First model-independent results by DAMA/LIBRA-phase2

Seventh Workshop on Theory, Phenomenology and Experiments in Flavour Physics
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R. Bernabei
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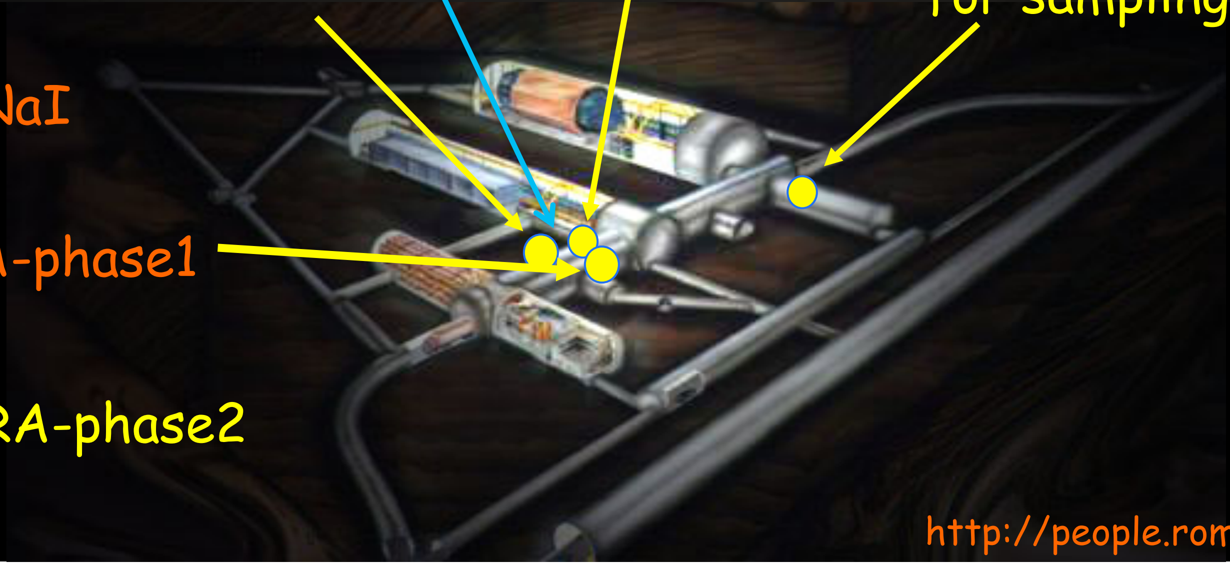
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

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

DAMA: an observatory for rare processes @LNGS



http://people.roma2.infn.it/dama

Relic DM particles from primordial Universe

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…

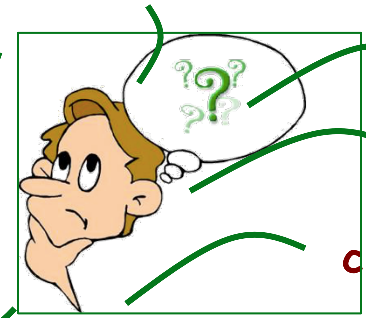
+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

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

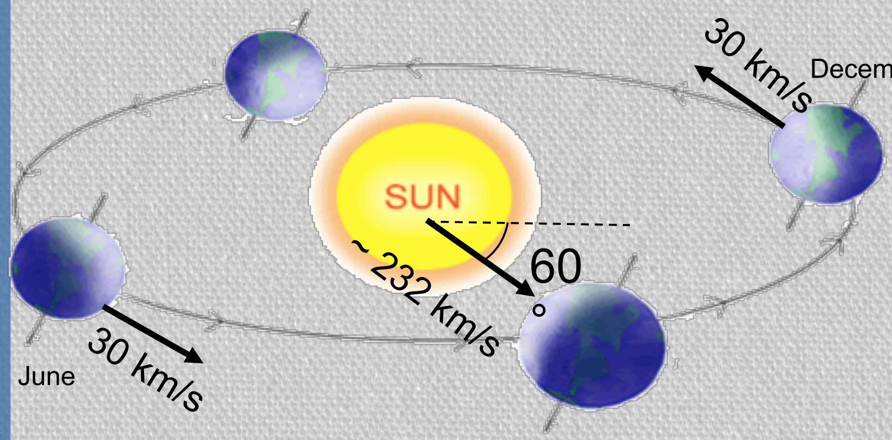
The DM annual modulation: a model independent signature to investigate the DM particles component in the galactic halo

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 of the DM annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

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



- v_{sun} ~ 232 km/s (Sun vel in the halo)
- v_{orb} = 30 km/s (Earth vel around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

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

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

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

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

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

Performances:

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

Results on rare processes:

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

data taking completed on July 2002, last data release 2003. Still producing results

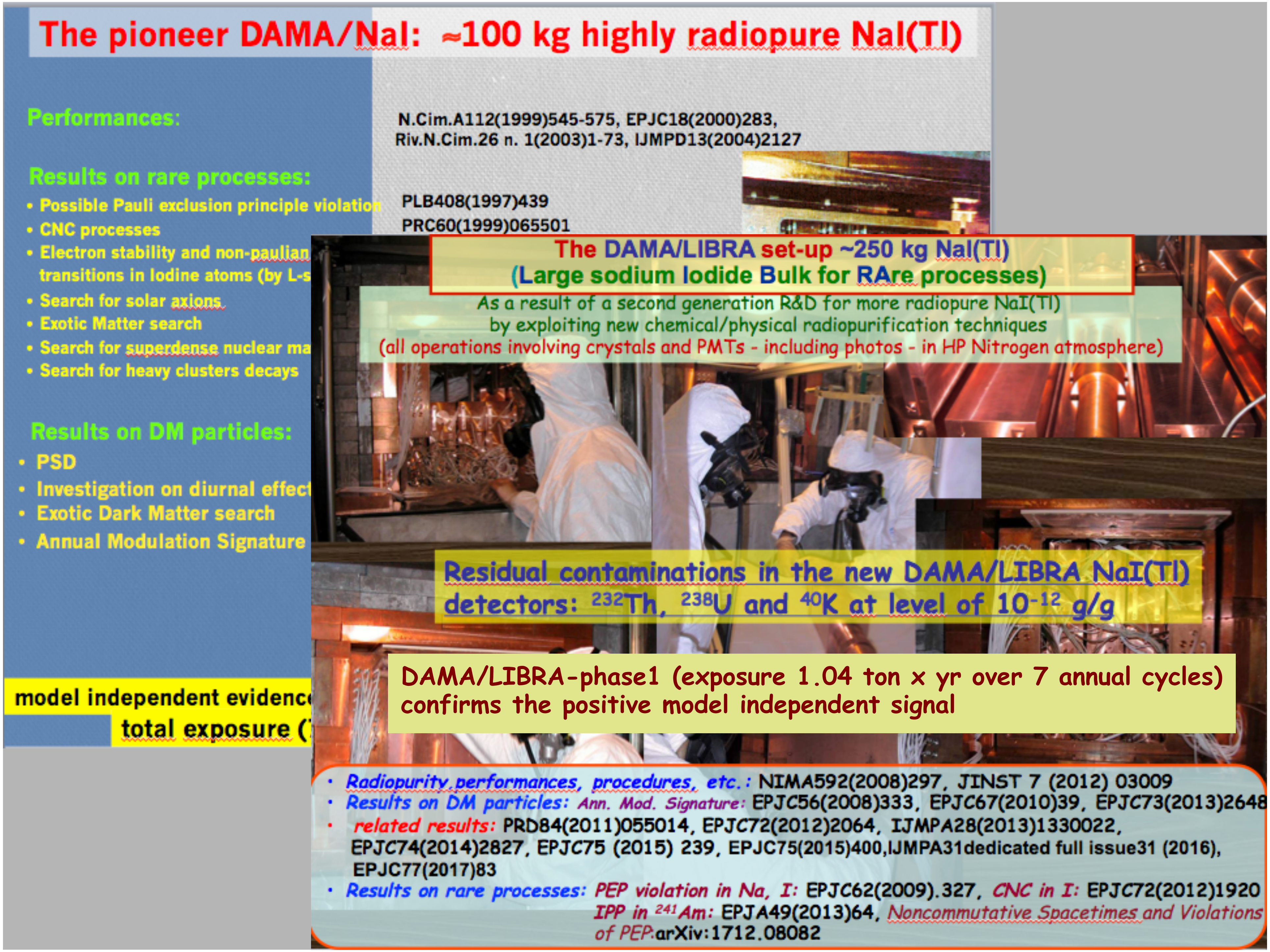
Results on DM particles:

- 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 6.3σ C.L.

total exposure (7 annual cycles) 0.29 ton × yr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Results on DM particles:
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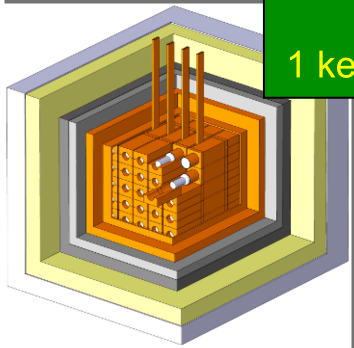
total exposure (
The DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)
As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP 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
DAMA/LIBRA-phase1 (exposure 1.04 ton x yr over 7 annual cycles) confirms the positive model independent signal
• Radiopurity,performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
• Results on DM particles: Ann. Mod. Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648
• related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC75 (2015) 239, EPJC75(2015)400,IJMPA31dedicated full issue31 (2016), EPJC77(2017)83
• Results on rare processes: PEP violation in Na, I: EPJC62(2009).327, CNC in I: EPJC72(2012)1920
IPP in ^{241}Am: EPJA49(2013)64, Noncommutative Spacetimes and Violations of PEP:arXiv:1712.08082

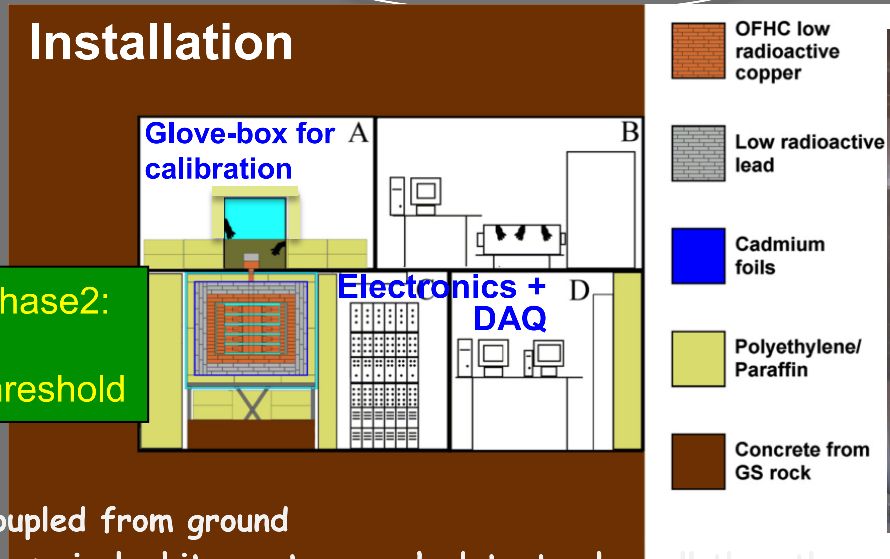
The DAMA/LIBRA-phase2 set-up

For details, radiopurity, performances, procedures, etc.
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 working in coincidence at the single ph. el. threshold



Typical DAMA/LIBRA-phase2:
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 production 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 Waweform Analyzer Acqiris DC270 (2chs per detector), 1 *Gsample/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 was done for the low energy
- DAQ with optical readout
- Some new electronic modules

DAMA/LIBRA – phase2

JINST 7(2012)03009

After a period of tests and optimizations in data taking in this new configuration

more IJMPA28(2013)1330022

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

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

DAMA/LIBRA – phase2

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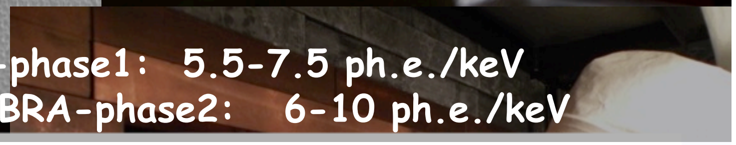
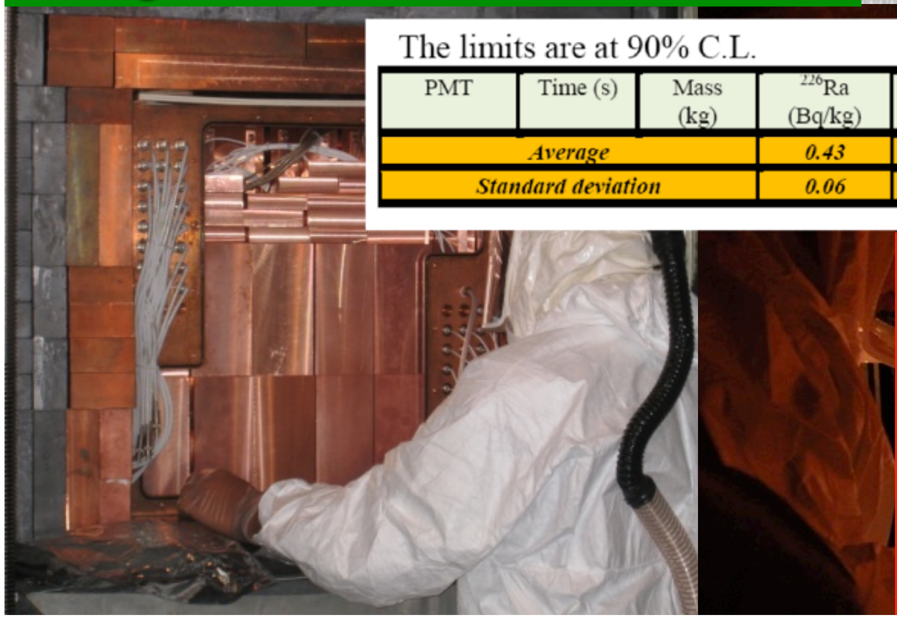


The limits are at 90% C.L.

PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
Average			*0.43*	*-*	*47*	*0.12*	*83*	*0.54*	*-*	*-*
Standard deviation			*0.06*	*-*	*10*	*0,02*	*17*	*0.16*	*-*	*-*



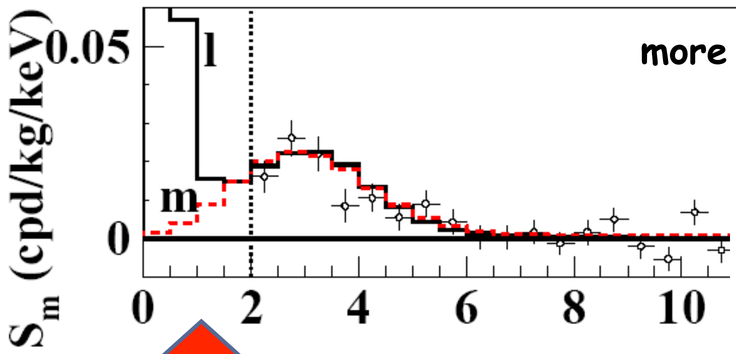
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes

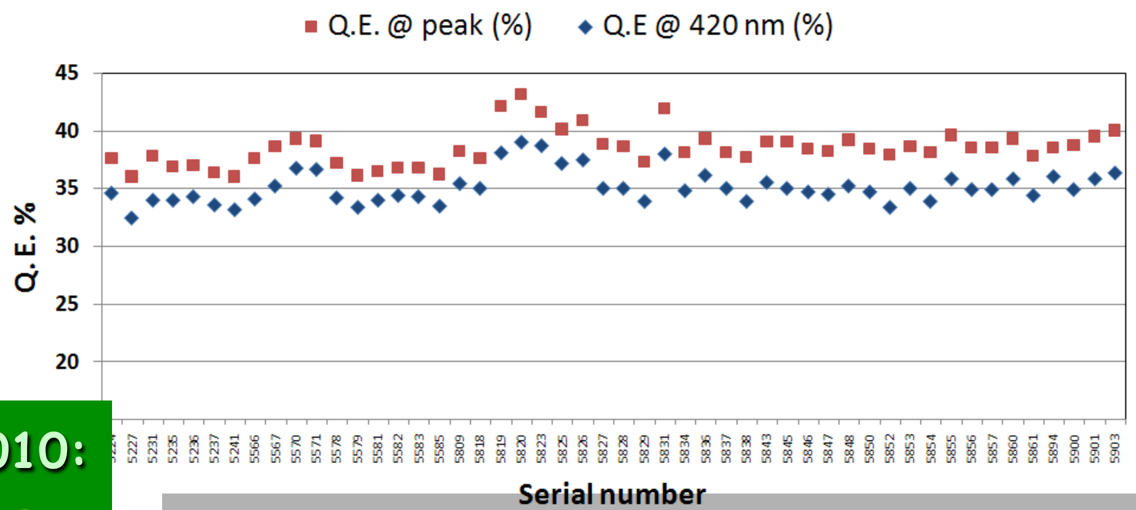
+ R&D in progress towards more future phase3

DAMA/LIBRA – phase2

JINST 7(2012)03009

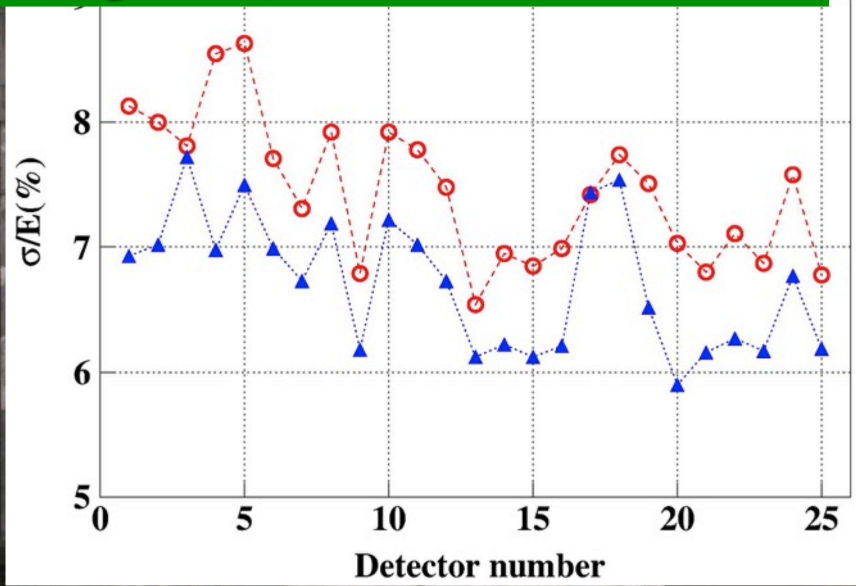
After a period of tests and optimizations in data taking in this new configuration





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

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



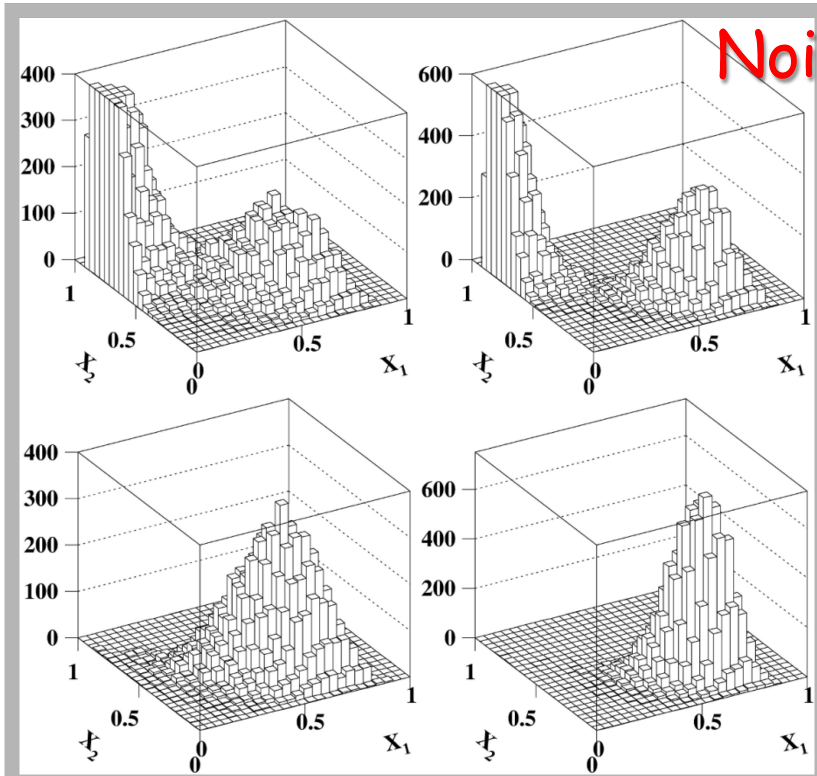
^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
-	47	0.12	83	0.54	-	-
-	10	0,02	17	0.16	-	-

- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes

\+ R&D in progress towards more future phase3

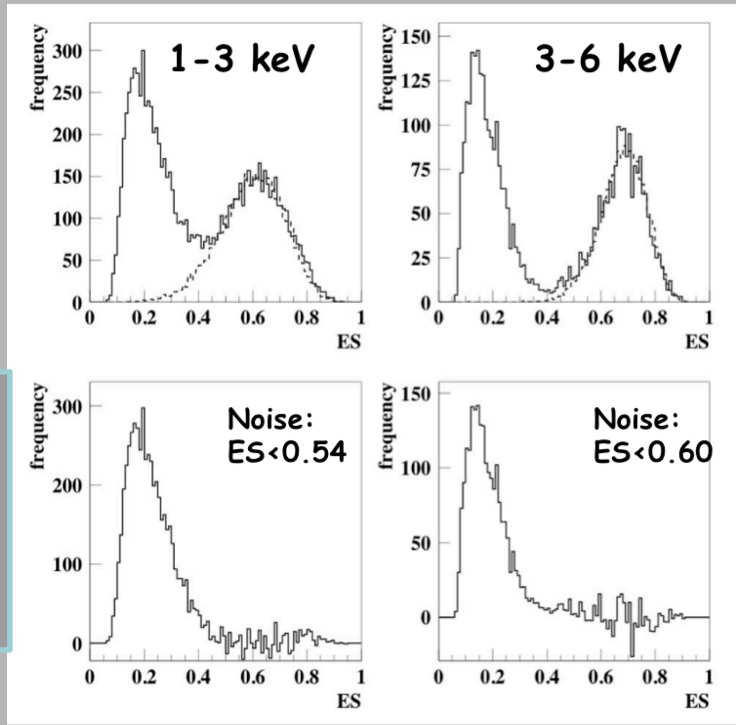
Noise rejection in phase2

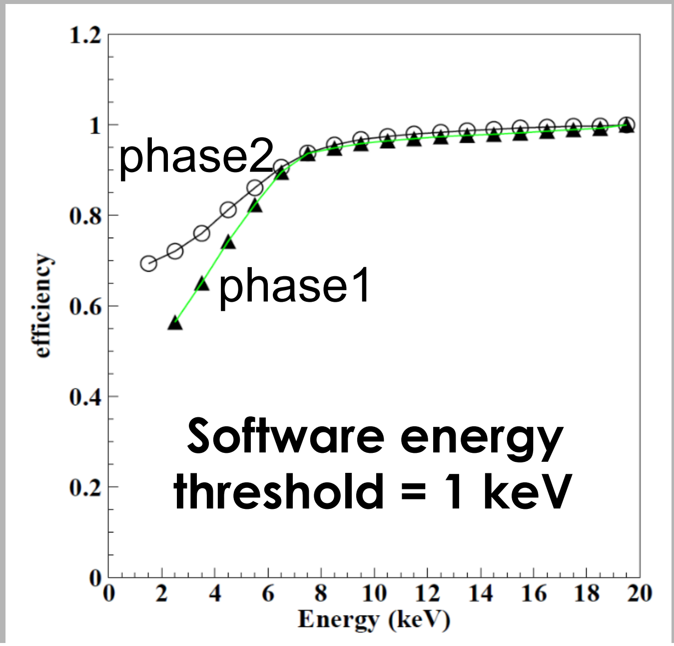
JINST 7(2012)03009



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

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





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

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

DAMA/LIBRA-phase2 data taking

Second upgrade at end of 2010:
all PMTs replaced with new ones of higher Q.E.

arXiv:1805.10486
JINST 7(2012)03009

Energy resolution @ 60 keV mean value:
prev. PMTs 7.5% (0.6% RMS)
new HQE PMTs 6.7% (0.5% RMS)

- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 6 a.c.: ≈ 1.3 x 10^8 events from sources
- ✓ Acceptance window eff. 6 a.c.: ≈ 3.4 x 10^6 events (≈1.4 x 10^5 events/keV)

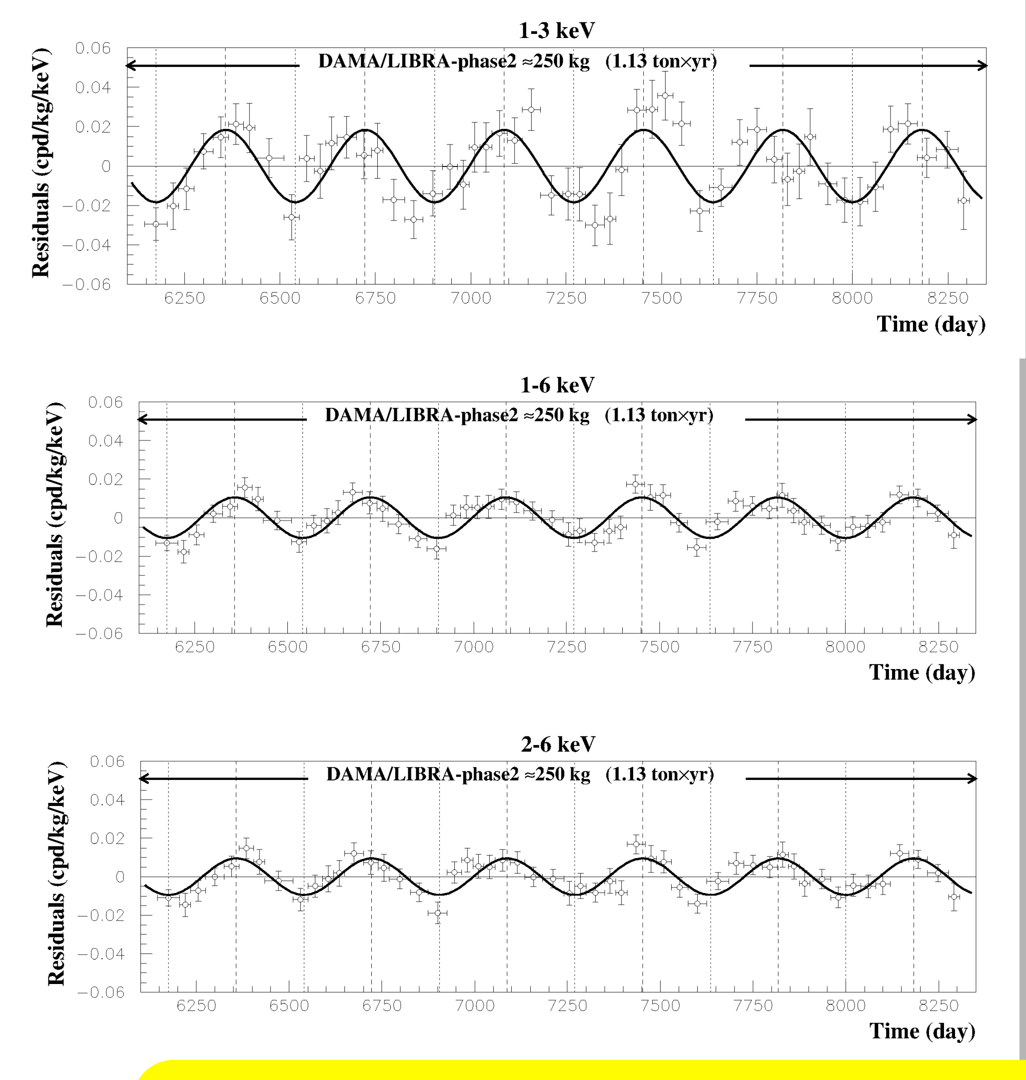
Annual Cycles	Period	Mass (kg)	Exposure	$(\alpha-\beta^2)$
I	Dec 23, 2010 - Sept. 9, 2011	commissioning		
II	Nov. 2, 2011 - Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 - Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 - Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 - Sept. 9, 2015	242.5	71180	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

Exposure first data release of DAMA/LIBRA-phase2: **1.13 ton x yr**
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.46 ton x yr**

DM Model Independent Annual Modulation Result

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

DAMA/LIBRA-phase2 (1.13 ton × yr)



Absence of modulation? No

- 1-3 keV: χ^2/dof=127/52 ⇒ P(A=0) = 3×10^{-8}
- 1-6 keV: χ^2/dof=150/52 ⇒ P(A=0) = 2×10^{-11}
- 2-6 keV: χ^2/dof=116/52 ⇒ P(A=0) = 8×10^{-7}

Fit on DAMA/LIBRA-phase2

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

1-3 keV

A=(0.0184±0.0023) cpd/kg/keV
χ^2/dof = 61.3/51 **8.0 σ C.L.**

1-6 keV

A=(0.0105±0.0011) cpd/kg/keV
χ^2/dof = 50.0/51 **9.5 σ C.L.**

2-6 keV

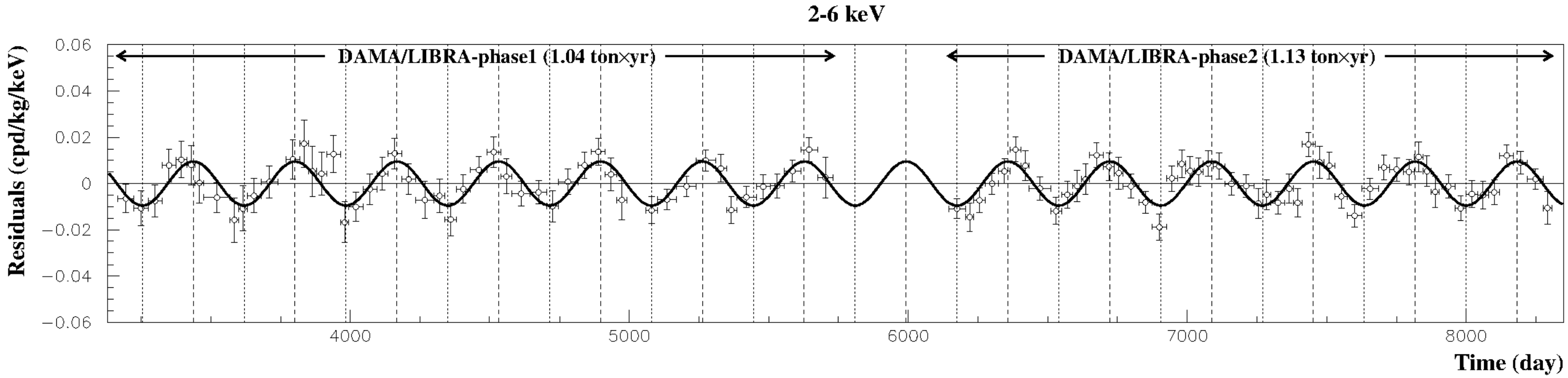
A=(0.0095±0.0011) cpd/kg/keV
χ^2/dof = 42.5/51 **8.6 σ C.L.**

The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 9.5σ C.L.

Model Independent DM Annual Modulation Result

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

DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.17 ton × yr)



Absence of modulation? No

- 2-6 keV: χ^2/dof=199.3/102 ⇒ P(A=0) =2.9×10^{-8}

Fit on DAMA/LIBRA-phase1+ DAMA/LIBRA-phase2

Acos[$\omega(t-t_0)$] ;
continuous lines: t_0 = 152.5 d, T = 1.00 y

2-6 keV

A=(0.0095±0.0008) cpd/kg/keV

χ^2/dof = 71.8/101 **11.9σ C.L.**

The data of DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.9 σ C.L.

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

	ΔE	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0184±0.0023	1.0000±0.0010	153±7	8.0σ
	(1-6) keV	0.0106±0.0011	0.9993±0.0008	148±6	9.6σ
	(2-6) keV	0.0096±0.0011	0.9989±0.0010	145±7	8.7σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0096±0.0008	0.9987±0.0008	145±5	12.0σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0103±0.0008	0.9987±0.0008	145±5	12.9σ

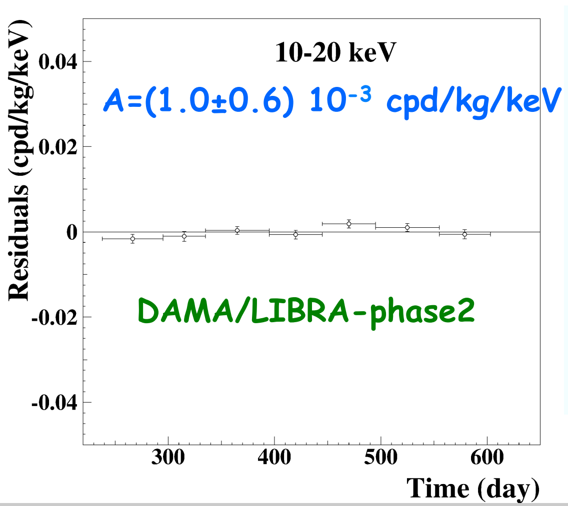
$A\cos[\omega(t-t_0)]$

DAMA/NaI (0.29 ton x yr) +
DAMA/LIBRA-ph1 (1.04 ton x yr) +
DAMA/LIBRA-ph2 (1.13 ton x yr)

total exposure = 2.46 ton×yr

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
→ statistically consistent with zero

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

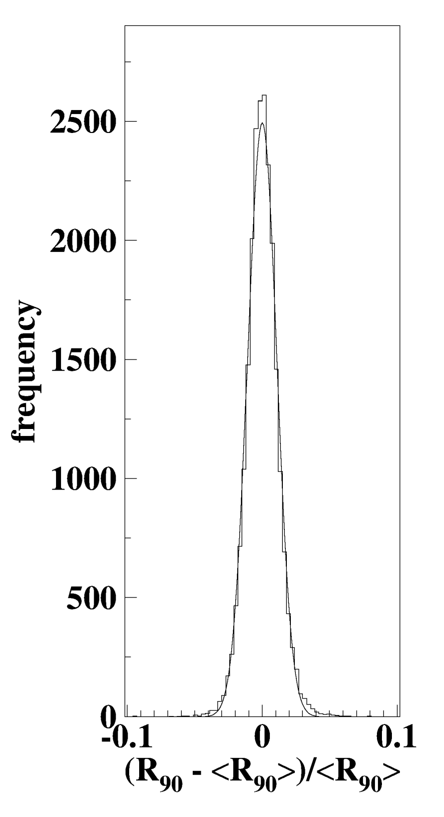
- R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods

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

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

consistent with zero

DAMA/LIBRA-phase2



$\sigma \approx 1\%$, fully accounted by statistical considerations

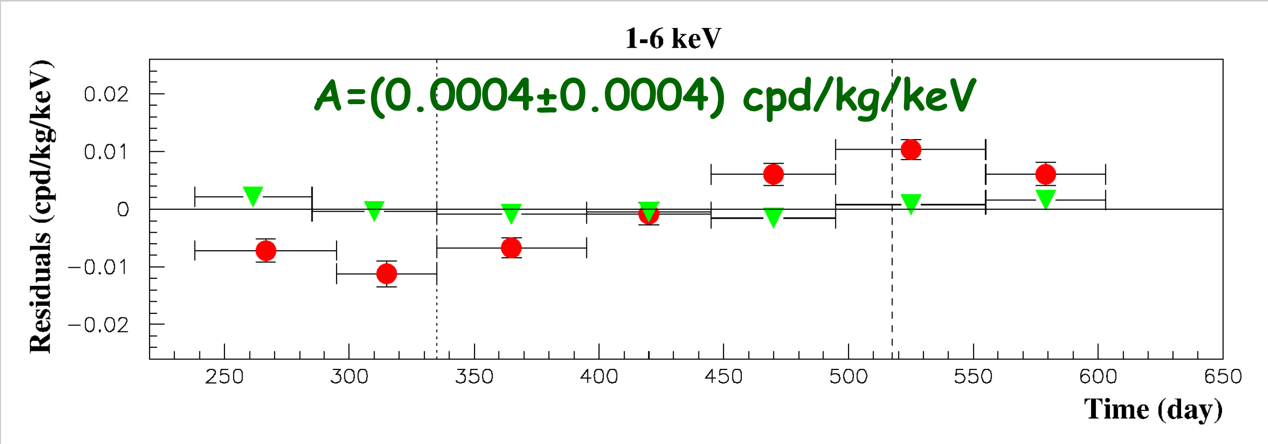
+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

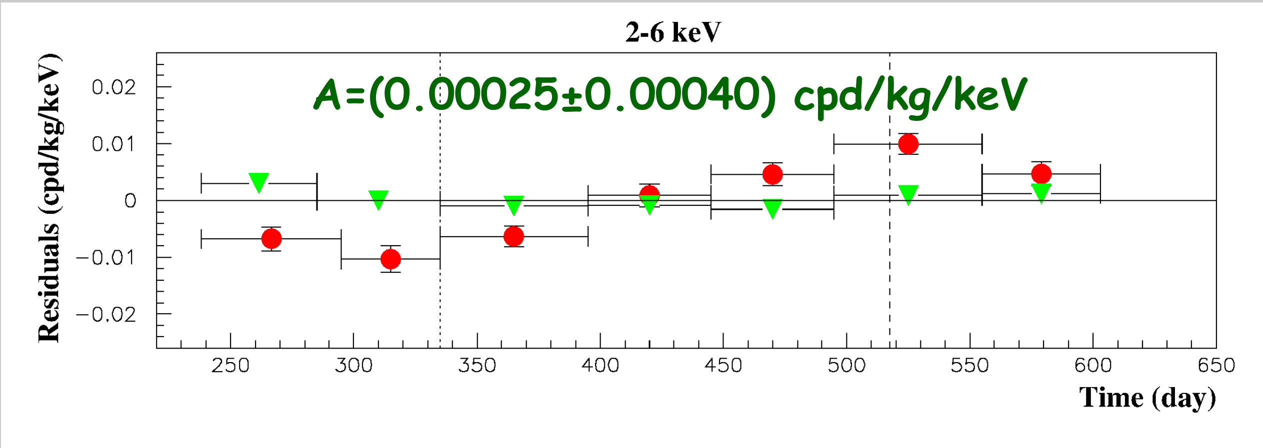
No modulation above 6 keV
This accounts for all sources of bckg and is consistent with the studies on the various components

DM Model Independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.13 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

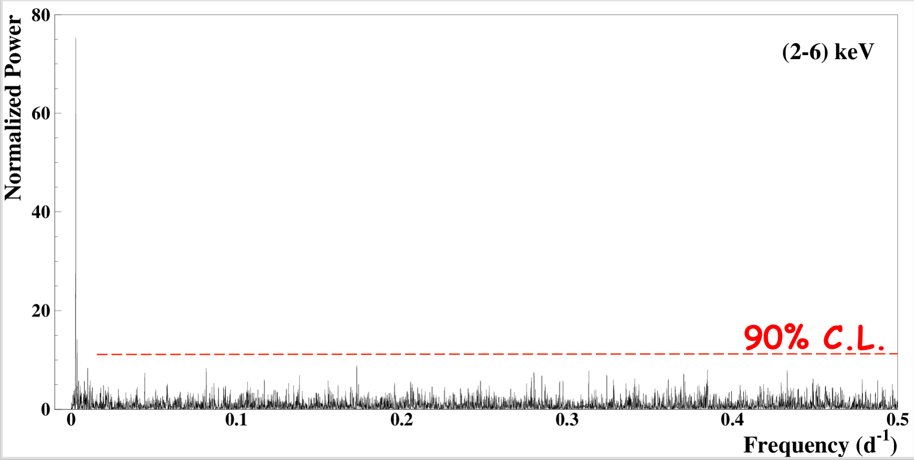
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

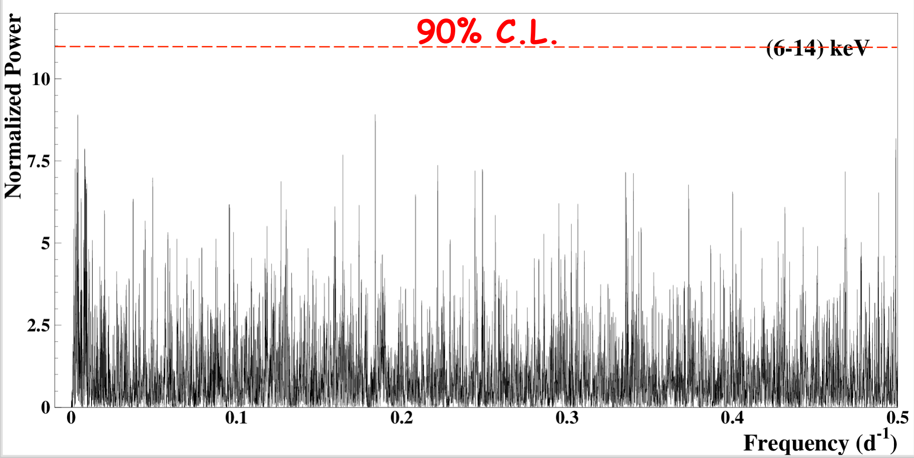
The analysis in frequency

(according to Phys. Rev. D 75 (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

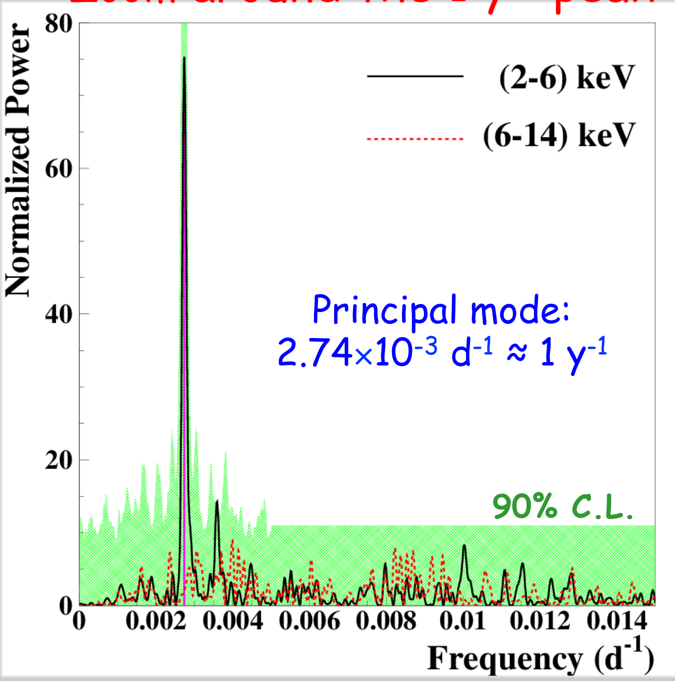
The whole power spectra up to the Nyquist





DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (20 yr)
total exposure: 2.46 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

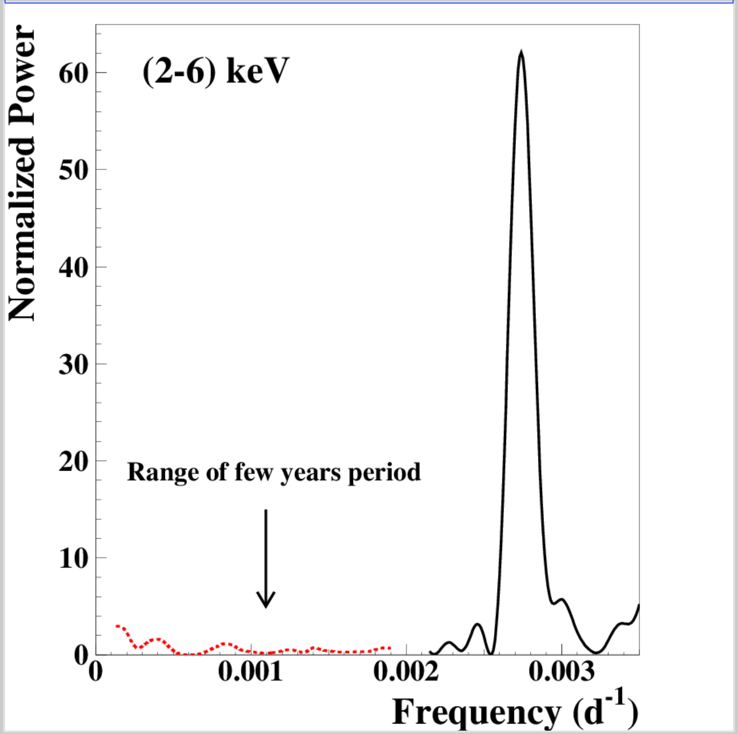
Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region

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

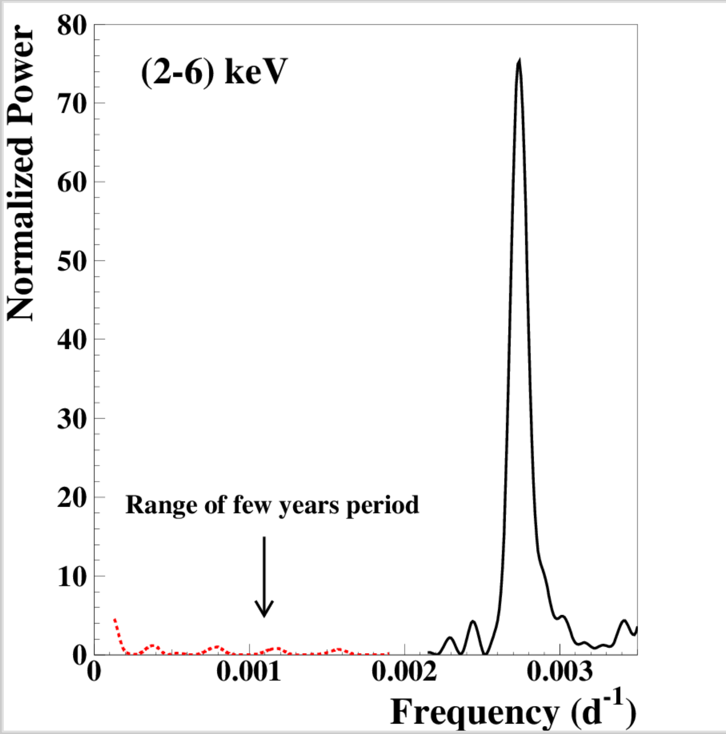
We calculated annual baseline counting rates – that is the averages on all the detectors (j index) of $flat_j$ (i.e. the single-hit scintillation rate of the j-th detector averaged over the annual cycle)

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)



DAMA/NaI + DAMA/LIBRA-(ph1+ph2)



<u>No statistically significant peak at lower frequency</u>

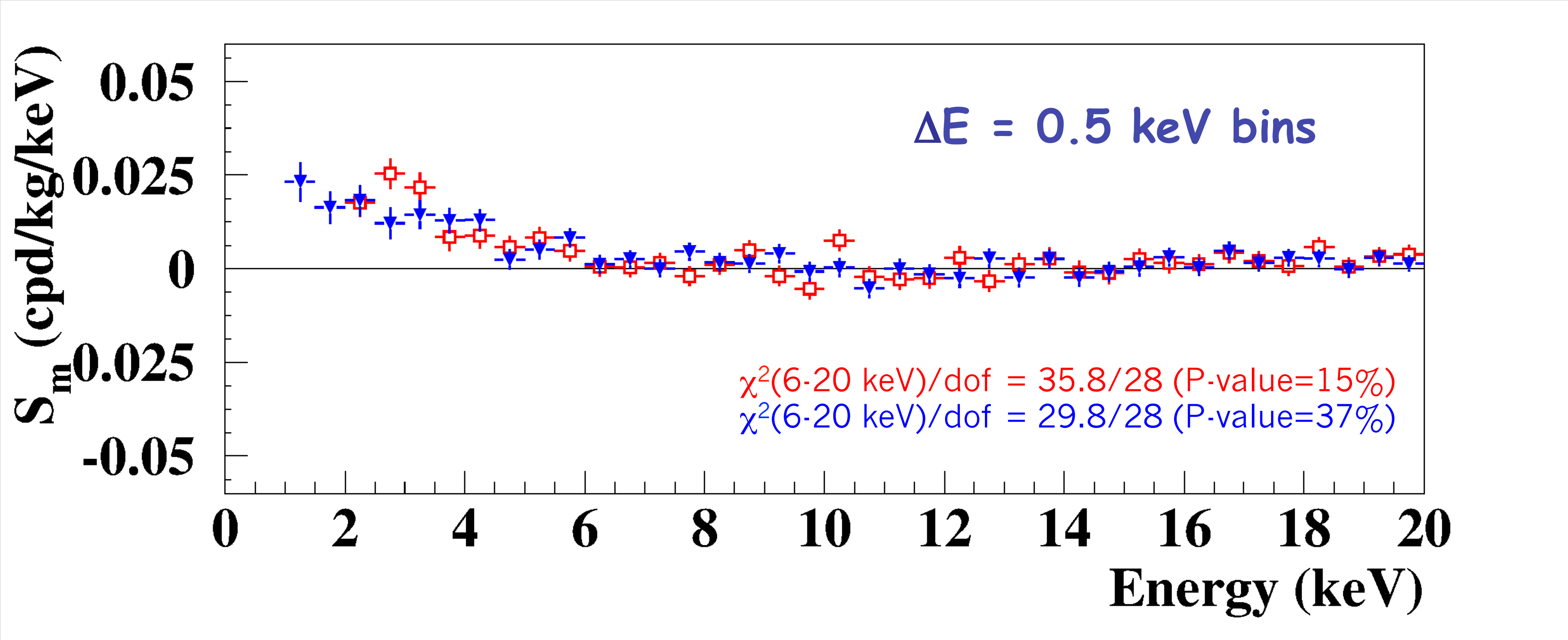
Energy distribution of the modulation amplitudes

Max-likelihod 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
vs
DAMA/LIBRA-phase2



The S_m energy distributions obtained in DAMA/NaI+DAMA/LIBRA-ph1 and in DAMA/LIBRA-ph2 are consistent in the (2–20) keV energy interval:

$\chi^2 = \Sigma\,(r_1 - r_2)^2/(\sigma_1^2+\sigma_2^2)$

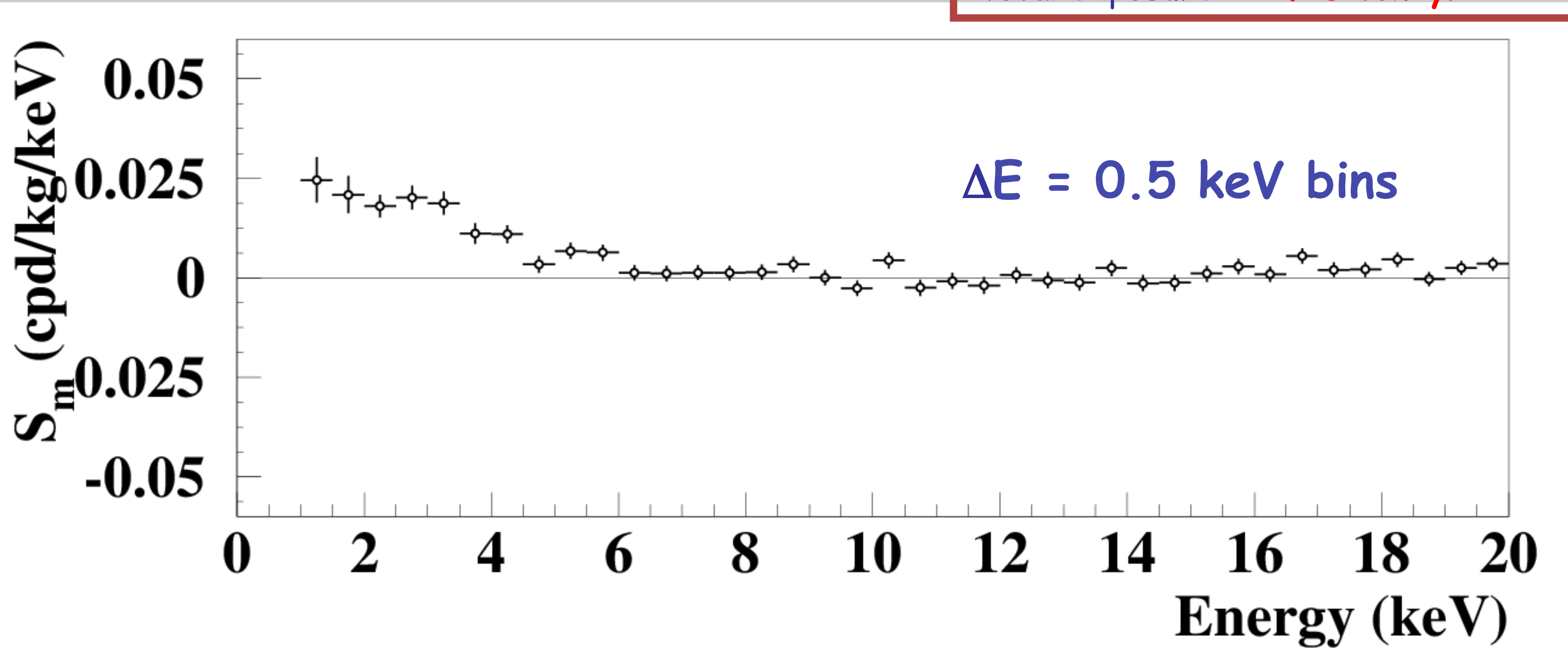
(2-20) keV	χ^2 /d.o.f.=32.7/36	(P=63%)
(2-6) keV	χ^2 /d.o.f.=10.7/8	(P=22%)

Energy distribution of the modulation amplitudes

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

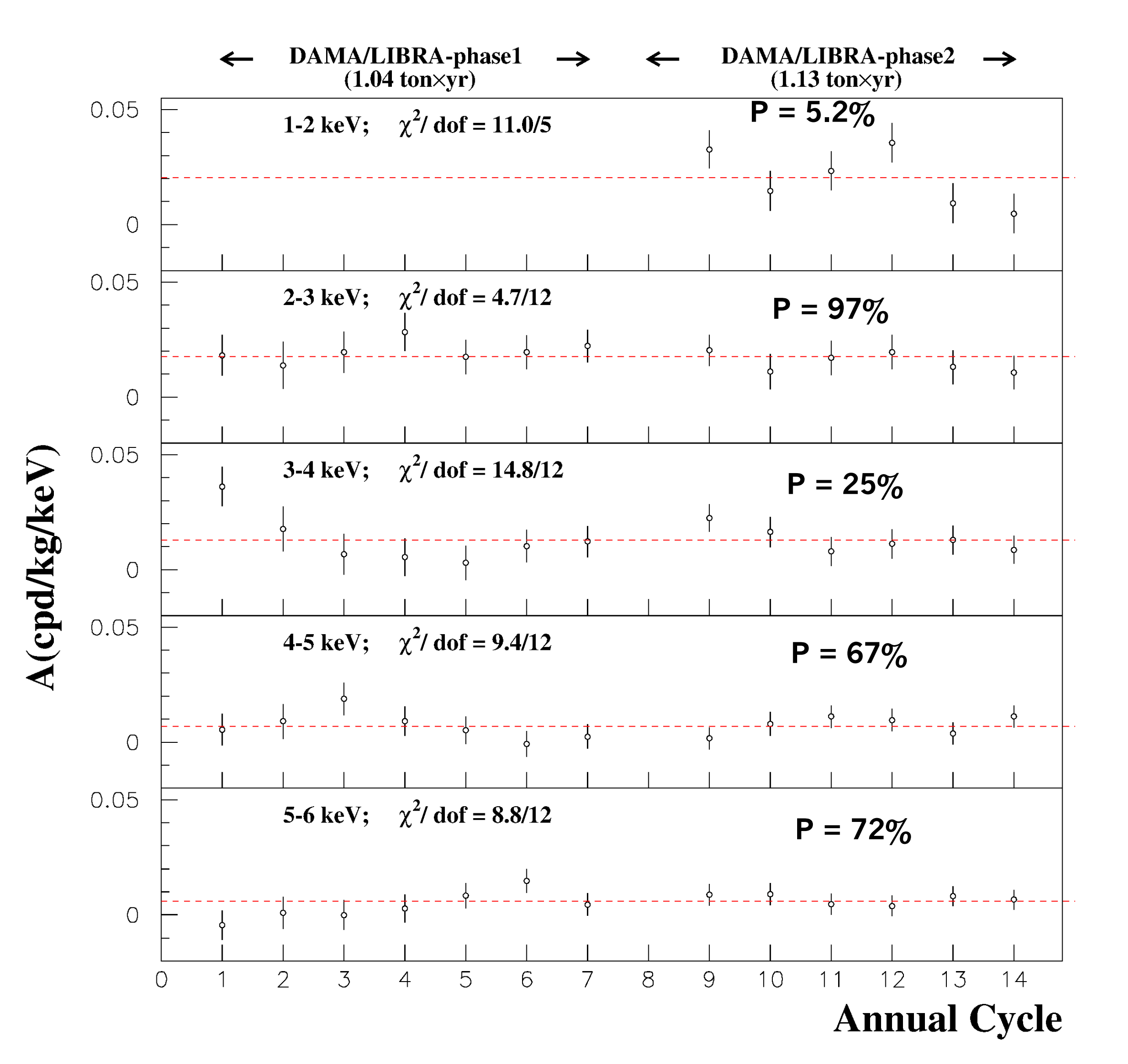
here $T=2\pi/\omega=1$ yr and t_0= 152.5 day

DAMA/NaI
+ DAMA/LIBRA-phase1
+ **DAMA/LIBRA-phase2**
total exposure: ≈ **2.46 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 19.0 for 16 degrees of freedom (upper tail probability 27%)
- The S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 42.6 for 28 degrees of freedom (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 11% and 25%.

S_m values for each annual cycle



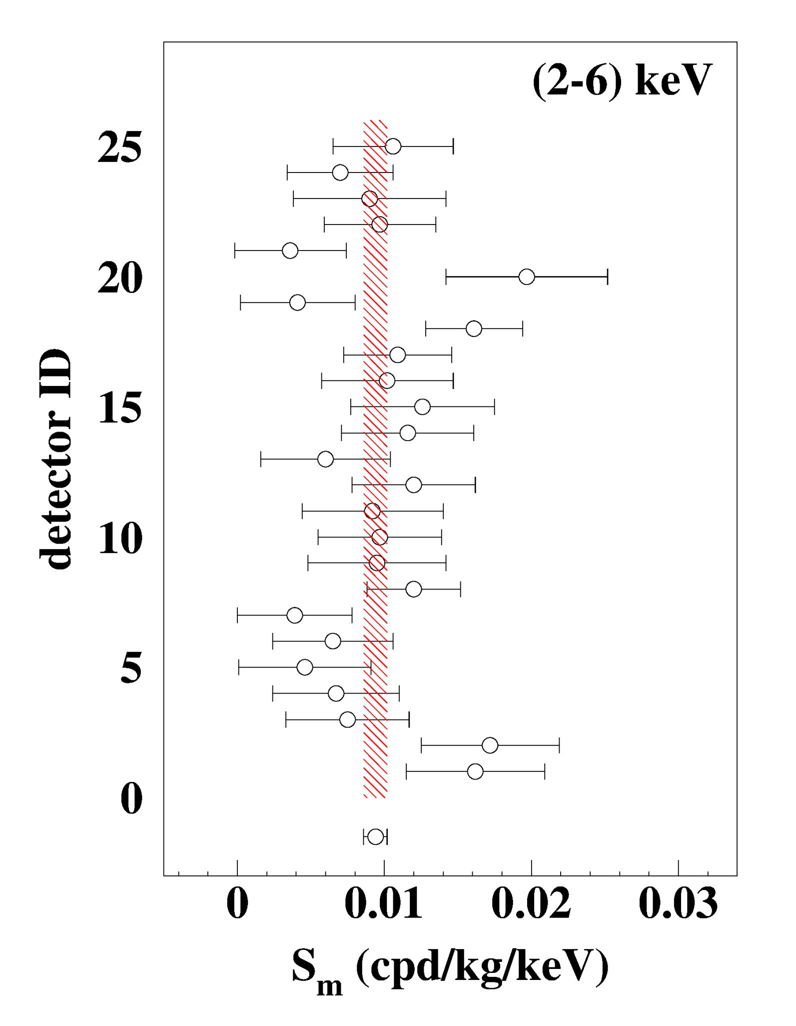
DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2

total exposure: 2.46 ton×yr

Energy Bin (keV)	run test probability	
	Lower	Upper
1-2	70%	70%
2-3	50%	73%
3-4	85%	35%
4-5	88%	30%
5-6	88%	30%

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

S_m values for each detector



DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: **2.17 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 value ±1σ

χ^2/dof = 23.9/24 d.o.f.

The signal is well distributed over all the 25 detectors.

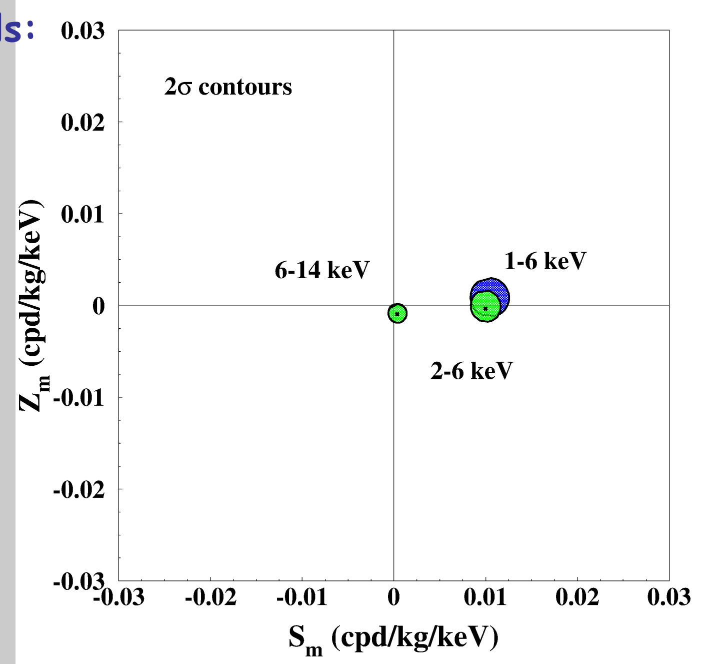
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 [total exposure: 2.46 ton × yr]

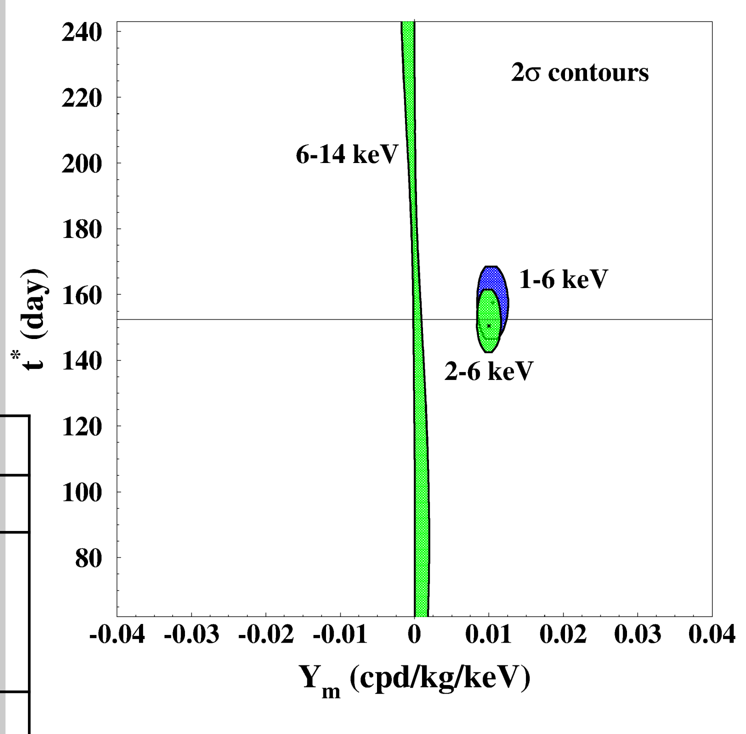
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

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)

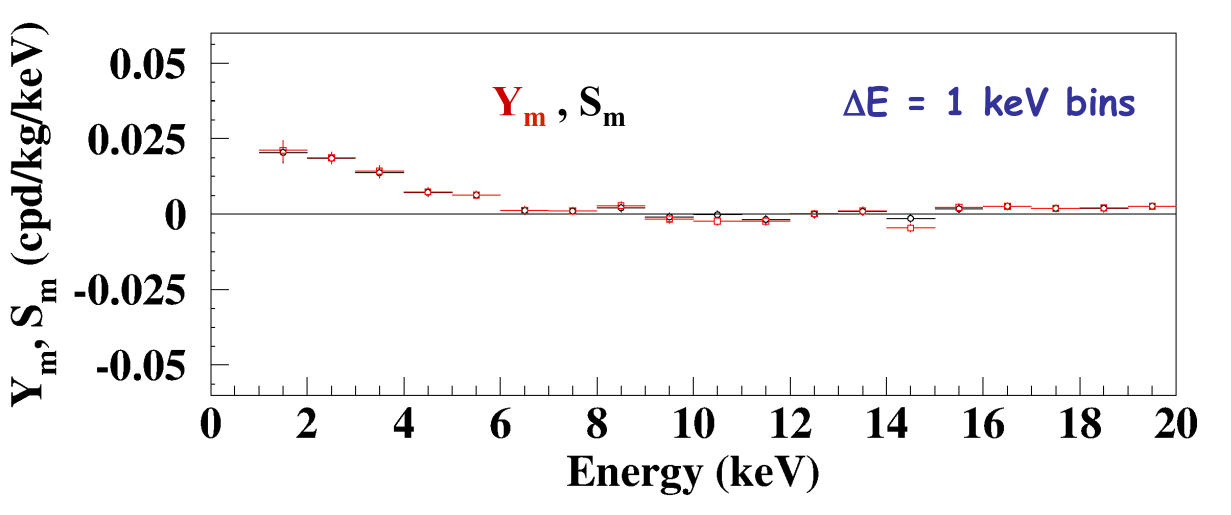


E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0100 ± 0.0008	- 0.0003 ± 0.0008	0.0100 ± 0.0008	150.5 ± 5.0
6-14	0.0003 ± 0.0005	-0.0009 ± 0.0006	0.0010 ± 0.0013	undefined
DAMA/LIBRA-ph2				
1-6	0.0105 ± 0.0011	0.0009 ± 0.0010	0.0105 ± 0.0011	157.5 ± 5.0

Phase vs energy

DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2
total exposure: 2.46 ton × yr

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

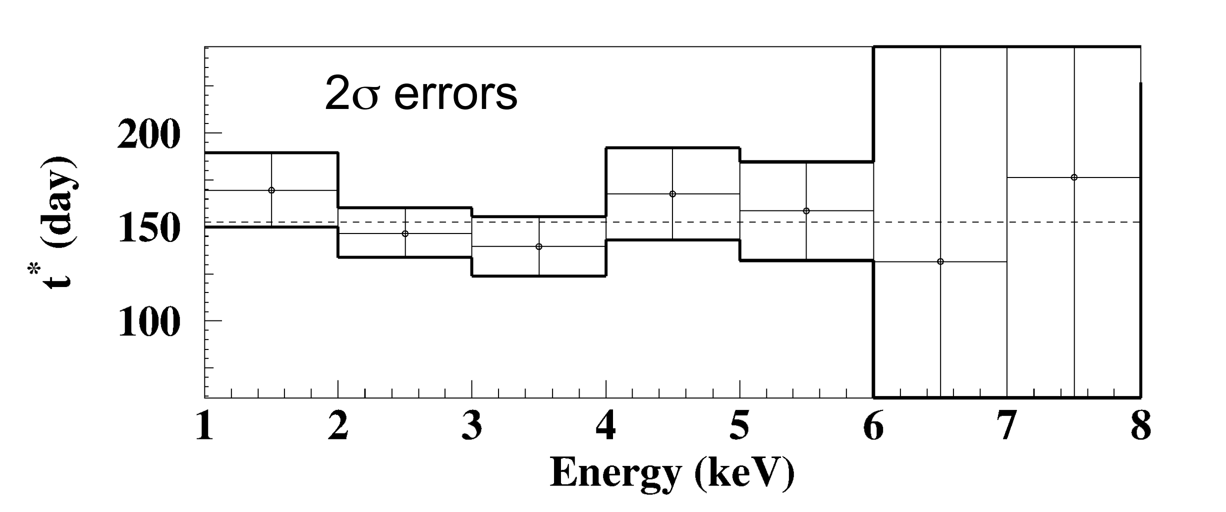


For DM signals:

$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

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



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

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
Temperature (°C)	(0.0012 ± 0.0051)	-(0.0002 ± 0.0049)	-(0.0003 ± 0.0031)	(0.0009 ± 0.0050)	(0.0018 ± 0.0036)	-(0.0006 ± 0.0035)
Flux N_2 (l/h)	-(0.15 ± 0.18)	-(0.02 ± 0.22)	-(0.02 ± 0.12)	-(0.02 ± 0.14)	-(0.01 ± 0.10)	-(0.01 ± 0.16)
Pressure (mbar)	$(1.1 \pm 0.9)\times10^{-3}$	$(0.2 \pm 1.1)\ )\times10^{-3}$	$(2.4 \pm 5.4)\times10^{-3}$	$(0.6 \pm 6.2)\times10^{-3}$	$(1.5 \pm 6.3)\times10^{-3}$	$(7.2 \pm 8.6)\times10^{-3}$
Radon (Bq/m^3)	(0.015 ± 0.034)	-(0.002 ± 0.050)	-(0.009 ± 0.028)	-(0.044 ± 0.050)	(0.082 ± 0.086)	(0.06 ± 0.11)
Hardware rate above single ph.e. (Hz)	$-(0.12 \pm 0.16)\times10^{-2}$	$(0.00 \pm 0.12)\times10^{-2}$	$-(0.14 \pm 0.22)\times10^{-2}$	$-(0.05 \pm 0.22)\times10^{-2}$	$-(0.06 \pm 0.16)\times10^{-2}$	$-(0.08 \pm 0.17)\times10^{-2}$

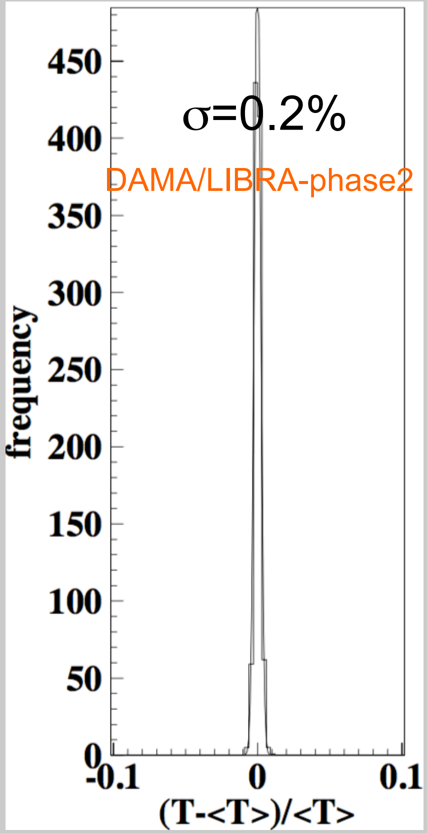
All the measured amplitudes well compatible with zero
+ none can account for the observed effect
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

Temperature

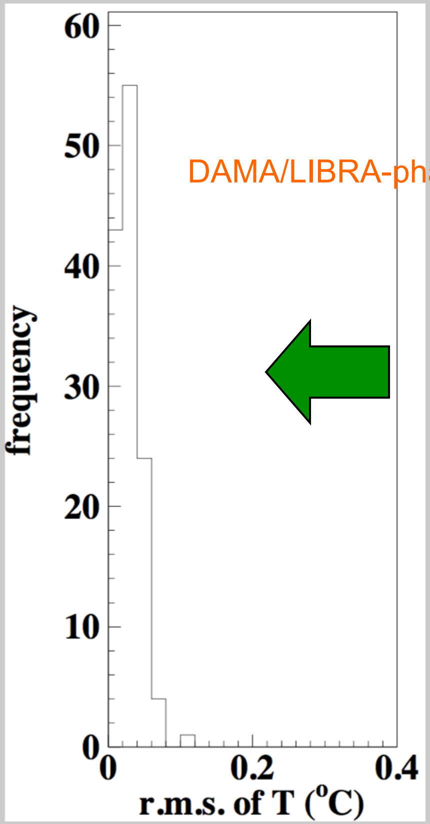
- **Detectors in Cu housings directly in contact with multi-ton shield →huge heat capacity (≈10^6 cal/^{0}C)**
- **Experimental installation continuosly air conditioned (2 independent systems for redundancy)**
- **Operating T of the detectors continuously controlled**

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

	T (°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)



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



Distribution of the root mean square values of the operating T within periods with the same calibration factors (typically ≈7days):

mean value ≈ 0.03°C

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

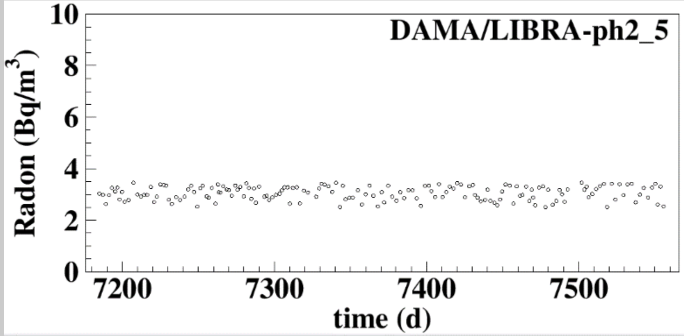
<10^{-4} cpd/kg/keV (< 0.5% $S_m^{observed}$)

An effect from temperature can be excluded

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

Radon

- Three-level system to exclude Radon from the detectors:
- Walls and floor of the inner installation sealed in Supronyl (2×10^{-11} cm^2/s permeability).
- Whole shield in plexiglas box maintained in HP Nitrogen atmosphere in slight overpressure with respect to environment
- Detectors in the inner Cu box in HP Nitrogen atmosphere in slight overpressure with respect to environment continuously since several years



Time behaviours of the environmental radon in the installation (i.e. after the Supronyl), from which in addition the detectors are excluded by other two levels of sealing!

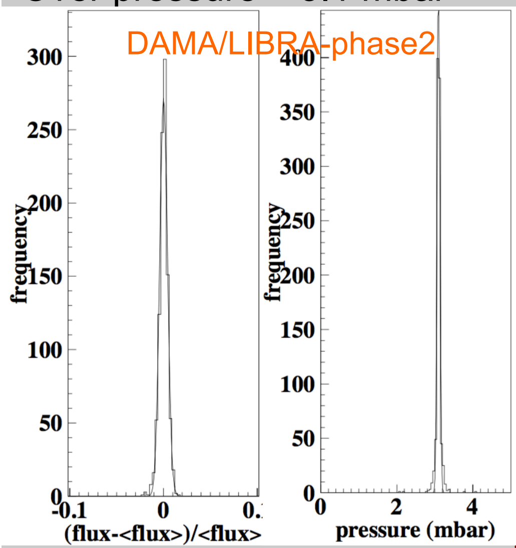
measured values at level of sensitivity of the used radonmeter

Amplitudes for annual modulation of Radon external to the shield:

	Radon (Bq/m^3)
DAMA/LIBRA-ph2_2	(0.015 ± 0.034)
DAMA/LIBRA-ph2_3	-(0.002 ± 0.050)
DAMA/LIBRA-ph2_4	-(0.009 ± 0.028)
DAMA/LIBRA-ph2_5	-(0.044 ± 0.050)
DAMA/LIBRA-ph2_6	(0.082 ± 0.086)
DAMA/LIBRA-ph2_7	(0.06 ± 0.11)

<flux> ≈ 320 l/h

Over pressure ≈ 3.1 mbar



NO DM-like modulation amplitude in the time behaviour of external Radon (from which the detectors are excluded), of HP Nitrogen flux and of Cu box pressure

Investigation in the HP Nitrogen atmosphere of the Cu-box

- Study of the double coincidences of γ's (609 & 1120 keV) from ^{214}Bi Radon daughter
- Rn concentration in Cu-box atmosphere $<5.8 \cdot 10^{-2}$ Bq/m^3 (90% C.L.)
- By MC: $<2.5 \cdot 10^{-5}$ cpd/kg/keV @ low energy for *single-hit* events(enlarged matrix of detectors and better filling of Cu box with respect to DAMA/NaI)
- An hypothetical 10% modulation of possible Rn in Cu-box:

$<2.5 \times 10^{-6}$ cpd/kg/keV ($<0.01\%$ $S_m^{observed}$)

An effect from Radon can be excluded

+ any possible modulation due to Radon would always fail some of the peculiarities of the signature and would affect also other energy regions

- 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.

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

(See e.g. also EPJC 56 (2008) 333, EPJC 72(2012) 2064, IJMPA 28 (2013) 1330022)

EPJC74(2014)3196

Modulation amplitudes

Source		$\Phi^{(n)}_{0,k}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)		$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2}-10^{-1}$ eV)	1.08×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8\times10^{-6}$	[2, 7, 8]	$\ll 8\times10^{-7}$	$\ll 7\times10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3\times10^{-3}$	[2, 7, 8]	$\ll 3\times10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha,n)\to$ n (1-10 MeV)	$\simeq 0.9\times10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6\times10^{-4}$	[2, 7, 8]	$\ll 6\times10^{-5}$	$\ll 5\times10^{-3}$
	$\mu\to$ n from rock (>10 MeV)	$\simeq 3\times10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7\times10^{-4}$	(see text and [2, 7, 8])	$\ll 9\times10^{-6}$	$\ll 8\times10^{-4}$
	$\mu\to$ n from Pb shield (>10 MeV)	$\simeq 6\times10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4\times10^{-3}$	(see text and footnote 3)	$\ll 2\times10^{-5}$	$\ll 1.6\times10^{-3}$
	$\nu\to$ n (few MeV)	$\simeq 3\times10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7\times10^{-5}$	(see text)	$\ll 2\times10^{-6}$	$\ll 2\times10^{-4}$
	direct μ	$\Phi^{(\mu)}_0\simeq 20\ \mu$ m^{-2}d^{-1} [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0\simeq 6\times10^{10}\ \nu$ cm^{-2}s^{-1} [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

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

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

\+ In no case neutrons (of whatever origin), muon or muon induced events, solar ν can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail (and – in addition - quantitatively negligible amplitude with respect to the measured effect).

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

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**

Final model independent result
DAMA/NaI+DAMA/LIBRA-phase1+phase2

Presence of modulation over 20 annual cycles at 12.9 σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 20 independent experiments of 1 year each one

The total exposure by former DAMA/NaI, DAMA/LIBRA-phase1 and phase2 is 2.46 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 (0.999±0.001)* yr, well compatible with the 1 yr period, as expected for the DM signal**

3) **Measured phase (145±5)* 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 (1—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: (0.0103 ± 0.0008)* cpd/kg/keV (12.9 σ C.L.).**

* Here 2-6 keV energy interval

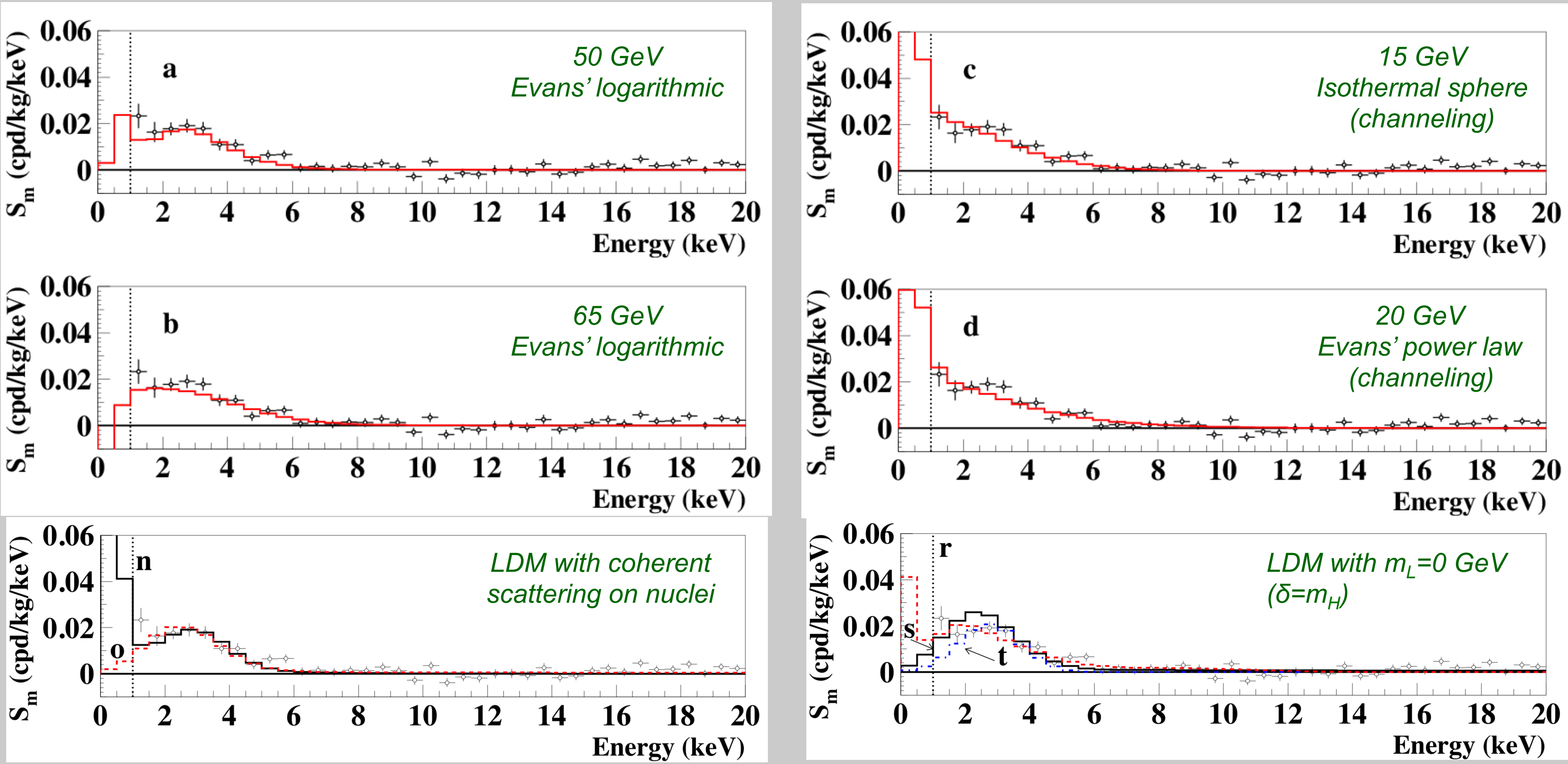
No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

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

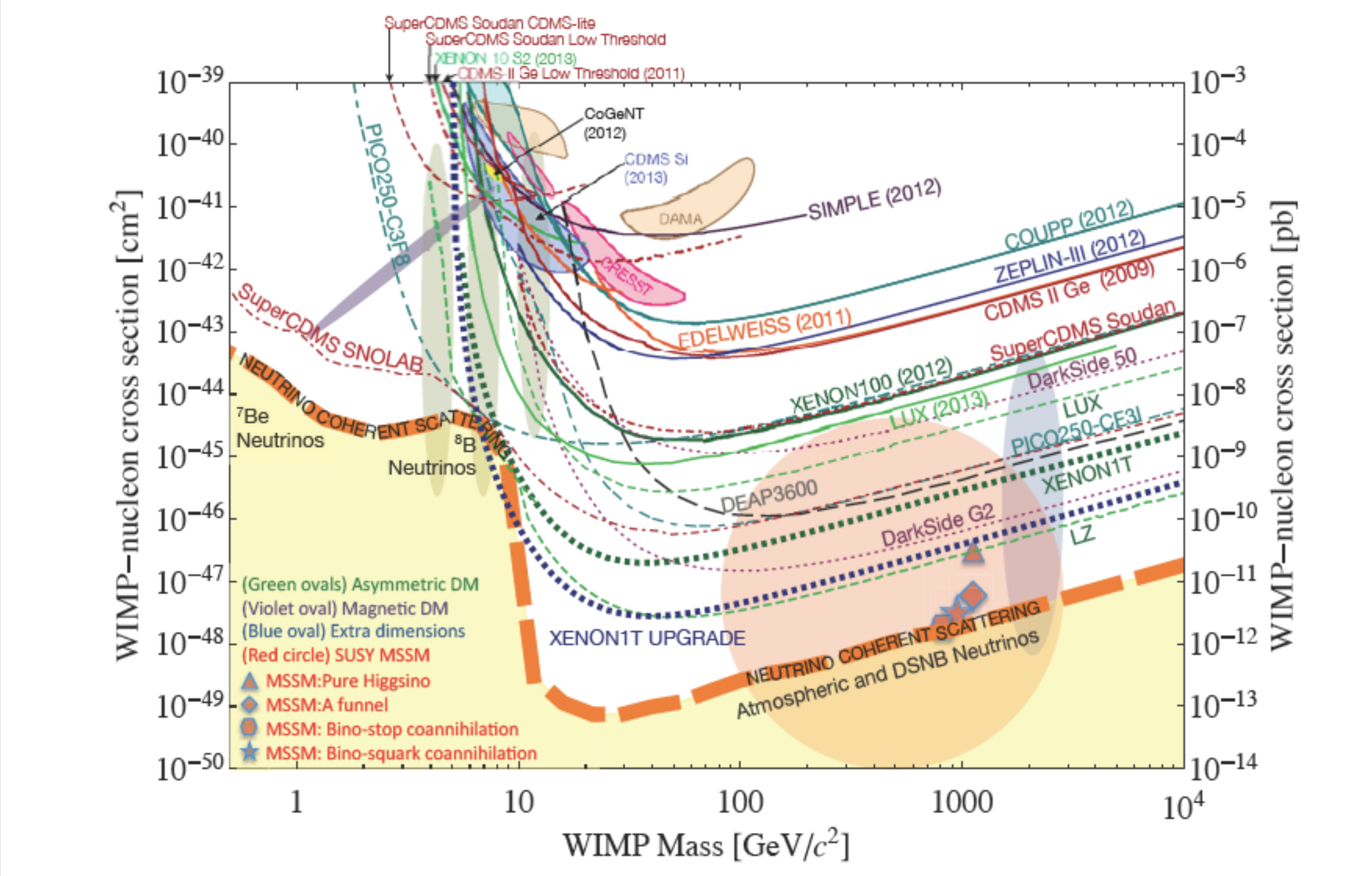
Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

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</u> <u>scenarios</u>

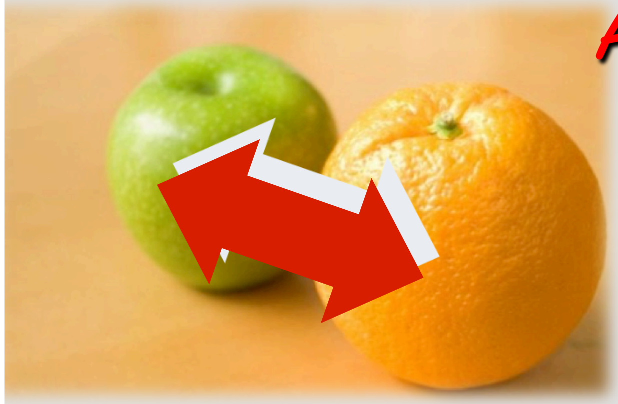


Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



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

About interpretation and comparisons



See e.g.: Riv.N.Cim.26 ono.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022

…models…

- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- 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…

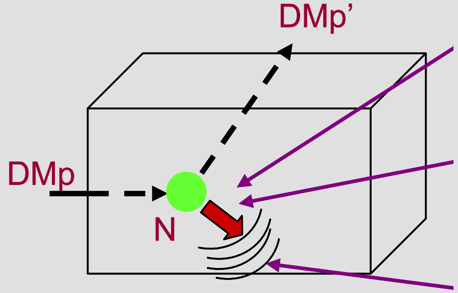
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities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

Uncertainty in experimental parameters, as well as 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 experiment can – at least in principle - be directly compared in a model independent way with DAMA so far

example…

case of DM particles inducing elastic scatterings on target-nuclei, SI case



Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

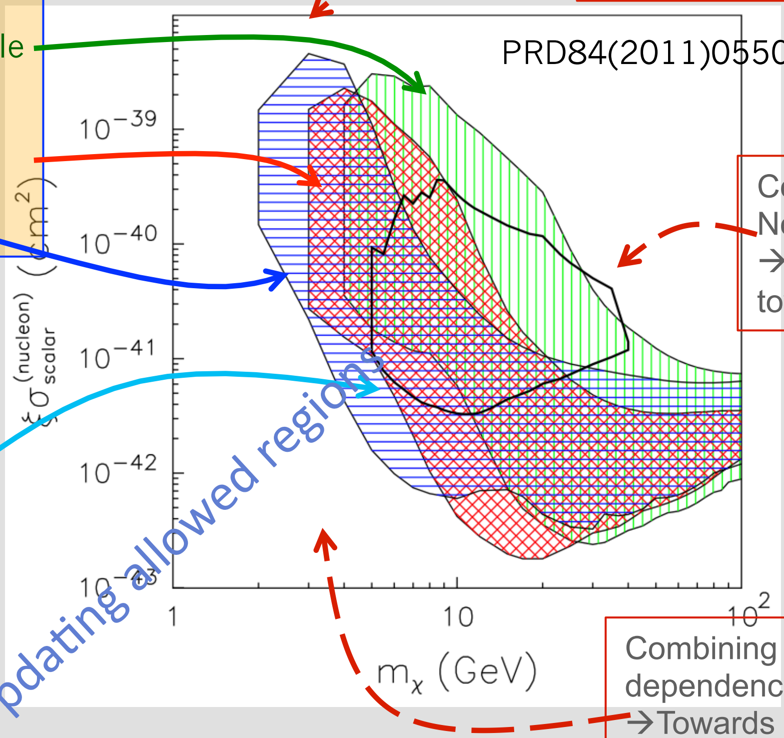
Including the Migdal effect
→Towards lower mass/higher σ

DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent Quenching Factors (red);

7.5 σ C.L.

CoGeNT; qf at fixed assumed value

1.64 σ C.L.



PRD84(2011)055014, IJMPA28(2013)1330022

Co-rotating halo,
Non thermalized component
→ Enlarge allowed region towards larger mass

Combining channeling and energy dependence of q.f. (AstrPhys33 (2010) 40)
→Towards lower σ

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

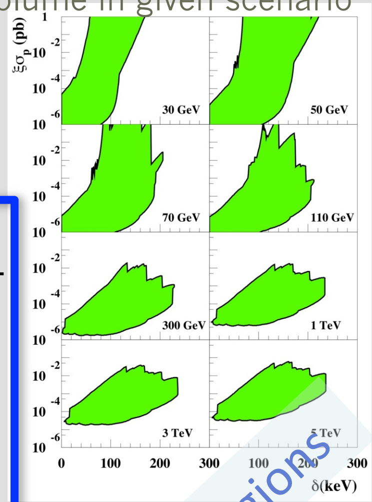
Other examples

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



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

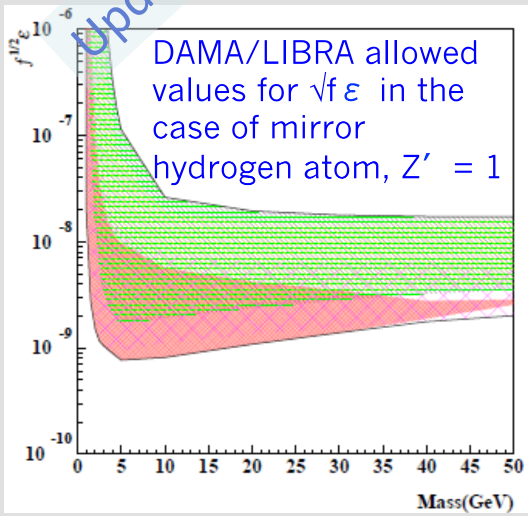
- For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with A~205, which are present as a dopant at the 10^{-3} level in NaI(Tl) crystals.
- large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

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)**

- 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.

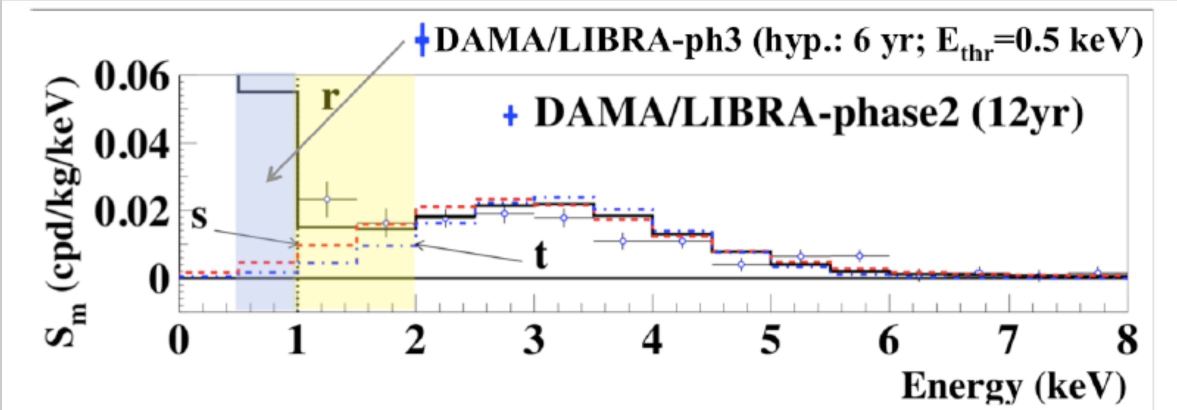
$\sqrt{f} \cdot \epsilon$ coupling const. and fraction of mirror atom



Updating allowed regions

Running phase2 and towards future DAMA/LIBRA-phase3 with software energy threshold below 1 keV

Enhancing sensitivities for DM corollary aspects, other DM features, second order effects and other rare processes:

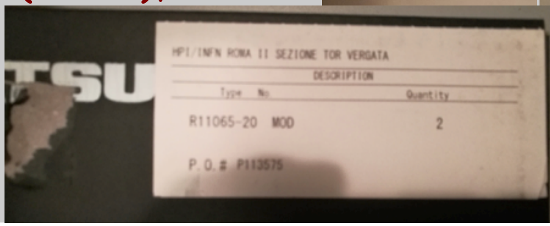


- R&D towards possible DAMA/LIBRA-phase3 continuing: i) new protocols for possible modifications of the detectors; ii) alternative strategies under investigation; moreover, 4 new PMT prototypes from a dedicated R&D with HAMAMATSU already at hand.
- Improving the light collection of the detectors (and accordingly the light yields and the energy thresholds). Improving the electronics.
- **Other possible option**: new ULB crystal scintillators (e.g. $ZnWO_4$) placed in between the DAMA/LIBRA detectors to add also a high sensitivity directionality meas.

The presently-reached metallic PMTs features:

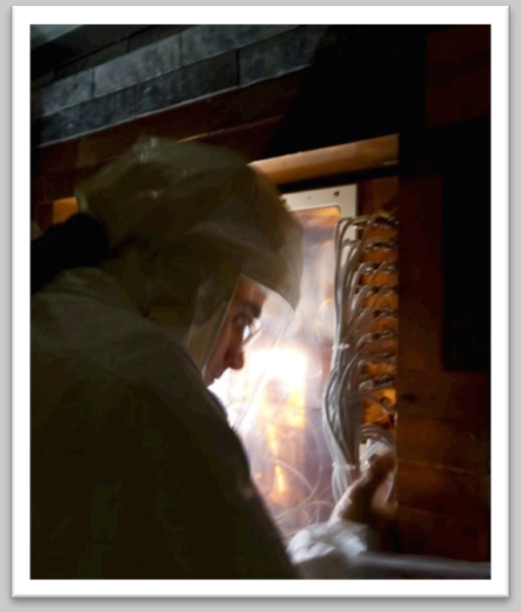
- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- Radiopurity at level of 5 mBq/PMT (^{40}K), 3-4 mBq/PMT (^{232}Th), 3-4 mBq/PMT (^{238}U), 1 mBq/PMT (^{226}Ra), 2 mBq/PMT (^{60}Co).

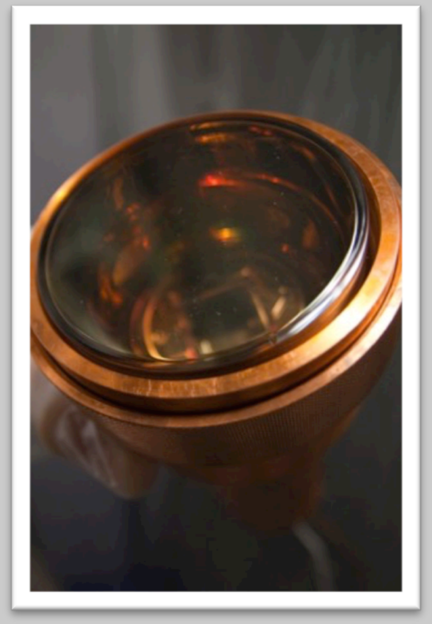
4 prototypes at hand



Conclusions

- Model-independent positive evidence for the presence of DM particles in the galactic halo at **12.9σ** C.L. (20 independent annual cycles with 3 different set-ups: 2.46 ton × yr)
- Modulation parameters determined with increasing precision
- New investigations on different peculiarities of the DM signal exploited 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**





- DAMA/LIBRA-phase2 continuing data taking
- **DAMA/LIBRA – phase3 R&D in progress**
- R&D for a possible DAMA/1ton - full sensitive mass - set-up, proposed to INFN by DAMA since 1996, **continuing at some extent** as well as **some other R&Ds**
- New corollary analyses in progress
- Continuing investigations of rare processes other than DM