New results on DM with MM as a possible candidate

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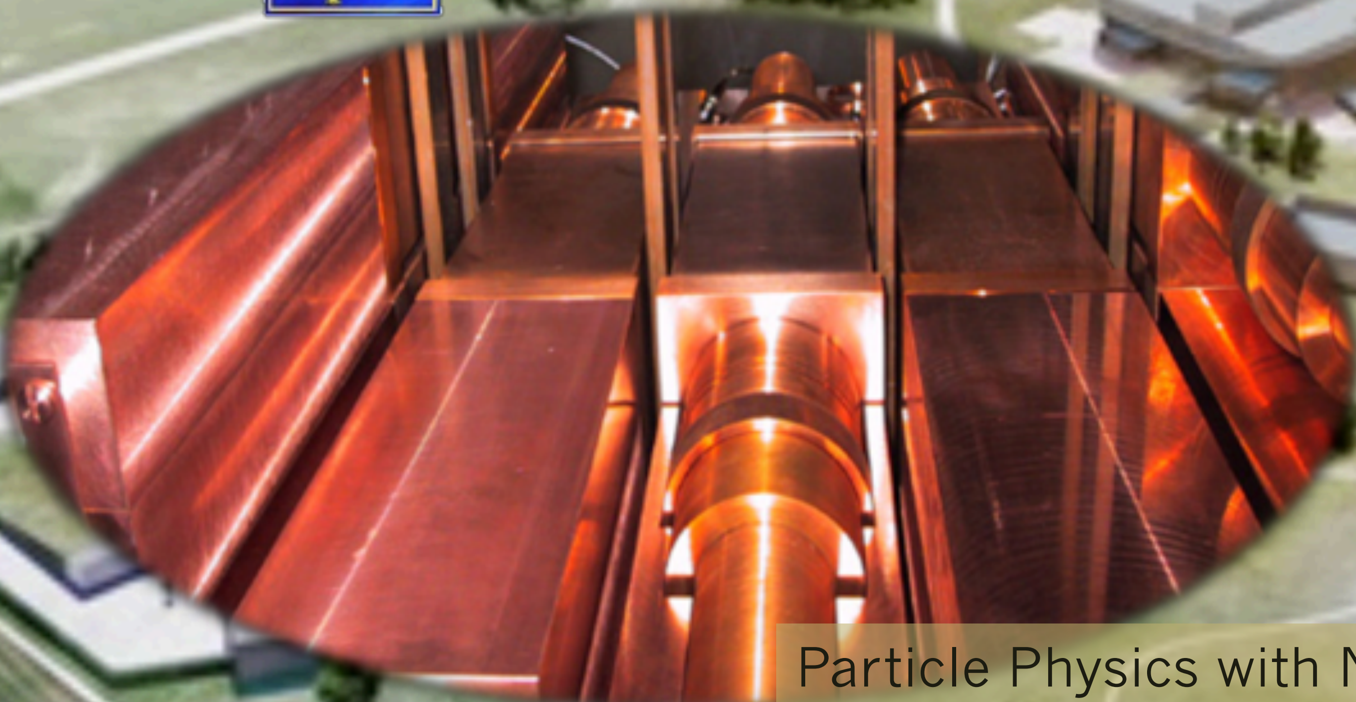
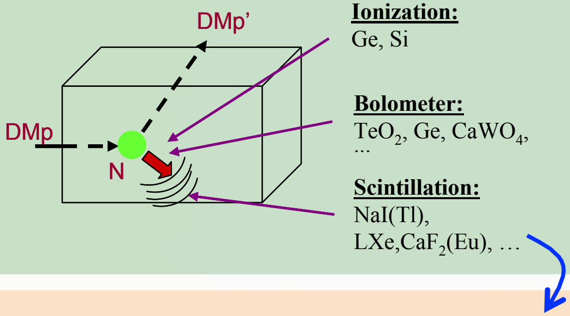


Particle Physics with Neutrons at the ESS
Nordita, Stockholm, Sweden
December 10-14, 2018

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



- Inelastic Dark Matter: **W + N → W* + N**

  → W has 2 mass states $\chi+$, $\chi-$ with δ mass splitting

  → Kinematical constraint for the inelastic scattering of $\chi-$ on a nucleus

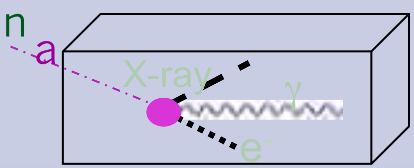
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

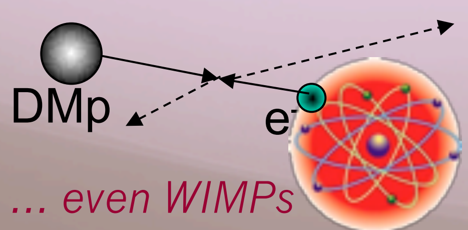
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

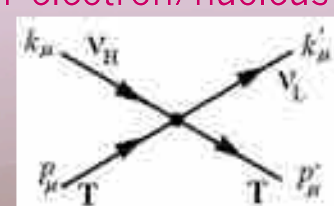


… even WIMPs

- 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



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

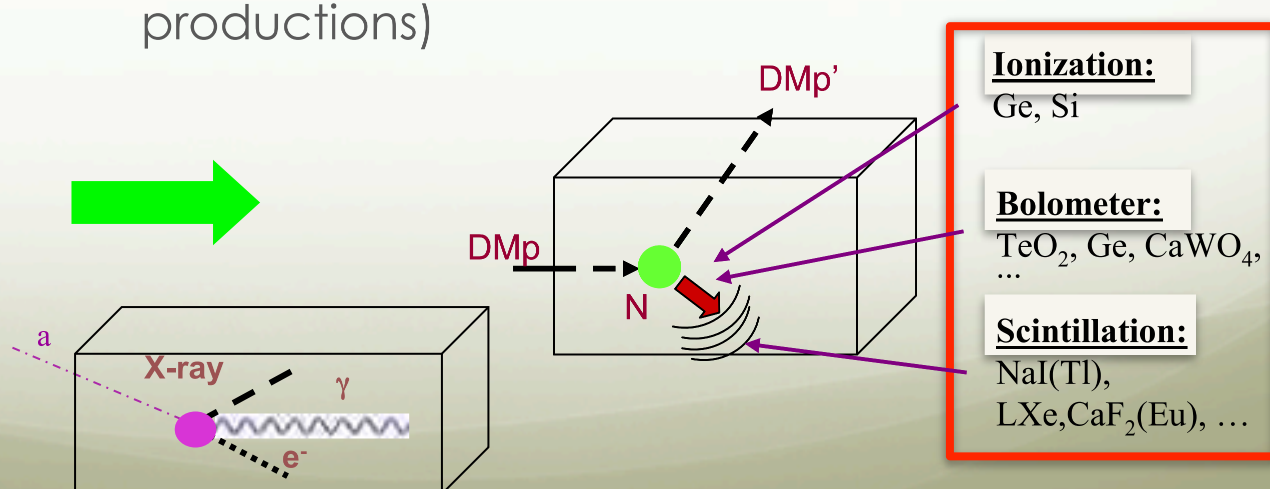
… also other ideas …

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)



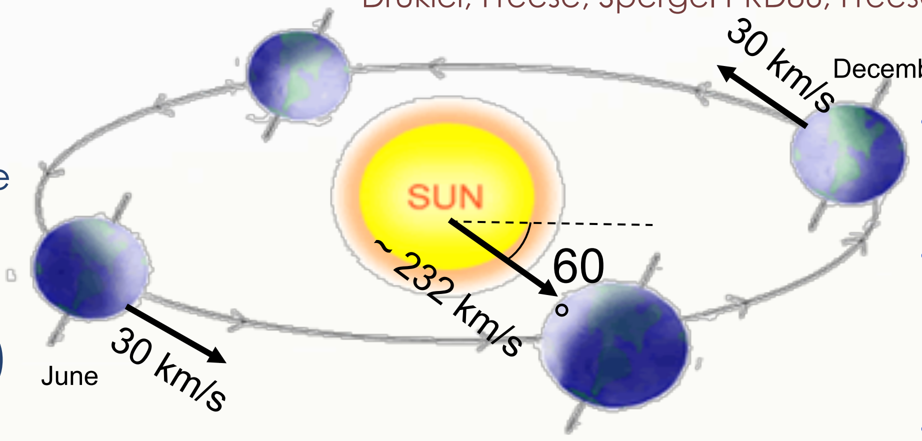
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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)

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

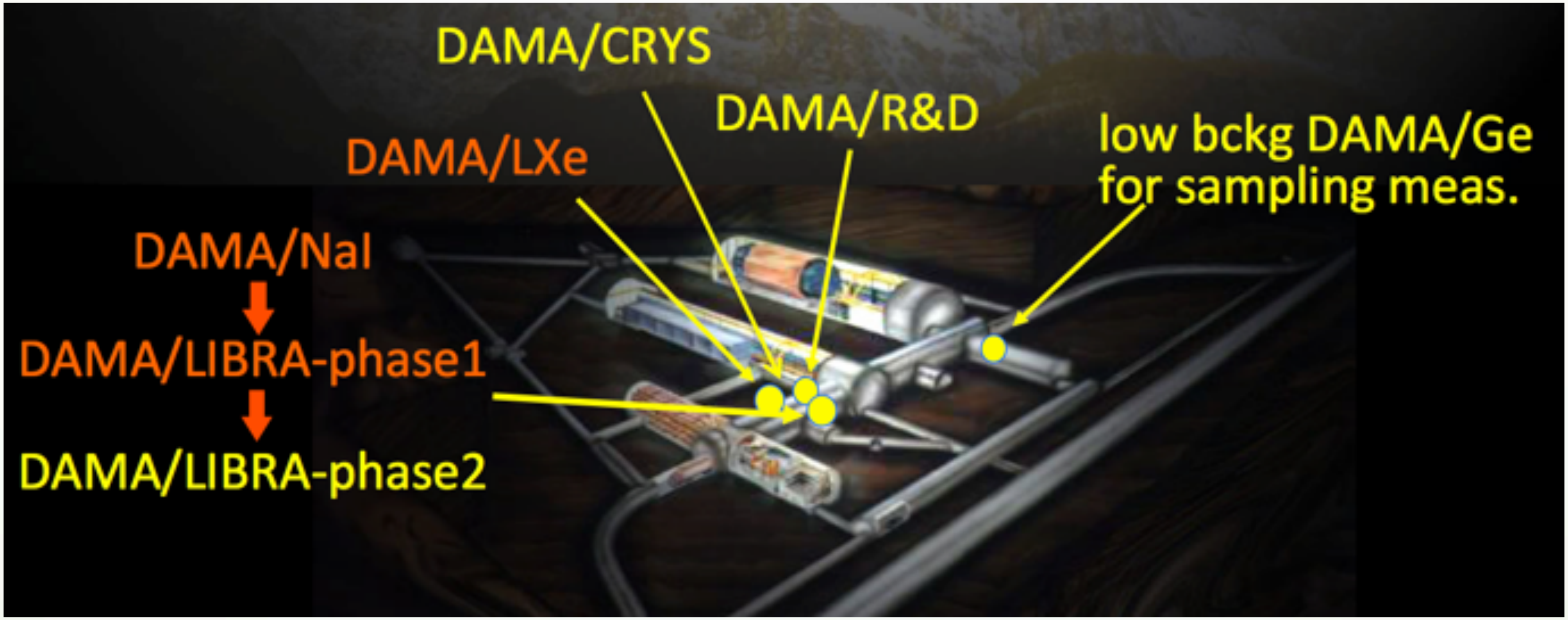
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

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

DAMA set-ups

an observatory for rare processes @ LNGS



Collaboration:

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

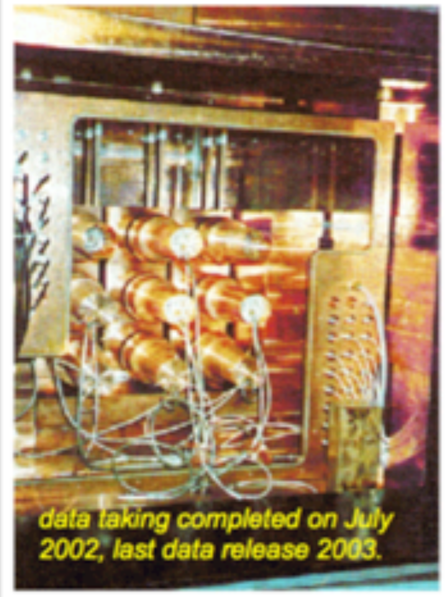
+ by-products and small scale expts.: INR-Kiev + other institutions

+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

+ in some studies on ββ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

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

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



Performances:

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

Results on rare processes:

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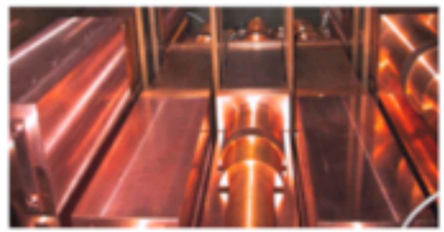
The DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

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



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

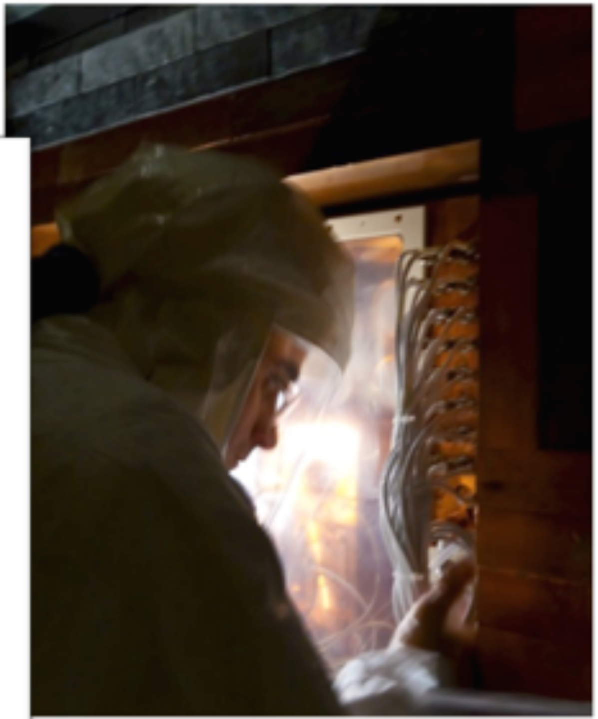
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles,
  - Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  - Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, 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

JINST 7(2012)03009
Universe 4 (2018) 116
Bled Workshop in Physics
19, 2 (2018) 27

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



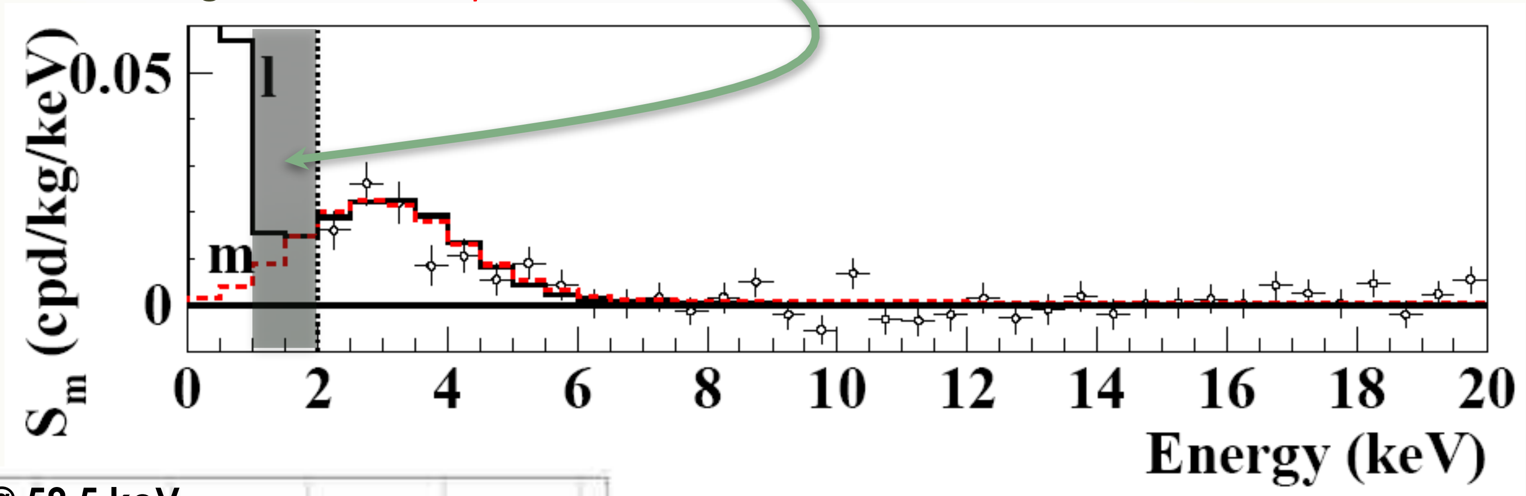
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak

DAMA/LIBRA–phase2

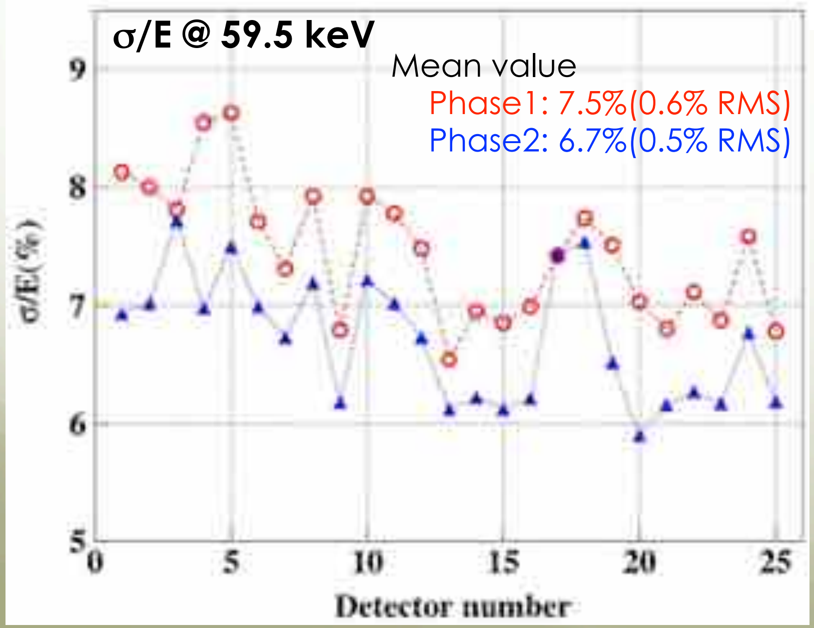
JINST 7(2012)03009
Universe 4 (2018) 116
Bled Workshop in Physics 19, 2 (2018) 27

Lowering software energy threshold below 2 keV:

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



The resolution:



PMTs contaminations:

	^{226}Ra (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)
Mean Contamination	0.43	47	0.12	83	0.54
Standard Deviation	0.06	10	0.02	17	0.16

The light responses:

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

DAMA/LIBRA-phase2 data taking

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

Energy resolution @ 60 keV mean value:

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

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

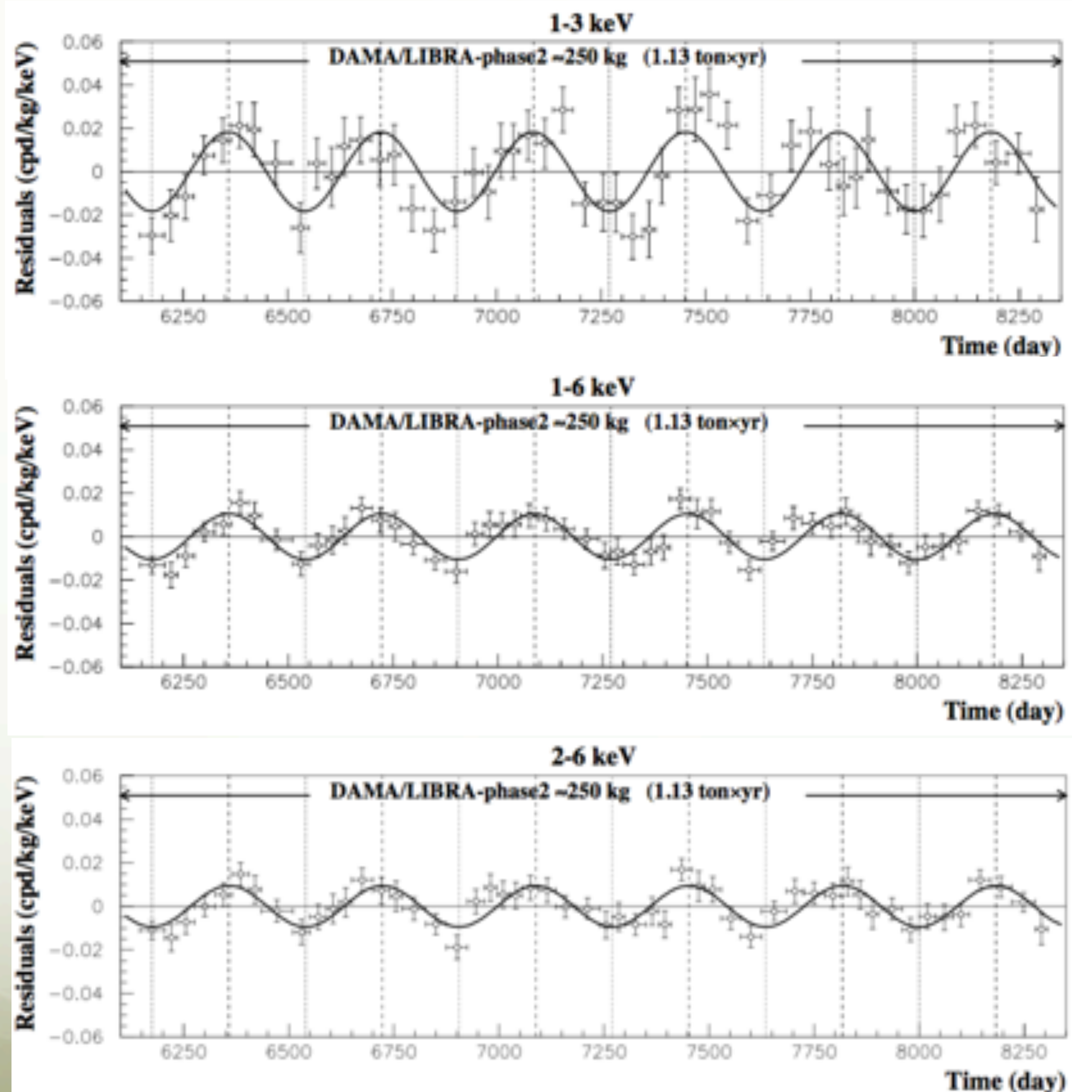
Exposure first data release of DAMA/LIBRA-phase2: **1.13 ton × yr**

Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.46 ton × 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

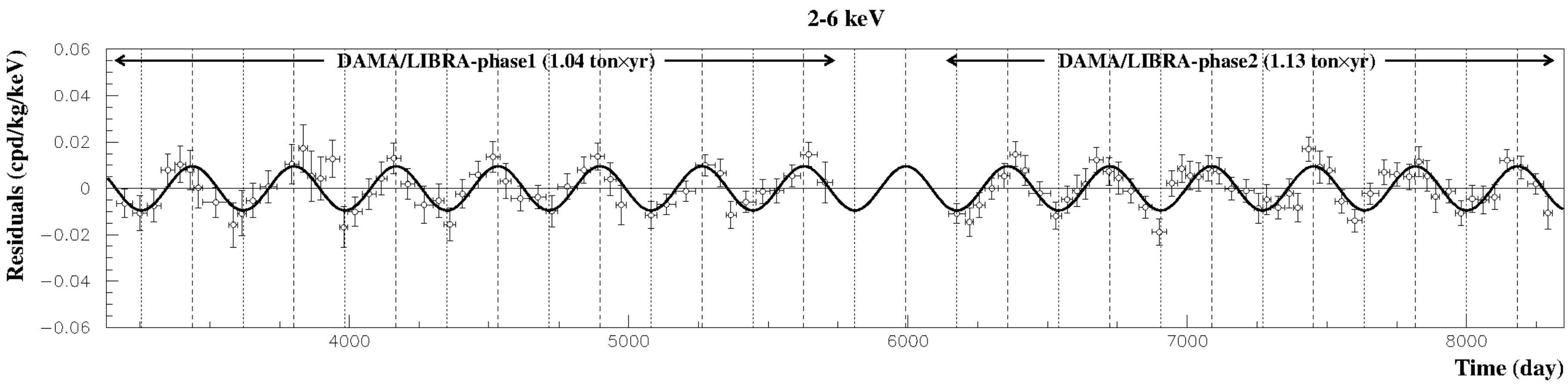
χ^2/dof = 42.5/51 **8.6 σ C.L.**

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

DM model-independent 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

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

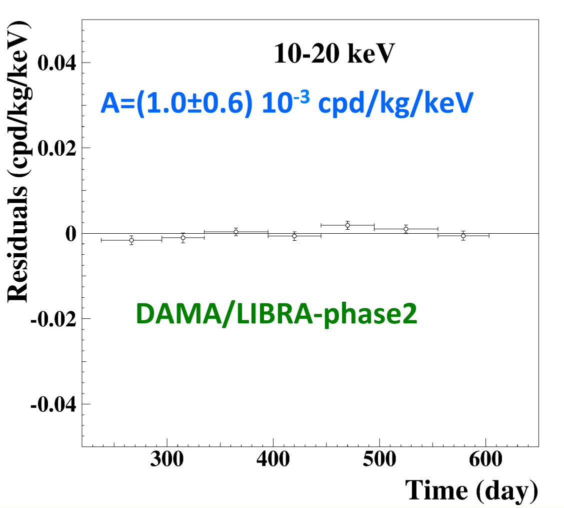
DAMA/LIBRA-ph1 (1.04 ton x yr)

DAMA/LIBRA-ph2 (1.13 ton x yr)

total exposure = 2.46 ton×yr

Rate behaviour above 6 keV

- **No Modulation above 6 keV**

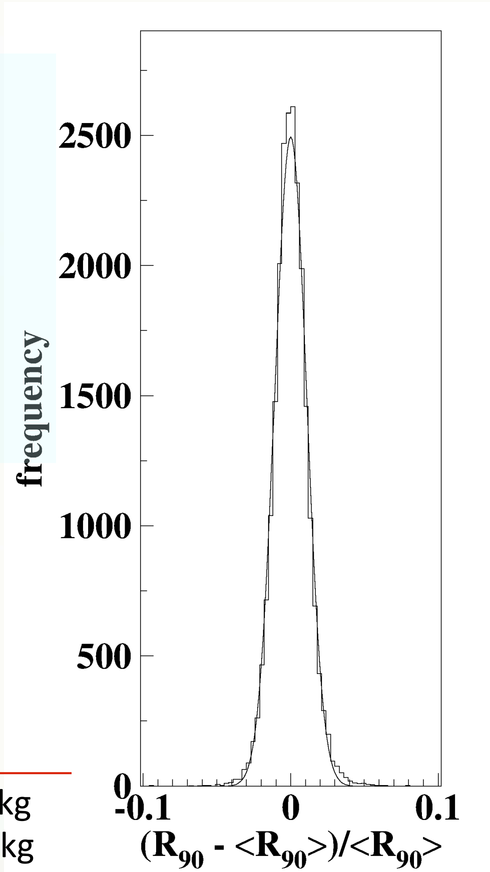


Mod. Ampl. (6-14 keV): cpd/kg/keV

(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

DAMA/LIBRA-phase2



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

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

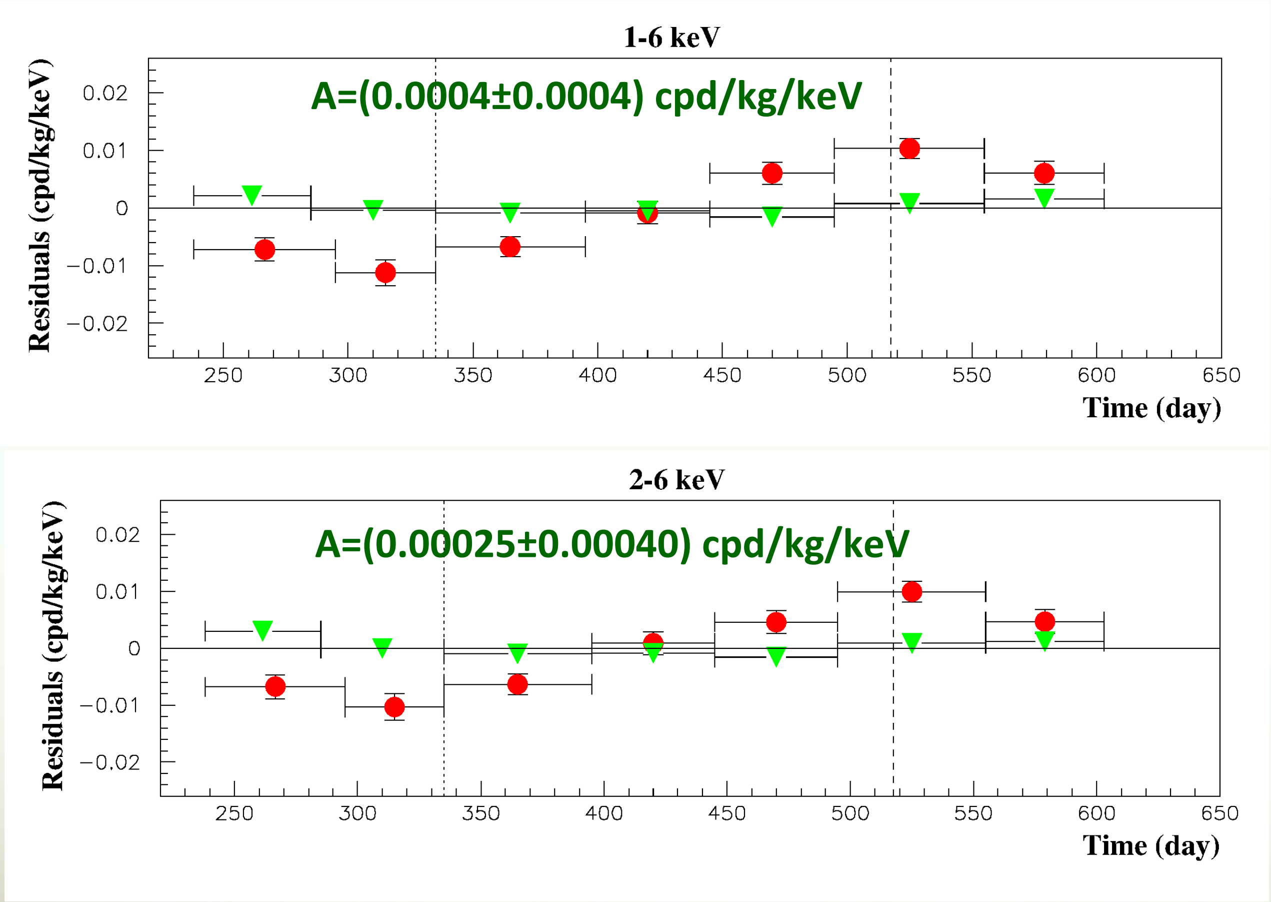
+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

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

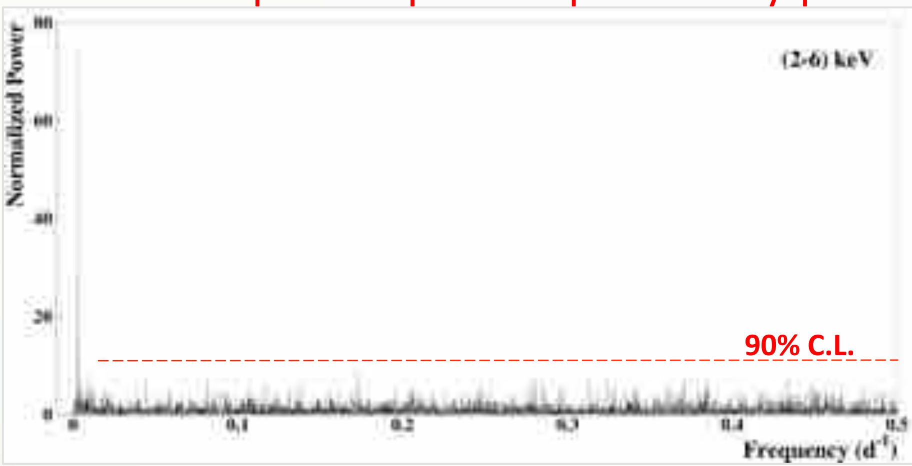
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

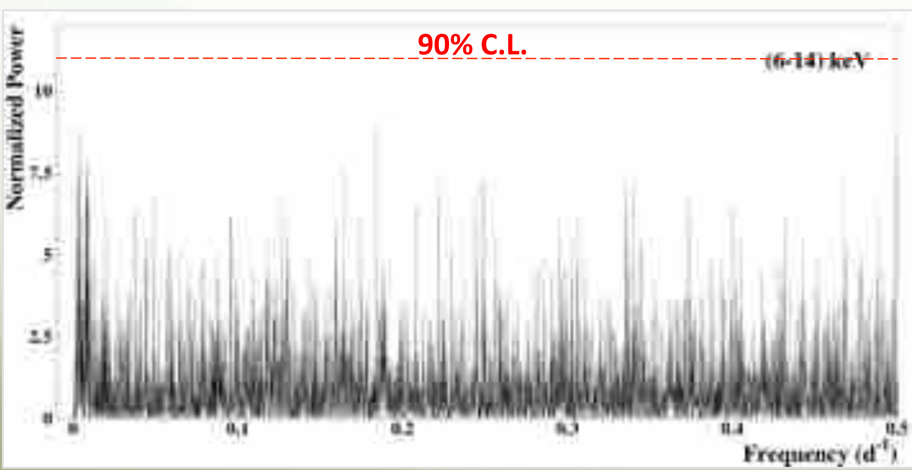
The analysis in frequency

(according to PRD75 (2007) 013010)

To perform the Fourier analysis of the data in a wide region of frequency, the single-hit scintillation events have been grouped in 1 day bins

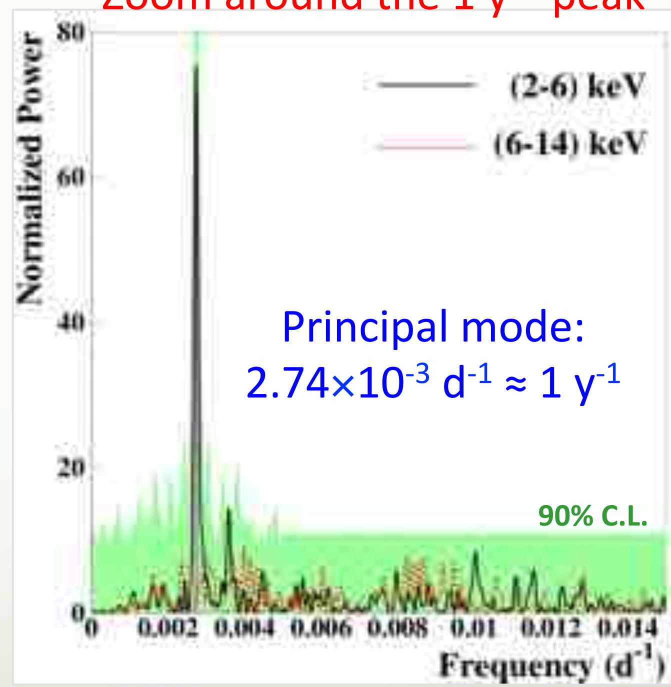
The whole power spectra up to the Nyquist





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

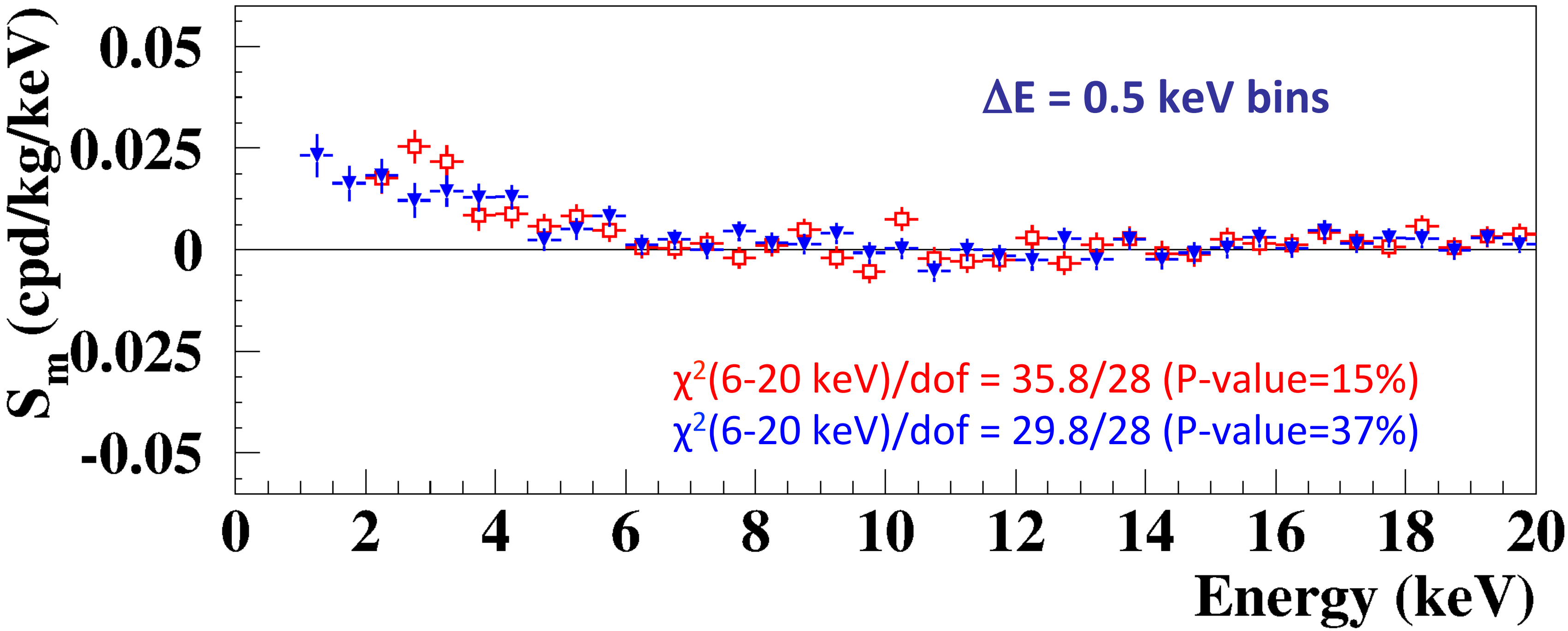
Energy distribution of the modulation amplitudes

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
vs
DAMA/LIBRA-phase2



The two 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%)

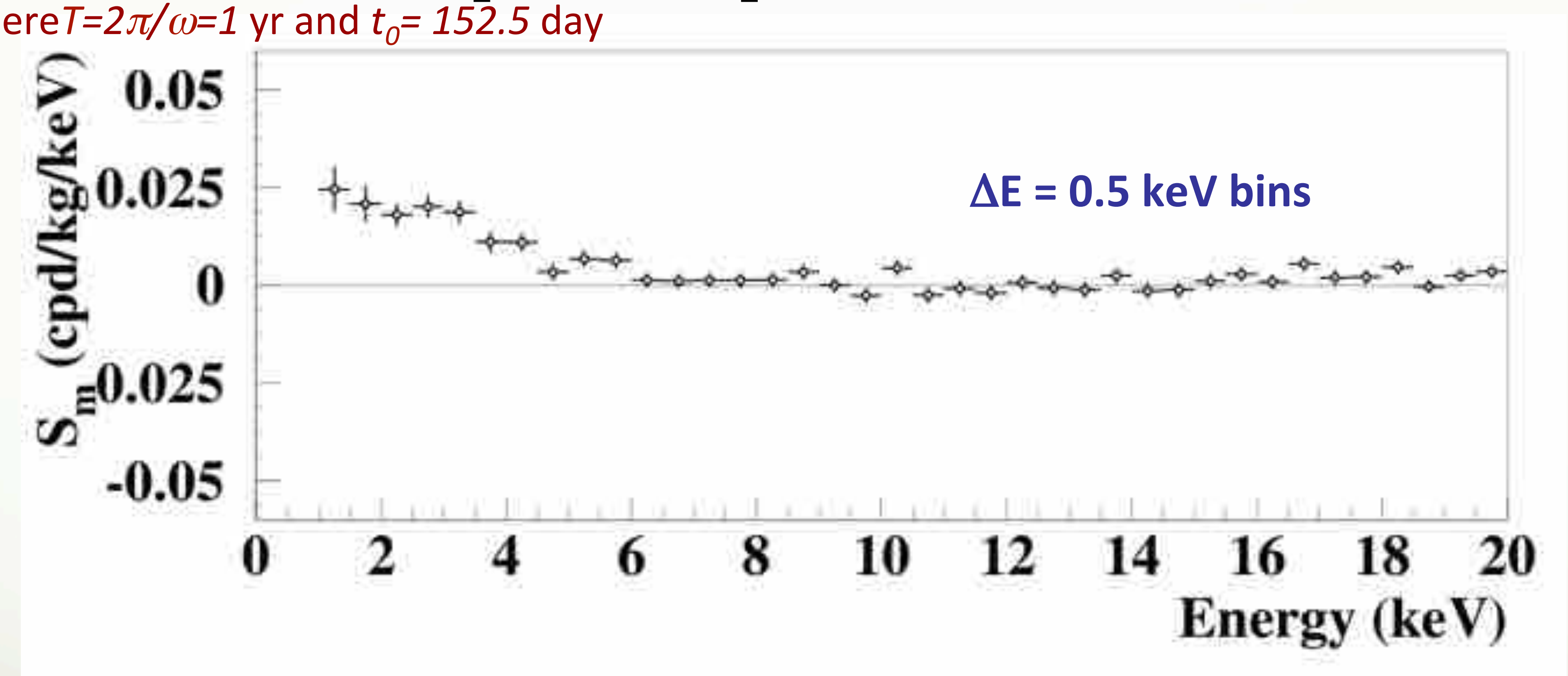
Energy distribution of the modulation amplitudes

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

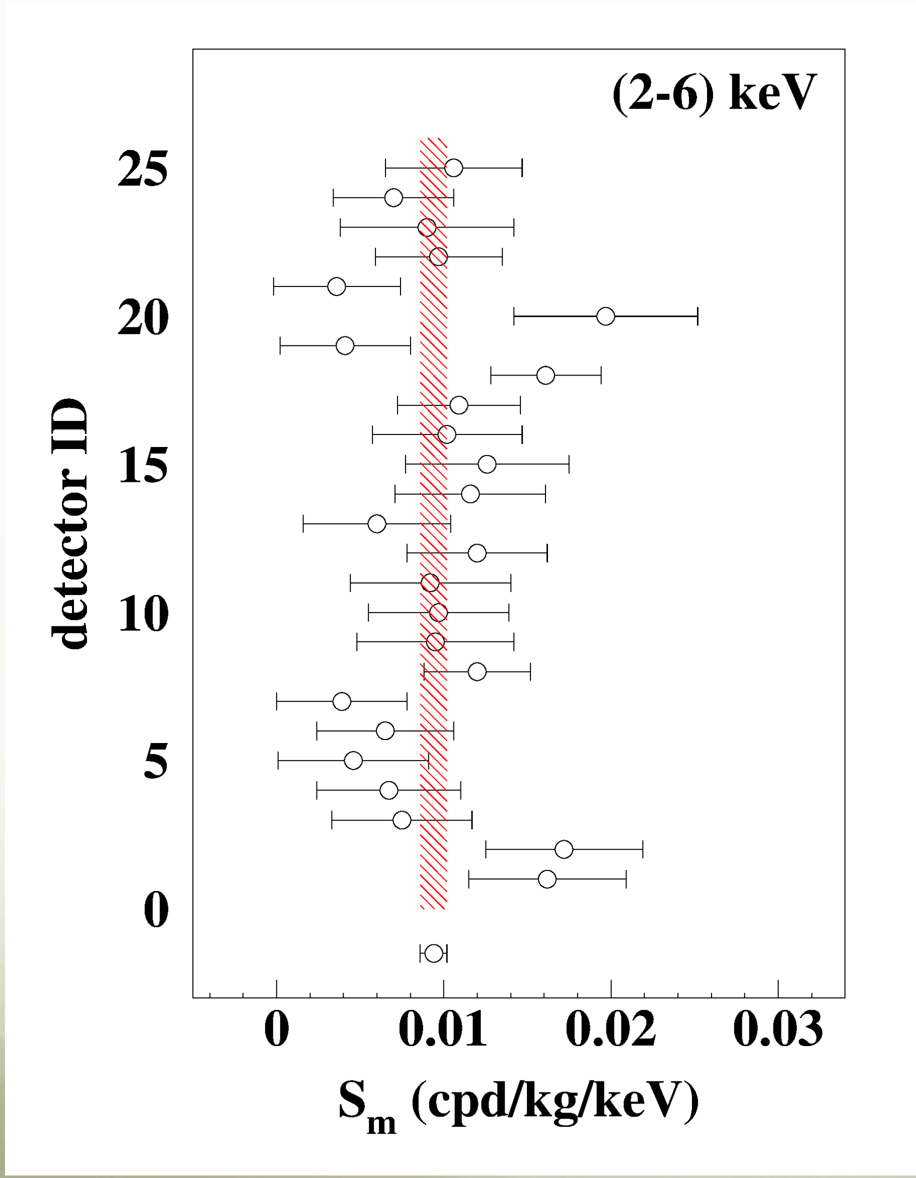
DAMA/NaI + DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2 (2.46 ton×yr)



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%).
- In (6–20) keV χ^2/dof = 42.6/28 (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 11% and 25%.

S_m 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 $S_m \pm 1\sigma$

χ^2/dof = 23.9/24 d.o.f.

The signal is well distributed over all the 25 detectors.

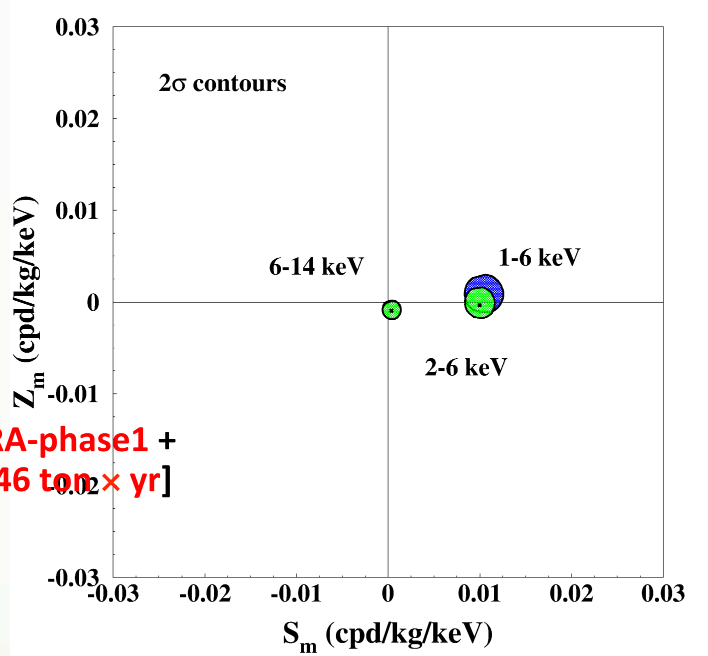
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

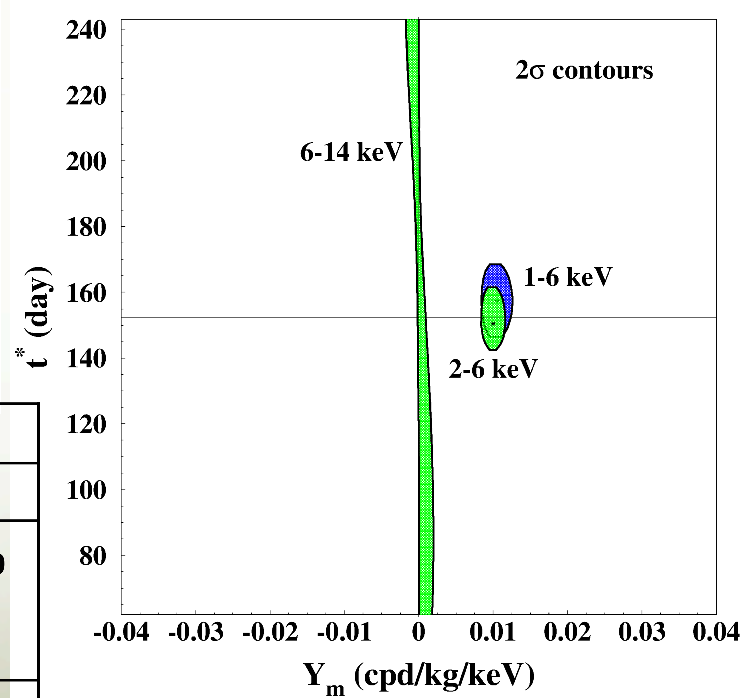
For Dark Matter signals:

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

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



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



E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0100 ± 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

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 ± 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)

- Contributions to the total neutron flux at LNGS;
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by:
  - neutrons,
  - muons,
  - solar neutrinos.

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

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

Modulation amplitudes

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

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

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

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

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

NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196, IJMPA31(2017)issue31, Universe4(2018)03009, Beld19,2(2018)27

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

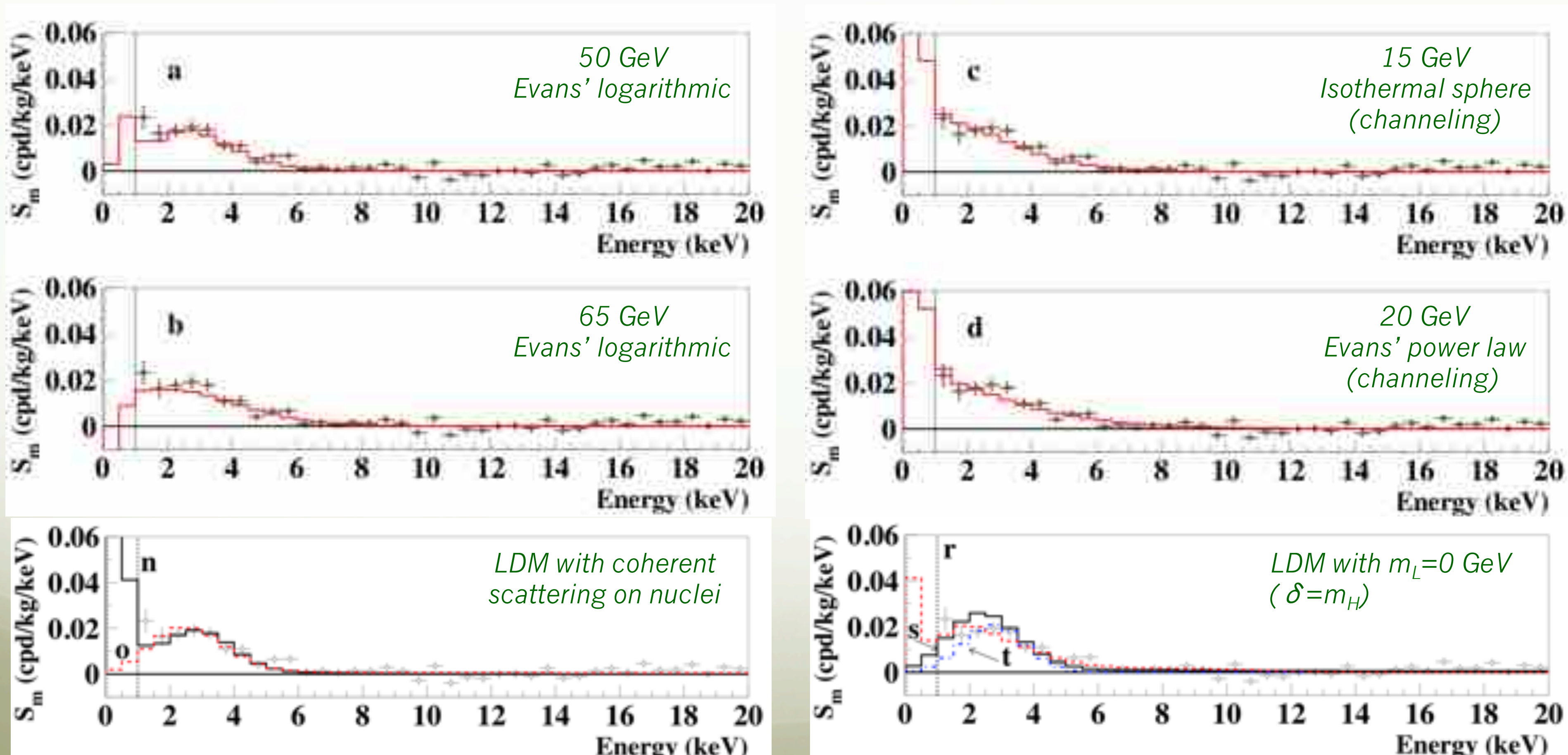
+ they cannot satisfy all the requirements of annual modulation signature

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

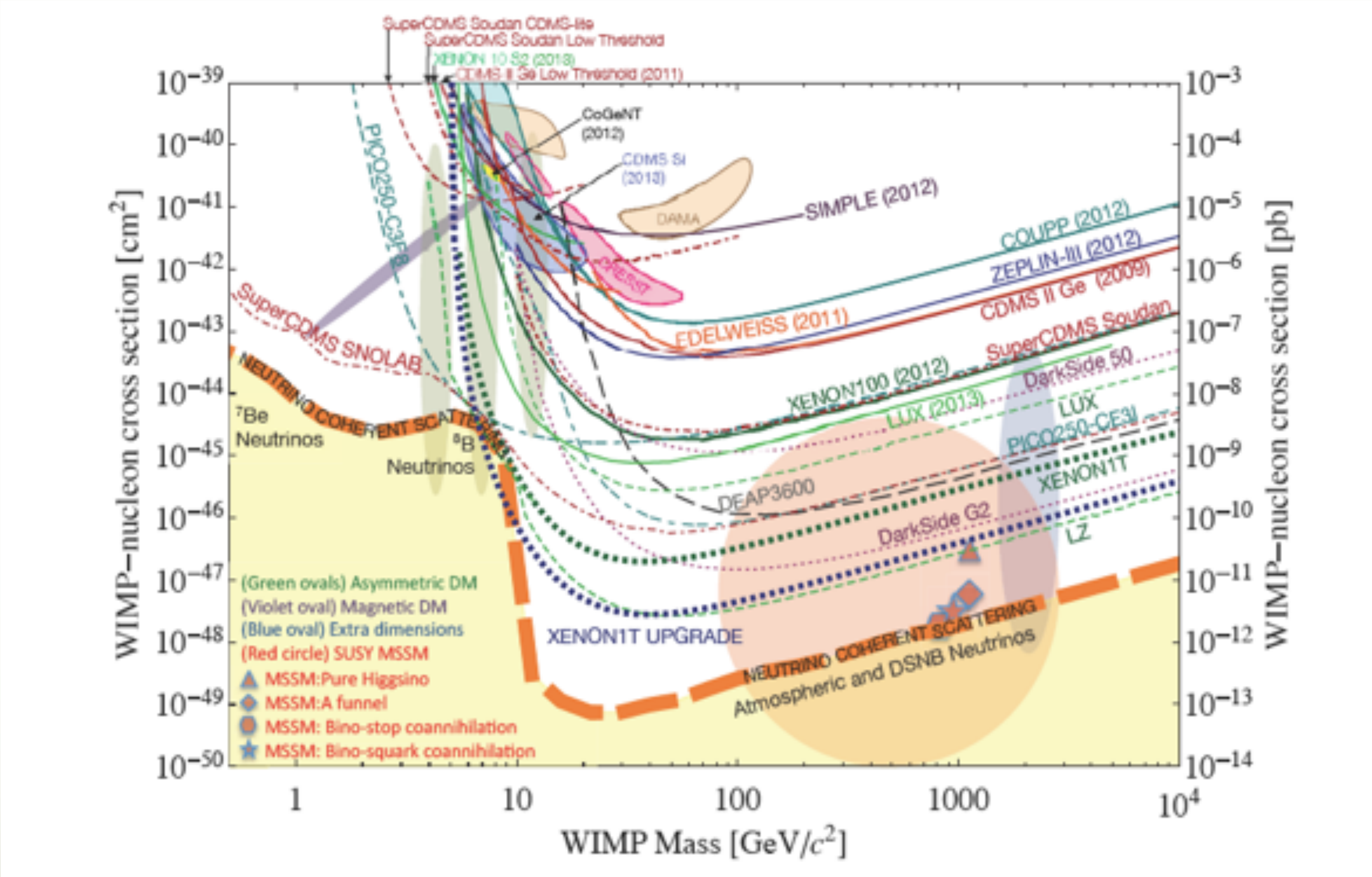
Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

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

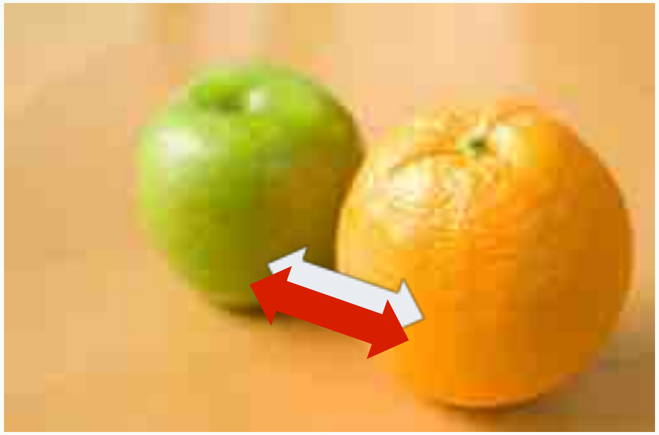
Just few <u>examples</u> of interpretation of the annual modulation in terms of candidate particles in <u>some scenarios</u>



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 interpretations and comparisons

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(2013)1330022

…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
- 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, …
- …

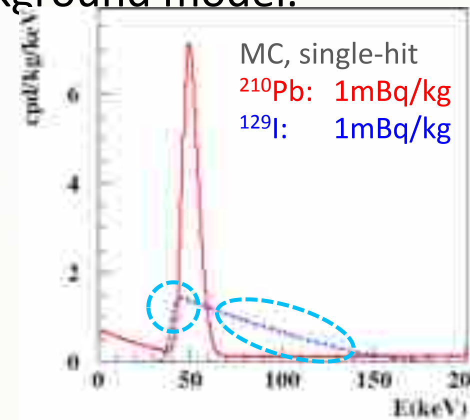
Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA

An example: the case of the latest COSINE-100

Several open problems: among them I will discuss a few.

- Results based only on the subtraction of what they consider the background model.
- The counting rate is three/four times that of DAMA.
- The background model has some faults. For example:
- ^{129}I completely forgotten in Cosine-100 data analysis
- Thus, ^{210}Pb significantly overestimated
- Others (^{3}H, …)



Internal ^{210}Pb seems to give the main (≈60%) contribution in 2-6 keV region, but , as shown, the assumed value is wrong: < 1.2 cpd/kg/keV

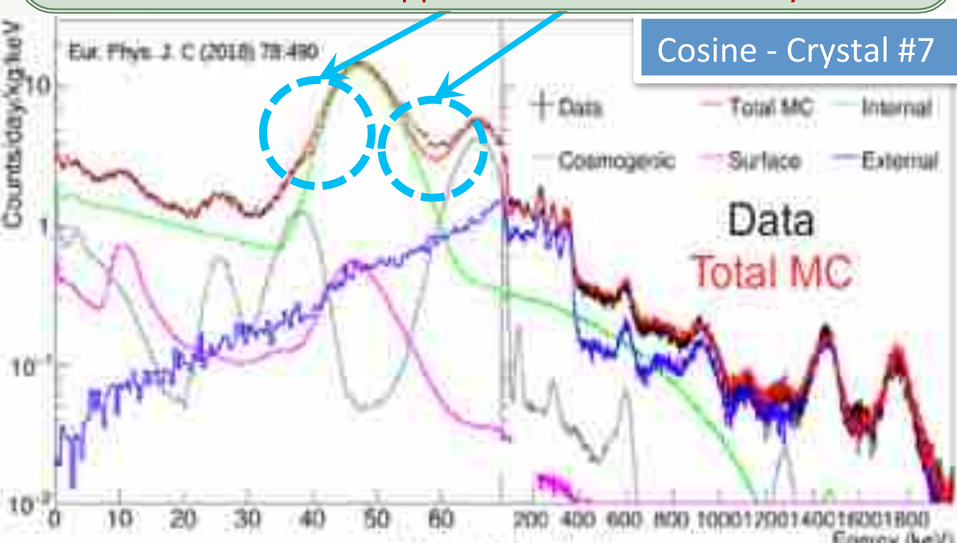
Very important discrepancies (note the log scale) in the reconstruction of the structure at ≈ 45 keV, due to:

1. Missing contribute of ^{129}I
2. Overestimate contribute of ^{210}Pb

In green the spectrum, the ^{210}Pb peak height is ≈ 14cpd/kg/keV, that is ≈ 2mBq/kg

But the measured α rate in crystal 7 is (1.54±0.4) mBq/kg and this should be an upper limit for ^{210}Pb activity!

Cosine - Crystal #7



Cosine - Crystal #7

Components	Background 2-6 keV (dru)
Internal ^{210}Pb	1.50 +/- 0.07
Internal ^{40}K	0.05 +/- 0.01
Surface ^{210}Pb	0.38 +/- 0.21
^{3}H (Cosmogenic)	0.58 +/- 0.54
^{109}Cd (Cosmogenic)	0.09 +/- 0.09
Other cosmogenic	0.05 +/-0.03
External	0.03 +/- 0.02
Total expected	2.70 +/- 0.59
Data	2.64 +/- 0.05

To be revised

<< 2.4

- expected << observed
- Uncertainties per crystal: 0.6 cpd/kg/keV
- → Total uncer. ≈0.6/√6 = 0.25 cpd/kg/keV

Still large space for DM signal

… more on COSINE-100

- The methodology of the background subtraction, used by Cosine-100, is strongly discouraged and deprecated because of the impossibility to have a precise knowledge of the background contribution in particular at low energy, leading to large systematic uncertainties.
- Thus, it is a **dangerous** way to claim sensitivities by the fact not supported by large counting rate.
- Even considering the background model as correct, the analysis has fault.
- They get null residuals in each crystal (even always negative) starting from a wrong bckg hypothesis!

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Table 4 Fitted background events in units of dru (counts/day/keV/kg) in the (2–6) keV energy interval

	Crystal-1	Crystal-2	Crystal-3	Crystal-4	Crystal-6	Crystal-7
Internal						
^{40}K	0.10 ±0.02	0.20 ± 0.02	0.10 ± 0.01	0.10 ±0.01	0.05 ± 0.01	0.05 ±0.01
^{210}Pb	2.50 ± 0.10	1.69 ± 0.09	0.57 ± 0.05	0.71 ± 0.05	1.46 ± 0.07	1.50 ± 0.07
Other ($\times 10^{-4}$)	7.0±0.1	15±1	7.3±0.1	7.7±0.1	14±1	14±1
Cosmogenic						
^{3}H	2.35 ± 0.90	0.81 ± 0.40	1.54 ± 0.77	1.97 ± 0.66	0.69 ± 0.67	0.58 ± 0.54
^{109}Cd	0.05 ±0.04	0.009 ±0.009	0.13 ± 0.06	0.29 ± 0.15	0.08 ± 0.08	0.09 ± 0.09
Other	–	–	0.02 ± 0.01	0.09 ± 0.04	0.06 ± 0.03	0.05 ± 0.03
Surface						
^{210}Pb	0.64 ± 0.64	0.51 ± 0.51	1.16 ± 0.51	0.22 ± 0.16	0.34 ± 0.20	0.38 ± 0.21
External						
	0.03 ± 0.02	0.05 ± 0.04	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.03	0.03 ± 0.02
Total simulation						
	5.68 ± 1.04	3.28 ± 0.67	3.57 ± 0.76	3.41 ± 0.75	2.74 ± 0.61	2.70 ± 0.51
Data						
	5.64 ± 0.10	3.27 ± 0.07	3.35 ± 0.07	3.19 ± 0.05	2.62 ± 0.05	2.64 ± 0.05
Data−model=	−0.04±1.04	−0.01±0.67	−0.22±0.76	−0.22±0.75	−0.12±0.61	−0.06±0.51

Data−model = −0.105±0.276 cpd/kg/keV

→ **S_0<0.36 cpd/kg/keV 90%CL in the (2-6) keV energy region**

Still large space for DM

Since time, by simple and direct determination in DAMA: S_0<0.25 cpd/kg/keV in (2-4) keV (DAMA/LIBRA-phase1), even less in phase2

In conclusion: Cosine-100 low energy analysis is **wrong** and the exclusion plot **meaningless**

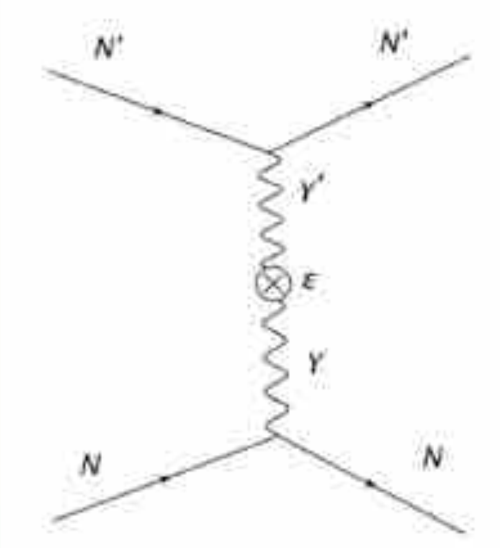
DAMA annual modulation effect and Asymmetric mirror matter

EPJC75(2015)400

Asymmetric mirror matter: mirror parity spontaneously broken at the electroweak scale $\Rightarrow$ mirror sector becomes heavier and deformed copy of ordinary sector; mirror hydrogen can be stable and a good DM candidate

Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$

$$\mathcal{N}' + \mathcal{N} \rightarrow \mathcal{N}' + \mathcal{N}$$



mirror atom scattering off the ordinary target nuclei in the NaI(Tl) detectors of DAMA/LIBRA set-up with Rutherford-like cross sections.

$$\frac{d\sigma_{A,A'}}{dE_R} = \frac{\mathcal{C}_{A,A'}}{E_R^2 v^2}$$

and

$$\mathcal{C}_{A,A'} = \frac{2\pi\epsilon^2\alpha^2 Z^2 Z'^2}{M_A} \mathcal{F}_A^2 \mathcal{F}_{A'}^2$$

Knowing that $\Omega_{B'}/\Omega_B \approx 5$, two cases are considered:

- ***Separate baryogenesis***. $\eta = n_B/n_\gamma$ and $\eta' = n_{B'}/n'_\gamma$ are equal, and $n'_\gamma/n_\gamma \ll 1$. The $m_{N'}$ can be **tens of GeV**.
- ***Co-genesis*** of baryon and mirror baryon asymmetries. $n_{B'} = n_B$, we need $m_{N'}/m_N \approx 5$, which singles out the mass of dark atom of **about 5 GeV**.

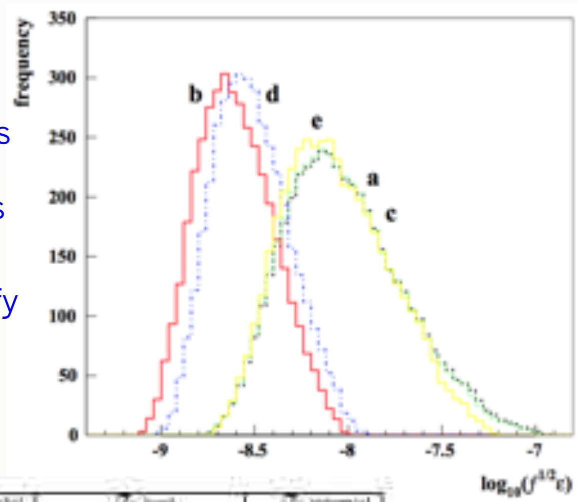
DAMA annual modulation effect and Asymmetric mirror matter

EPJC75(2015)400

- ❑ Case of $m_{N'}$ = 5 GeV
- ❑ Free parameter in the analysis:
  - ε = coupling constant
  - f = fraction of mirror atoms in the halo

- For all the scenarios, various existing uncertainties in nuclear and particle physics quantities are considered.
- The allowed intervals identify the values corresponding to C.L. larger than 5σ from the null hypothesis

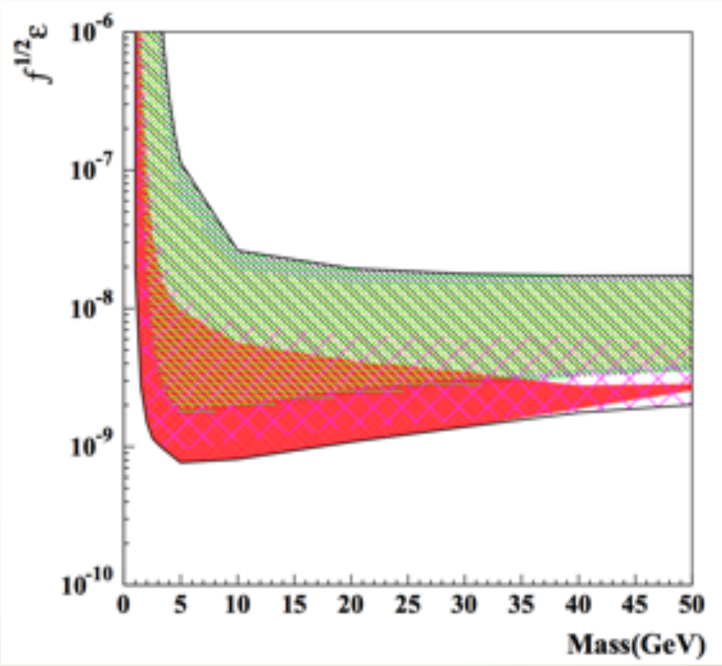
Results on the $\sqrt{f}\varepsilon$ parameter in the considered scenarios



Scenario	Quenching Factor	Channeling	Migdal	$\sqrt{f}\varepsilon$ best	$\sqrt{f}\varepsilon$ interval ($\times 10^{-9}$)
a	Q_I [illegible]	no	no	4.61 × 10^{-9} (9.3σ C.L.)	1.86–4.12 (all) 1.73–11.4
b	Q_I [illegible]	yes	no	2.56 × 10^{-9} (9.3σ C.L.)	1.16–2.93 (all) 0.77–8.22
c	Q_I [illegible]	no	yes	4.40 × 10^{-9} (9.2σ C.L.)	1.82–4.47 (all) 1.72–10.7
d	Q_{II} [illegible]	no	no	2.44 × 10^{-9} (9.5σ C.L.)	1.00–2.48 (all) 0.94–12.5
e	Q_{III} [illegible]	no	no	5.18 × 10^{-9} (9.1σ C.L.)	2.24–5.26 (all) 1.89–60.1

The allowed values for $\sqrt{f}\varepsilon$ in the case of mirror hydrogen atom, Z′ = 1, ranges between **7.7×10^{-10} to 1.1×10^{-7}**. The values within this overall range are **well compatible with cosmological bounds**. In particular, the best fit values among all the considered scenarios gives **$\sqrt{f}\varepsilon_{b.f.} = 2.4 \times 10^{-9}$**

- When the assumption $m_{N'} \simeq 5m_p$ is released, allowed regions obtained by marginalizing all the models



- These allowed intervals identify the $\sqrt{f}\varepsilon$ values corresponding to C.L. larger than 5σ from the null hypothesis, that is $\sqrt{f}\varepsilon$ = 0.

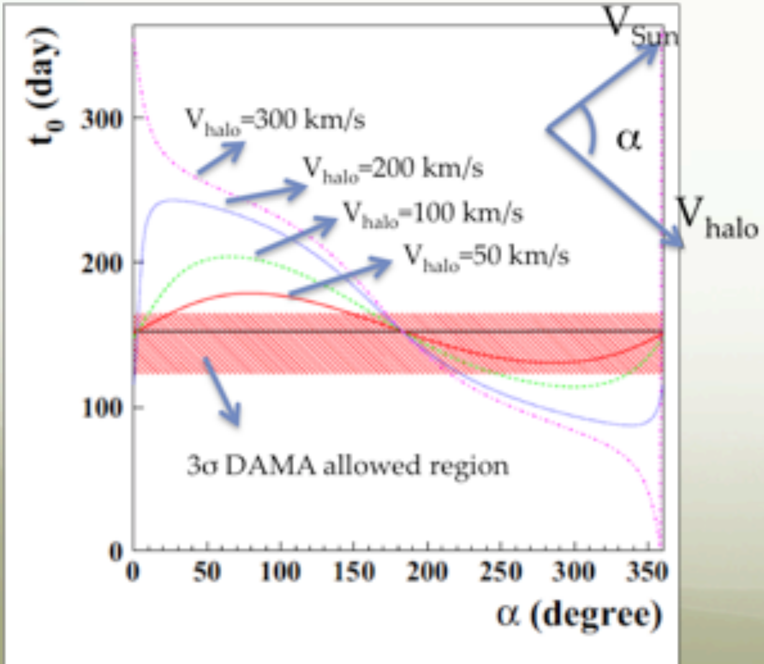
DAMA annual modulation effect and Symmetric mirror matter

EPJC77(2017)83

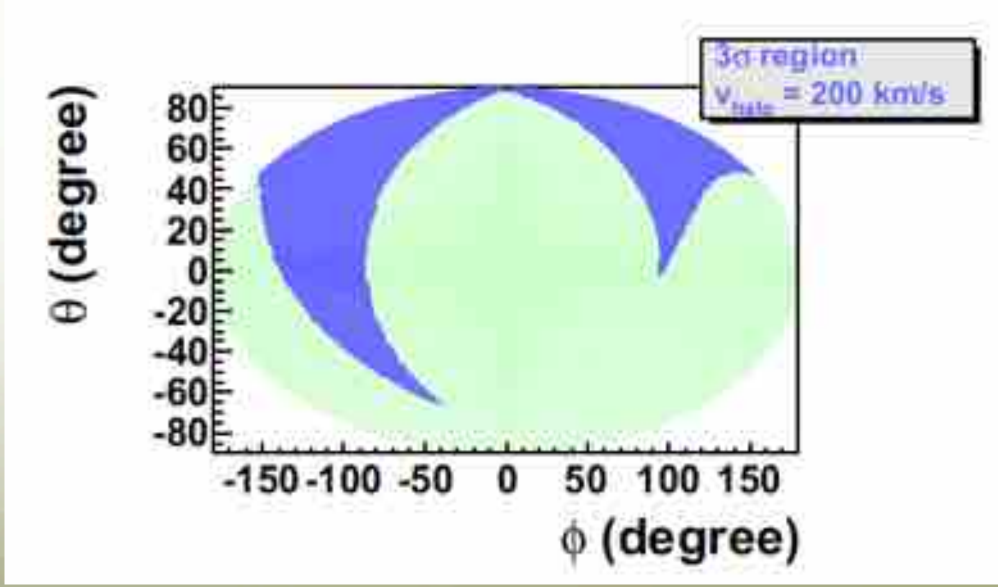
Symmetric mirror matter:

- an exact duplicate of ordinary matter from parallel hidden sector, which chemical composition is dominated by mirror Helium, while it can also contain significant fractions of heavier elements as Carbon and Oxygen.
- halo composed by a bubble of Mirror particles of different species; Sun is travelling across the bubble which is moving in the Galactic Frame (GF) with v_{halo} velocity;
- the mirror particles in the bubble have Maxwellian velocity distribution in a frame where the bubble is at rest; cold and hot bubble with temperature from 10^4 K to 10^8 K
- interaction via photon - mirror photon kinetic mixing

Examples of expected phase of the annual modulation signal (case of halo moving on the galactic plane)



The blue regions correspond to directions of the halo velocities in GC (θ, ϕ) giving a phase compatible at 3σ with DAMA phase



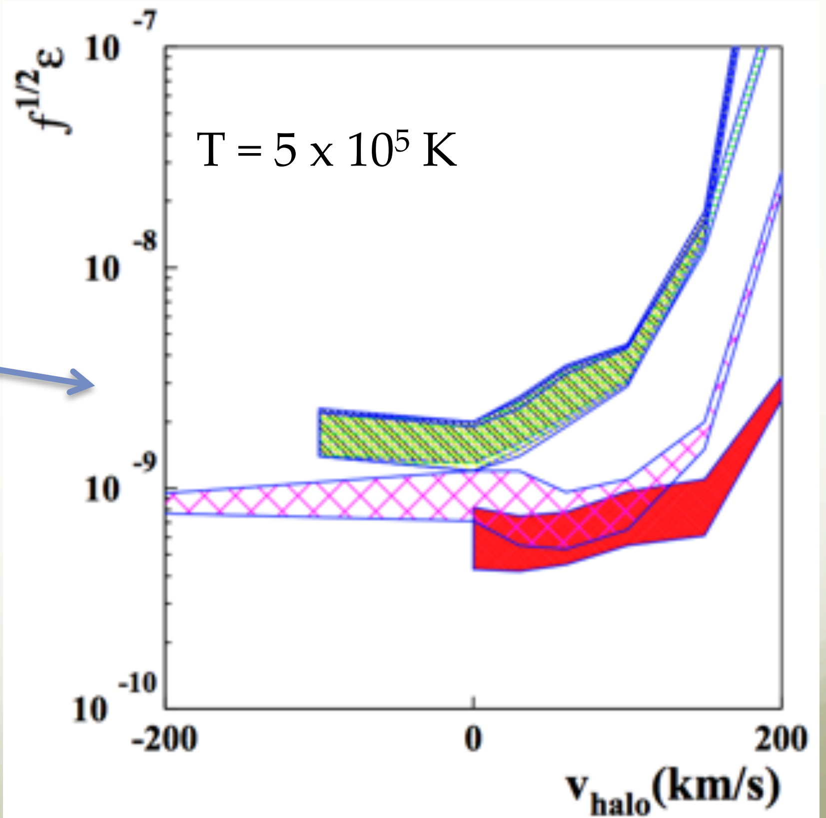
DAMA annual modulation effect and Symmetric mirror matter

EPJC77(2017)83

Symmetric mirror matter:

- Results refers to halo velocities parallel or anti-parallel to the Sun ($\alpha = 0, \pi$). For these configurations the expected phase is June 2
- The free parameters in the analysis are v_{halo} (positive values correspond to halo moving in the same direction of the Sun while negative values correspond to opposite direction) and the equilibrium Temperature, T, of the halo

Mirror matter composition	H (%)	He (%)	C (%)	O (%)	Fe (%)
H′, He′	25	75	–	–	–
H′, He′, C′, O′	12.5	75.	7.	5.5	–
H′, He′, C′, O′, Fe′	20	74	0.9	5.	0.1



DAMA/LIBRA allowed values for $\sqrt{f}\,\varepsilon$ in different scenarios

- For all the scenarios, various existing uncertainties in nuclear and particle physics quantities are considered.
- The allowed intervals identify the values corresponding to C.L. larger than 5σ from the null hypothesis

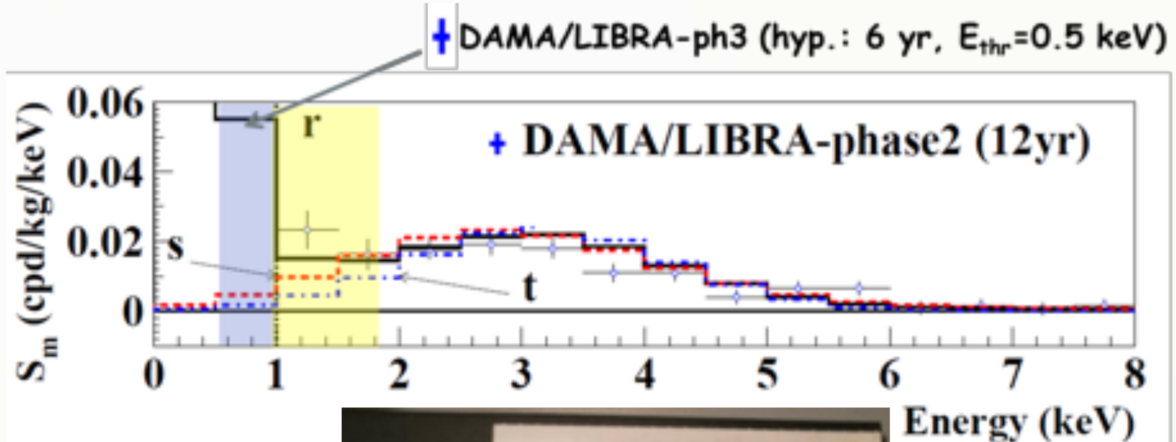
$\sqrt{f} \cdot \epsilon$ coupling const. and DM fraction as mirror atom

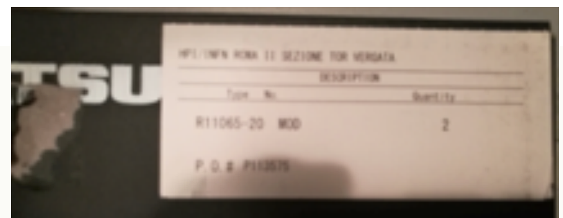
Many configurations and halo models favored by the DAMA annual modulation effect corresponds to couplings values well compatible with cosmological bounds.

Running phase2 and towards 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:

- The light collection of the detectors can further be improved
- Light yields and the energy thresholds will improve accordingly
- The electronics can be improved too





- Chosen strategy:
  1. new development of high Q.E. PMTs with increased radio-purity.
  2. new miniaturized low background per-amps directly mounted on the low background voltage dividers.
  3. S/N increase by decreasing noise.

The presently-reached metallic PMTs features:

- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- Radio-purity 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).

several prototypes from a dedicated R&D with HAMAMATSU 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**

- It is not enough to run NaI(Tl) detectors **of any quality** to be directly comparable with DAMA (see the case of **Cosine-100**).
- 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