Dark Matter with DAMA/LIBRA

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EPS-HEP Conference
European Physical Society conference on High Energy Physics 2021
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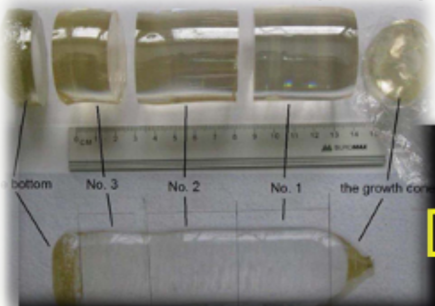
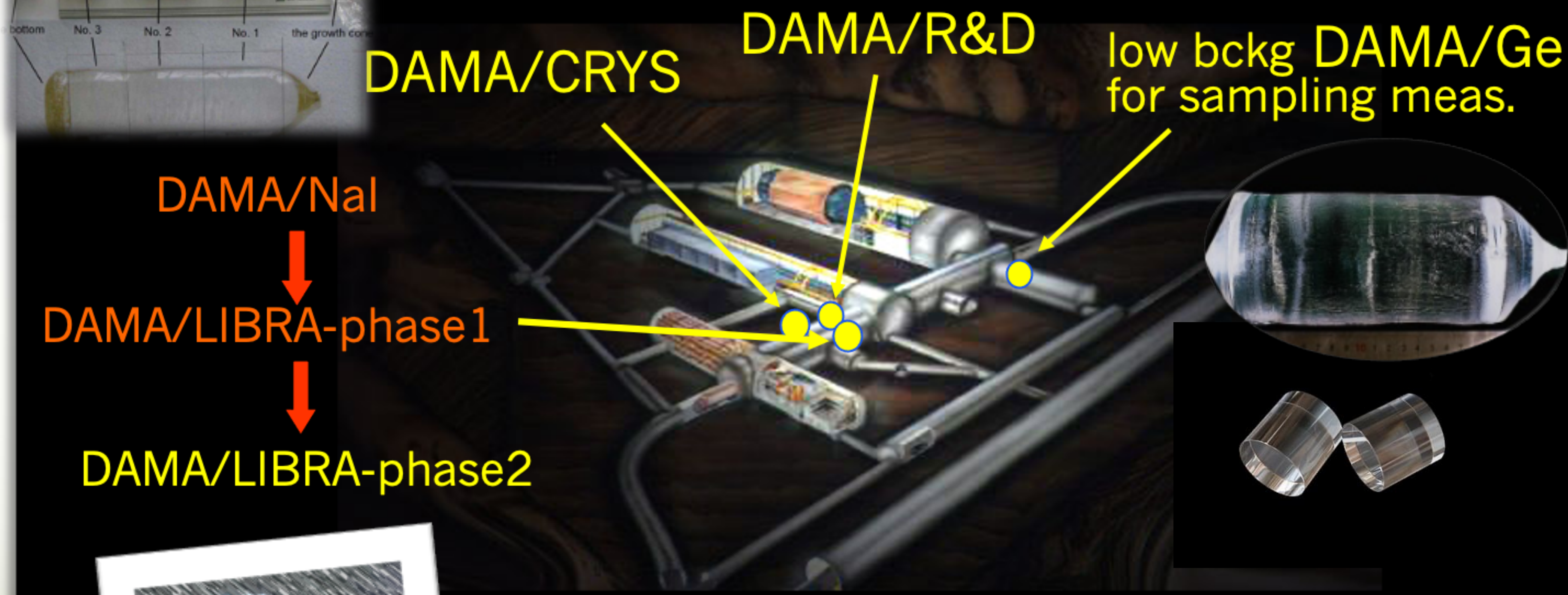
DAMA set-ups

an observatory for rare processes @ LNGS

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





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

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

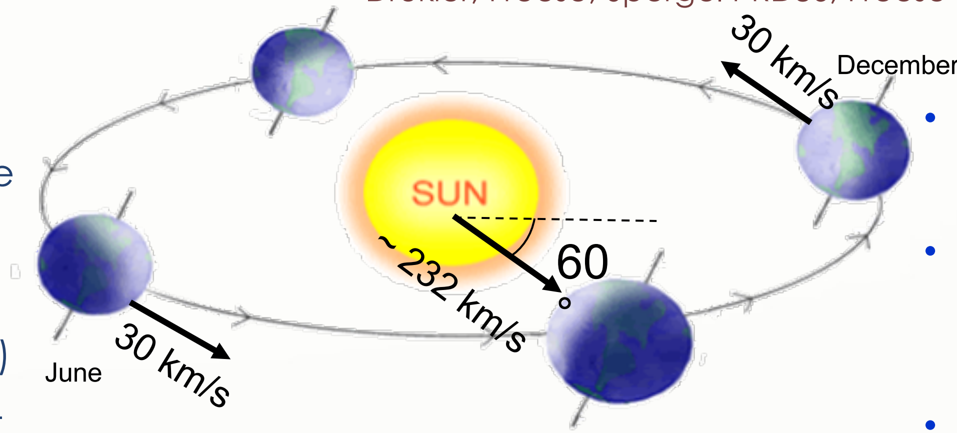
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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.

Requirements:

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

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



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

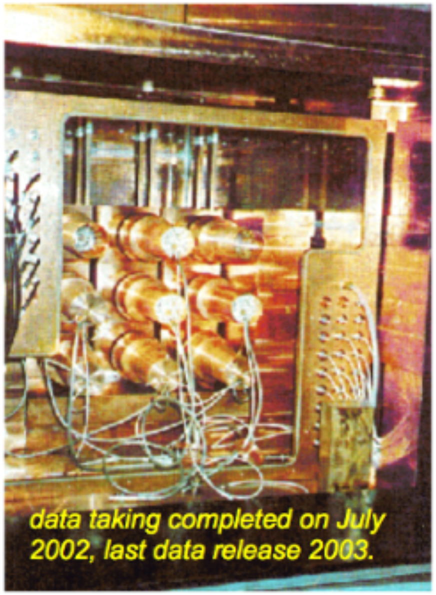
$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

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

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 6.3σ C.L.

total exposure (7 annual cycles) 0.29 ton×yr

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

Perform

Results

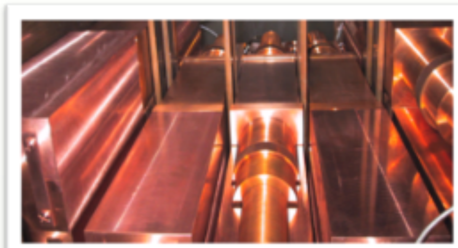
- Possi
- CNC
- Elect in loc
- Searc
- Exoti
- Searc
- Searc

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

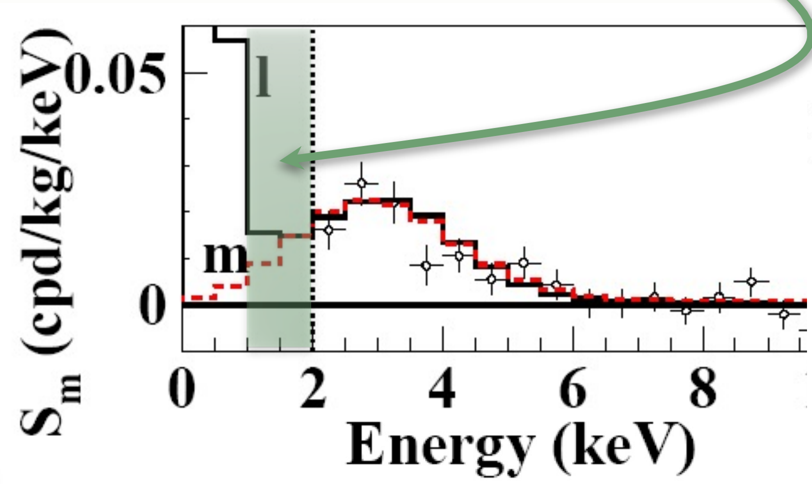
JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4) (2019) 317
PPNP114(2020)103810

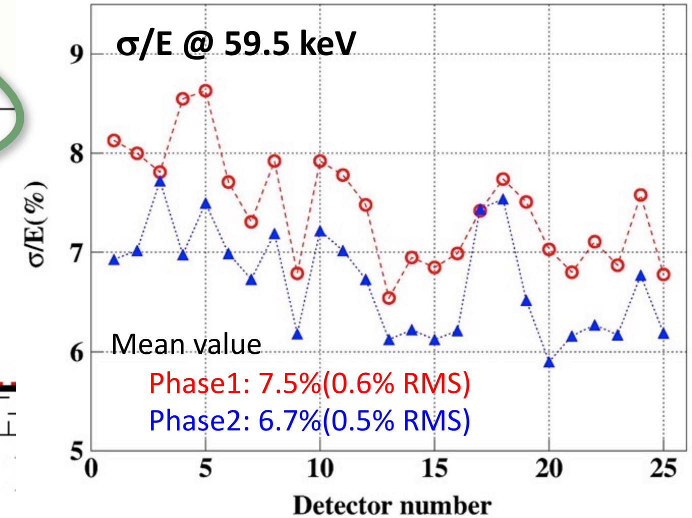
Lowering software energy threshold below 2 keV:

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

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

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





The contaminations:

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

The light responses:

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

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)

- ✓ 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)

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**

New data release July 2021

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

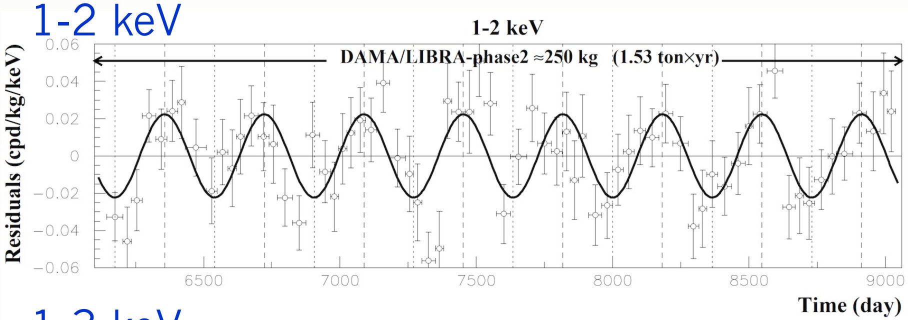
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.86 ton × yr**

DM model-independent Annual Modulation Result

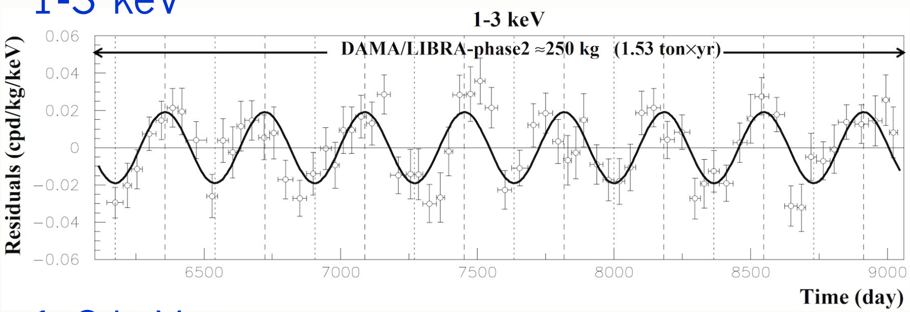
DAMA/LIBRA-phase2 (1.53 ton × yr)

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

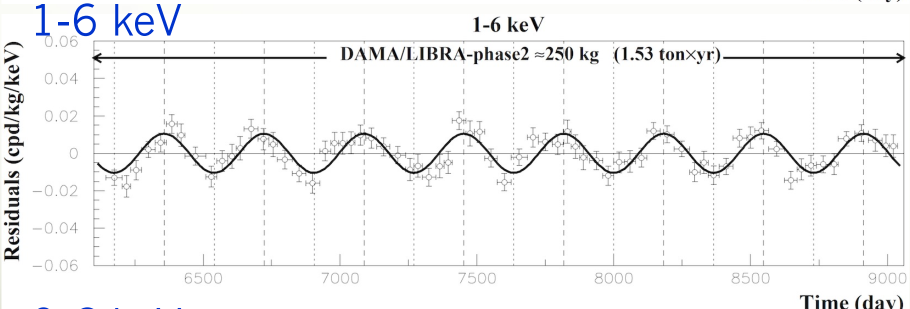
1-2 keV



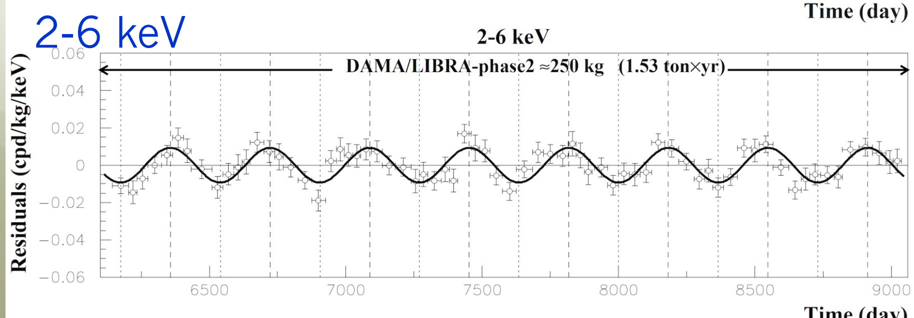
1-3 keV



1-6 keV



2-6 keV



Absence of modulation? No

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

Fit on DAMA/LIBRA-phase2

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

1-2 keV

A=(0.0224±0.0030) cpd/kg/keV
χ^2/dof = 75.8/68 **7.4 σ C.L.**

1-3 keV

A=(0.0191±0.0020) cpd/kg/keV
χ^2/dof = 81.6/68 **9.7 σ C.L.**

1-6 keV

A=(0.01048±0.00090) cpd/kg/keV
χ^2/dof = 66.2/68 **11.6 σ C.L.**

2-6 keV

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

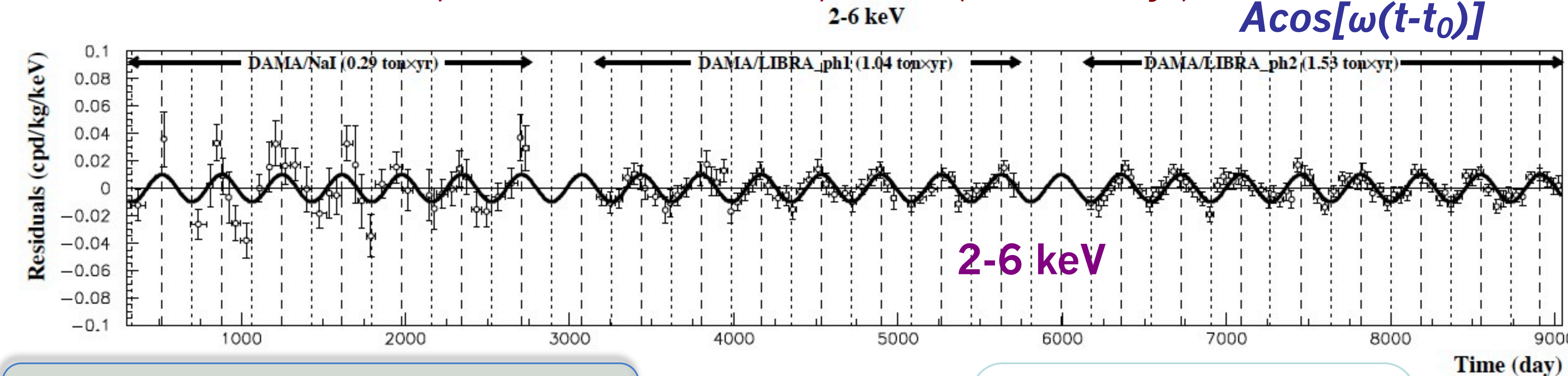
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6σ C.L.

DM model-independent Annual Modulation Result

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

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

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



Absence of modulation? No

χ^2/dof=311/156 ⇒ P(A=0) =2.3×10^{-12}

continuous lines: t_0 = 152.5 d, T = 1.00 y

A=(0.00996±0.00074) cpd/kg/keV

χ^2/dof = 130/155 **13.4 σ C.L.**

DAMA/NaI (0.29 ton x yr)
DAMA/LIBRA-ph1 (1.04 ton x yr)
DAMA/LIBRA-ph2 (1.53 ton x yr)

total exposure = 2.86 ton×yr

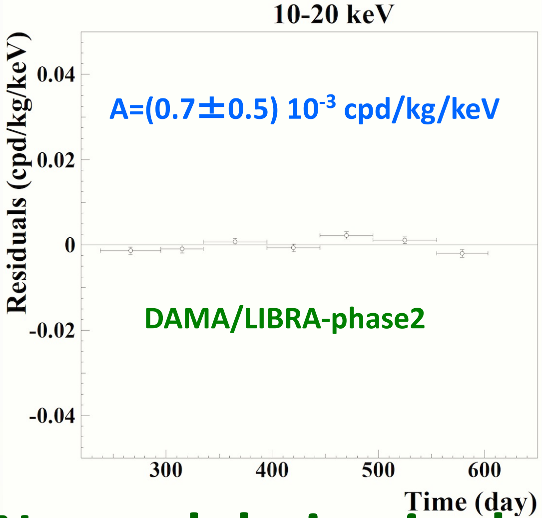
Releasing period (*T*) and phase (t_0) in the fit

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

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

Rate behaviour above 6 keV

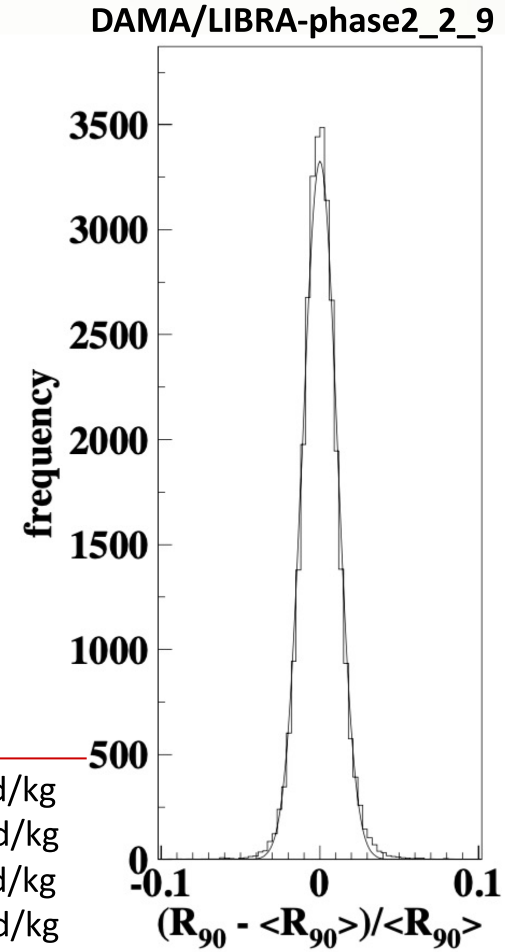
• No Modulation above 6 keV



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

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

→ statistically consistent with zero



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

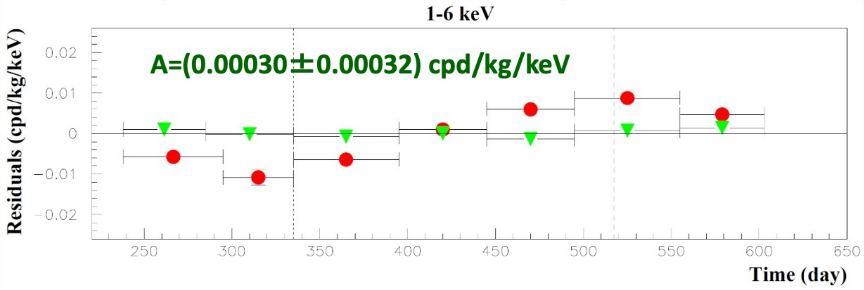
Period	Mod. Ampl.
DAMA/LIBRA-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg
DAMA/LIBRA-ph2_8	-(0.18±0.13) cpd/kg
DAMA/LIBRA-ph2_9	(0.08±0.14)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

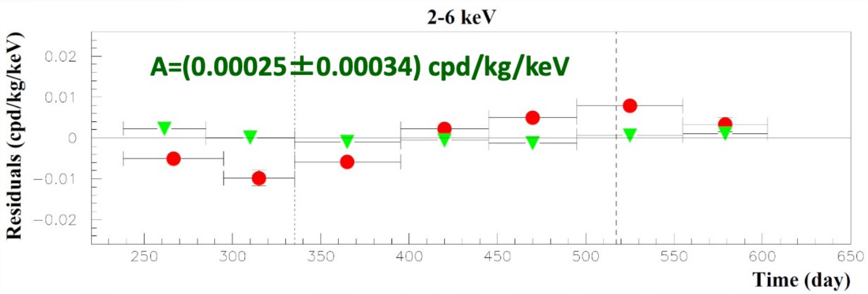
No modulation above 6 keV

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

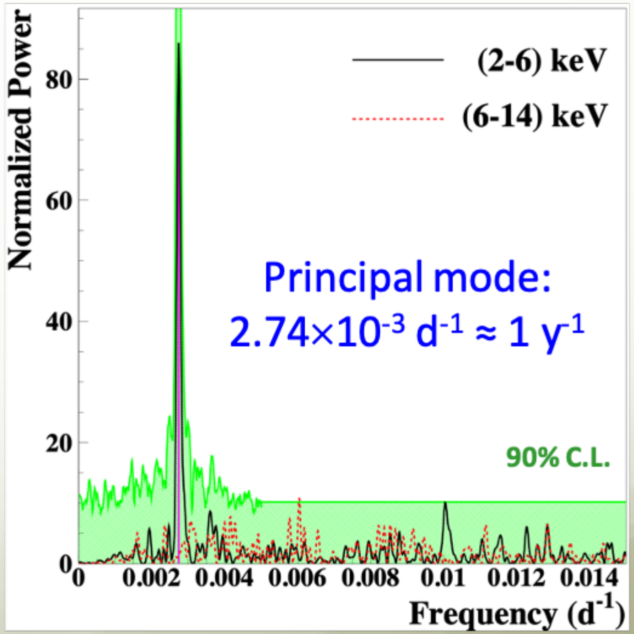
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

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

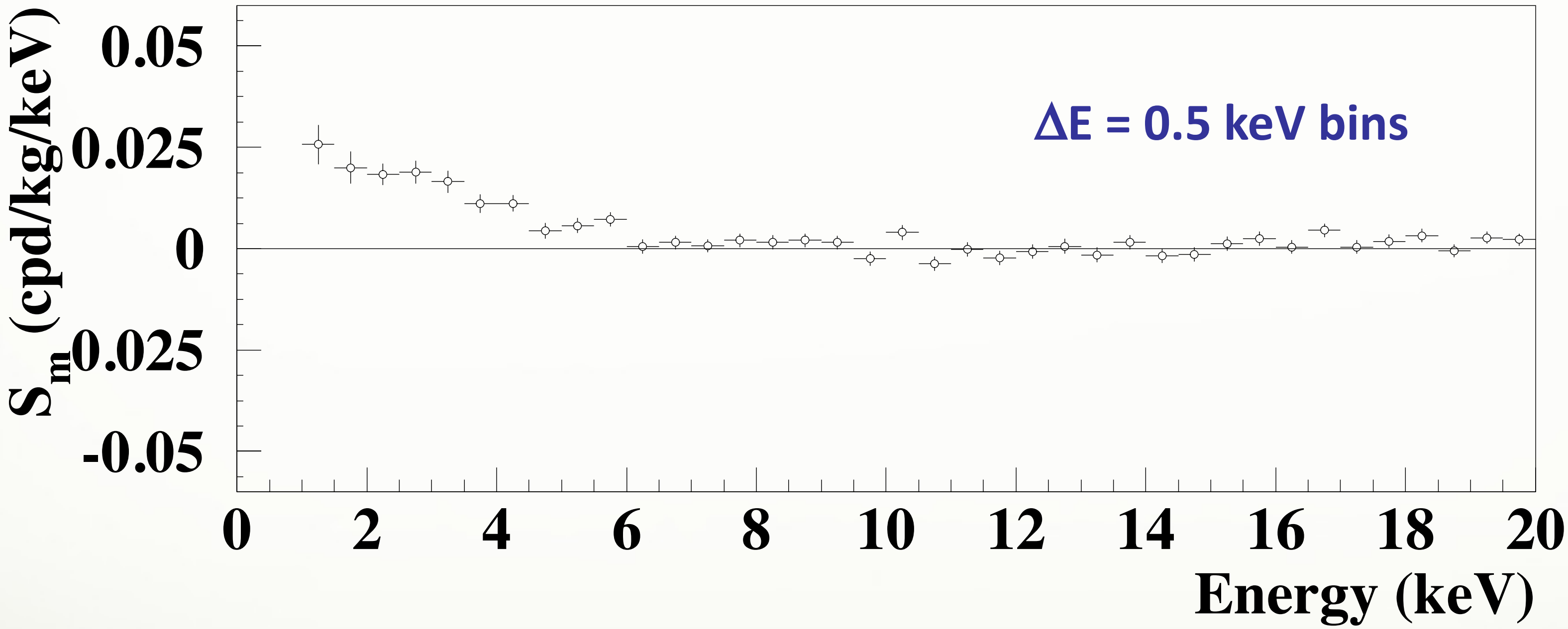
Energy distribution of the modulation amplitudes

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%.

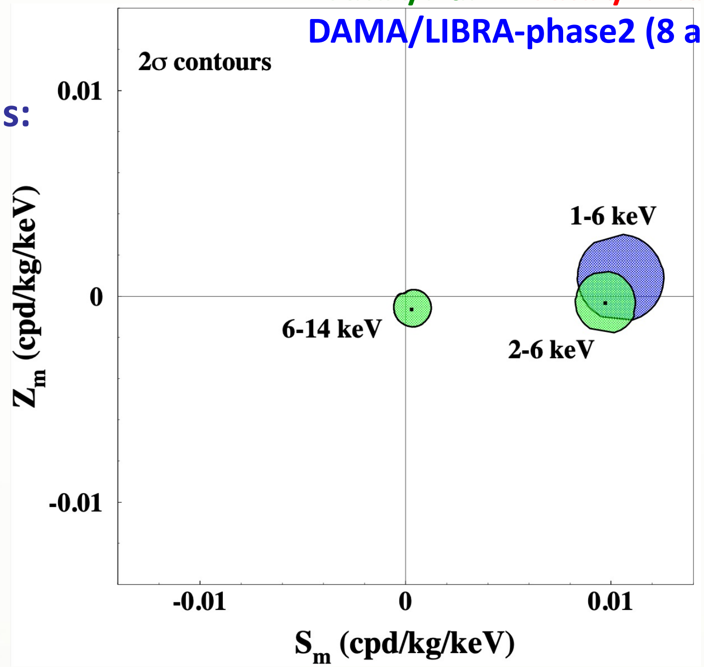
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

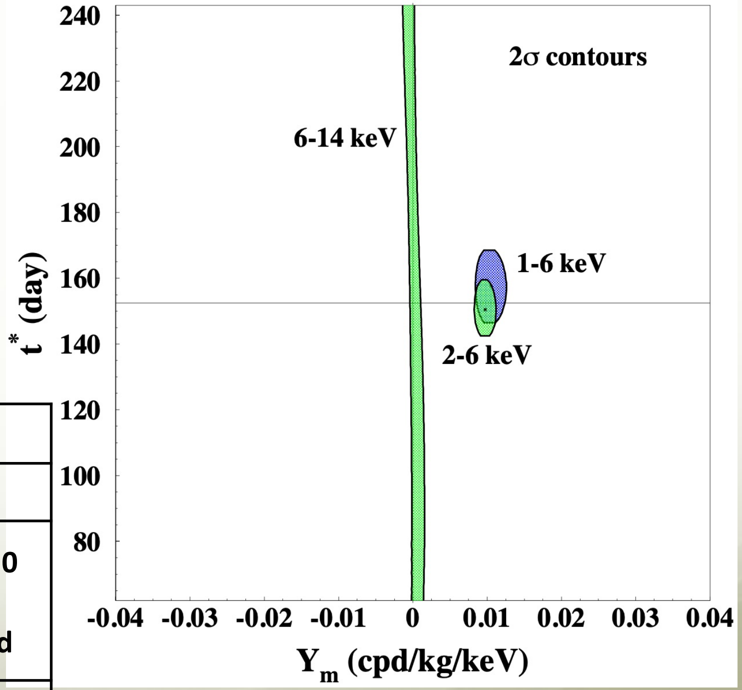
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]

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)

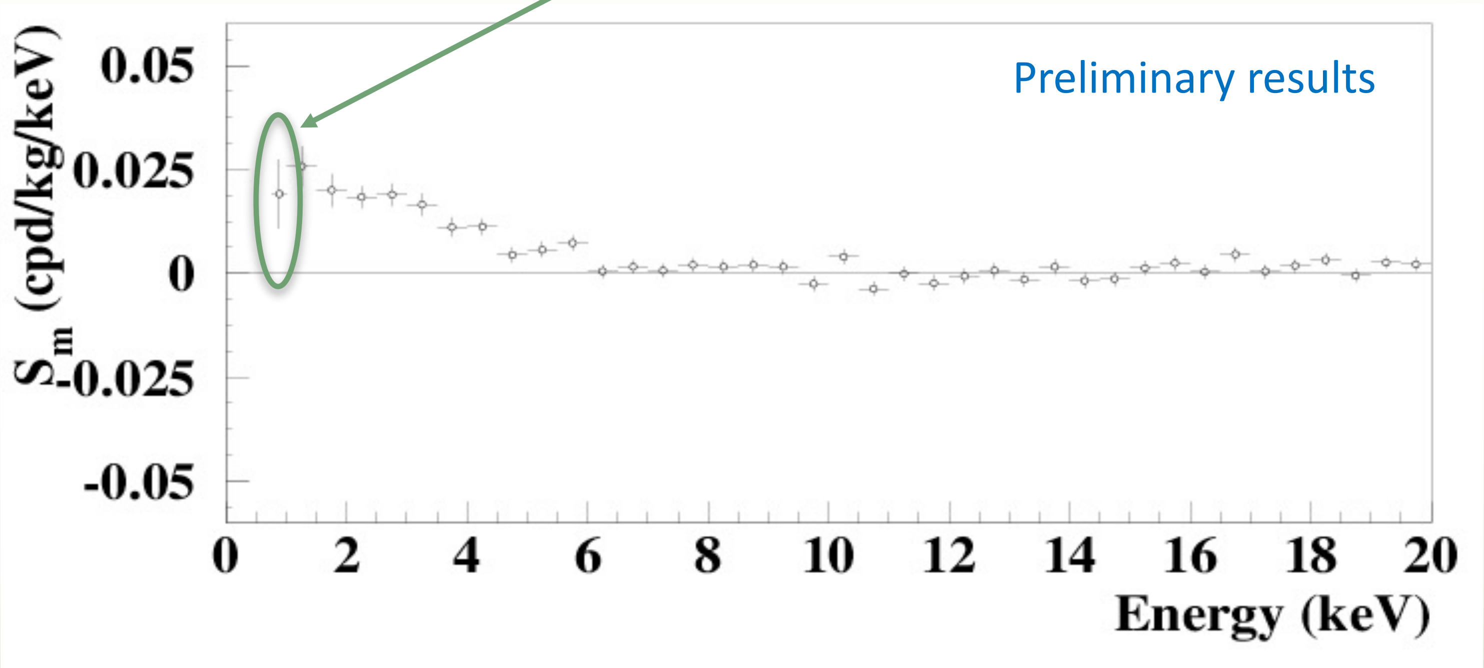


E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0097 ± 0.0007	- 0.0003 ± 0.0007	0.0097 ± 0.0007	150.5 ± 4.0
6-14	0.0003 ± 0.0005	-0.0006 ± 0.0005	0.0007 ± 0.0010	undefined
1-6	0.0104 ± 0.0007	0.0002 ± 0.0007	0.0104 ± 0.0007	153.5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

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

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

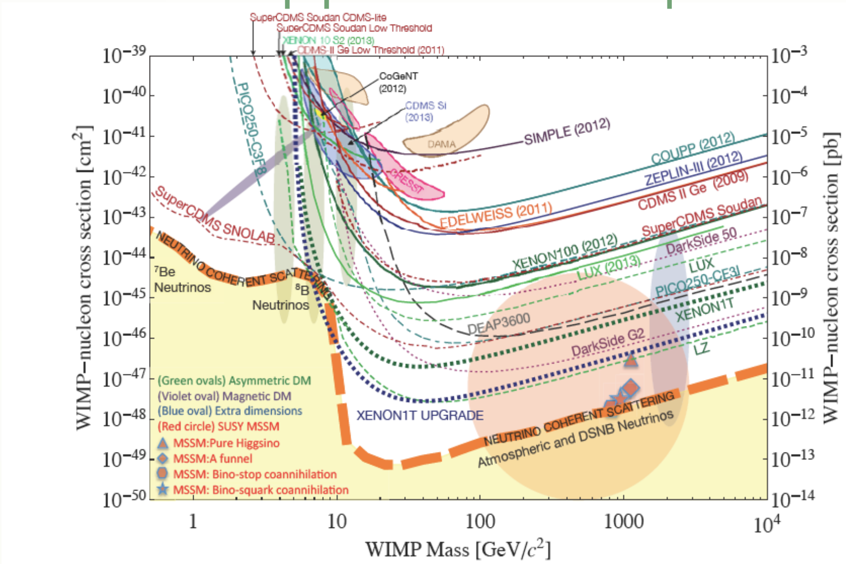
NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196, IJMPA31(2017)issue31, Universe4(2018)116, Bled19(2018)27,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

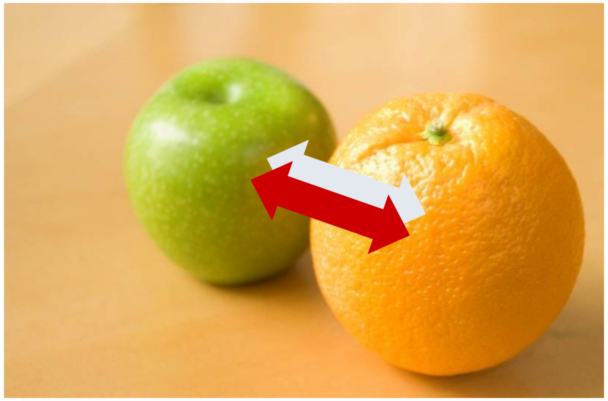
+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

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, …
- …

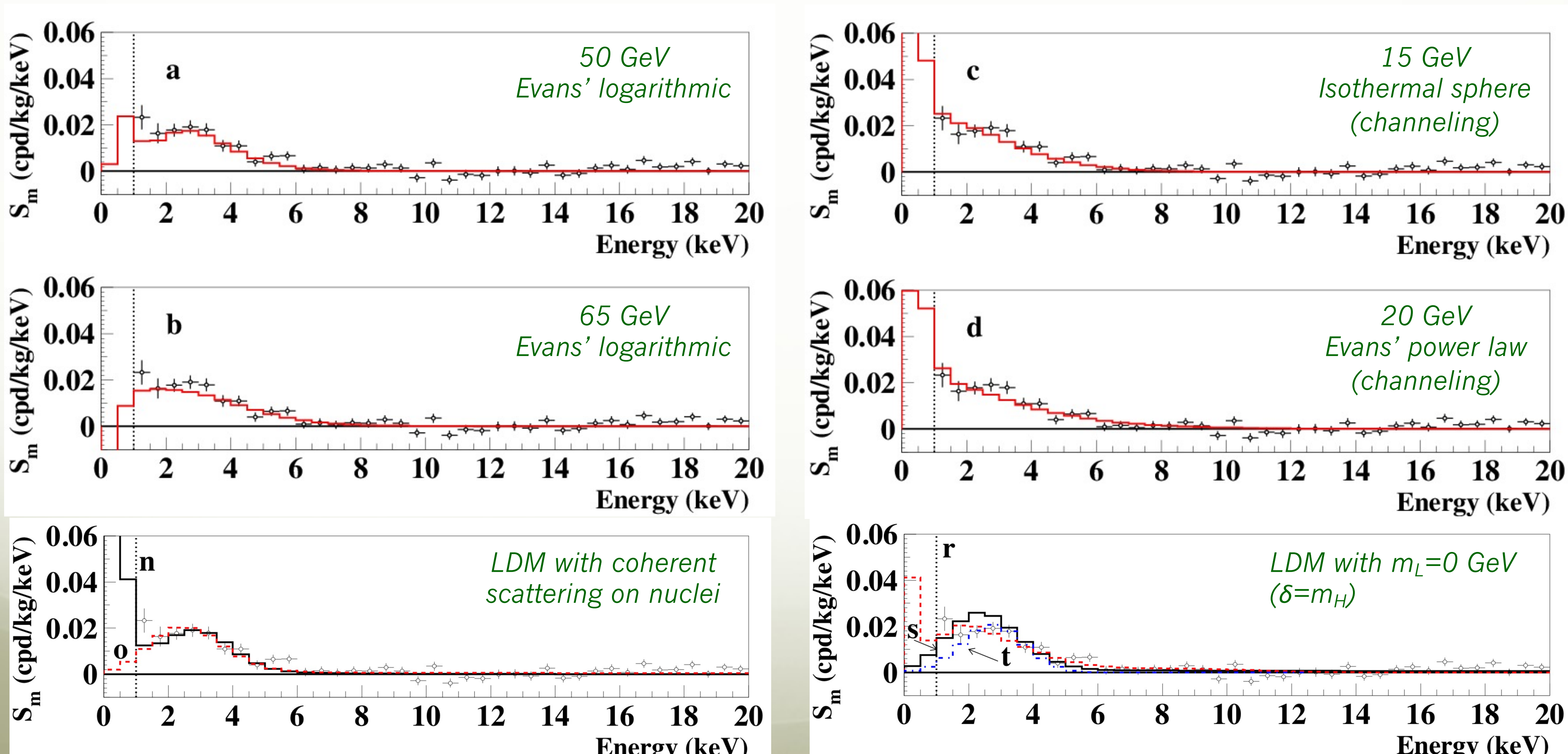
Uncertainty in experimental parameters, and necessary **assumptions** on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with **a fixed set** of assumptions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

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

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

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

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



Examples of model-dependent analyses

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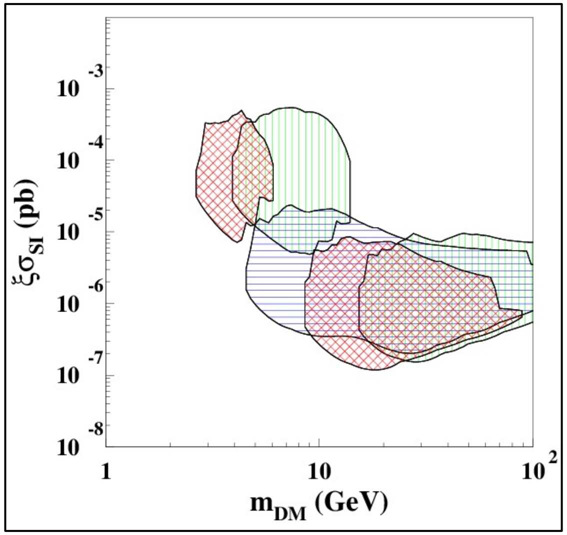
A large (but not exhaustive) class of halo models and uncertainties are considered

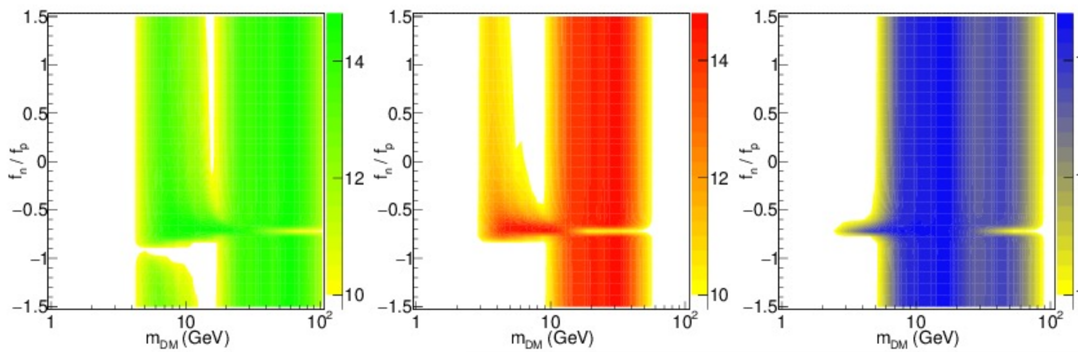
E_{th}=1 keV; old data release



DM particles elastically scattering off target nuclei – SI interaction

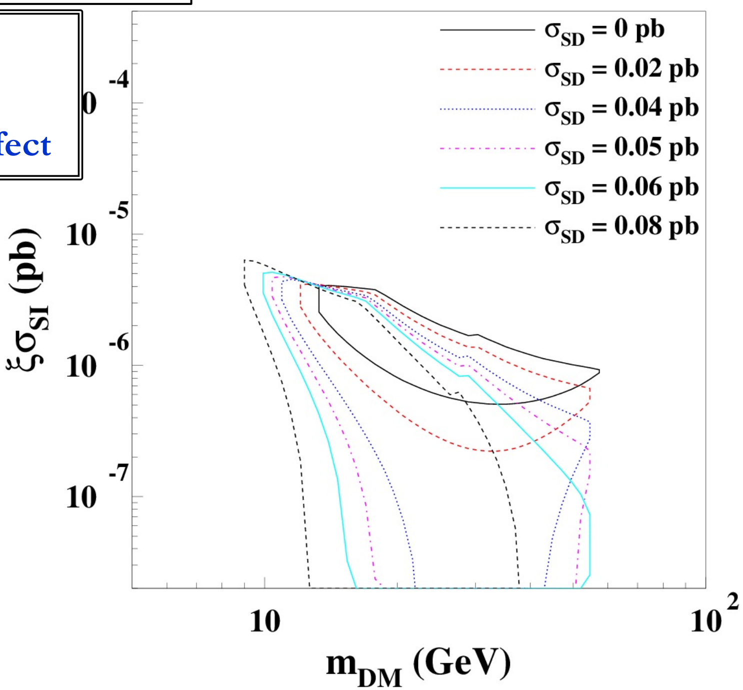
$$\sigma_{SI}(A,Z) \propto m_{red}^2(A,DM)\left[f_p Z + f_n(A-Z)\right]^2$$

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

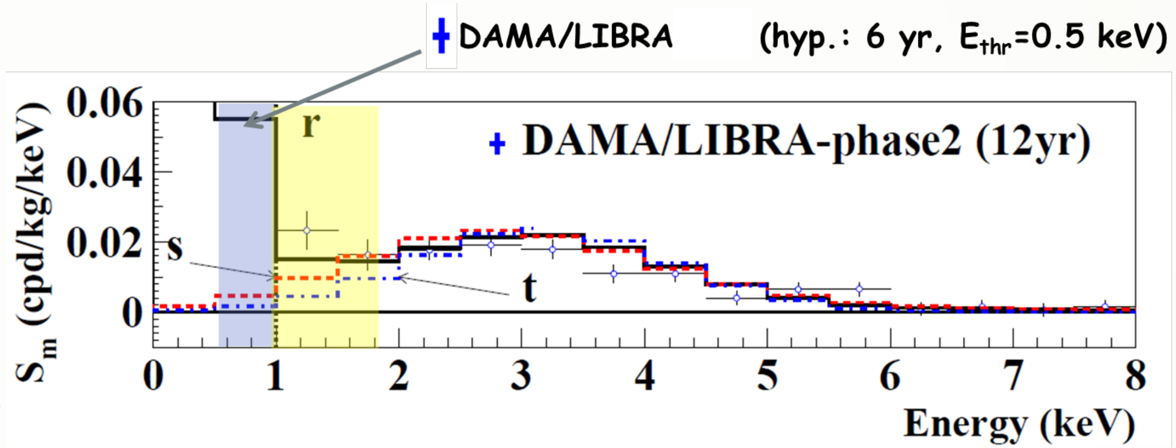


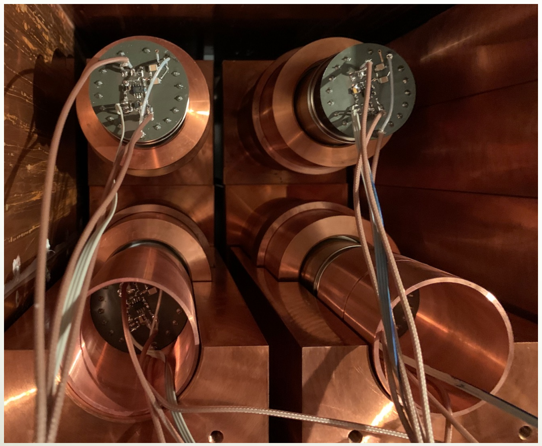
- Two bands at low mass and at higher mass;
- Good fit for low mass DM candidates at $f_n/f_p \approx$ -53/74 = -0.72 (signal mostly due to ^{23}Na recoils).
- The inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support 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 with lower software energy threshold below 1 keV with high efficiency

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

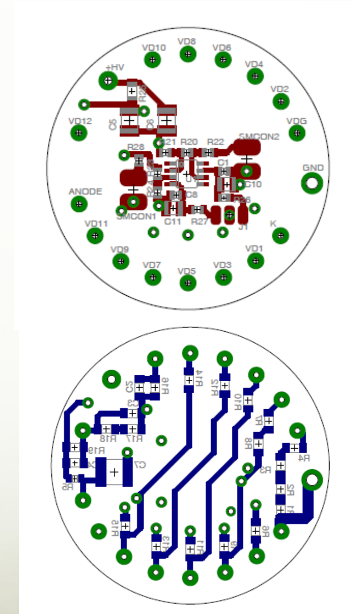
- After a dedicated R&D on new high Q.E. PMTs with increased radio-purity
- After the study of possible new protocols for possible modifications of the detectors





an alternative strategy has been chosen, upgrading the hardware:

- new miniaturized low background **pre-amps** directly installed on the low-background supports of the **voltage dividers** of the low background high Q.E. **PMTs** of phase2
- higher vertical resolution 14bit digitizers

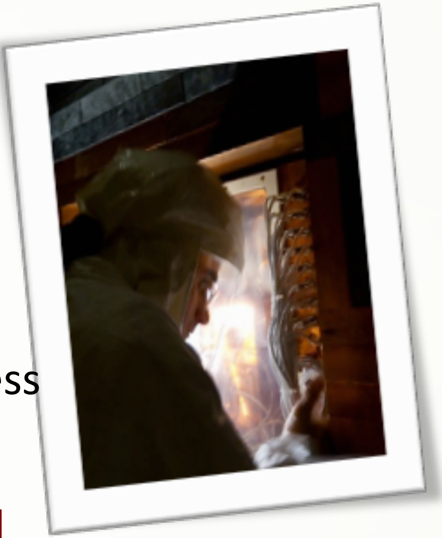


Design of the voltage divider and preamplifier mounted on the Pyralux support

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

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 **continuing data taking**
- Preliminary efforts towards 0.75 keV software energy threshold done
- DAMA/LIBRA–phase2 towards lower software **energy threshold of 0.5 keV**. New divider/amp systems and new 14bit digitizers
- Continuing investigations of **rare processes** other than DM
- Other pursued ideas: **$ZnWO_4$ anisotropic scintillator** for DM **directionality**. Response to nuclear recoils measured.