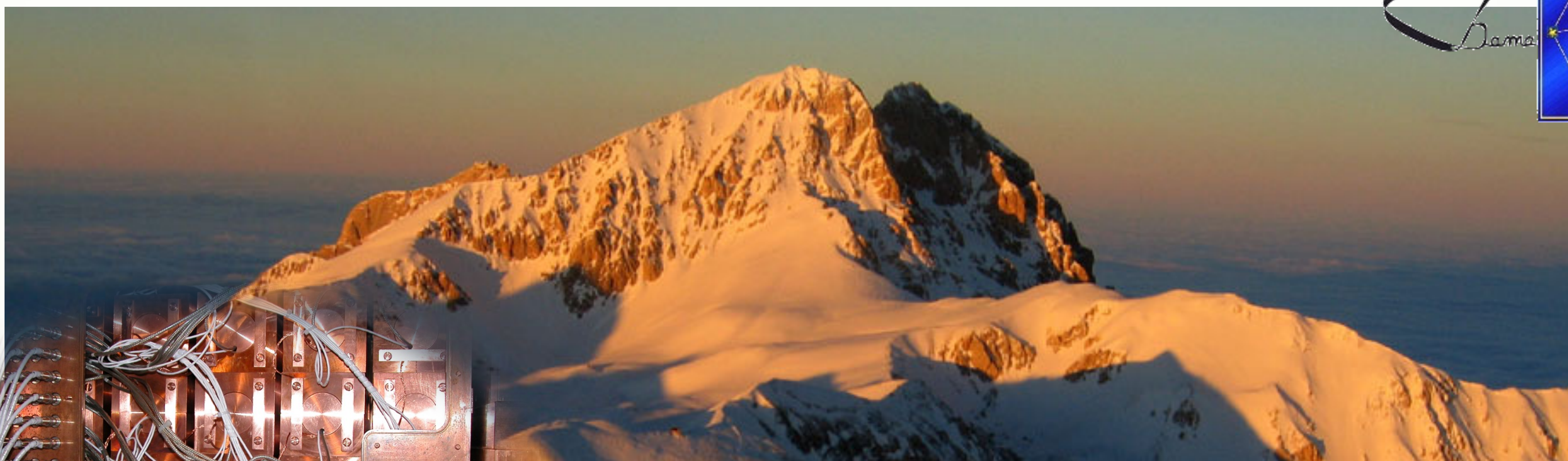
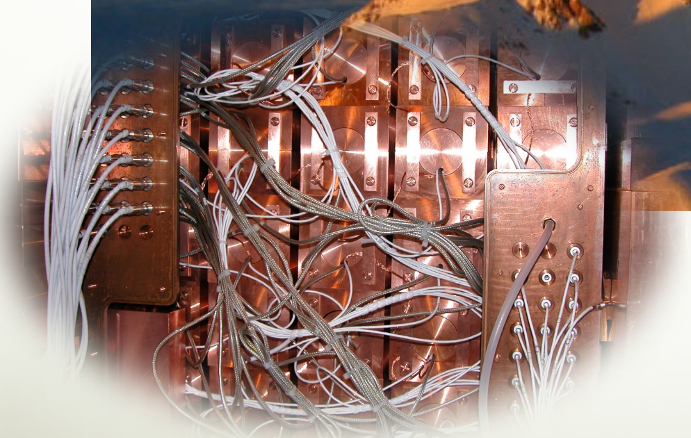
DAMA/LIBRA results and PEP violations studies





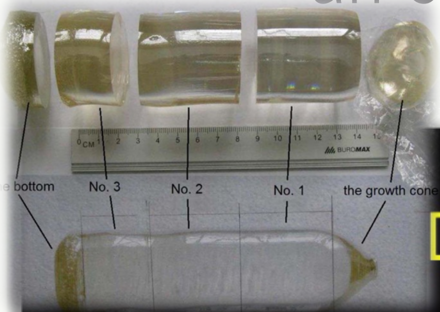
P. Belli
INFN – Roma Tor Vergata

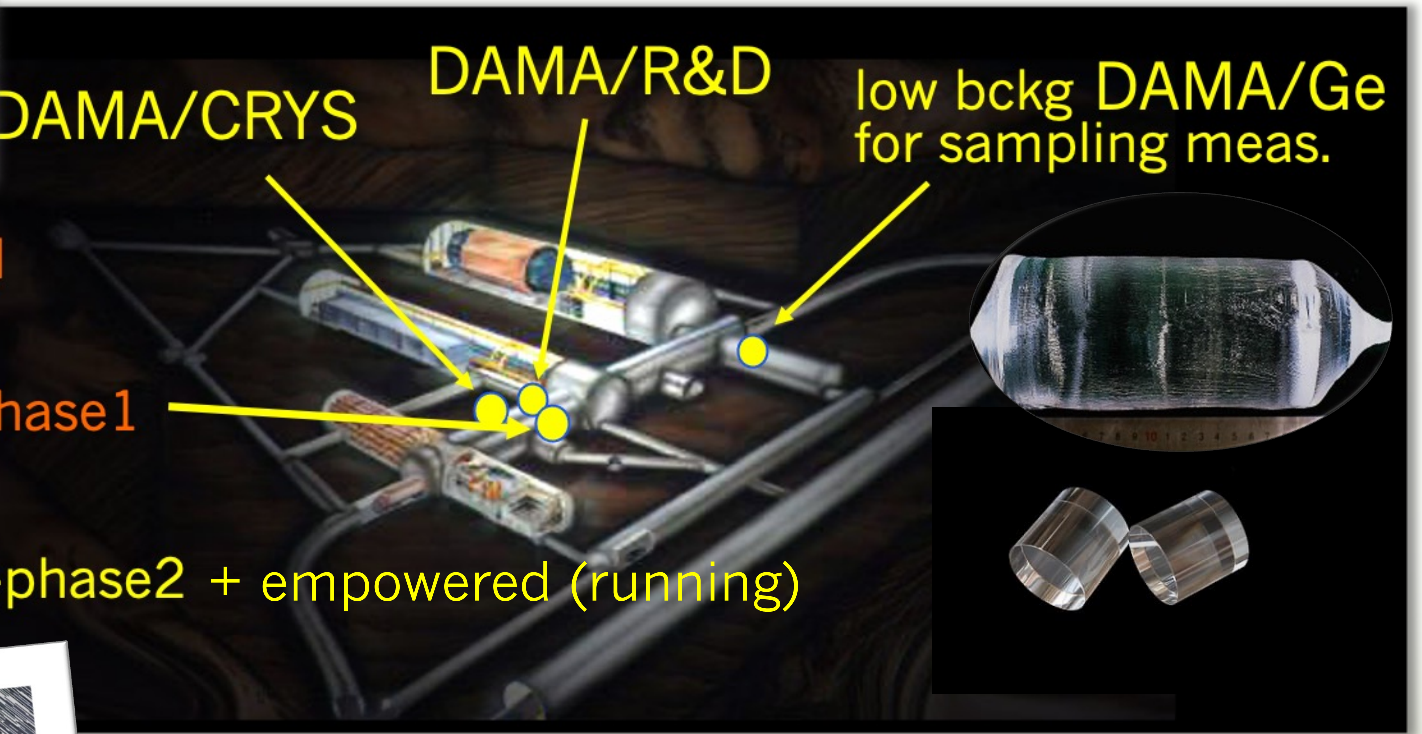
ECT* Workshop on "Nuclear and Atomic transitions as laboratories for high precision tests of Quantum Gravity inspired models", Trento, Sept 19-23, 2022

DAMA set-ups

an observatory for rare processes @ LNGS

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





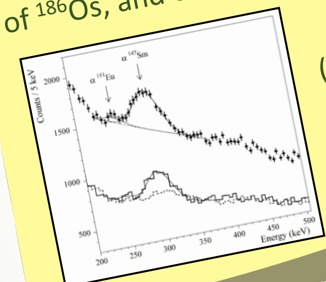
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

+ 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

Main results obtained by DAMA in the search for rare processes

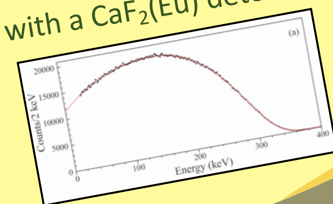
- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{144}Sm, ^{154}Sm, ^{150}Nd,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

Relic DM particles from primordial Universe

SUSY (as neutralino or sneutrino in various scenarios)

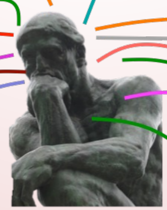
the sneutrino in the Smith and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not yet foreseen by theories



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

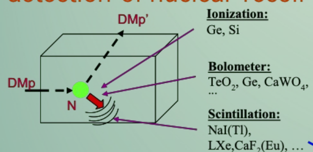
etc...

multi-component non-baryonic DM?

Accelerators:
- can demonstrate the existence of some possible DM candidates
- cannot credit that a certain particle is the Dark Matter solution or the "single" Dark Matter particle solution...

+ DM candidates and scenarios exist on which accelerators cannot give any information

- Scatterings on nuclei
  → detection of nuclear recoil energy

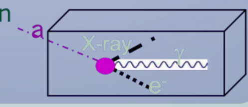


- Inelastic Dark Matter: **W + N → W* + N**
  → W has 2 mass states χ+ , χ- with δ mass splitting
  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

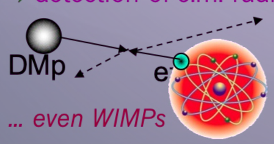
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei
  → detection of recoil nuclei + e.m. radiation

- Conversion of particle into e.m. radiation
  → detection of γ, X-rays, e⁻



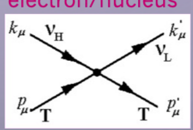
- Interaction only on atomic electrons
  → detection of e.m. radiation



... even WIMPs

- Interaction of light DMp (LDM) on e⁻ or nucleus with production of a lighter particle
  → detection of electron/nucleus recoil energy

e.g. sterile ν



... also other ideas ...

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

DM direct detection method using a model independent approach and a low-background widely-sensitive target material

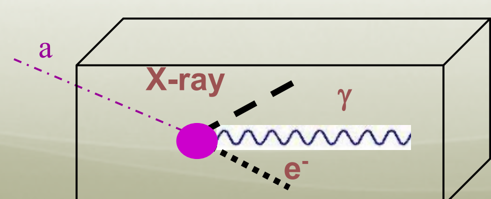
The **annual modulation**: a model independent signature for the investigation of DM particles component in the galactic halo

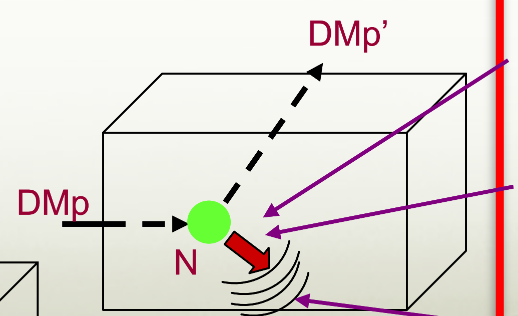
Direct detection experiments

The direct detection experiments can be classified in **two 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 ***model-independent* signature**

2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)





Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, …

Scintillation:
NaI(Tl), LXe, CaF_2(Eu), …

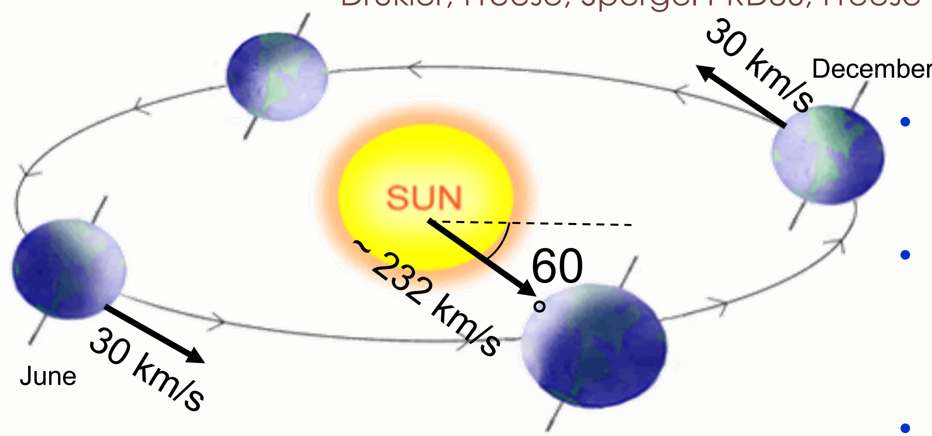
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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)

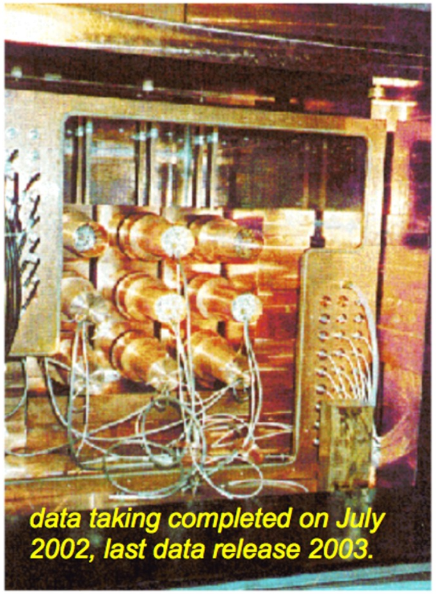
$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

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

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

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



Performances:

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

Results on rare processes:

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

Results on DM particles:

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

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

total exposure (7 annual cycles) 0.29 ton×yr

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

Perform

Results

- Possi
- CNC
- Elect in loc
- Searc
- Exoti
- Searc
- Searc

Results

- PSD
- Inves
- Exot
- Annu

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

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

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

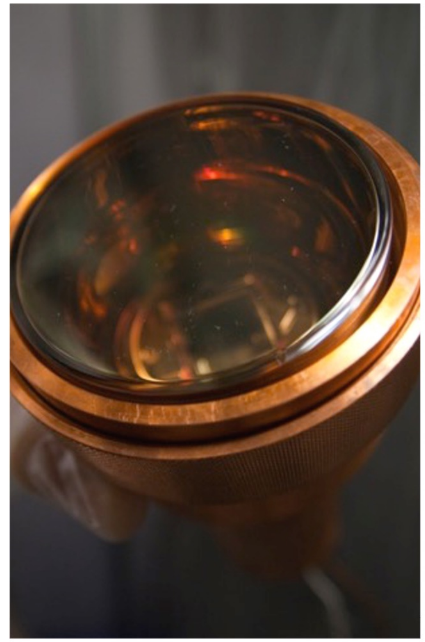
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles,
  - Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  - Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, EPJC75(2015)400, IJMPA31(2016) dedicated issue, EPJC77(2017)83
- Results on rare processes:
  - PEPv: EPJC62(2009)327, arXiv1712.08082;
  - CNC: EPJC72(2012)1920;
  - IPP in ^{241}Am: EPJA49(2013)64

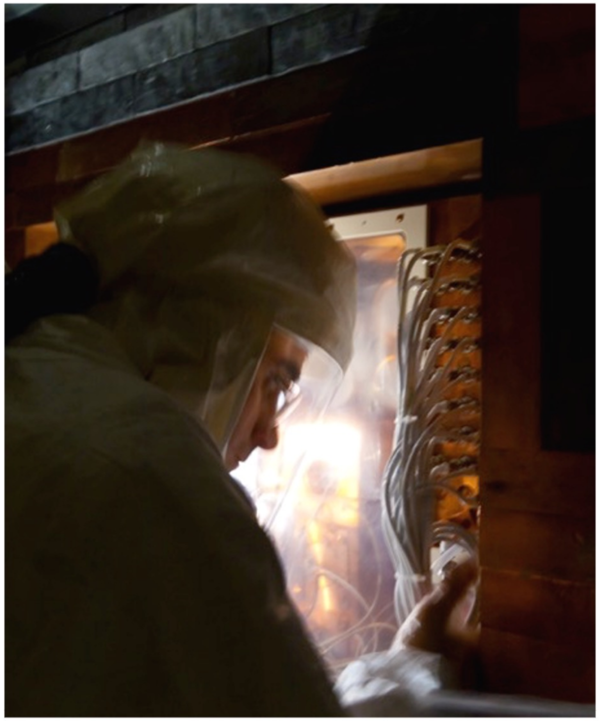
DAMA/LIBRA–phase1 (7 annual cycles, 1.04 ton×yr) confirmed the model-independent evidence of DM: reaching 9.3σ C.L.

DAMA/LIBRA–phase2

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

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4) (2019) 317
PPNP114(2020)103810
NPAE 22(2021) 329
arXiv:2209.00882





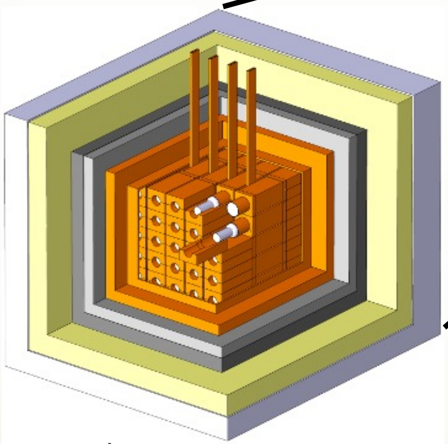
Goal: software energy threshold at 1 keV – accomplished

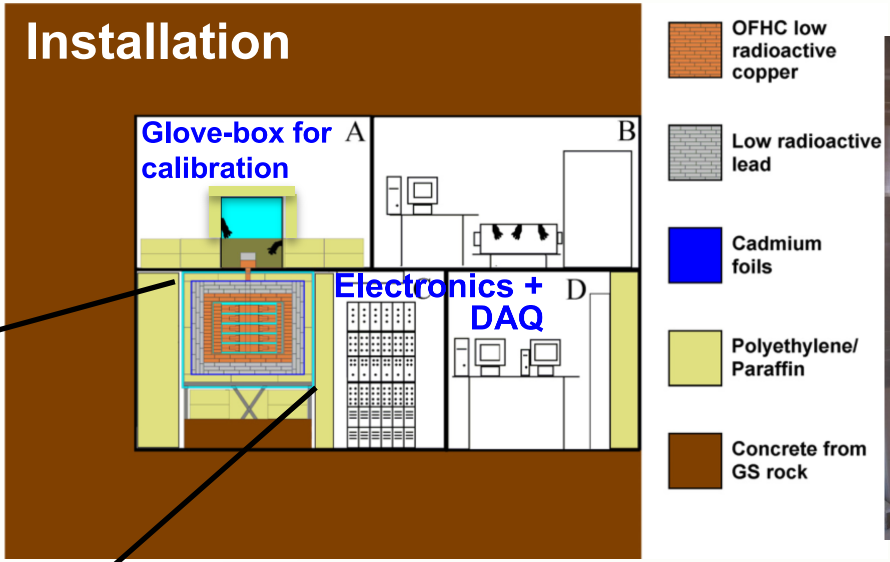
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak

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**



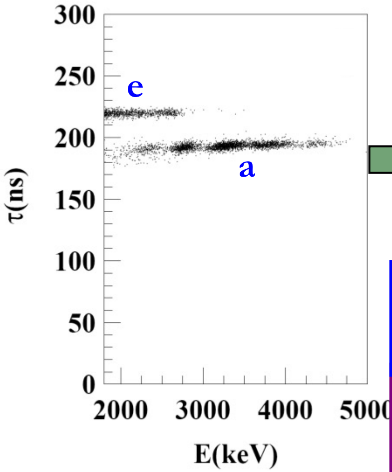


- Whole setup decoupled from ground
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- Dismounting/Installing protocol in HPN_2
- All the materials selected for low radioactivity

- 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

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

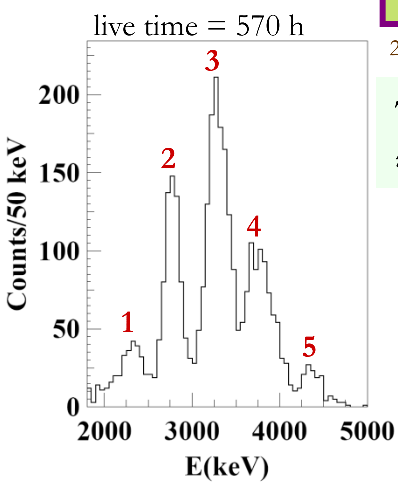
Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling

^{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



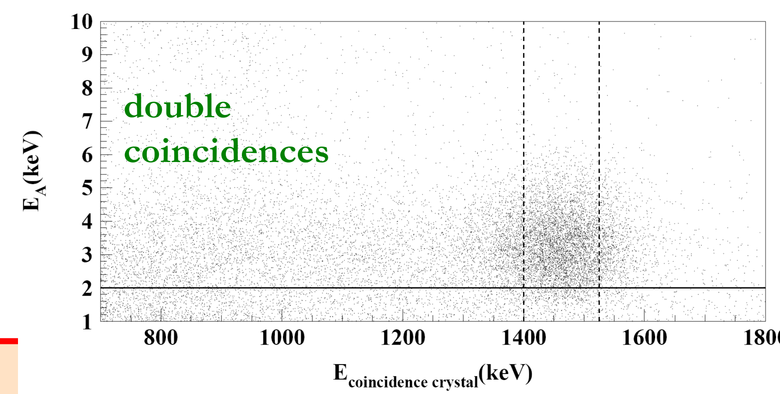
^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

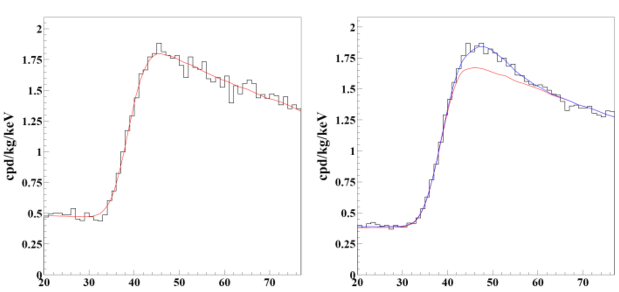
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U

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

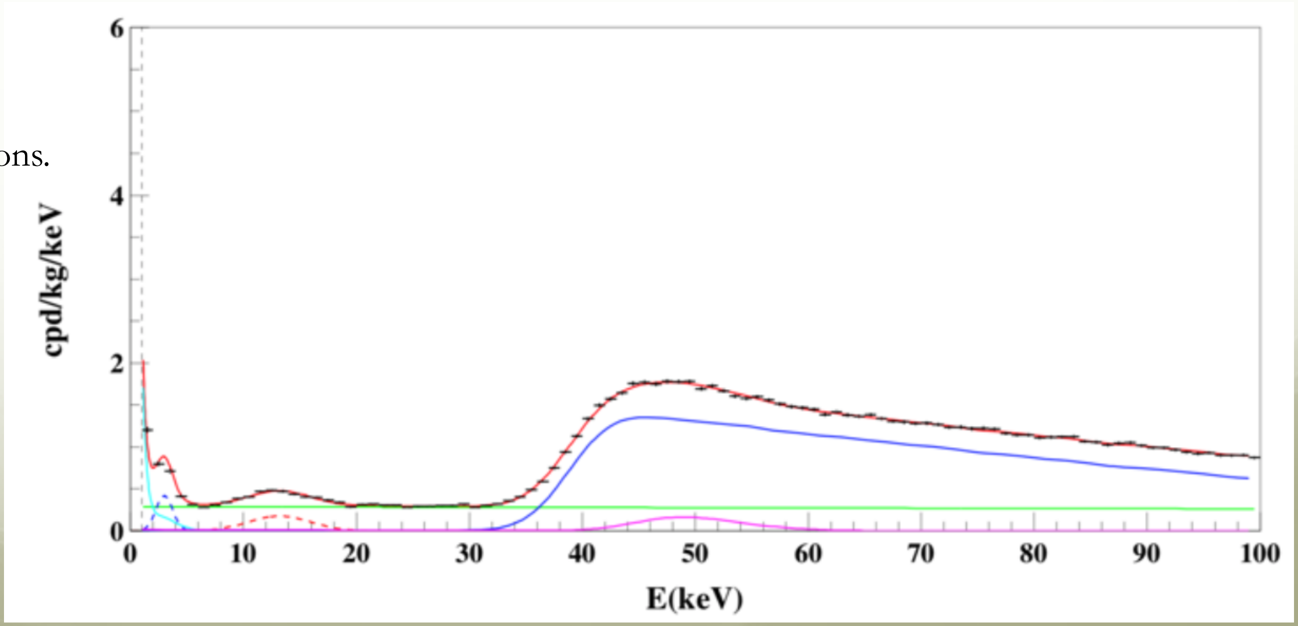
^{210}Pb in the new detectors: (5 − 30) μBq/kg.

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

... more on NIMA592(2008)297

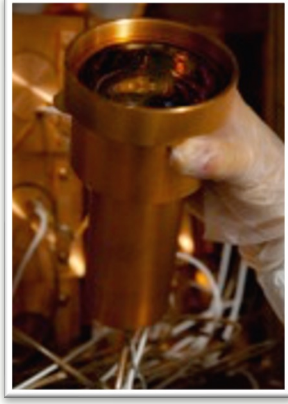
DAMA/LIBRA energy spectrum

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



DAMA/LIBRA-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)

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

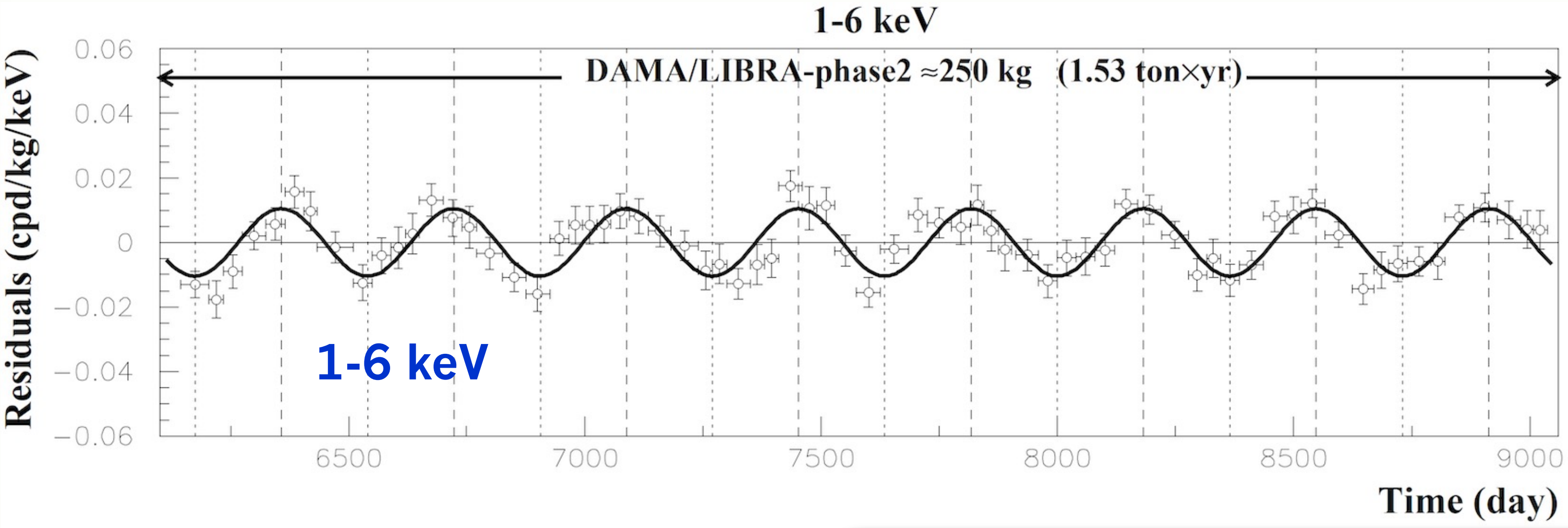
Exposure with this data release of DAMA/LIBRA-phase2: **1.53 ton × yr**

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

DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.53 ton × yr)

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



Absence of modulation? No

χ^2/dof = 202/69 (1-6 keV)

Fit on DAMA/LIBRA-phase2

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

1-6 keV

A=(0.01048±0.00090) cpd/kg/keV

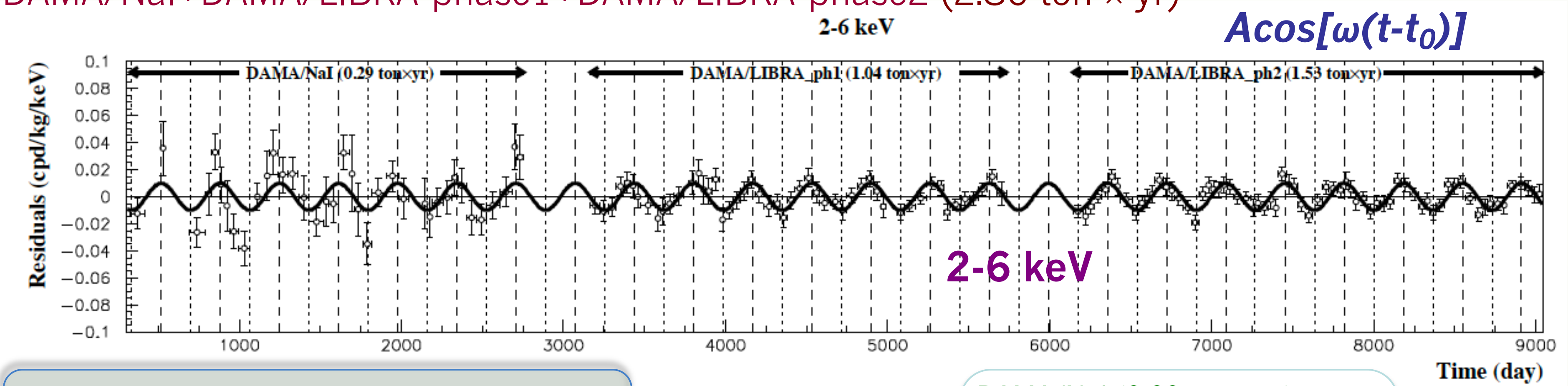
χ^2/dof = 66.2/68 **11.6 σ C.L.**

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

DM model-independent Annual Modulation Result

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

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



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.**

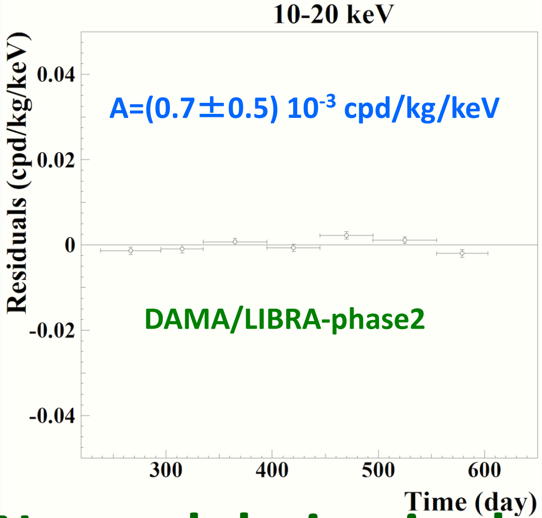
Releasing period (*T*) and phase (t_0) in the fit

	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.

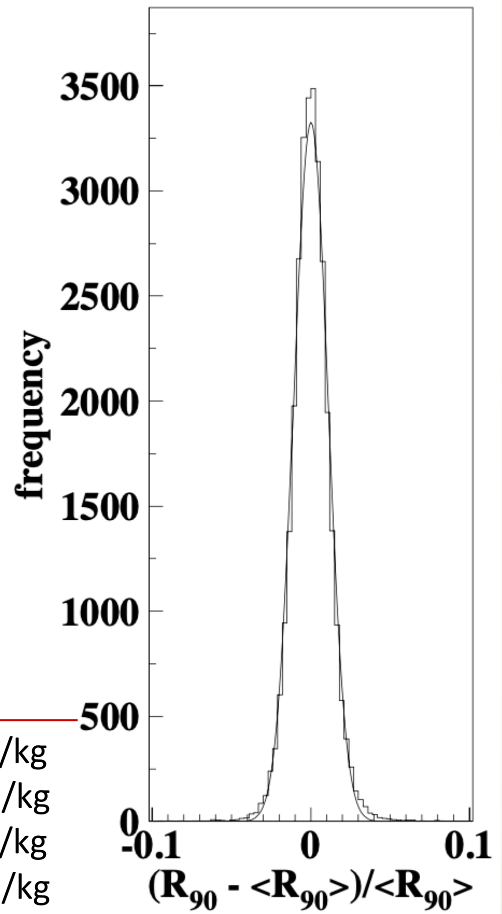
Rate behaviour above 6 keV

- **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

DAMA/LIBRA-phase2_2_9



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**

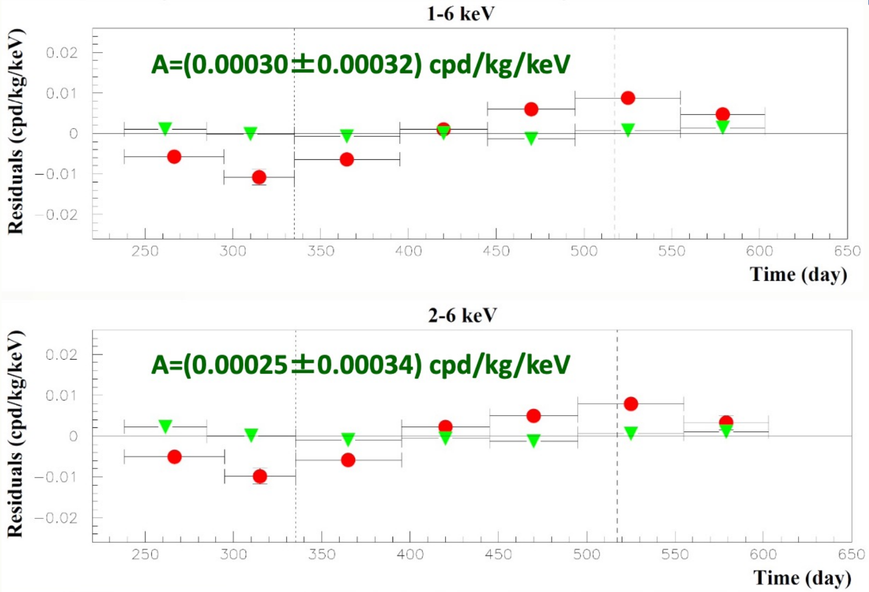
+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

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

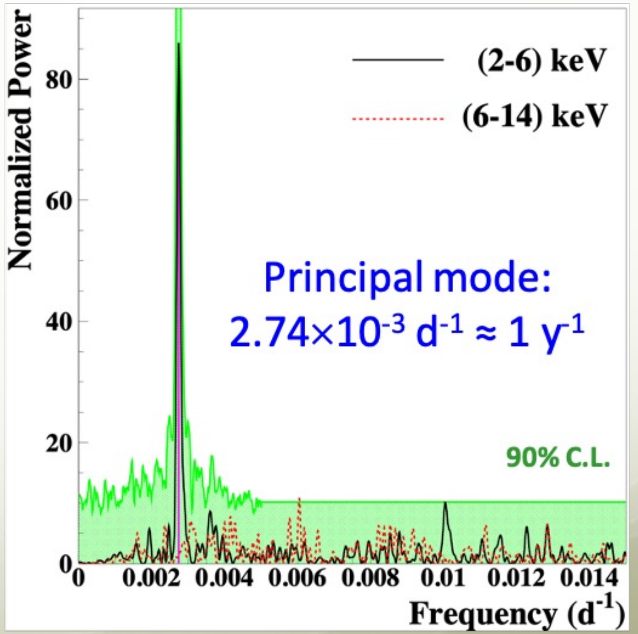
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The analysis in frequency

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

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

Zoom around the 1 y^{-1} peak



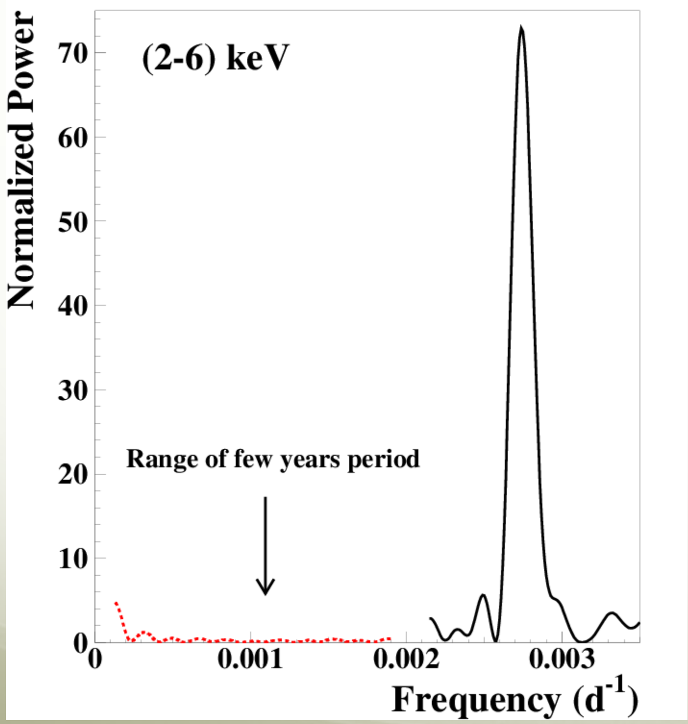
Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

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

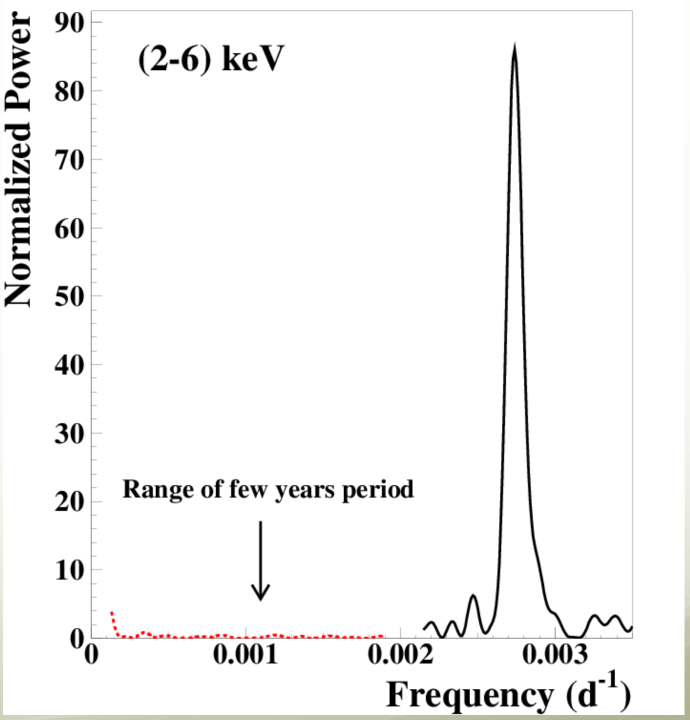
We calculated annual baseline counting rates – that is the averages on all the detectors (j index) of $flat_j$ (i.e. the single-hit scintillation rate of the j-th detector averaged over the annual cycle)

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

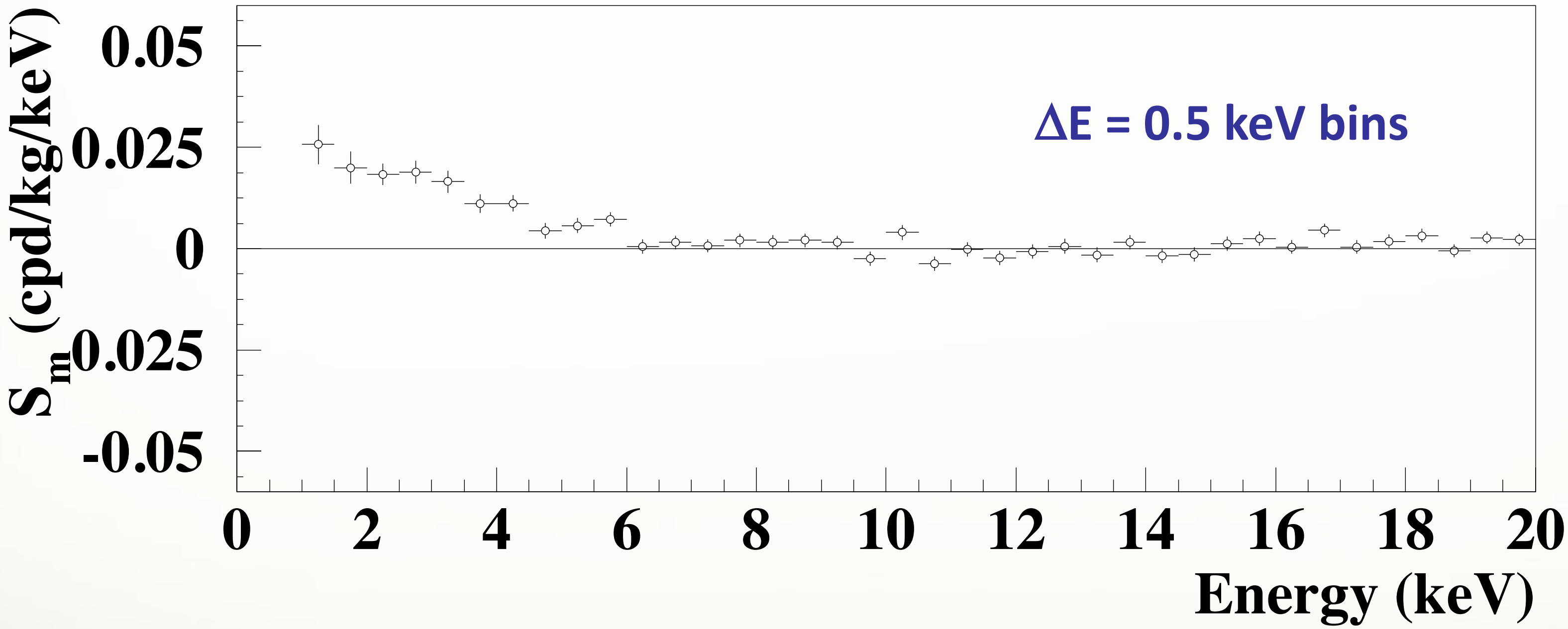
Energy distribution of the modulation amplitudes

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

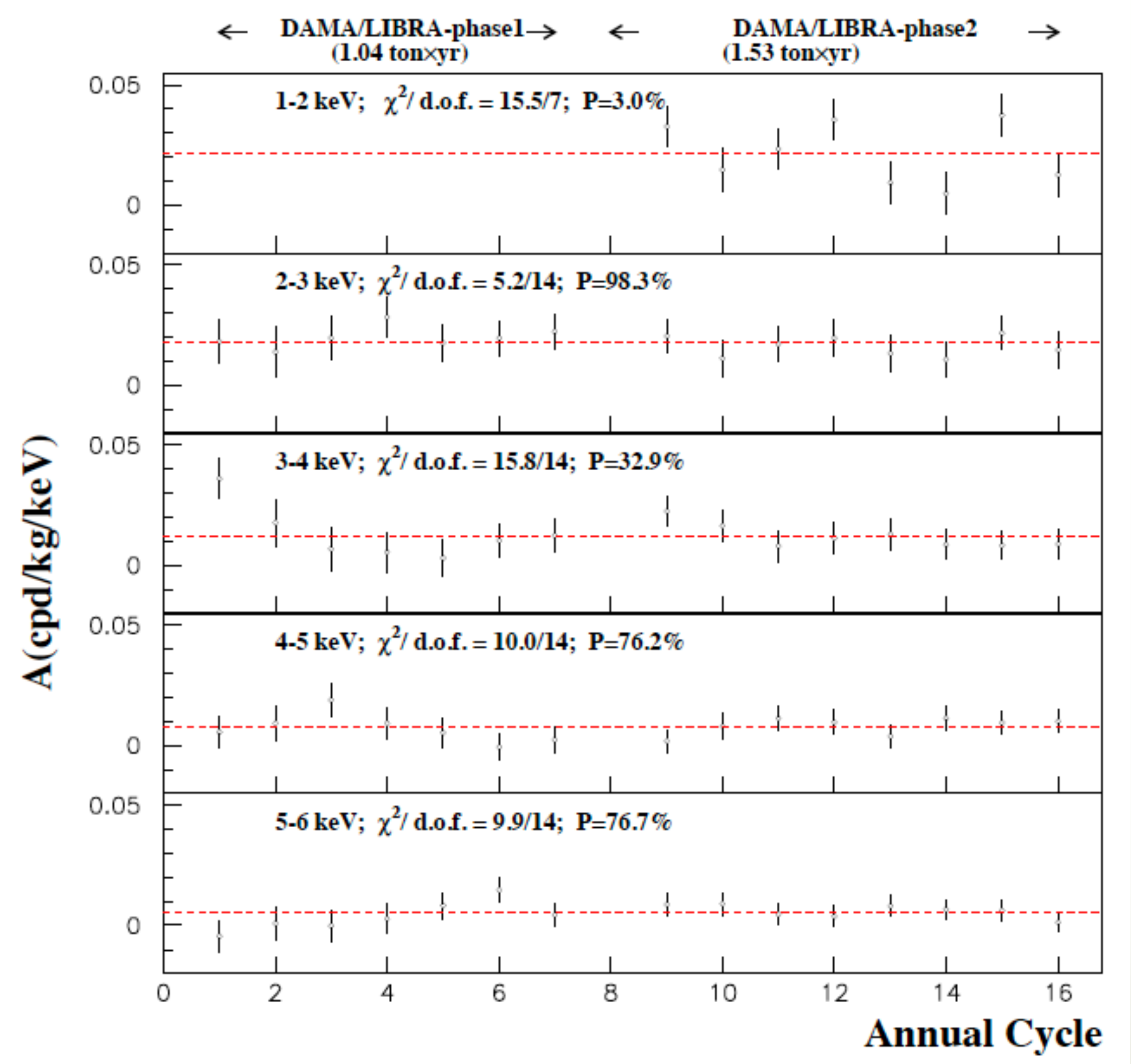
DAMA/NaI + DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2 (2.86 ton×yr)



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%.

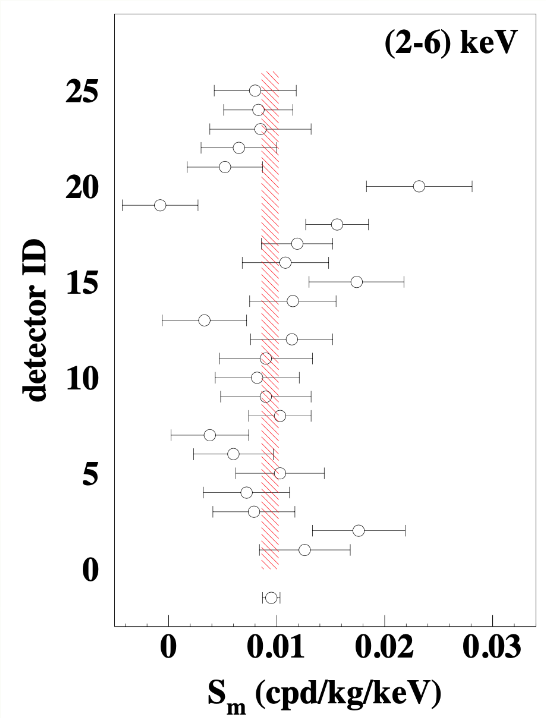
S_m for each annual cycle



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



S_m for each detector

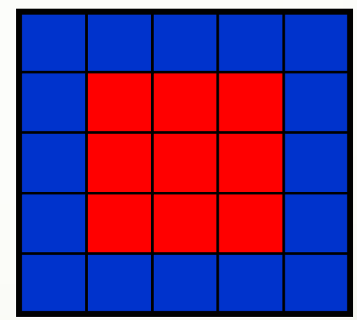
DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2
total exposure: 2.57 ton×yr

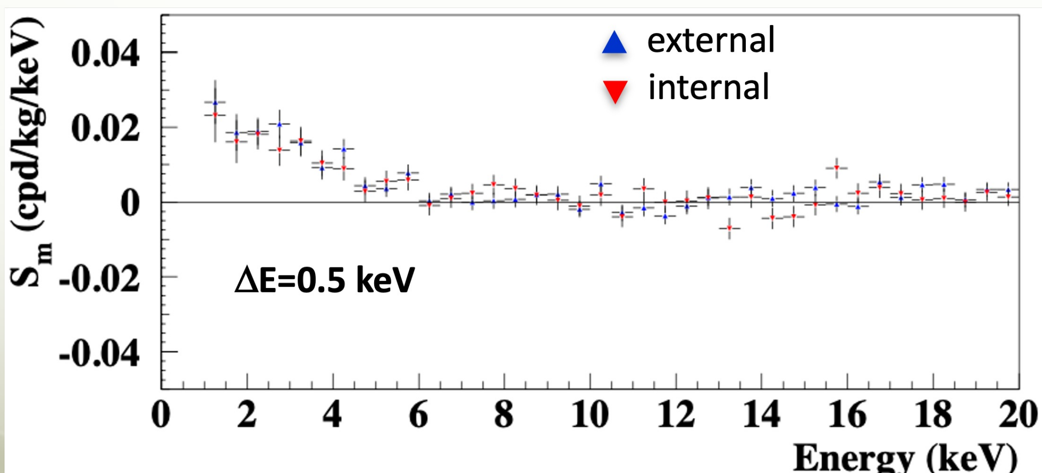
S_m in (2 - 6) keV for each of the 25 detectors (1σ error)

Shaded band = weighted averaged $S_m \pm 1\sigma$

- 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

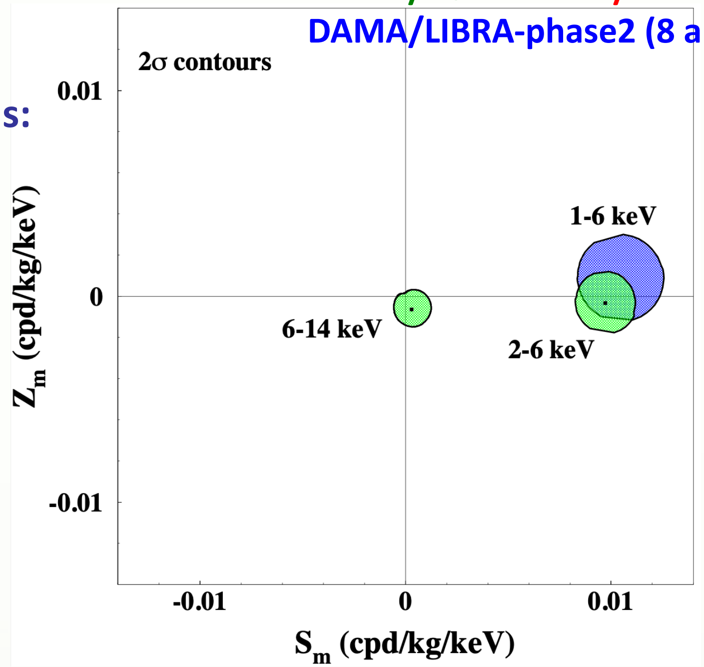
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

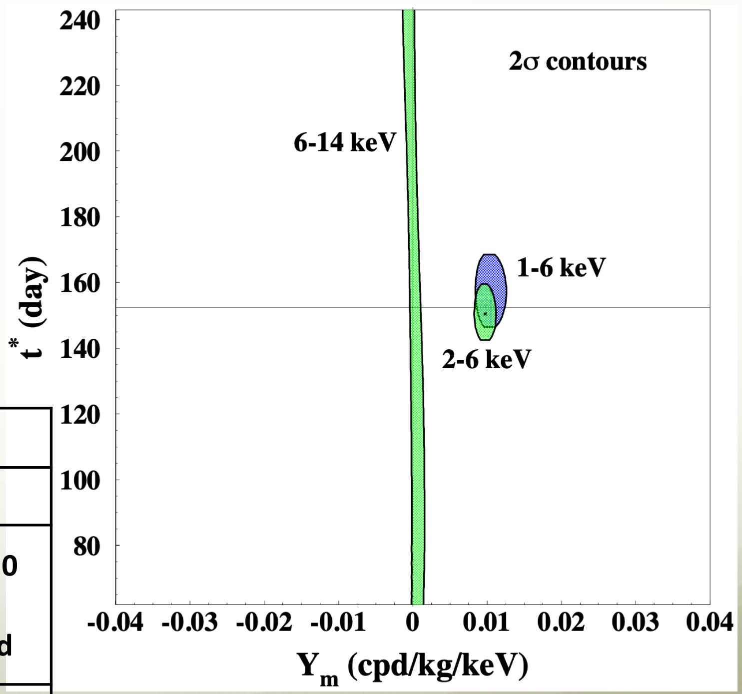
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]

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)



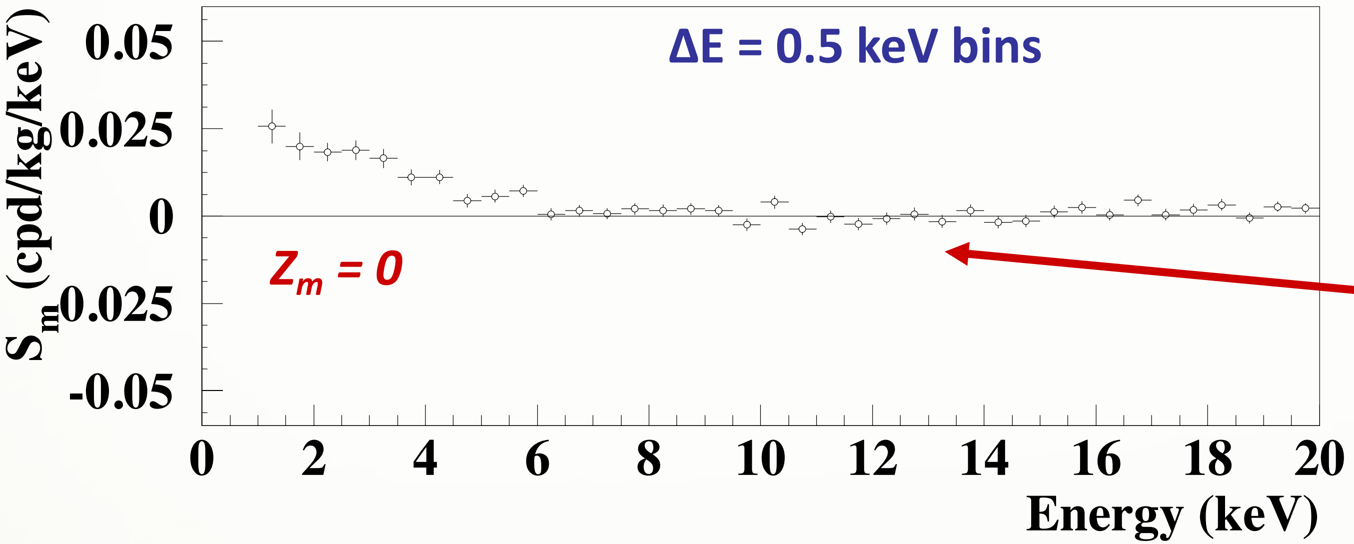
E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0097 ± 0.0007	- 0.0003 ± 0.0007	0.0097 ± 0.0007	150.5 ± 4.0
6-14	0.0003 ± 0.0005	-0.0006 ± 0.0005	0.0007 ± 0.0010	undefined
1-6	0.0104 ± 0.0007	0.0002 ± 0.0007	0.0104 ± 0.0007	153.5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

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

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

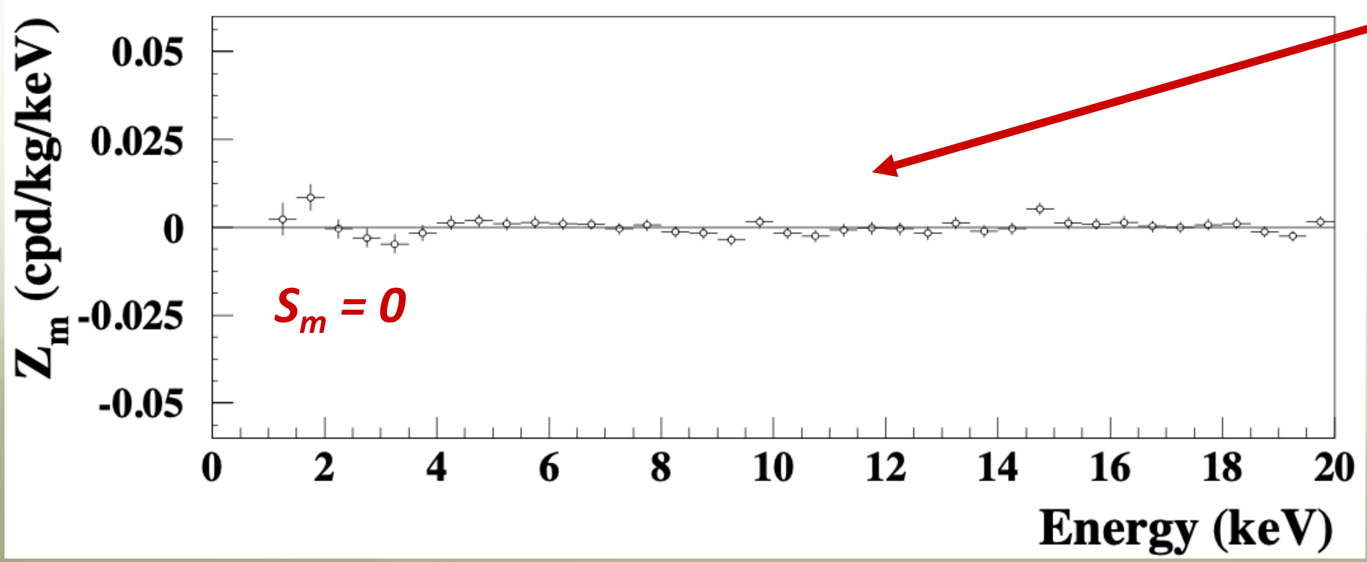
t_0 = *152.5 day* (2nd June)

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

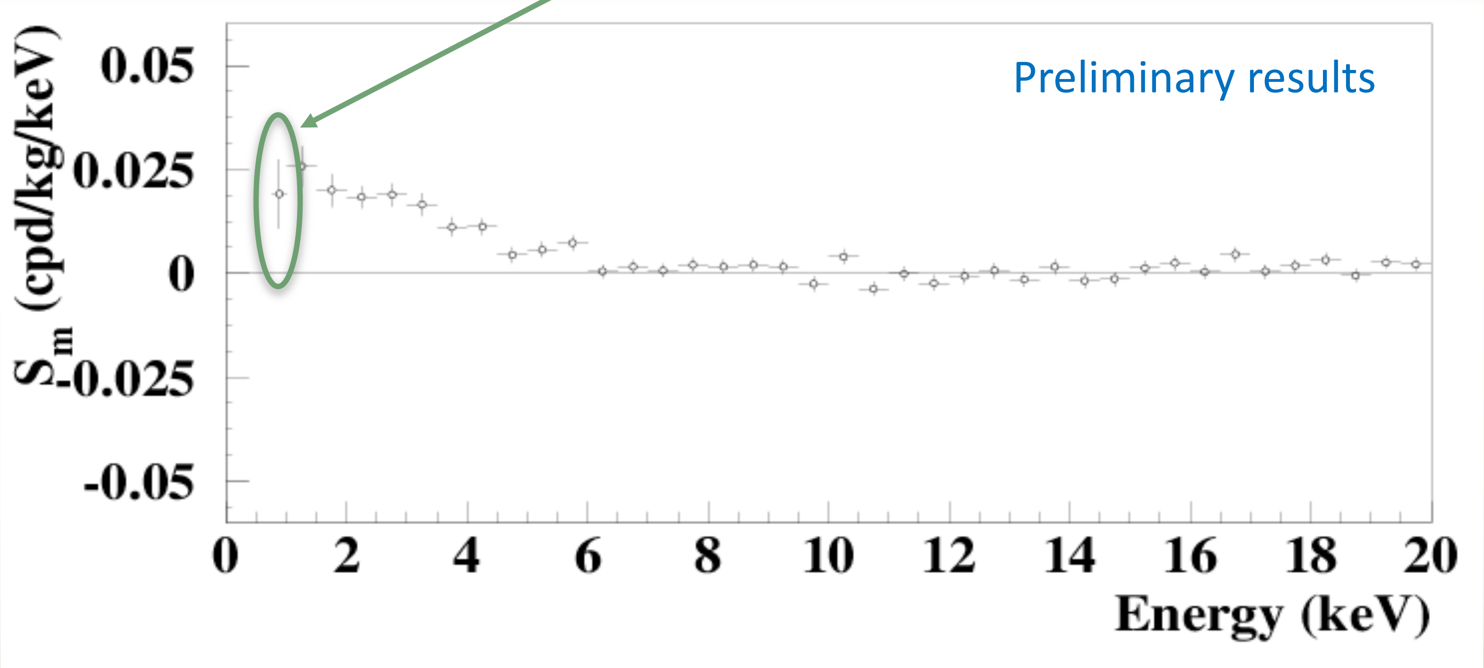


The χ^2 test in (1-20) keV energy region (χ^2/dof = 40.6/38 probability of 36%) supports the hypothesis that the Z_m values are simply fluctuating around zero.

Efforts towards lower software energy threshold

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

New data point with the 8 a.c. of **DAMA/LIBRA-phase2** **(1.53 ton×yr)**



- A clear modulation is also present below 1 keV, from 0.75 keV, while S_m values compatible with zero are present just above 6 keV
- This preliminary result suggests the necessity to lower the software energy threshold and to improve the experimental error on the first energy bin

Few comments on analysis procedure in DAMA/LIBRA

arXiv:2209.00882

- Data taking of each annual cycle starts before the expected **minimum** (Dec) of the DM signal and ends after its expected **maximum** (June)
- Thus, assuming a **constant background** within each annual cycle:
  - ✓ any possible decay of **long–term–living isotopes** cannot mimic a DM positive signal with all its peculiarities
  - ✓ it may only lead to **underestimate** the observed S_m, depending on the radio-purity of the set-up

Claims (JHEP2020,137, arXiv:2208.05158) that the DAMA annual modulation signal may be biased by a slow variation only in the low-energy *single-hit* rate, possibly due to *some background* with odd behaviour increasing with time ➔ already **confuted** quantitatively (see e.g. Prog. Part. Nucl. Phys. 114, 103810, 2020 and here)

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

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

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

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

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

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

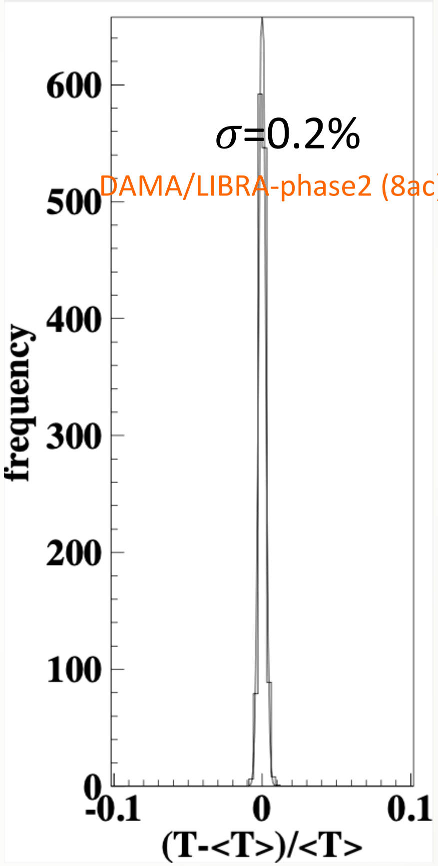
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

Temperature

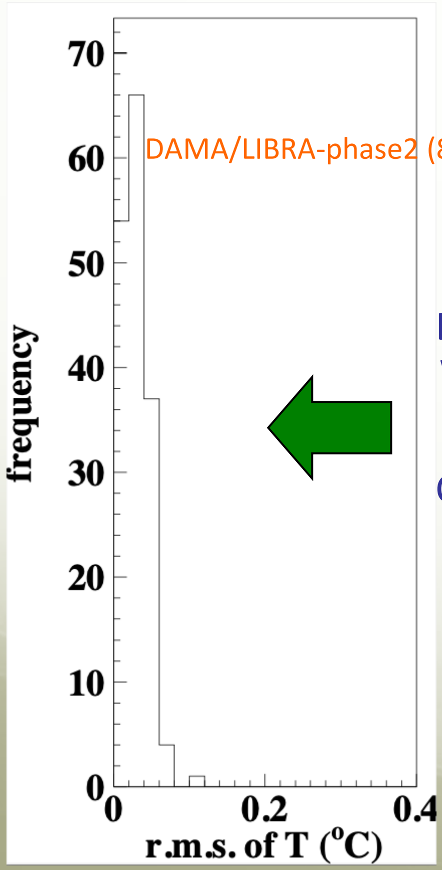
- Detectors in Cu housings directly in contact with multi-ton shield →huge heat capacity (≈10^6 cal/^{0}C)
- Experimental installation continuously air conditioned (2 independent systems for redundancy)
- Operating T of the detectors continuously controlled

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 ± 0.0049)
DAMA/LIBRA-ph2_4	-(0.0003 ± 0.0031)
DAMA/LIBRA-ph2_5	(0.0009 ± 0.0050)
DAMA/LIBRA-ph2_6	(0.0018 ± 0.0036)
DAMA/LIBRA-ph2_7	-(0.0006 ± 0.0035)
DAMA/LIBRA-ph2_8	-(0.0029 ± 0.0039)
DAMA/LIBRA-ph2_9	(0.0014 ± 0.0033)



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



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

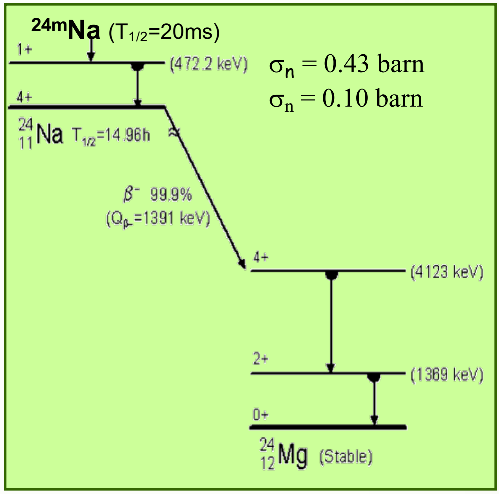
+ Any possible modulation due to temperature would always fail some of the peculiarities of the signature

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:

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

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

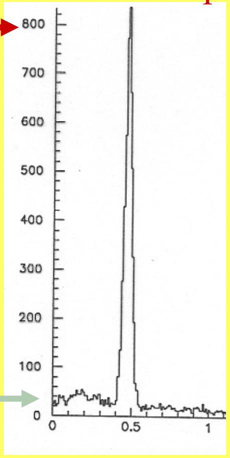
Already excluded also by R_{90} analysis

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; → $\Phi_k = \Phi_{0,k}\left(1+\eta_k \cos\omega\left(t-t_k\right)\right)$
- 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]	–	$< 8 \times 10^{-6}$	[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, $(\alpha, n) \rightarrow$ 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]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \rightarrow$ 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])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \rightarrow$ 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)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \rightarrow$ 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.

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

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

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<10^{-4} cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**<10^{-4} cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**<1-2 ×10^{-4} cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**<10^{-4} cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**<10^{-4} cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**<3×10^{-5} cpd/kg/keV**

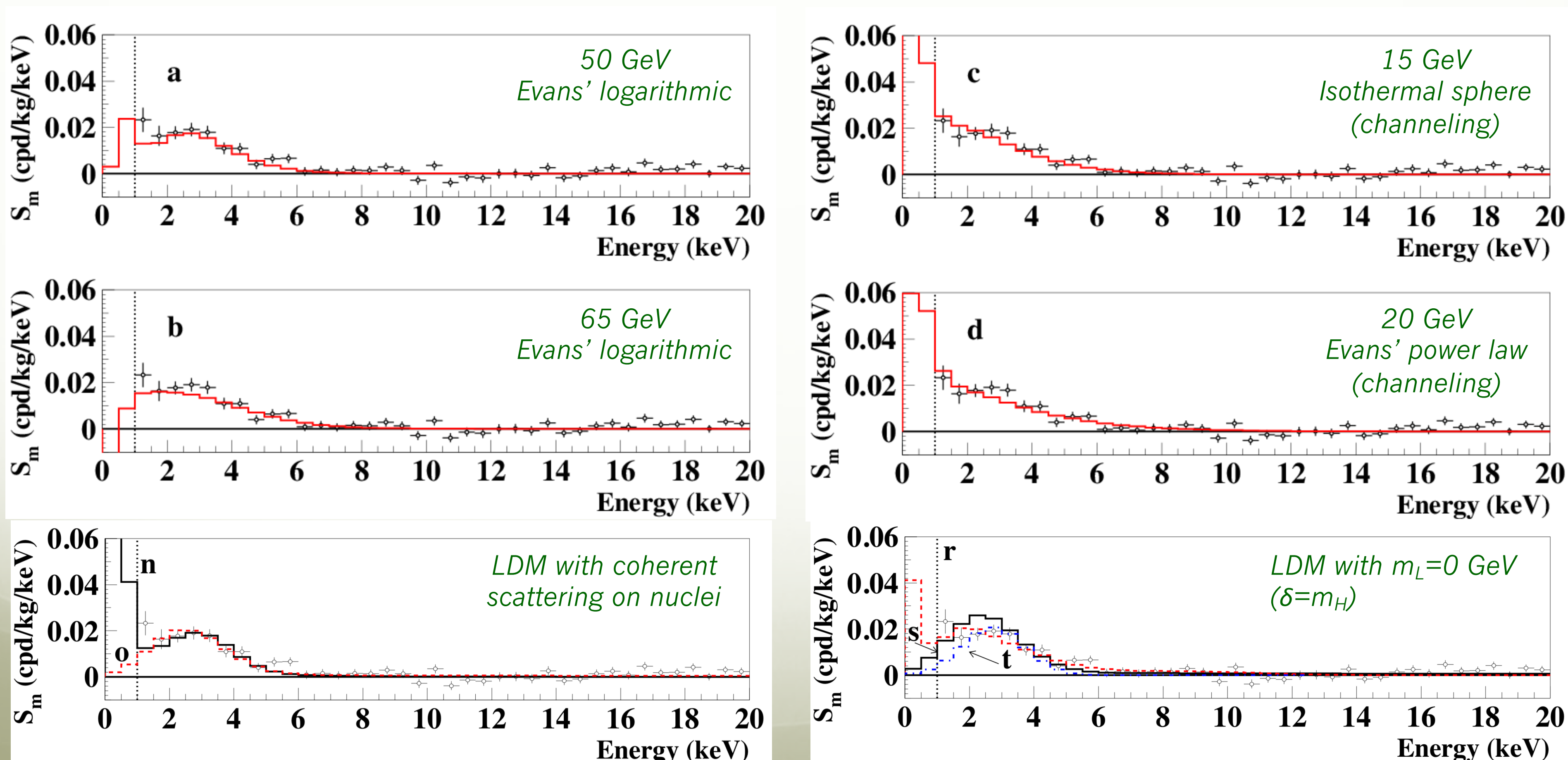
+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

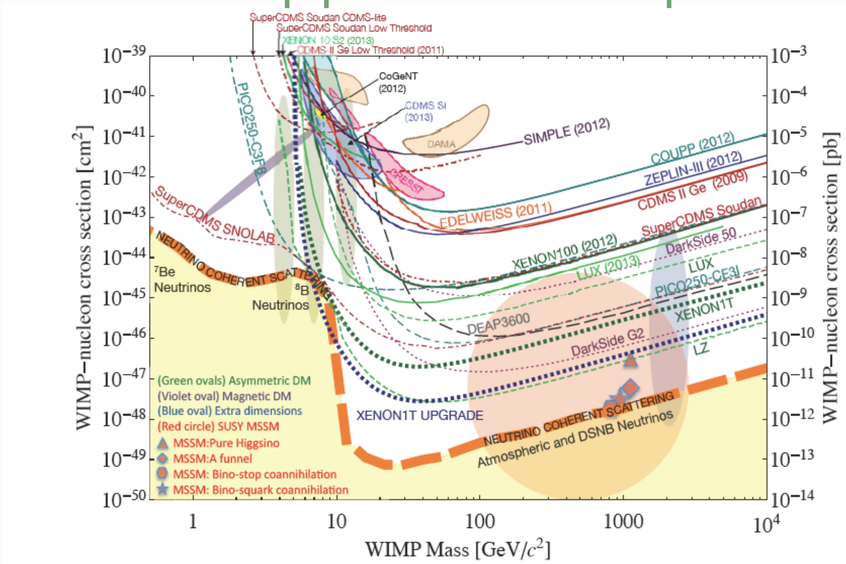
Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

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

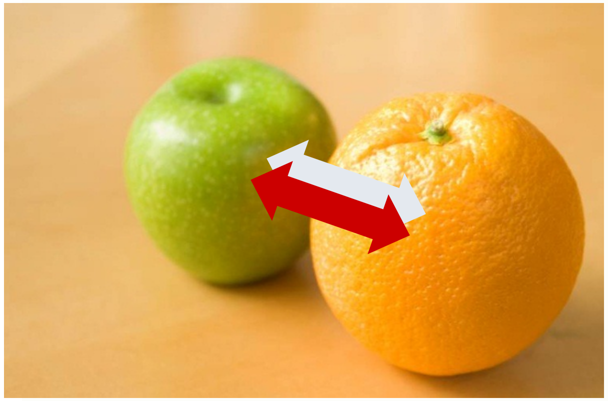
- Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios
- E_{th}=1 keV; old data release



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**.

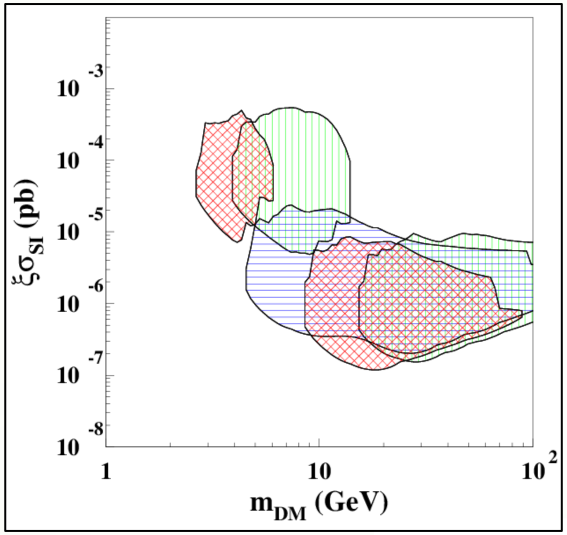
No direct model-independent comparison among expts with different target-detectors and different approaches

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

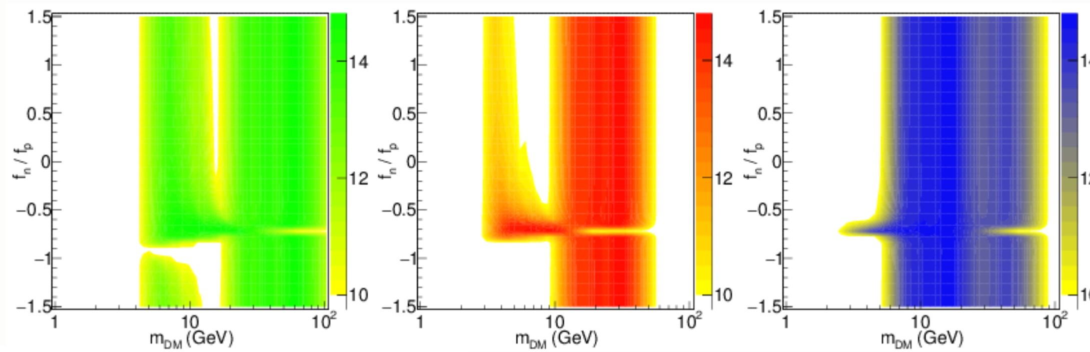
E_{th}=1 keV; old data release



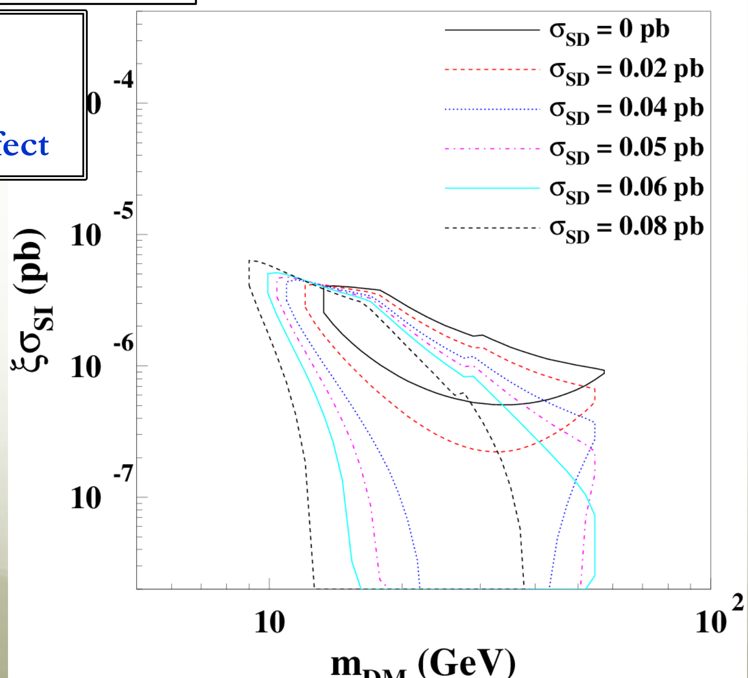
DM particles elastically scattering off target nuclei – SI interaction

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

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



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



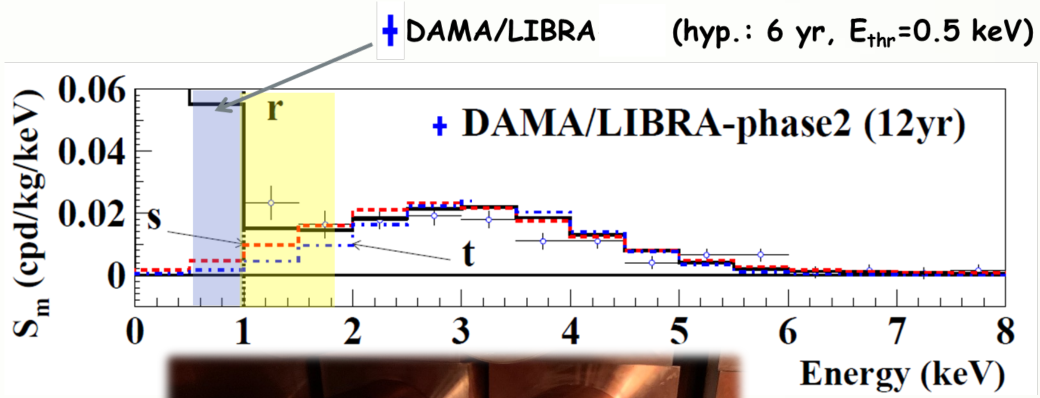
Even a relatively small SD (SI) contribution can drastically change the allowed region in the (m_{DM}, $\xi\sigma_{SI(SD)}$) plane

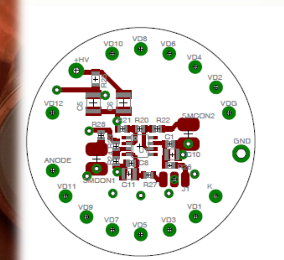
- Two bands at low mass and at higher mass;
- Good fit for low mass DM candidates at $f_n/f_p \approx -53/74 = -0.72$ (signal mostly due to ^{23}Na recoils).
- The inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support for f_n/f_p=1 low mass DM candidates either including or not the channeling effect.
- The case of isospin-conserving f_n/f_p=1 is well supported at different extent both at lower and larger mass.

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

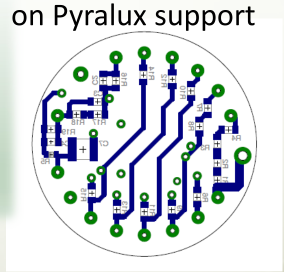
Enhancing experimental sensitivities and improving DM corollary aspects, other DM features, second order effects and other rare processes

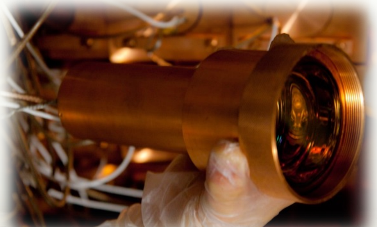
1) During fall 2021, DAMA/LIBRA–phase2 set-up was heavily upgraded
2) The upgrade basically consisted on:
   a. equipping all the PMTs with new low-background voltage dividers with pre-amps on the same board
   b. the use of Transient Digitizers with higher vertical resolution (14 bits).
3) After a dedicated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

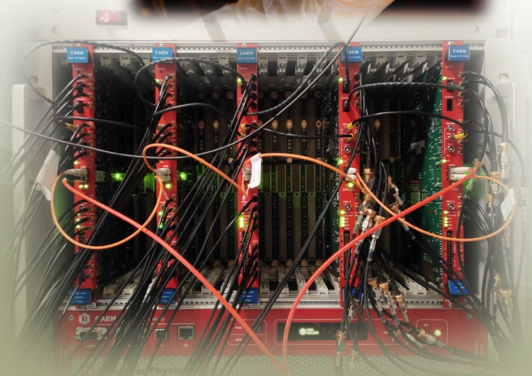




Voltage divider + preamp on Pyralux support







The features of the voltage divider+preamp system:

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

Shortly, daq is composed by 5 TD's, CAEN VME VX1730, dynamic range of 14 bit (that is vertical resolution of 0.122 mV/digit), vertical window of 2 V, sampling frequency of 500 MSa/s, 16 chs; the daq acquires three traces for each detector (the two PMTs and the high-energy sum of them). The read-out is made by a daisy-chain of optical fibers directly connected to the daq pc

Features of the DM signal

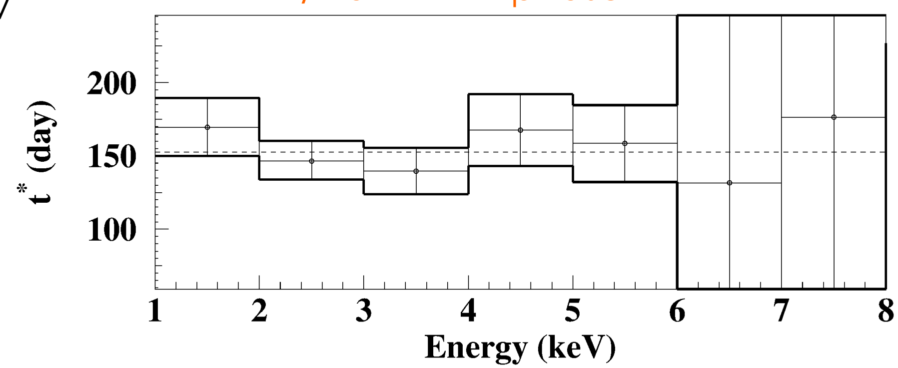
Investigated by the different stages of DAMA; improvements foreseen by DAMA/LIBRA-phase2-empowered with lower software energy threshold

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

High exposure and lower energy threshold can allow further investigation on:

- the nature of the DM candidates
- possible diurnal effects on the sidereal time
- astrophysical models

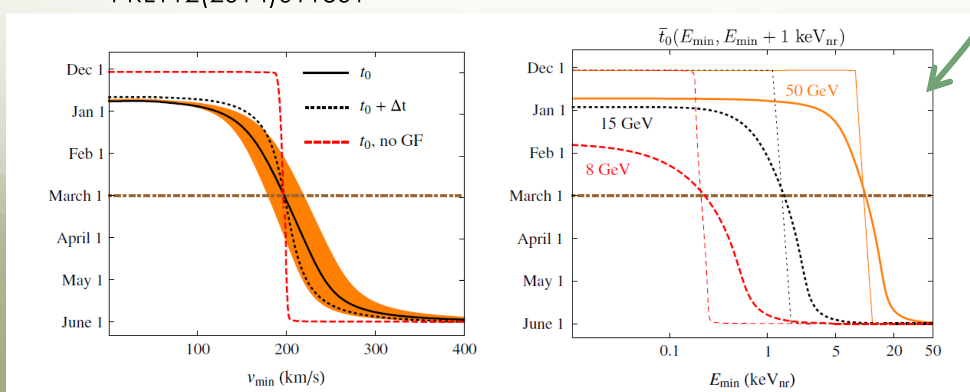
DAMA/NaI+LIBRA-phase2



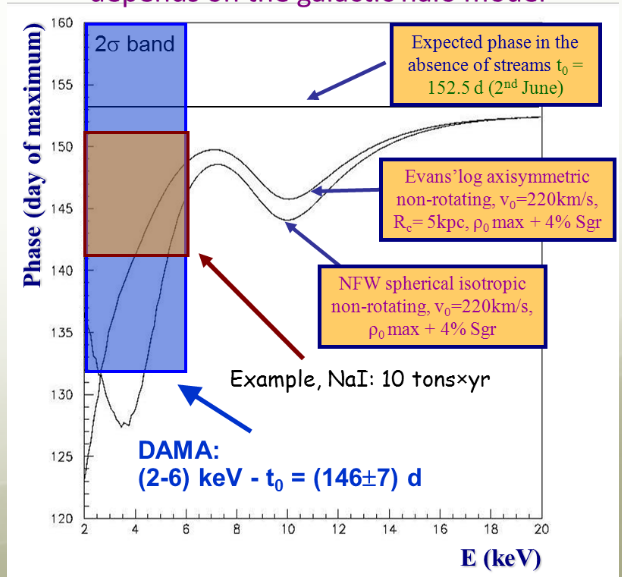
The annual modulation phase depends on :

- Presence of **streams** (as SagDEG and Canis Major) in the Galaxy
- Presence of **caustics**
- Effects of gravitational **focusing of the Sun**

PRL112(2014)011301



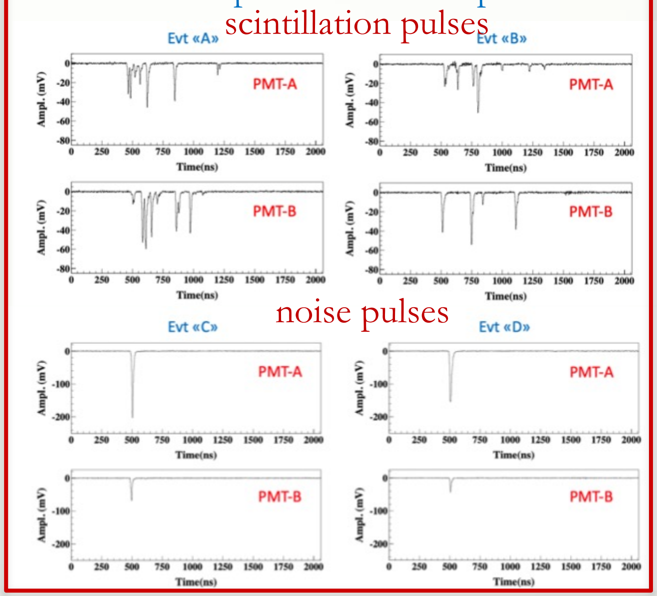
The effect of the streams on the phase depends on the galactic halo model



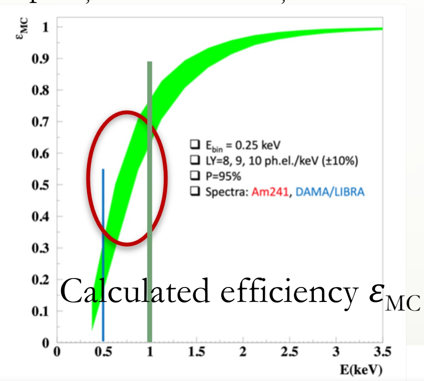
The software energy threshold is 0.5 keV with suitable efficiency

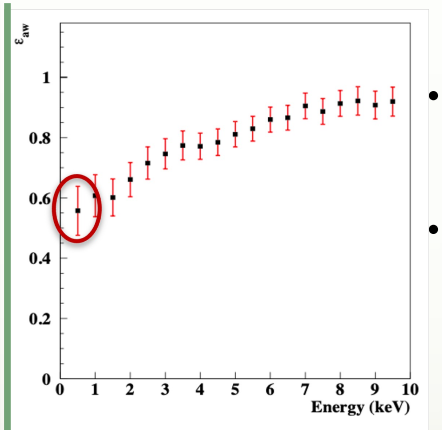
- Higher resolution (0.122 mV/digit) of the 14-bit TDs makes appreciable the improvements coming from the new voltage-dividers-plus-preamps on the same board in terms of baseline noise
- The distributions of the baselines show a very stable operational feature
- The baseline fluctuations are more than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



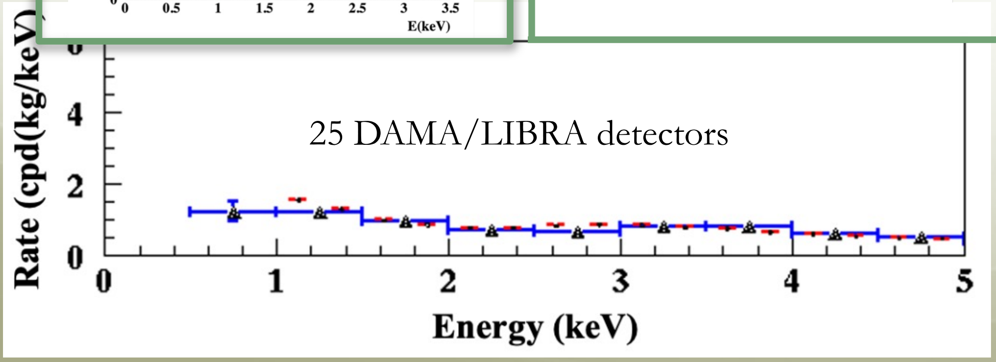
(#p.e.$_A$>1) .AND. (#p.e.$_B$>1)
#p.e.$_{A,B}$>1 → tm600$_{A,B}$> ~25 ns





- 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

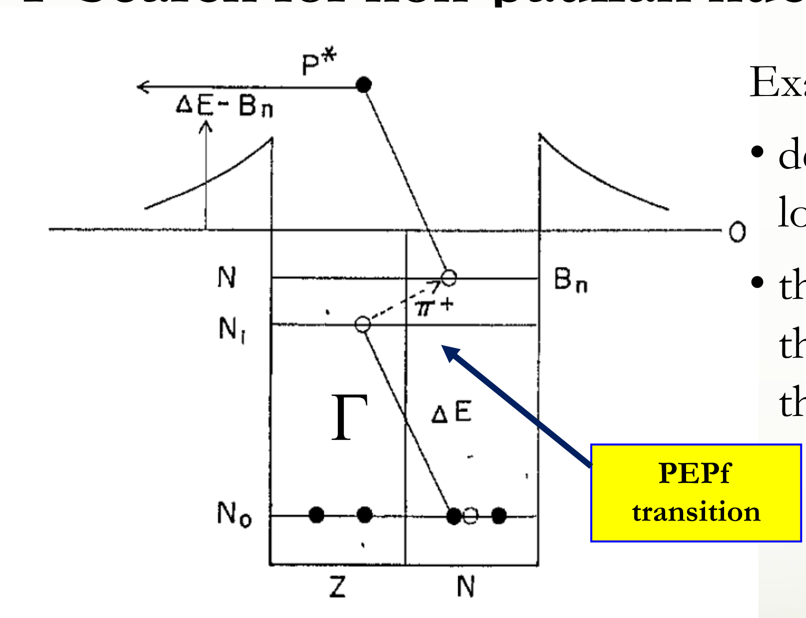


Energy spectrum of the *single-hit* scintillation events – already corrected for the efficiencies – in the new configuration (blue, exposure 2350 kg×d) and in DAMA/LIBRA–phase2 (red, the energy threshold was 1 keV, 1.53 ton×yr).

What can DAMA say about PEP violation?

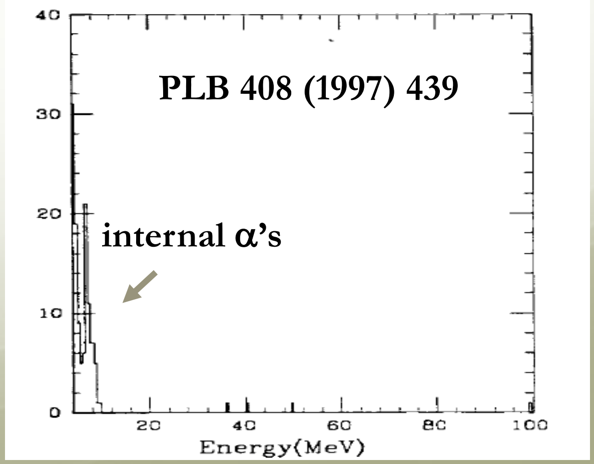
Underground experimental site and highly radiopure set-up allow to reduce background due to environmental radioactivity, increasing the sensitivity to **PEP forbidden transitions**

1–Search for non-paulian nuclear processes



Example of a process PEP violating:

- deexcitation of a nucleon from the shell N_i to the N_0 lower (full) shell
- the energy is converted to another nucleon at shell N through strong interaction, resulting to excitation to the unbound region (analogy: Auger emission)



This process was studied in 1997 with DAMA/NaI set-up obtaining a sensitivity of

$$\tau > 0.7 \times 10^{25} \text{ y for } ^{23}\text{Na (68\% C.L.)}$$

$$\tau > 0.9 \times 10^{25} \text{ y for } ^{127}\text{I (68\% C.L.)}$$

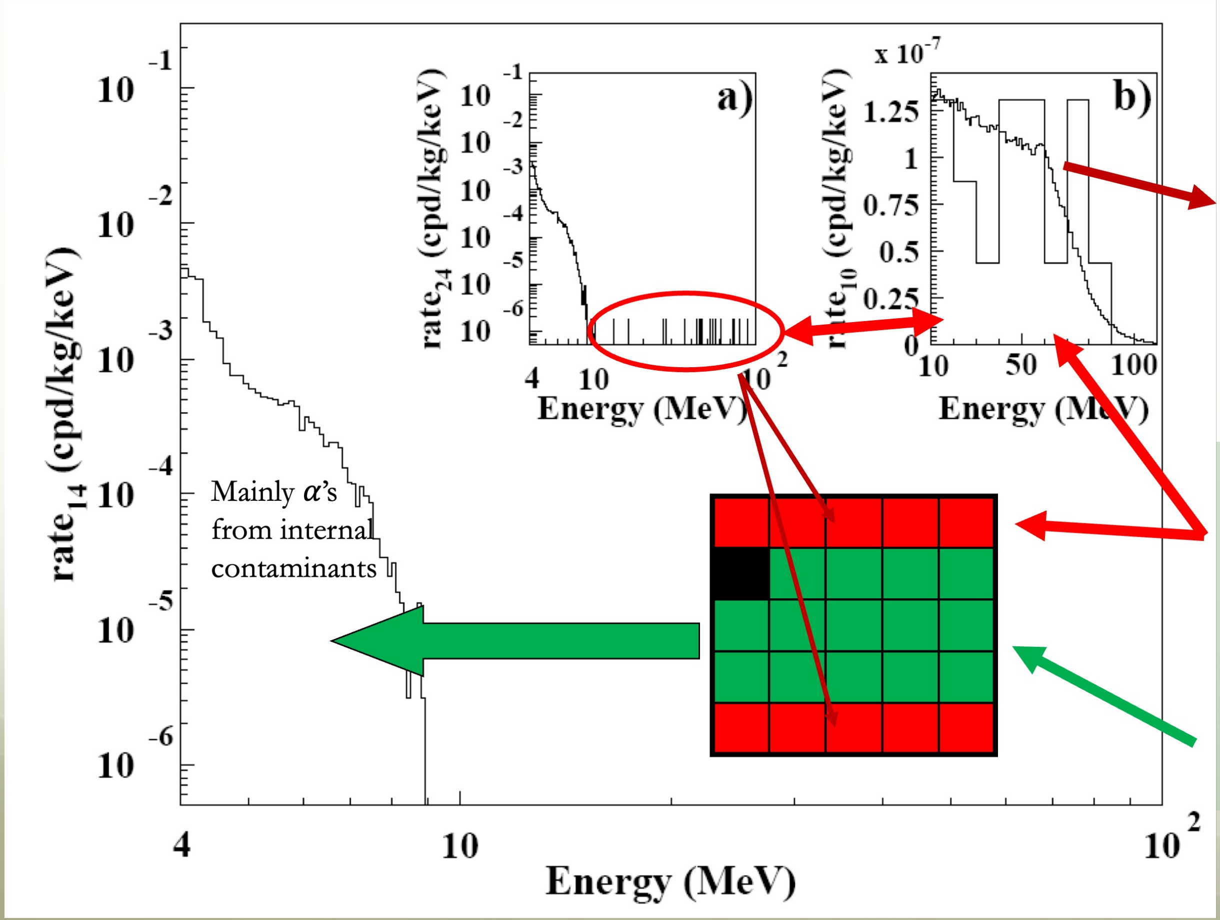
1–Search for non-paulian nuclear processes

EPJC 62 (2009) 327

570h running time of DAMA/LIBRA, optimized for very high energy

Above 10 MeV background due to very high energy muons possibly surviving the mountain.

For PEP violating nuclear processes: events where just one detector fires



Continous line: bckg muon events evaluated by MC not present in the inner core (veto)

For E > 10 MeV:

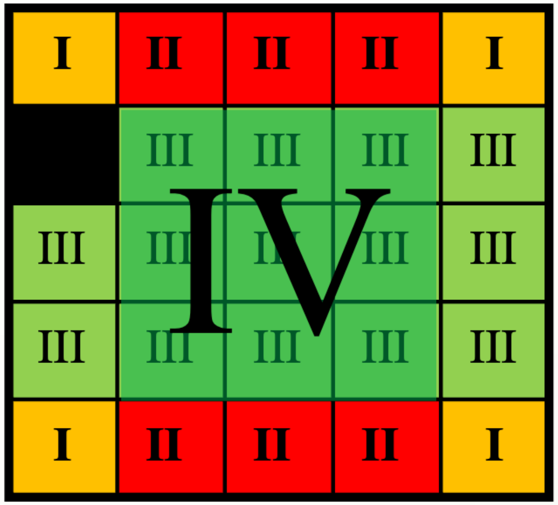
17 events in the upper/lower plane of detector (10 cryst.)

0 events in the central planes of detector (14 cryst.)

1–Search for non-paulian nuclear processes

EPJC 62 (2009) 327

Group (J) of considered detectors	Corresponding exposure ($N_J t$) (nuclei × s)	Expected background events (b_J)	Measured events (n_J)	Upper Limit on λ (90% C.L.) (s^{-1})
Just the 4 detectors at corners (I)	3.2×10^{32}	12.1	11	1.99×10^{-32}
Just the remaining 6 detectors in the upper and lower rows (II)	4.8×10^{32}	8.7	6	9.33×10^{-33}
Just the 14 central detectors (III)	1.1×10^{33}	2.2	0	2.06×10^{-33}
Just the 9 core detectors (IV)	7.2×10^{32}	0.057	0	3.19×10^{-33}
Combined analysis (I+II+III):				1.63×10^{-33}



$$\Gamma = \Gamma(^{23}Na) + \Gamma(^{127}I) = \hbar\lambda \leq 1.1 \times 10^{-54}\, MeV$$

The width of a single nucleon transition to the i[th] occupied state, Γ_i, can be expressed as

$$\Gamma_i = \delta_i^2 \tilde{\Gamma}_i$$

- δ_i is the mixing probability of non-fermion statistics allowing for the transition to the occupied state i;
- $\tilde{\Gamma}_i$ is the width of the corresponding PEP-allowed transition whenever the final state would be empty

Calculated within the Nuclear Physics framework

PEP violation "grade"

Case	^AX	$\tilde{\Gamma}$ (MeV)	δ^2 Upper Limit (90% C.L.)
a)	^{23}Na	1.65	1.7×10^{-55}
	^{127}I	4.64	
b)	^{23}Na	4.59	6.8×10^{-56}
	^{127}I	11.1	

a) Fermi momentum distribution with $k_F = 255$ MeV/c

b) Adopting the ^{56}Fe momentum distribution accounting for correlation effects

Lower limit on the mean life for non-paulian proton emission in frame b) (90% C.L.):

$\tau > 2 \times 10^{25}$ y for ^{23}Na

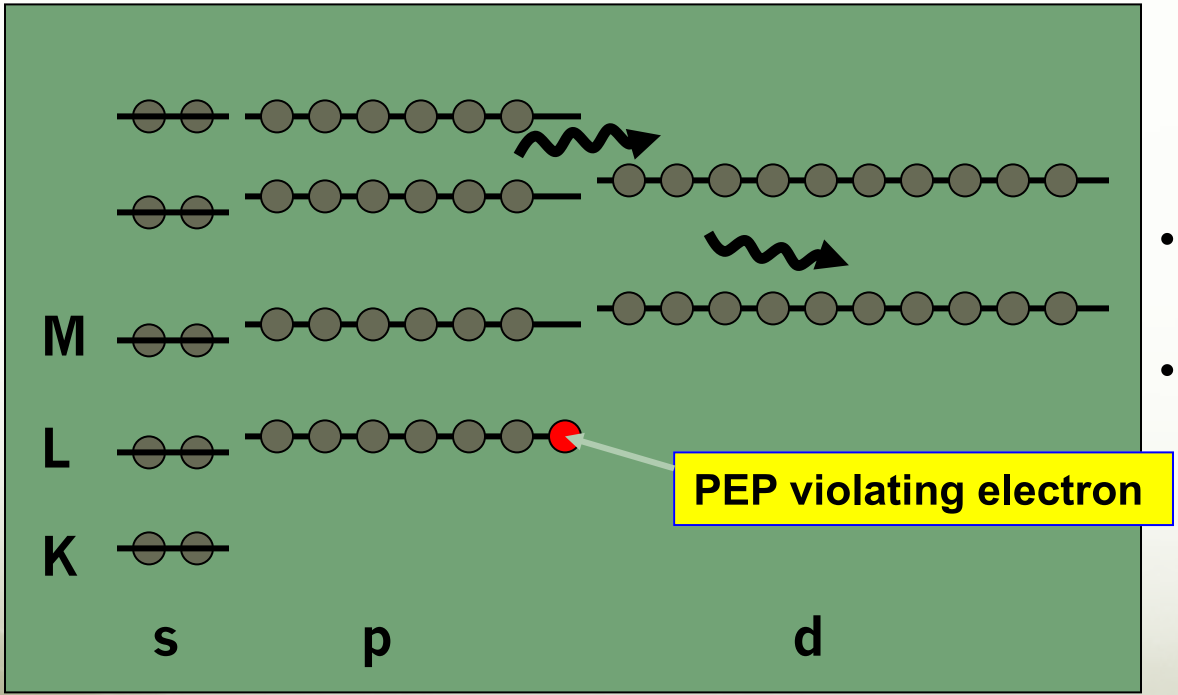
$\tau > 2.5 \times 10^{25}$ y for ^{127}I

cautious approach:

$$\delta^2 \lesssim 3 - 4 \times 10^{-55}$$

2–Search for PEP-violating electron transitions in atoms

- K and L shells of ^{127}I atoms were considered.
- The electron atomic transitions of ^{23}Na atoms are below or close to the experimental energy threshold of DAMA/LIBRA, thus only the case of electron atomic transitions of iodine atoms was considered.



Case of the L-shell of ^{127}I

- Electronic configuration schema of I anion (54 electrons) in $Na^{+}I^{-}$ crystal
- The total released energy (X-ray + Auger electrons) is approximately equal to L-shell ionization potential (≈ 5 keV)

2–Search for PEP-violating electron transitions in atoms

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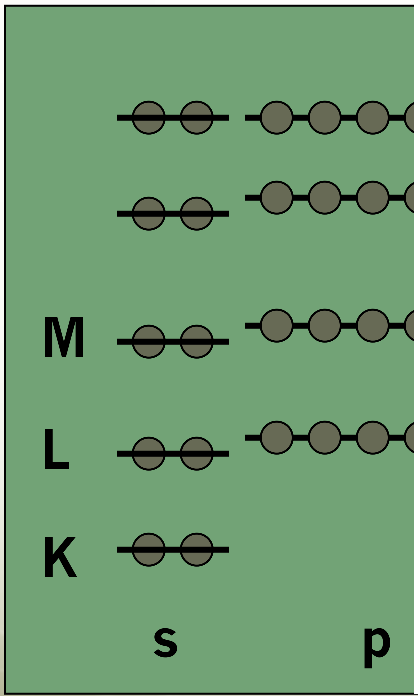

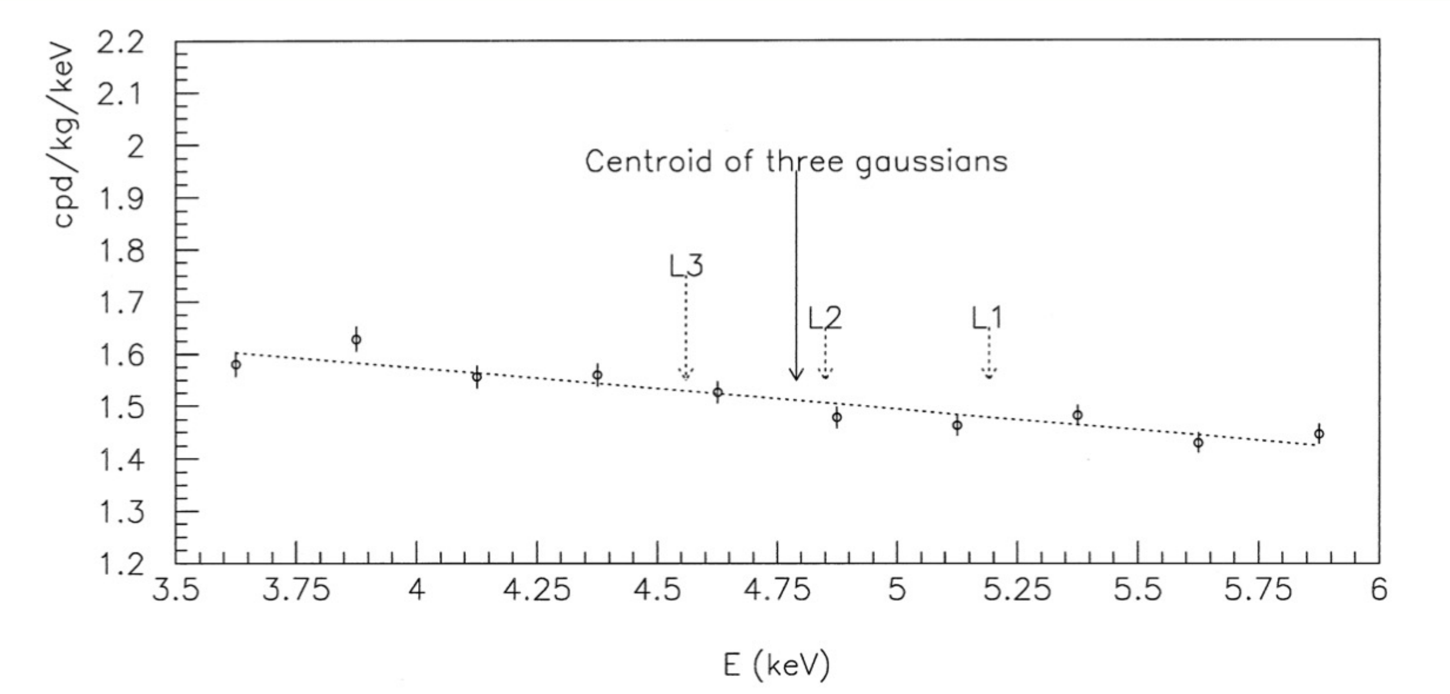

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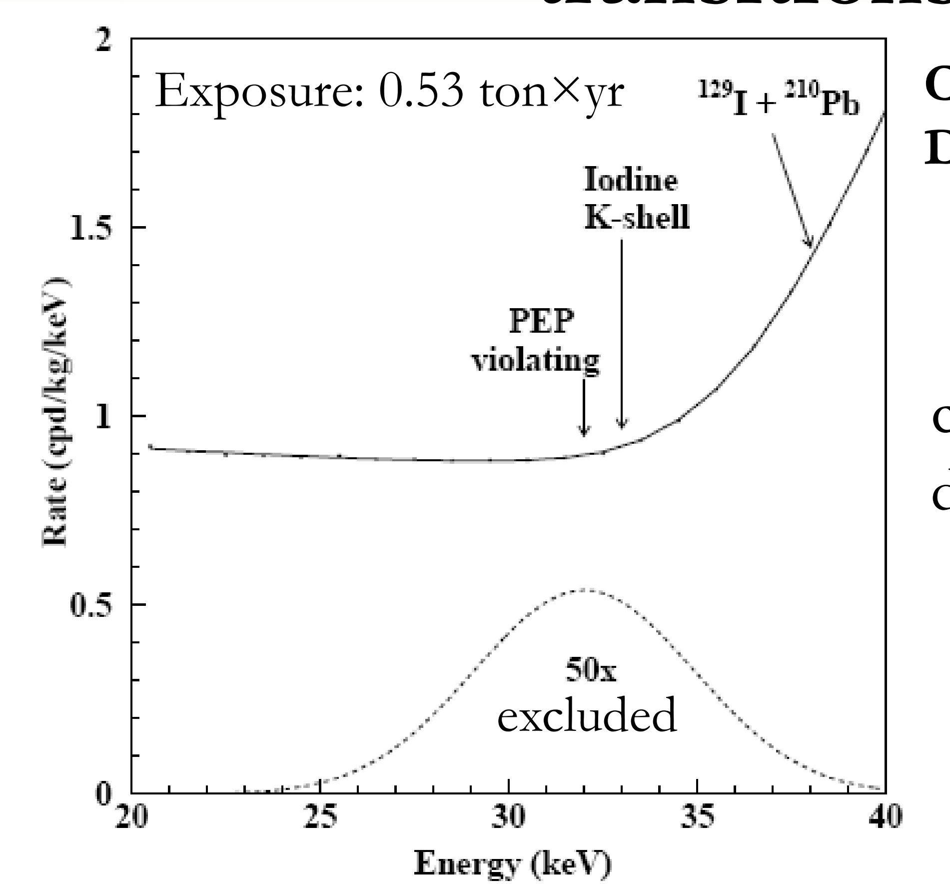
The process was studied in DAMA/NaI obtaining the sensitivity:
$\tau > 4.2 \times 10^{24}$ yr (68% C.L.) [PLB 460 (1999) 236]

2–Search for PEP-violating electron transitions in atoms



Case of the K-shell of ^{127}I, by DAMA/LIBRA **EPJC 62 (2009) 327**

$$\tau_{PV} > 4.7 \times 10^{30}\ \text{s (90\% C.L.)}$$

$$\tau^0 = \delta_e^2 \tau_{PV}$$

considering normal electromagnetic dipole transition to Iodine K-shell:

$$\tau^0 \approx 6 \times 10^{-17}\ \text{s}$$

$$\delta_e^2 < 1.28 \times 10^{-47}\ \text{(90\% CL)}$$

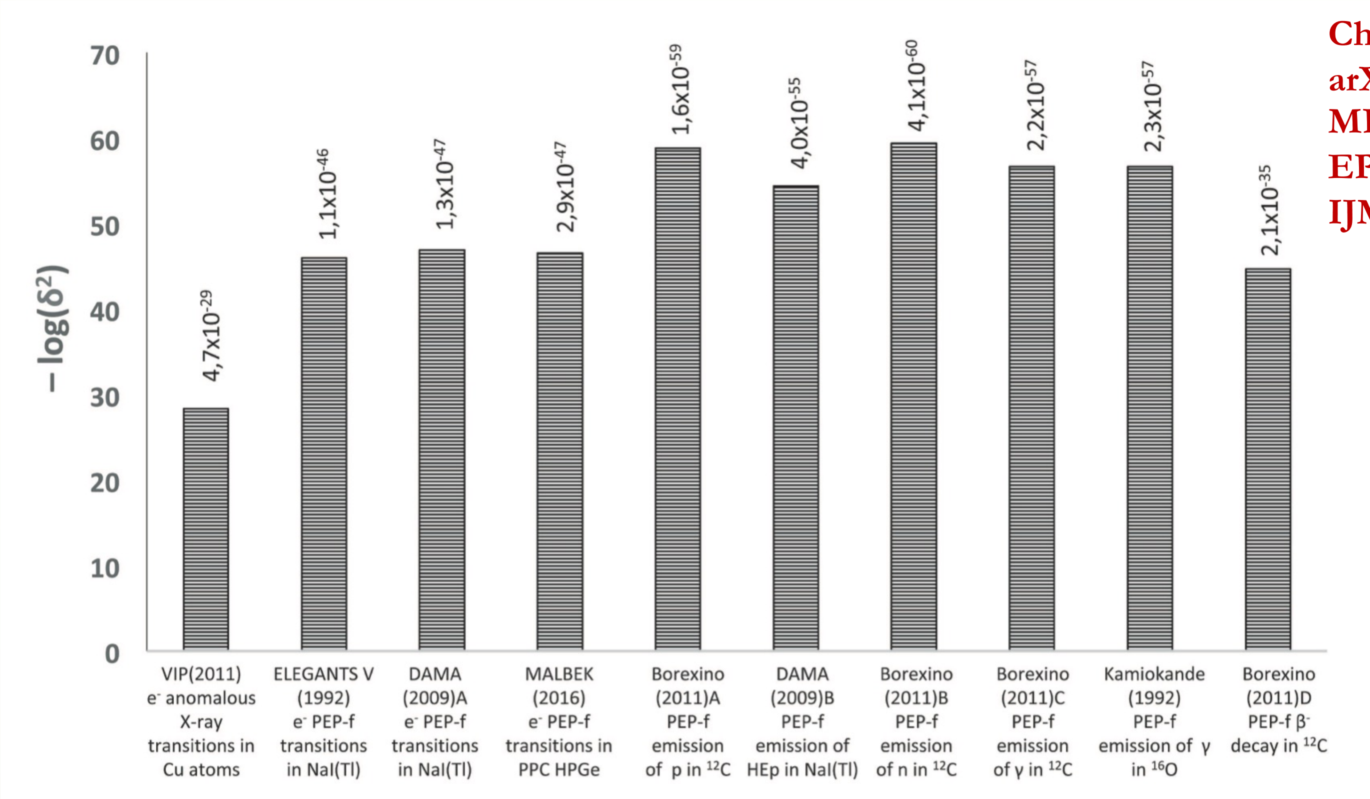
one order of magnitude more stringent than the limits available at that time

This limit can also be related to a possible finite size of the electron in composite models of quarks and leptons providing superficial violation of the PEP [PRL 68(1992)1826]

$$\delta_e^2 = \left[\frac{4}{3}\left(\frac{3}{7}\right)^5\left(\frac{Zr_0}{a_0}\right)^3\right]^2$$

The obtained upper limit on the electron size is: **r_0 < 5.7×10^{-18} cm** (energy scale E > 3.5 TeV)

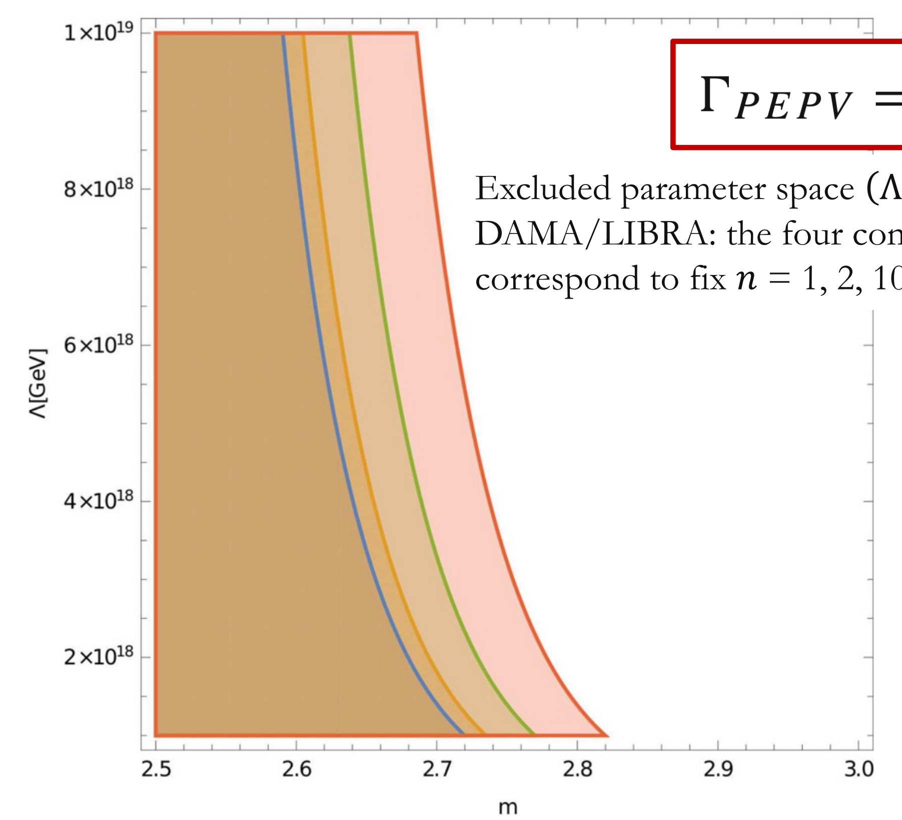
Limits (90% CL) on various PEP-violating channels



Chin. Phys. C 42 (2018) 094001
arXiv:1901.00390
MPLA 34 (2019) 1950236
EPJC 80 (2020) 795
IJMPA 35 (2020) 2042001

- A large class of non-perturbative Generalized Uncertainty Principles (GUP) inevitably leads to:
  - energy-dependent violations of the total angular momentum conservation rule
  - a tiny Pauli Exclusion Principle (PEP) violating transitions
- Bounds from PEP violation already rule out several GUP violations up to the quantum gravity Planck scale.

Limits (90% CL) on various PEP-violating channels



$$\Gamma_{PEPV} = n(\Lambda^{-1}P)^m \Gamma_{SM}$$

Excluded parameter space (Λ, m) from DAMA/LIBRA: the four contour limits correspond to fix $n = 1, 2, 10, 100$

Chin. Phys. C 42 (2018) 094001
arXiv:1901.00390
MPLA 34 (2019) 1950236
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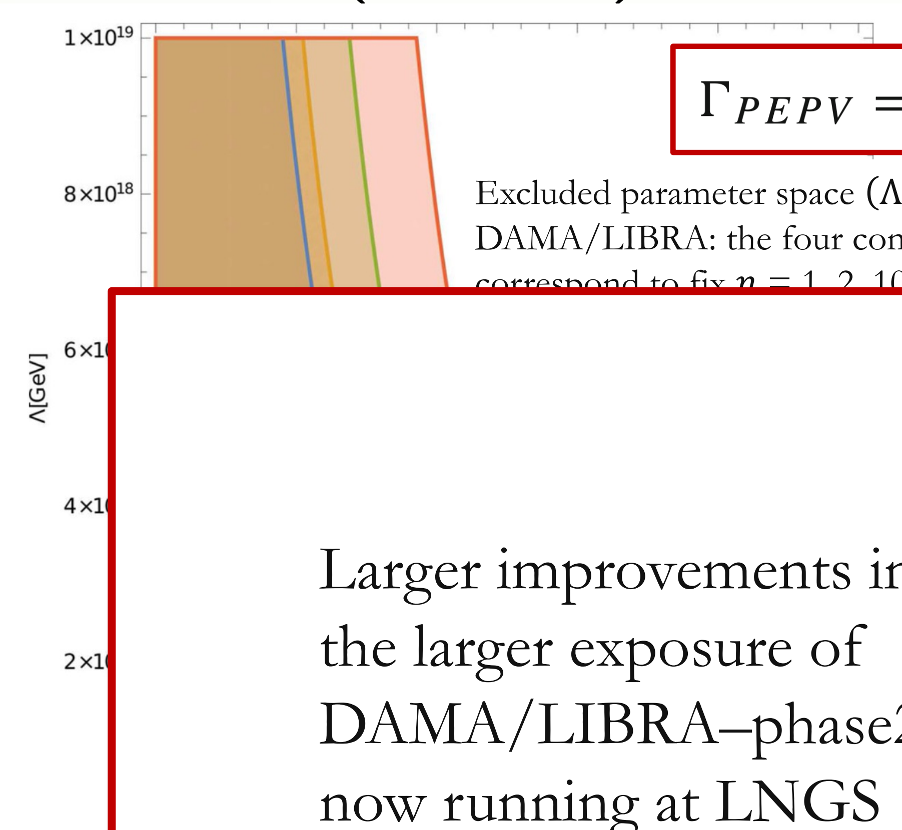
IJMPA 35 (2020) 2042001

- Very remarkably a large part of parameter space is already excluded at energies above the Planck scale and, in particular, for $m \lesssim 2.7$ nearly independently on the n value.
- The case $n = m = 1$ is already ruled out up to the Planck scale

Test of PEP violations from noncommutative quantum gravity:

- In atomic transitions → strong constraints on the noncommutative scale. In the magnetic-like θ-Poincaré scenario, $\Lambda < 10^{18}$ GeV is excluded
- In the electric-like phase, the limit is less stringent than the magnetic-like case, but still arriving to very high scale: $\Lambda > 5 \times 10^{16}$ GeV
- The most stringent bounds are from nuclear transitions. Such bounds rule out both the electric and the magnetic-like θ-Poincaré models with a noncommutative scale at the Planck scale energy

Limits (90% CL) on various PEP-violating channels



$$\Gamma_{PEPV} = n(\Lambda^{-1}P)^{m}\Gamma_{SM}$$

Excluded parameter space (Λ, m) from DAMA/LIBRA: the four contour limits correspond to fix $n = 1, 2, 10, 100$

Chin. Phys. C 42 (2018) 094001
arXiv:1901.00390
MPLA 34 (2019) 1950236
EPJC 80 (2020) 795
IJMPA 35 (2020) 2042001

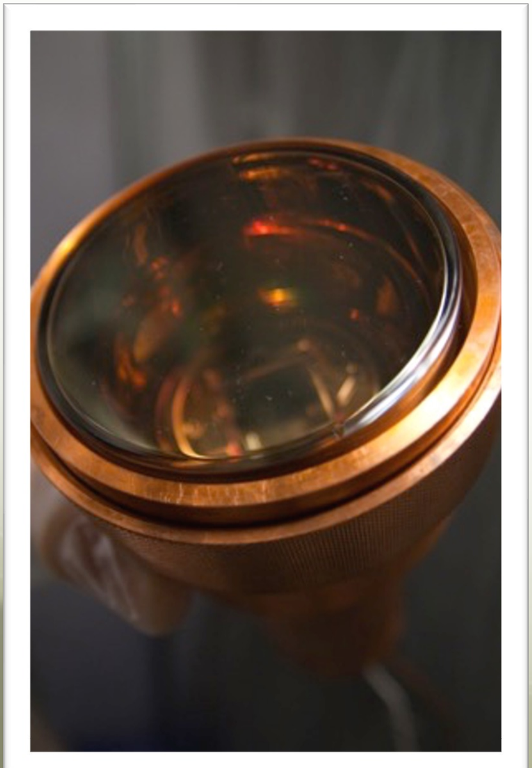
Larger improvements in the bounds can be set by the larger exposure of DAMA/LIBRA–phase2-empowered, now running at LNGS

but still arriving to very high scale: $\Lambda > 5 \times 10^{16}$ GeV

- The most stringent bounds are from nuclear transitions. Such bounds rule out both the electric and the magnetic-like θ-Poincaré models with a noncommutative scale at the Planck scale energy

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: lower software **energy threshold of 0.5 keV with suitable efficiency**. New divider/amp systems and new 14bit digitizers installed.
- DAMA/LIBRA–phase2 empowered **running**
- Works to improve the bounds in **PEP violations studies**
- Continuing investigations of **rare processes** other than DM
- Other pursued ideas: **$ZnWO_4$ anisotropic scintillator** for DM **directionality**. Response to nuclear recoils measured.