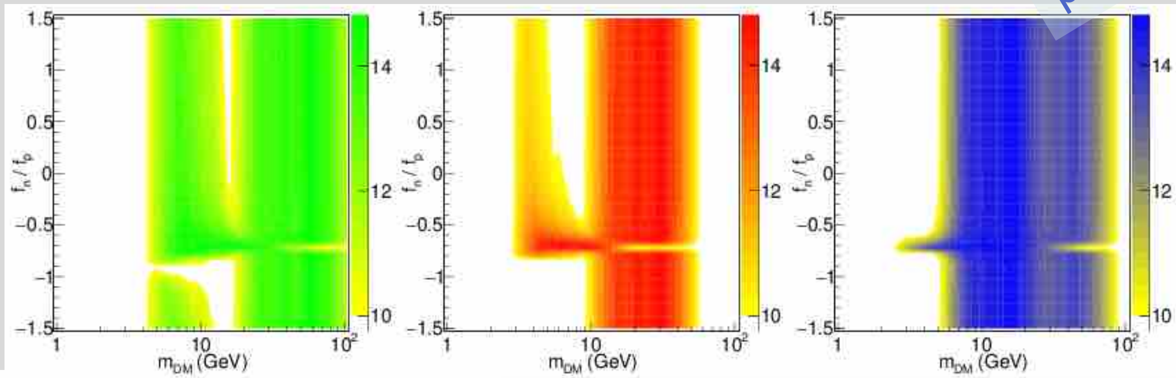
1. Constants q.f.
2. Varying q.f.(E_R)
3. With channeling effect

DM particles elastically scattering off target nuclei – SI interaction

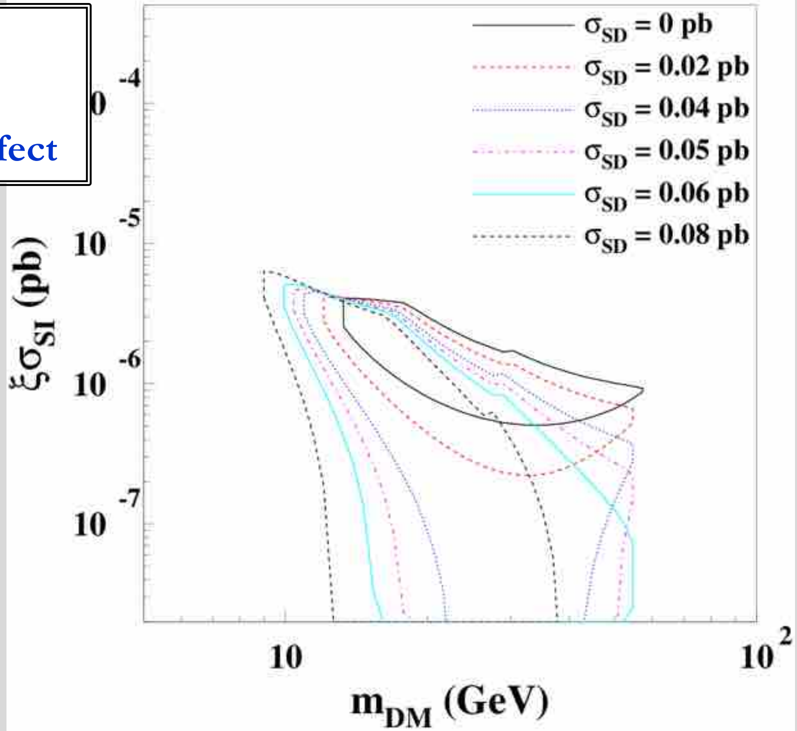
$$\sigma_{SI}(A,Z) \propto m_{red}^2(A,DM)\left[f_p Z + f_n(A-Z)\right]^2$$

Updating in progress

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.

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

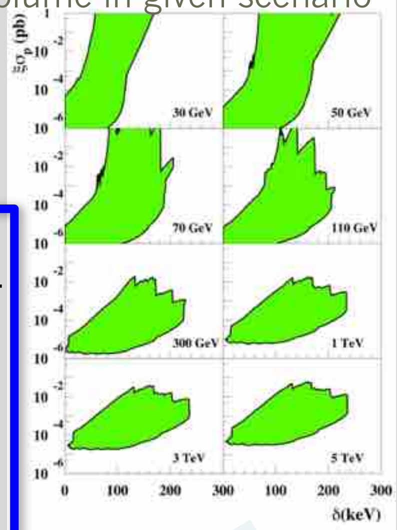
Other examples

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.

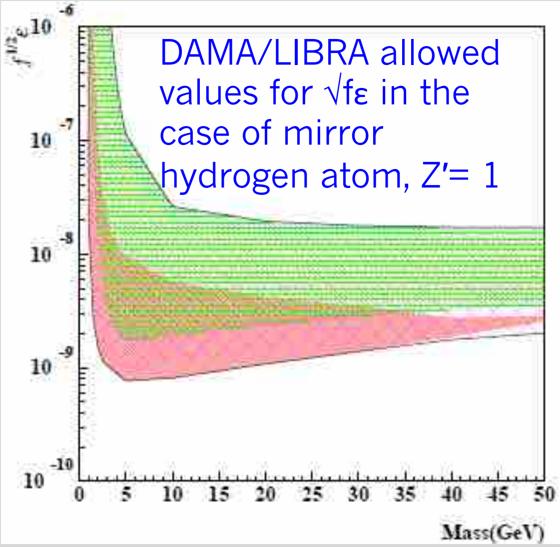
Mirror Dark Matter

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

Updating in progress

- 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.

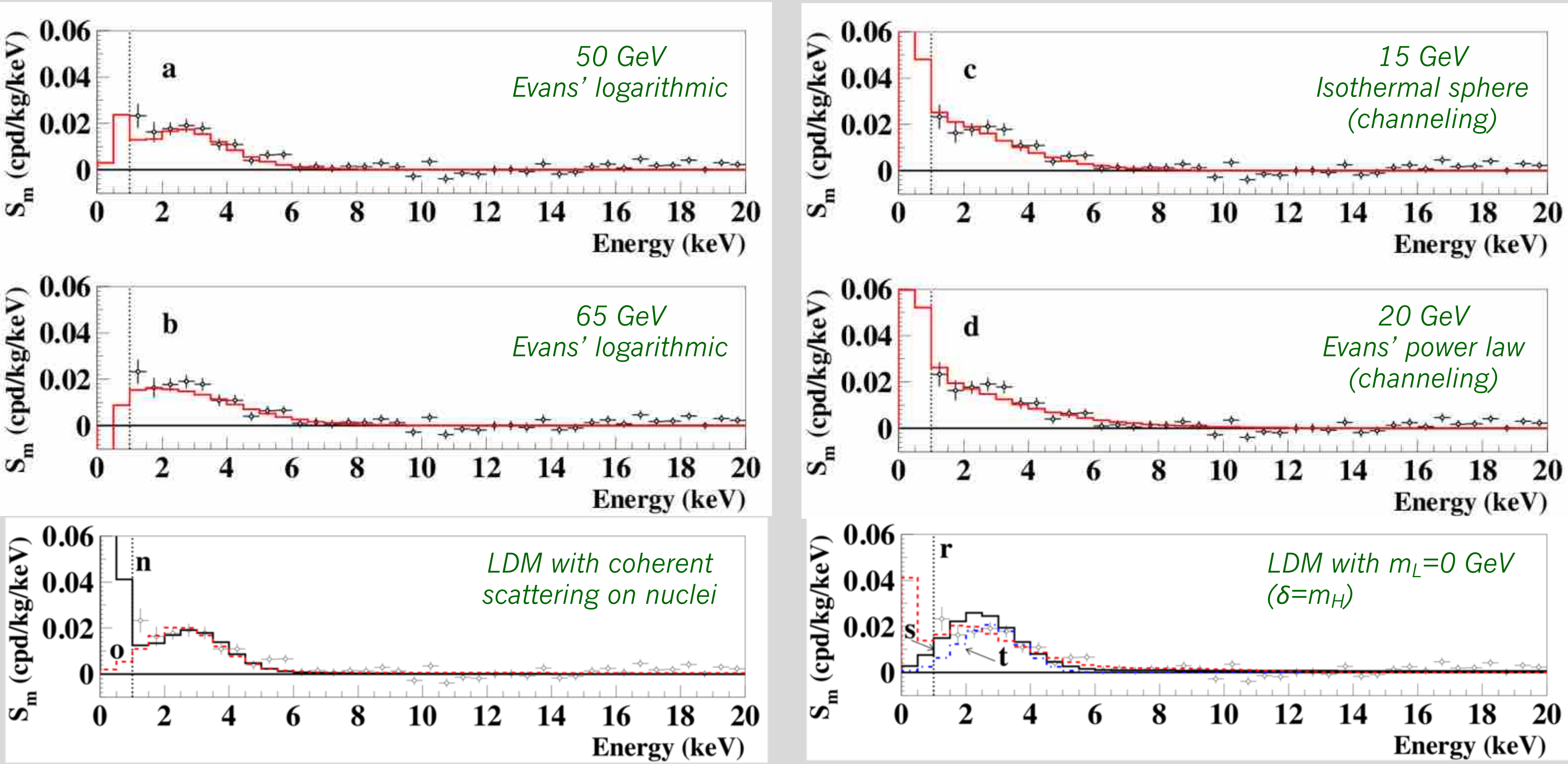
$\sqrt{f}\cdot\epsilon$ coupling const. and fraction of mirror atom



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 <u>examples</u> of interpretation of the annual modulation in terms of candidate particles in <u>some scenarios</u>
- E_{th}=1 keV; previous data release



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

In fact, as required by the DM annual modulation signature:

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

… and well compatible with several candidates (in many possible astrophysical, nuclear and particle physics scenarios)

… on recent «NaI(Tl)»:

Different all materials constituting detectors and set-ups

Not same powders purification methodologies

Different growing procedures with different features in the produced detectors

Tl concentration and uniformity

Different additives

Different protocols

Different set-ups' design, materials, procedures, ..

Different handling & assembling procedures

Different radiopurity (materials, purification procedures, protocols, handling, assembling, ...)

Different PMT, light guide or not, dedicated shield or not, …

Different calibration procedures and frequency

Different q.f.

Different event selection(s) procedures and qualities

Different analysis strategies

Well different exposure

Well different control/analysis of possible systematics

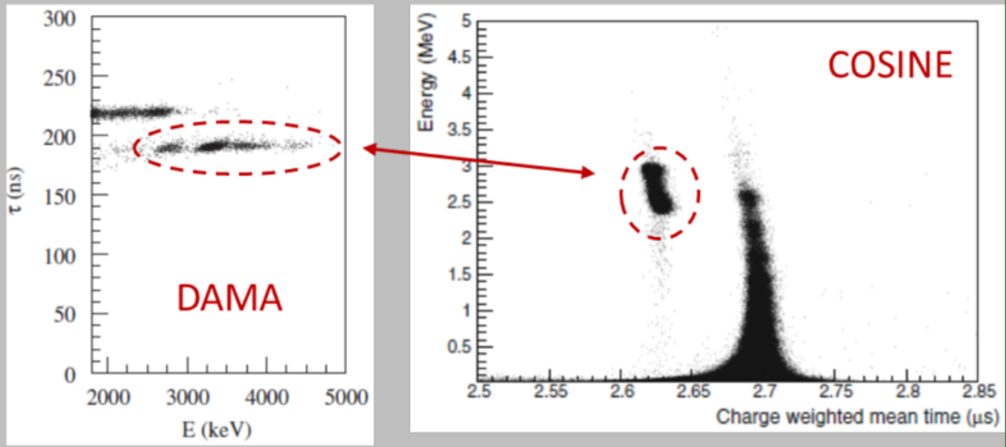
Well different years of set-up materials underground

Often different observable exploited with model-dependent approach

.….

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

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

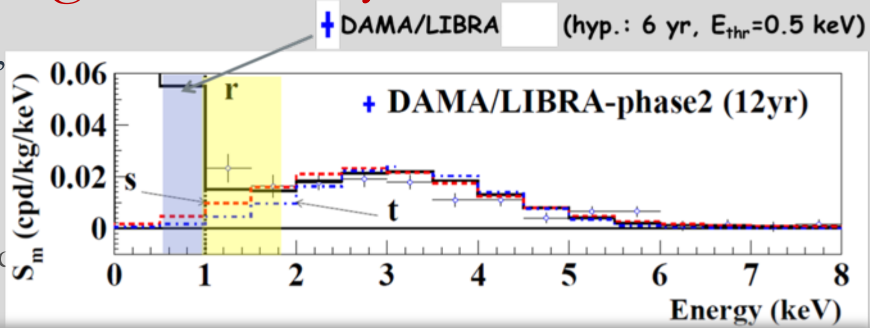
Enhancing experimental sensitivities and improving DM corollary aspects, other DM features, second order effects and other rare processes

1) During fall 2021, DAMA/LIBRA–phase2 set-up was heavily upgraded

2) The upgrade basically consisted on:

- new low-background voltage dividers with pre-amps on the same board
- Transient Digitizers with higher vertical resolution (14 bits)

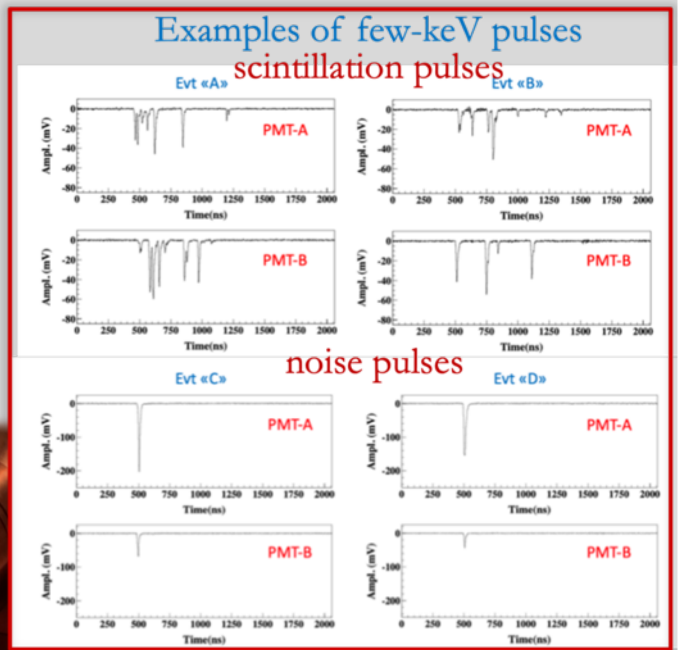
3) The data taking in this new configuration started on Dec, 1 2021

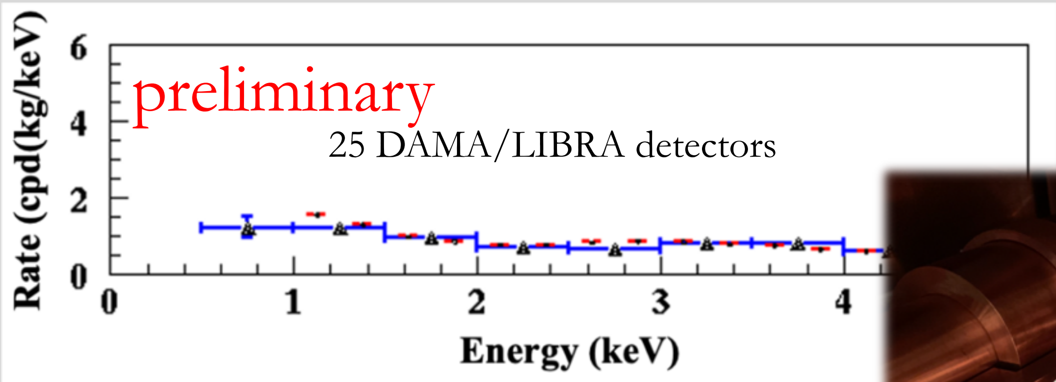


The features of the voltage divider+preamp system:

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

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





corrected for the efficiencies

new empowered configuration (blue, 2350 kg×d)

DAMA/LIBRA–phase2 (red, 1.53 ton×yr)

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3) The data taking

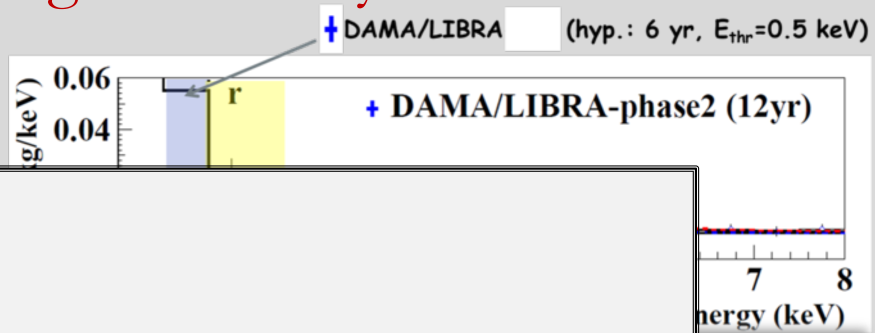
- Higher resolutio from the new v
- very stable oper
- The baseline flu previous config between 110 an
- Software Trigge
- The "noise" eve structures than

Shortly:

✓ the data acquisition system (daq) is composed by 5 TD's, CAEN VME VX1730 with the dynamic range of 14 bit (which corresponds to a vertical resolution of 0.122 mV/digit), vertical window of 2 V, sampling frequency of 500 MSa/s (2 ns time bin), and 250 MHz bandwidth.

✓ Each VME module has 16 channels; thus, the daq acquires three traces for each detector (from the two PMTs, A and B, and the high-energy sum of them, SUM-HE).

✓ The read-out of the digitizers is made by a daisy-chain on optical fiber directly connected to the daq computer



m:

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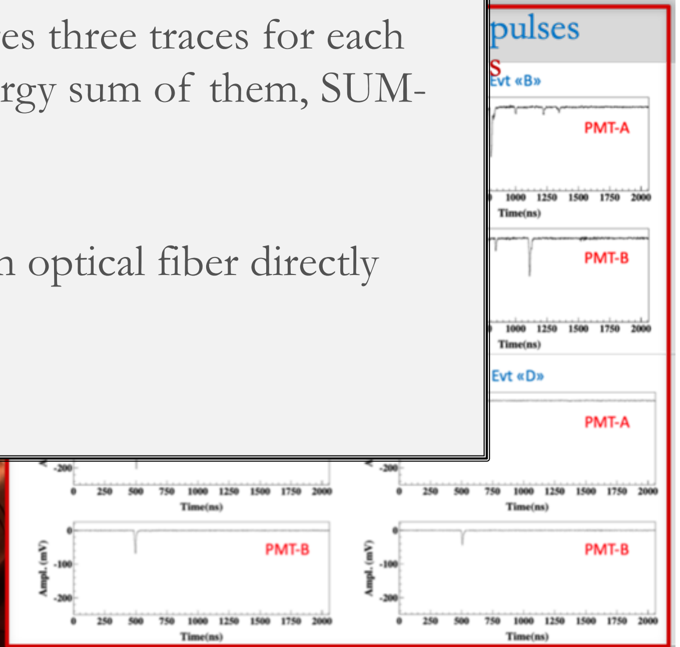
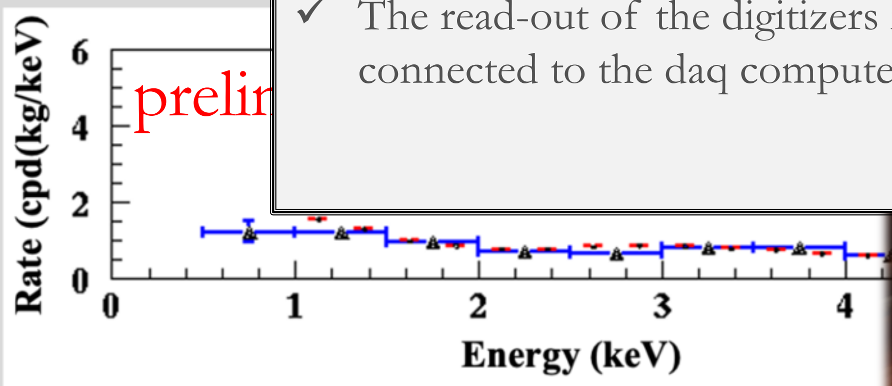
PMT





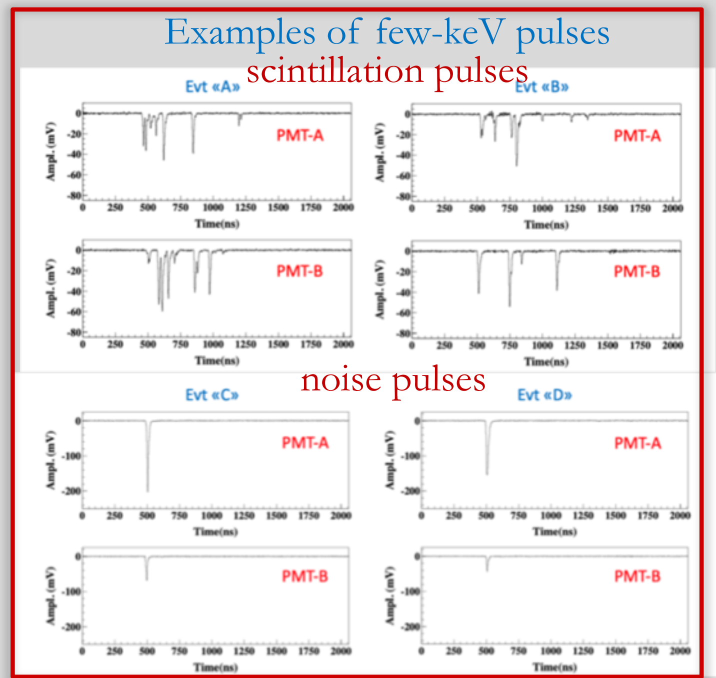
corrected for the efficiencies

new empowered configuration (blue, 2350 kg×d)

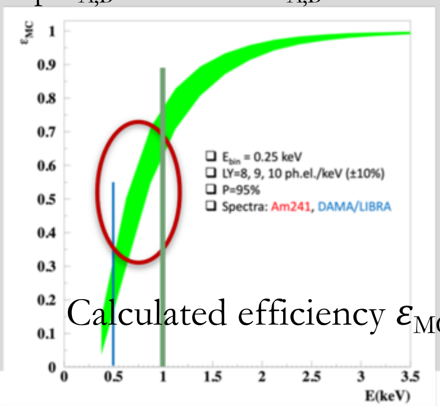
DAMA/LIBRA–phase2 (red, 1.53 ton×yr)

Software energy threshold @ 0.5 keV

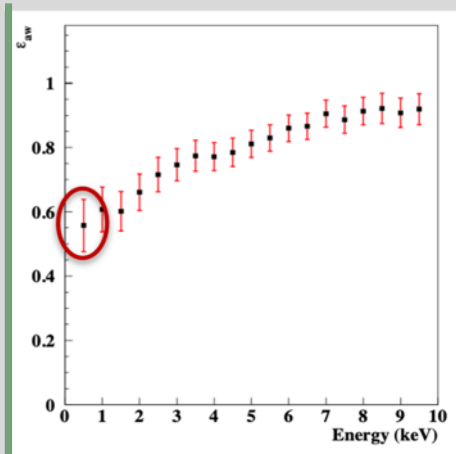
- Higher resolution (0.122 mV/digit) of the 14-bit TDs makes appreciable the improvements coming from the new voltage-dividers-plus-preamps on the same board in terms of baseline noise
- The distributions of the baselines show a very stable operational feature
- The baseline fluctuations are more than 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



$(\#p.e._A>1)$ .AND. $(\#p.e._B>1)$
$\#p.e._{A,B}>1 \rightarrow tm600_{A,B}> \sim 25$ ns

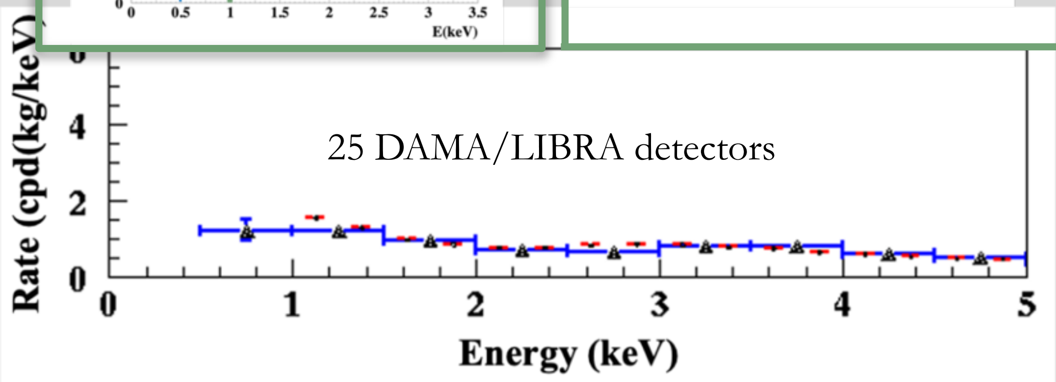


Calculated efficiency ε_{MC}



- 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.

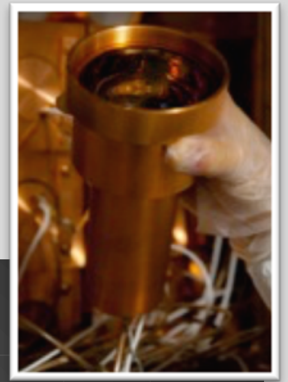
A suitable efficiency below 1 keV is possible in the new configuration



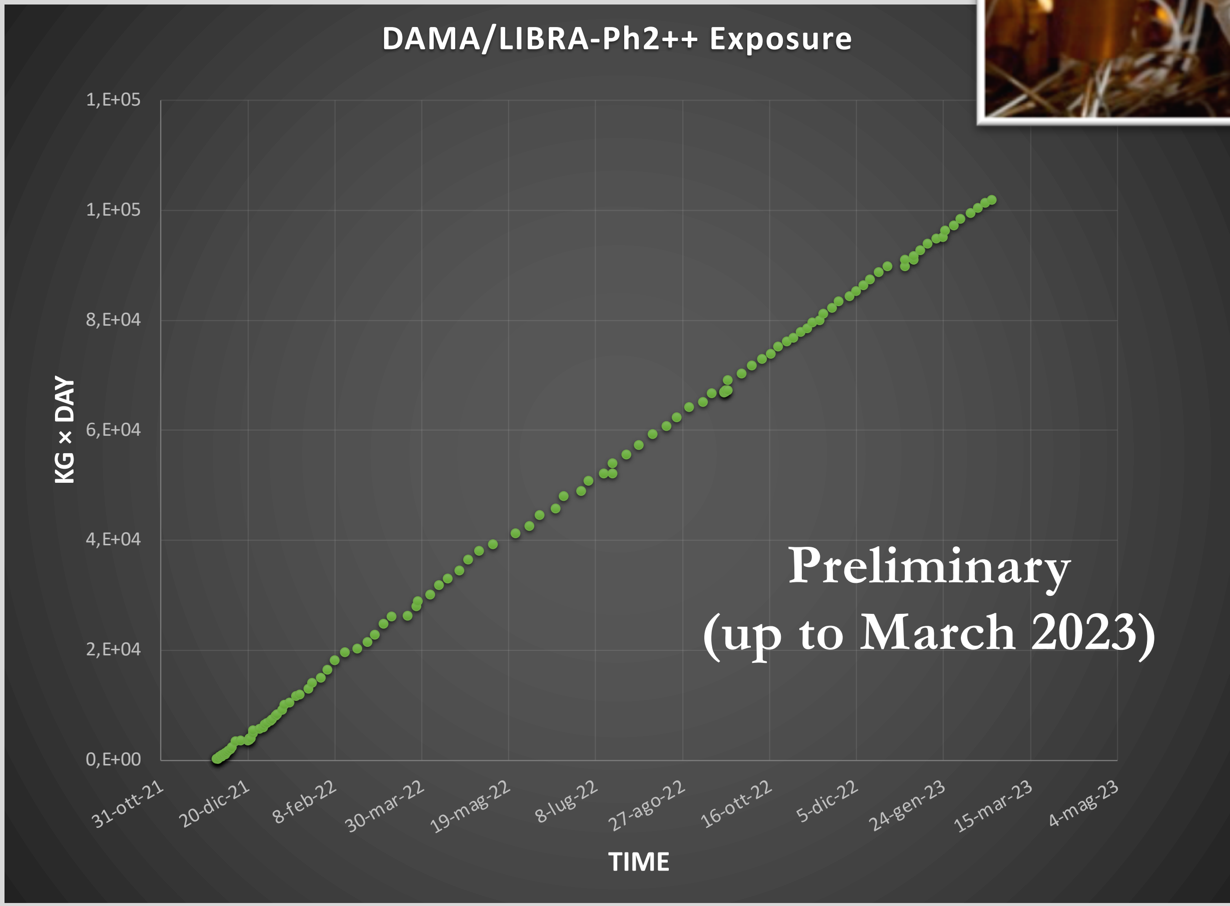
Energy spectrum of the *single-hit* scintillation events – already corrected for the efficiencies – in the new configuration (blue, exposure 2350 kg×d) and in DAMA/LIBRA–phase2 (red, the energy threshold was 1 keV, 1.53 ton×yr).

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: $\approx 3.5 \times 10^7$ events from sources
- ✓Acceptance window eff. per all crystals: $\approx 1.95 \times 10^7$ events ($\approx 7.8 \times 10^5$ events/keV)



Exposure of empowered DAMA/LIBRA-phase2 up to now: **0.28 ton × yr.**

$(\alpha - \beta^2) \approx 0.488$

Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2+empowered-phase2:

3.14 ton × yr

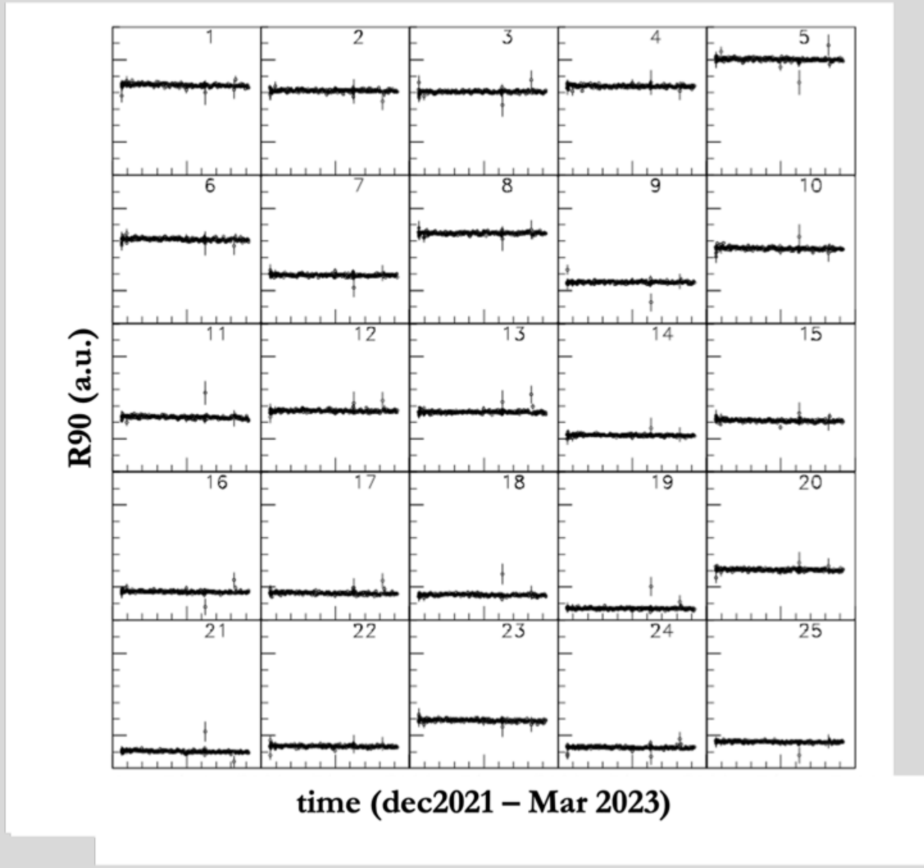
Stability of the energy scale and of the background

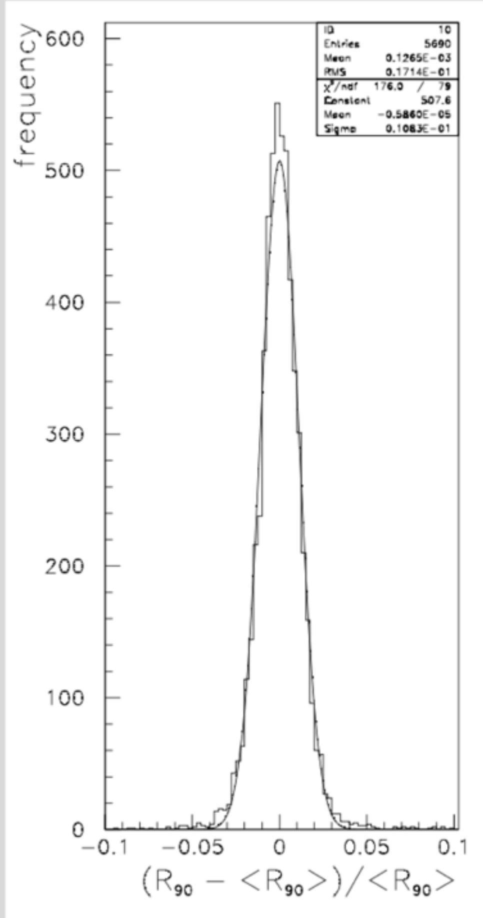
(DAMA/LIBRA_phase2 empowered)

- **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:

$$A_{mod\_R90} = (0.04 \pm 0.11) \text{ cpd/kg}$$

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

Features of the DM signal investigated by DAMA at various levels: higher sensitivities with DAMA/LIBRA-phase2 - empowered

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

High exposure and low energy threshold can allow investigation on:

- the nature of the DM candidates

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

- possible diurnal effects on the 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.

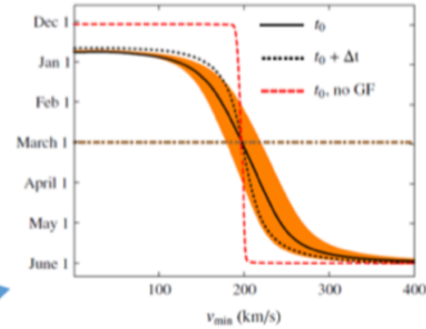
- astrophysical models

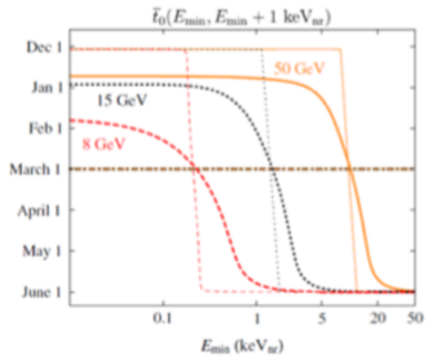
- ✓ velocity and position distribution of DM particles in the galactic halo, possibly due to:
  - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";
  - caustics in the halo;
  - gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");
  - possible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

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

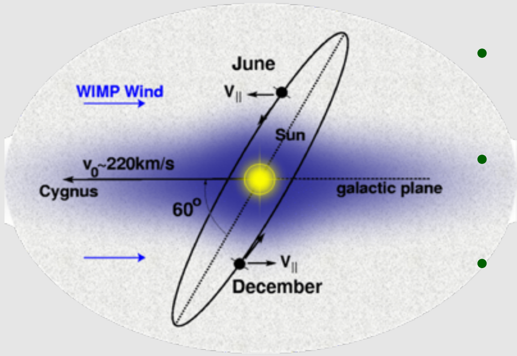
PRL112(2014)011301





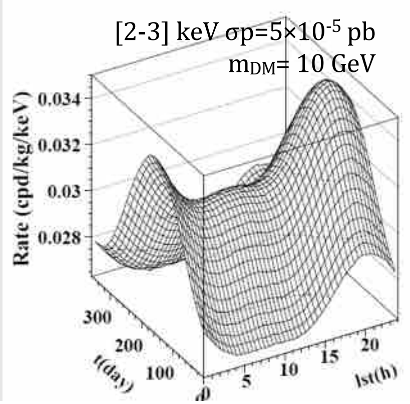
Towards D.M. investigation through directionality approach with $ZnWO_4$ anisotropic scintillators

Directionality: study of the correlation between the Earth motion in the galactic rest frame and the arrival direction of those Dark Matter candidates inducing just nuclear recoils



- Nuclear recoils strongly correlated with DM impinging direction (preferentially) opposite to the Sun velocity in the Galaxy
- light output and pulse shape depend on the direction of impinging particles with respect to crystal axes while no anisotropy for e/γ
- 2 independent ways to exploit directionality overcoming difficulties in trying to identify the very short track of nuclear recoils

Complementary information for some aspects



For a given model and expected rate as function of sidereal time and days of the year

+ **low bckg $ZnWO_4$ crystal scintillators with large volume and high scintillation properties is important also to investigate (with increasing sensitivity) ββ decay modes in Zn and W isotopes with source=detector approach**

Transition	Energy release ($Q_{\beta\beta}$) (keV)	Isotopic abundance (%)	Decay channels	Number of mother nuclei in 100 g of $ZnWO_4$ crystal
$^{64}Zn \to {}^{64}Ni$	1095.7(0.7)	49.17(75)	2ε, $\varepsilon\beta^+$	9.45×10^{22}
$^{70}Zn \to {}^{70}Ge$	998.5(2.2)	0.61(10)	$2\beta^-$	1.17×10^{21}
$^{180}W \to {}^{180}Hf$	144(4)	0.12(1)	2ε	2.31×10^{20}
$^{186}W \to {}^{186}Os$	489.9(1.4)	28.43(19)	$2\beta^-$	5.47×10^{22}

Developments and measurements of $ZnWO_4$ with INR-Kiev:

PLB658(2008)193, NPA826(2009)256, NIMA626-627(2011)31, J. Phys. G: Nucl. Part. Phys. 38(2011)115107 , EPJC73(2013)2276, Phys.Scr.90(2015)085301 , NIMA833(2016)77, NIMA935(2019)89, EPJA56(2020)83, JINST15(2020)C05055, NIMA1029(2022)166400, J. of Lumin. 249(2022)119028

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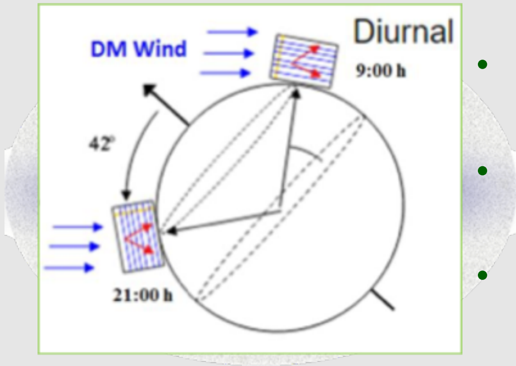

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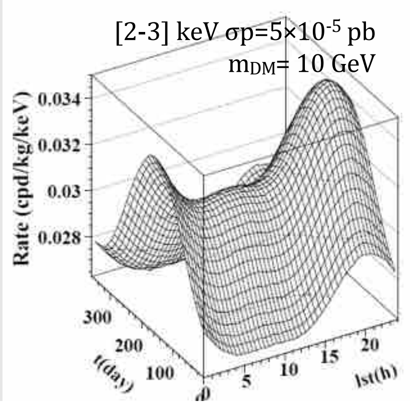

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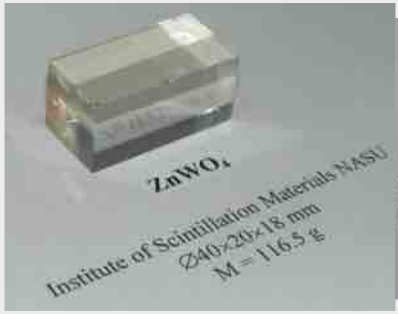
1. Developments of low bckg $ZnWO_4$ crystal scintillators

DAMA-Kiev

- Several 0.1-0.7 kg $ZnWO_4$ crystals grown by low- thermal gradient Czochralski method by exploiting different materials and techniques to test best possibility of qualities

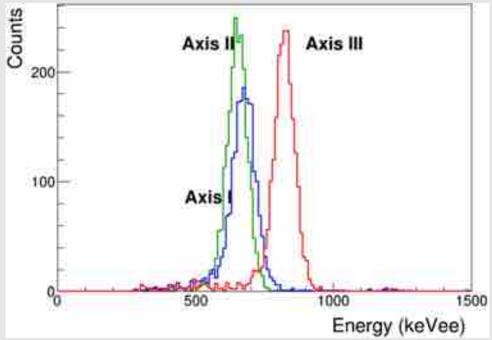


ZWO (699g, ISMA) Contamination (mBq/kg)	
^{232}Th	< 0.1
^{228}Ra	< 0.05
^{228}Th	0.002(1)
^{227}Ac	<0.003
$^{238}U+^{234}U$	<0.08
^{230}Th	<0.07
^{226}Ra	0.002(1)
^{210}Po	<0.06
^{40}K	<0.4
^{65}Zn	0.5(1)
α activity	0.18(3)

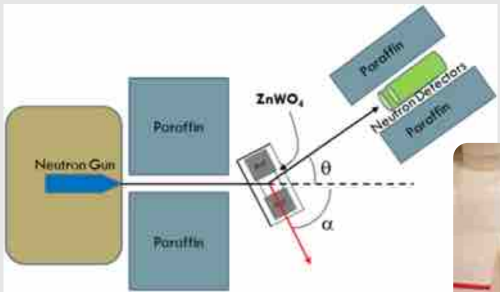
- Assembled inside a cavity (filled up with high-pure silicon oil) in central part of polystyrene light-guide 312 mm long

2. Quantifying anisotropy of light response with ^{241}Am α source

- Crystal irradiated at the same time with γ (^{22}Na) and α (^{241}Am) along the 3 crystal axes
- Different α energies obtained with Mylar foils and measured with Si detector
- Very efficient PSD capability to discriminate α and γ



3. Quantifying anisotropy of light response with n gun @ ENEA-Casaccia



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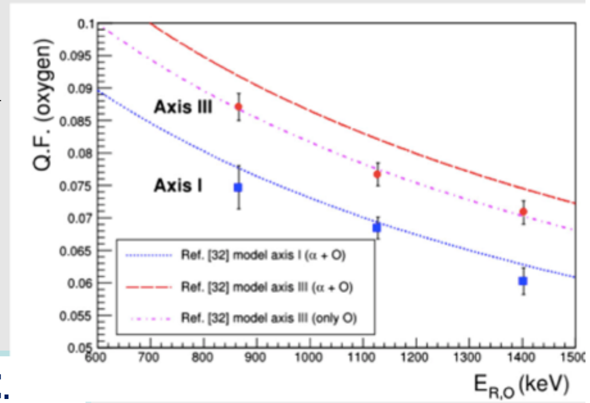
- ✓ Searching for coincidences between a scattered neutron at a fixed angle θ and scintillation event in $ZnWO_4$ in well defined time window (TOF)
- ✓ Once fixed the θ angle, the recoil direction and energy are fixed
- ✓ Measurements performed at different θ angles



Anisotropy for O nuclear recoils (energy down to hundreds keV) at 5.4 σ C.L.

4. Optical and scintillation properties of advanced $ZnWO_4$ crystal scintillators

High optical and scintillation properties $ZnWO_4$ crystal scintillators developed by using **low-thermal gradient Czochralski technique** after an extensive R&D including compound **stoichiometry variation**, **using** initial **WO_3** from **different producers** and **further purified**, and using **single** and **double crystallization with** and **without annealing** of the grown boules

Table 1
The samples of $ZnWO_4$ crystals used in the present study and the boules of origin.

Crystal boule	Sample size (mm^3)	Number of crystallizations	WO_3 tungsten trioxide	Compound stoichiometry
No. 75	10 × 10 × 2 ⌀30 × 60	Double	NIIC II	+0.3% of WO_3
No. 76	10 × 10 × 2 ⌀30 × 60	Double	Nippon Tungsten Co., Ltd	+0.25% of ZnO
No. 83	10 × 10 × 2 ⌀30 × 60	Single, annealed	NIIC I	+0.15% of WO_3
No. 84	10 × 10 × 2 ⌀30 × 60	Single, annealed	NIIC I	Stoichiometric
No. 85	10 × 10 × 2 ⌀30 × 60	Single, annealed	Japan New Metals Co., Ltd	Stoichiometric
No. 91	⌀30 × 67	Single, annealed	NIIC I	Stoichiometric
No. 94	⌀30 × 31 ⌀30 × 32	Single, annealed	NIIC I	Stoichiometric

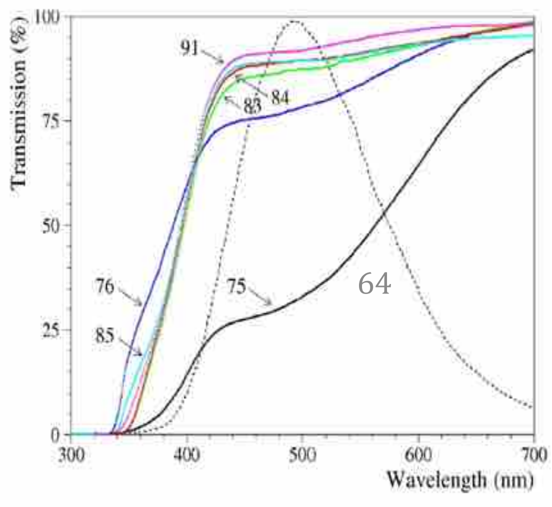
WO_3 of different origin:

- **NIIC I**: synthesized at Nikolaev Institute of Inorganic Chemistry, Novosibirsk, Russia (NIIC) with Si concentration <50 ppm and concentration of transition metals <1 ppm
- **NIIC II**: purified at the NIIC using an additional process of sublimation of tungsten chlorides;
- manufactured by **Nippon Tungsten** Co., Ltd. (Japan);
- manufactured by **Japan New Metals Co., Ltd** with a maximum Fe content <1 ppm and a maximum Mo content <10 ppm.

The **transmission** spectra **agree** with **literature** data. However, the transmission varies substantially **depending** on the sample **production protocol**. In particular, the sample produced by double crystallization (samples 75) is definitely of worse optical quality

Space for further improvements towards large sensitivities experiments
→ ongoing

Optical transmission



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WO_3 of different origin:

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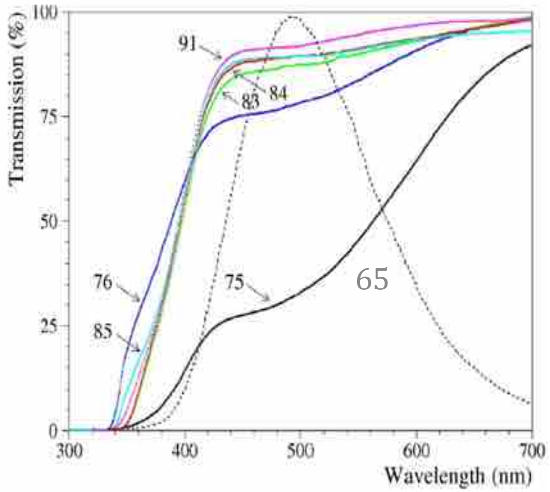
- [illegible] process of sublimation [illegible]
- [illegible] n);
- manufactured by **Japan New Metals Co., Ltd** with a maximum Fe content <1 ppm and a maximum Mo content <10 ppm.

The best optical and scintillation characteristics were obtained with $ZnWO_4$ crystal samples grown by **single crystallization** from the $ZnWO_4$ compound of the **stoichiometric composition** prepared from deeply purified WO_3, **annealed** in air atmosphere.

The **transmission** spectra **agree** with **literature** data. However, the transmission varies substantially **depending** on the sample **production protocol**. In particular, the sample produced by double crystallization (samples 75) is definitely of worse optical quality

Space for further improvements towards large sensitivities experiments
→ ongoing

Optical transmission



5. $ZnWO_4$ – work in progress

- ❖ A cryostat for relatively low temperature (about -50 °C) measurement with scintillation detectors realized; testing
- ❖ Lowering the energy threshold (new PMT with higher QE optimized to the fluorescence light emission and T operation)
- ❖ New measurements of anisotropy at low energy with MP320 Neutron Generator (E_n = 14 MeV) at ENEA-Casaccia
- ❖ Further improvement of the radio-purity

Developments of $ZnWO_4$ detectors and studies on $\beta\beta$ processes with INR-Kiev:

PLB658(2008)193, NPA826(2009)256, NIMA626-627(2011)31, J. Phys. G: Nucl. Part. Phys. 38(2011)115107 , EPJC73(2013)2276, Phys.Scr.90(2015)085301 , NIMA833(2016)77, NIMA935(2019)89, EPJA56(2020)83, JINST15(2020)C05055, NIMA1029(2022)166400, J. of Lumin. 249(2022)119028

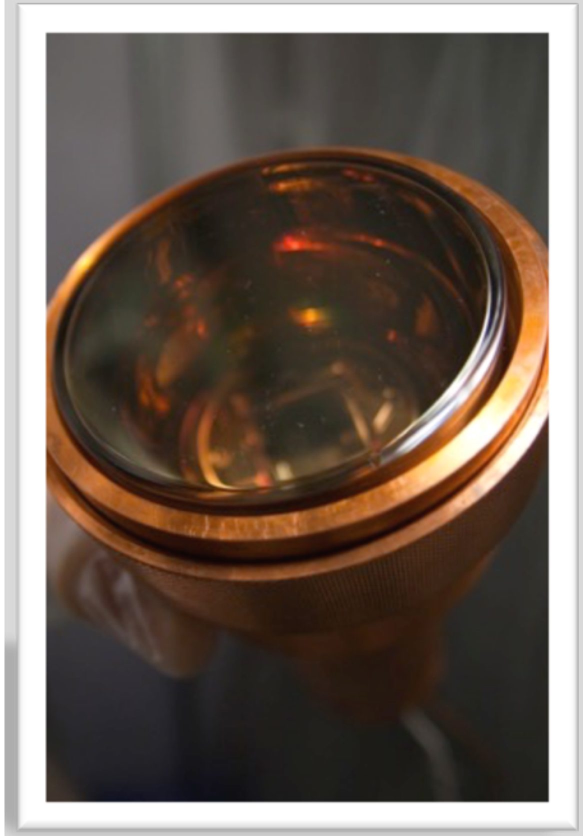
In conclusion , **advantages** in the use of **$ZnWO_4$** crystal scintillators:

- High level of radio-purity reachable;
- High light output, i.e. low energy threshold feasible;
- High stability in the running conditions;
- Very good anisotropic features for DM directionality and sensitivity to small and large mass DM candidates;
- Detectors with ~ kg masses;
- Investigation of $\beta\beta$ decay modes: $^{64}Zn \rightarrow ^{64}Ni$; $^{70}Zn \rightarrow ^{70}Ge$; $^{180}W \rightarrow ^{180}Hf$; $^{186}W \rightarrow ^{186}Hf$

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 total**)
- 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**

- **Corollary Model-dependent** analyses improve the C.L. and restrict the allowed parameters' space for the various scenarios – update in progress



- Preliminary efforts towards 0.75 keV software energy threshold done
- Efforts for an empowered DAMA/LIBRA–phase2 → software **energy threshold of 0.5 keV with high overall efficiency successful**. New divider/amp systems and new 14bit digitizers.
- DAMA/LIBRA–phase2-empowered **running**
- Detectors' developments and investigations of **rare processes** other than DM
- Other pursued ideas: **$ZnWO_4$ anisotropic scintillator** for DM **directionality**. Response to nuclear recoils measured.
- Continuing investigations of **rare processes** other than DM, also in the other DAMA set-ups (g_A, ^{106}Cd, ^{116}Cd, ^{150}Nd, Os, Zr, Hf, …)