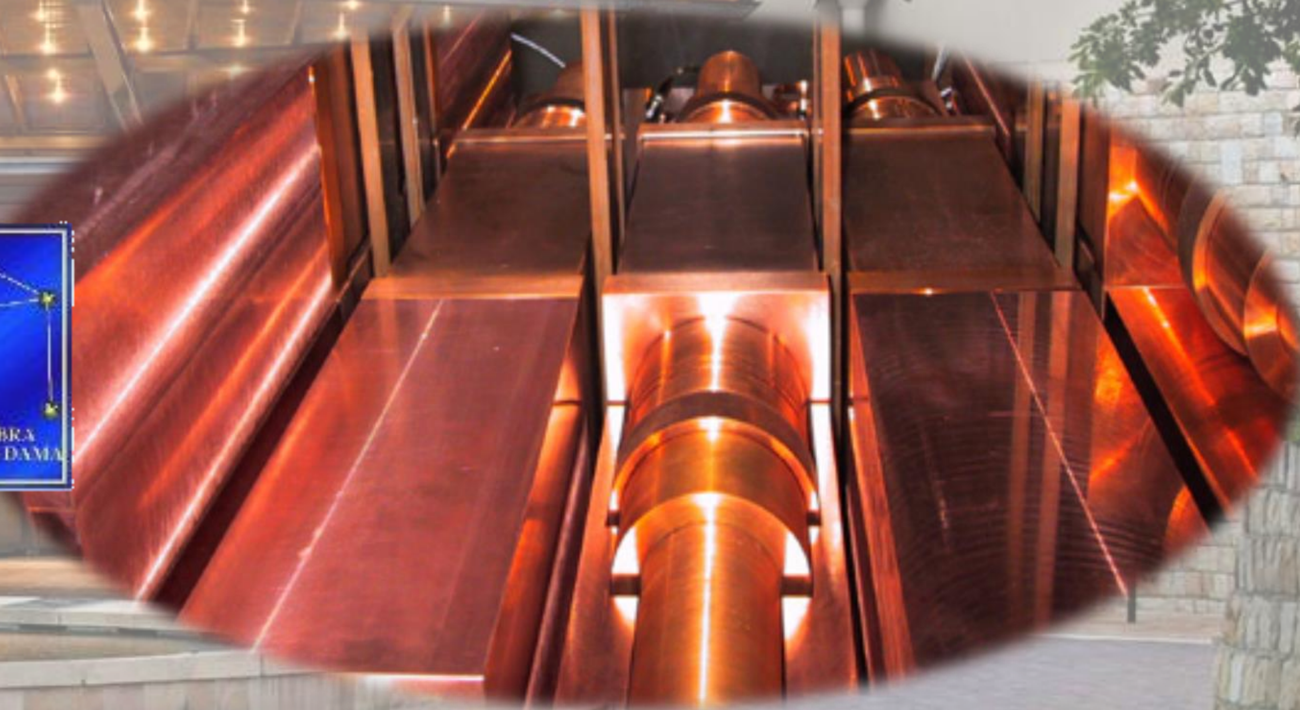
Annual Modulation with DAMA/LIBRA–phase2

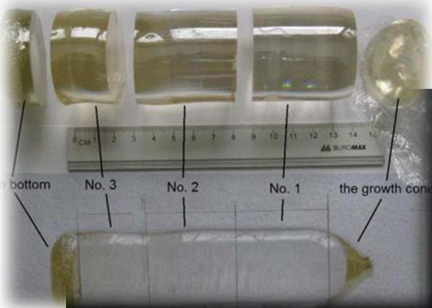


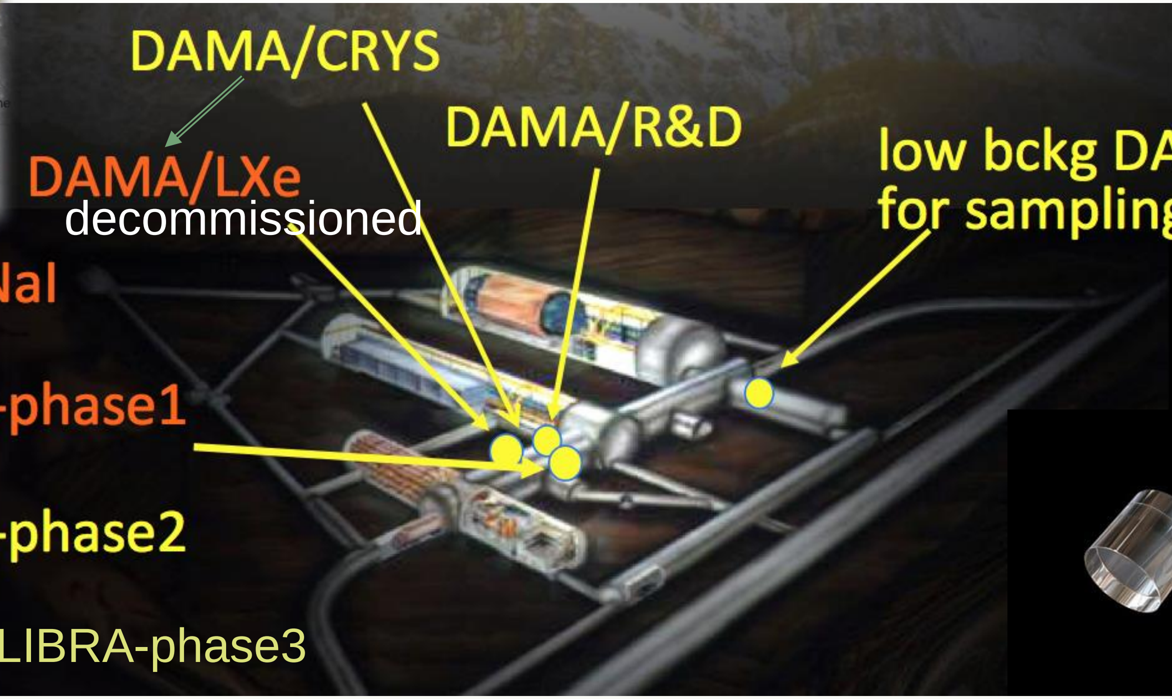
CNNP2020
Arabella Hotel in the Kogelberg Biosphere near Cape Town, South Africa
February 24-28, 2020

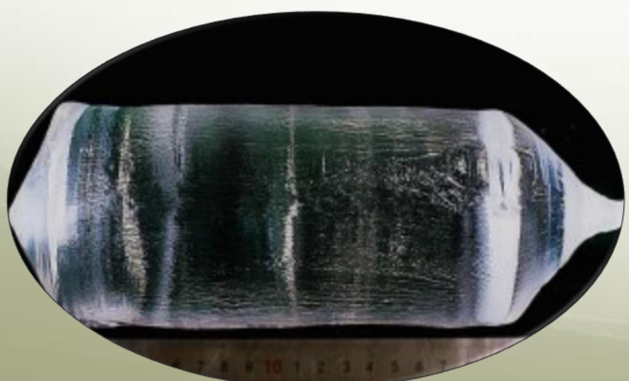
P. Belli
INFN – Roma Tor Vergata

DAMA set-ups

an observatory for rare processes @ LNGS







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

Relic DM particles from primordial Universe

SUSY (as neutralino or sneutrino in various scenarios)

the sneutrino in the Smith and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not yet foreseen by theories

etc…

axion-like (light pseudoscalar and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

heavy exotic canditates, as "4th family atoms", ...

Elementary Black holes, Planckian objects, Daemons

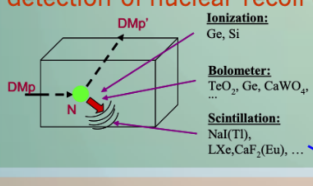
invisible axions, ν's

multi-component non-baryonic DM?

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

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

- Scatterings on nuclei
  → detection of nuclear recoil energy

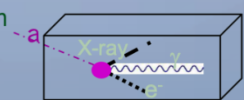


- Inelastic Dark Matter: **W + N → W* + N**
  → W has 2 mass states χ+ , χ- with δ mass splitting
  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

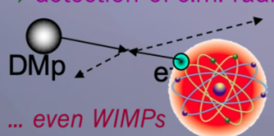
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

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

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



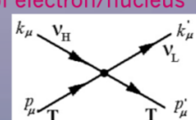
- Interaction only on atomic electrons
  → detection of e.m. radiation



… even WIMPs

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

e.g. sterile ν



… also other ideas …

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

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

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

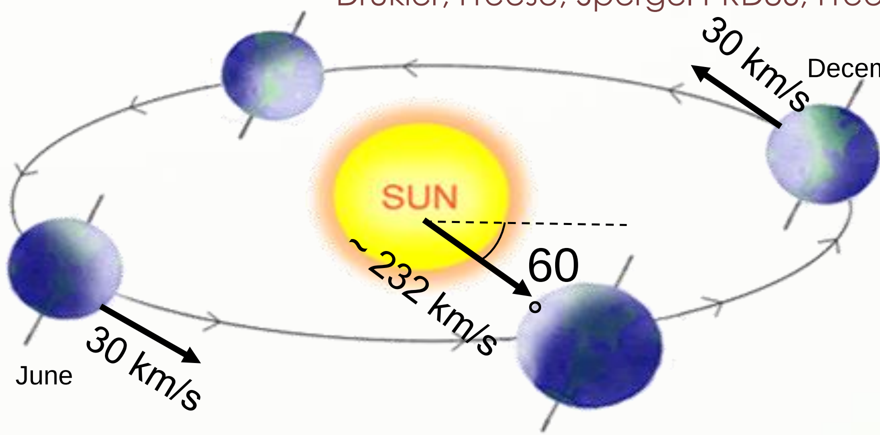
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

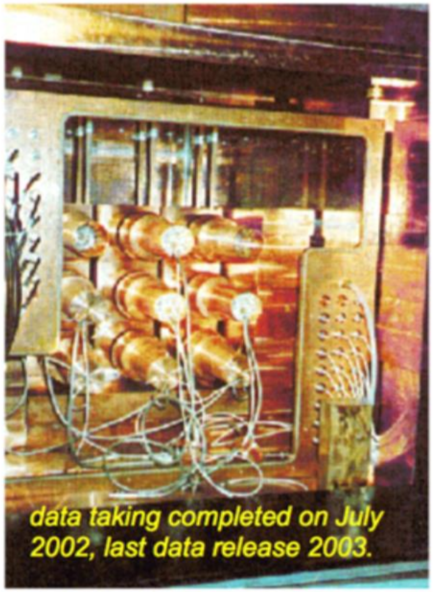
$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

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

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
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- **Ann**

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)

- 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

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

DAMA/LIBRA–phase2

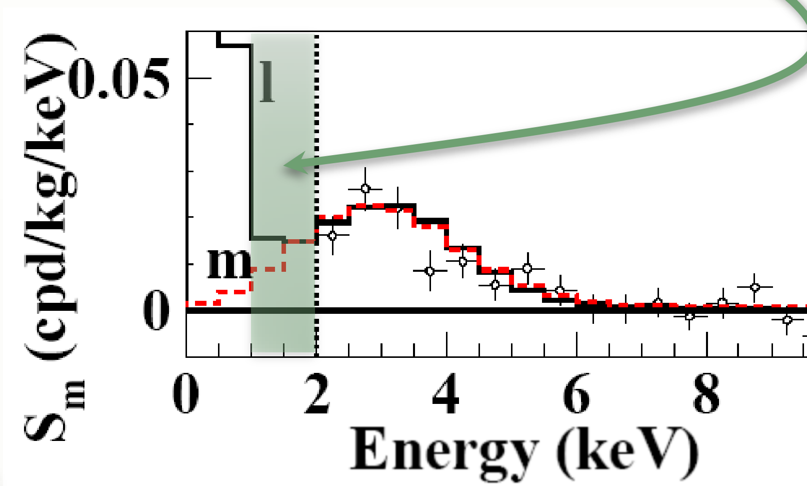
JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4) (2019) 317

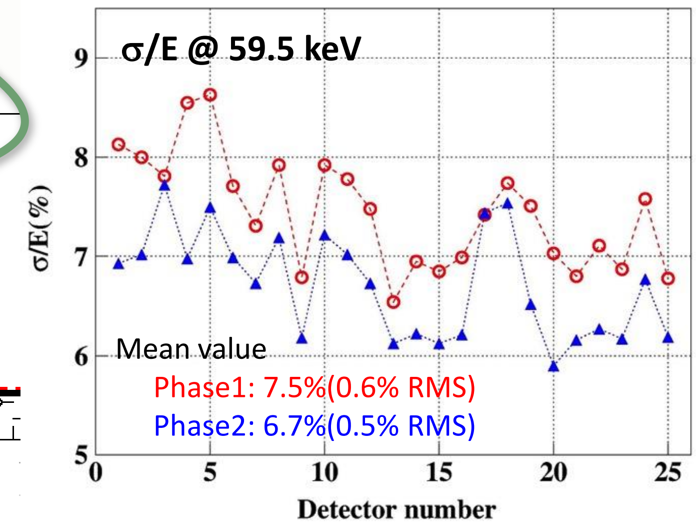
Lowering software energy threshold below 2 keV:

- 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

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.: $\approx 1.3 \times 10^8$ events from sources
- ✓ Acceptance window eff. 6 a.c.: $\approx 3.4 \times 10^6$ events ($\approx 1.4 \times 10^5$ events/keV)

Annual Cycles	Period	Mass (kg)	Exposure (kg × d)	(α-β^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

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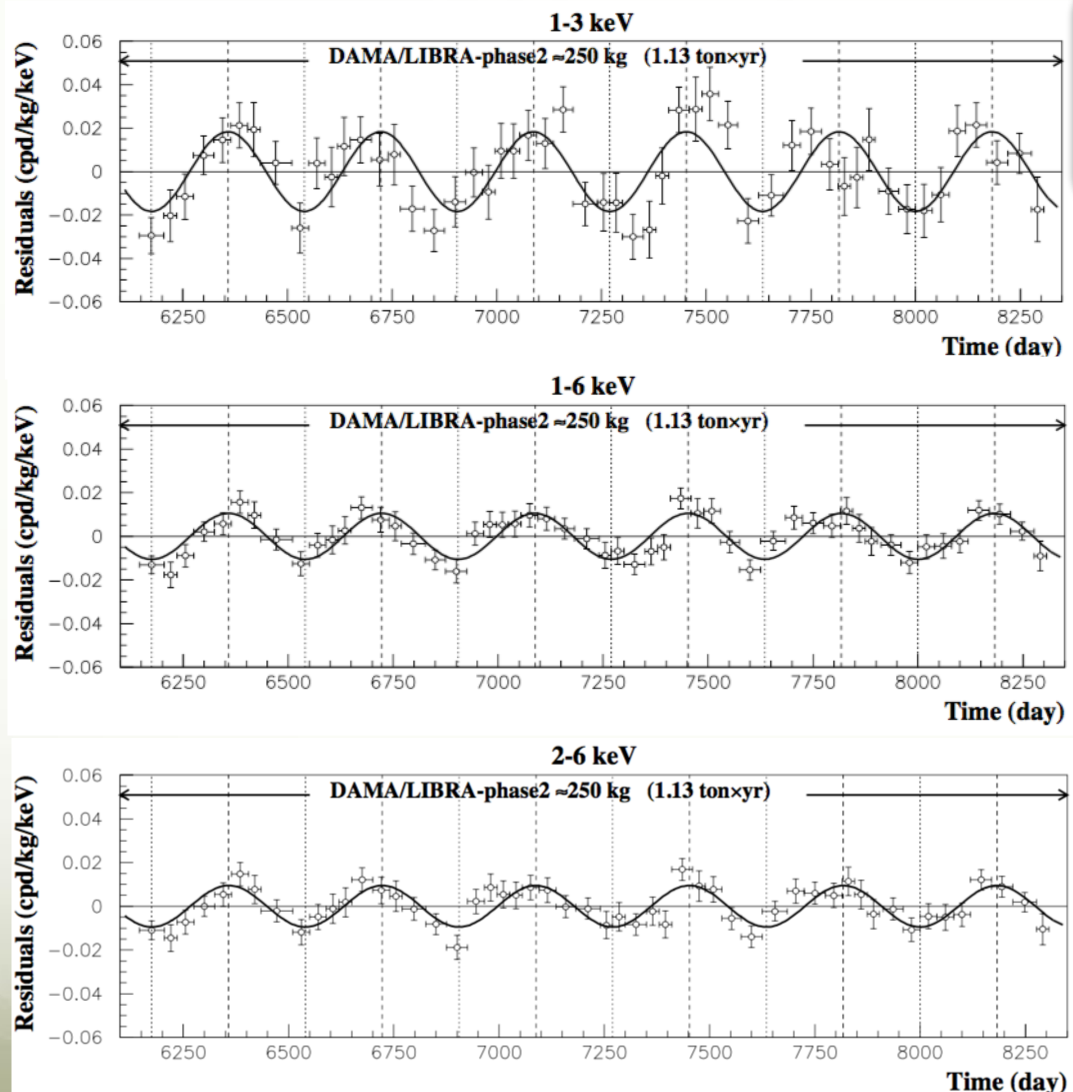
DAMA/LIBRA-phase2 (1.13 ton × yr)



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

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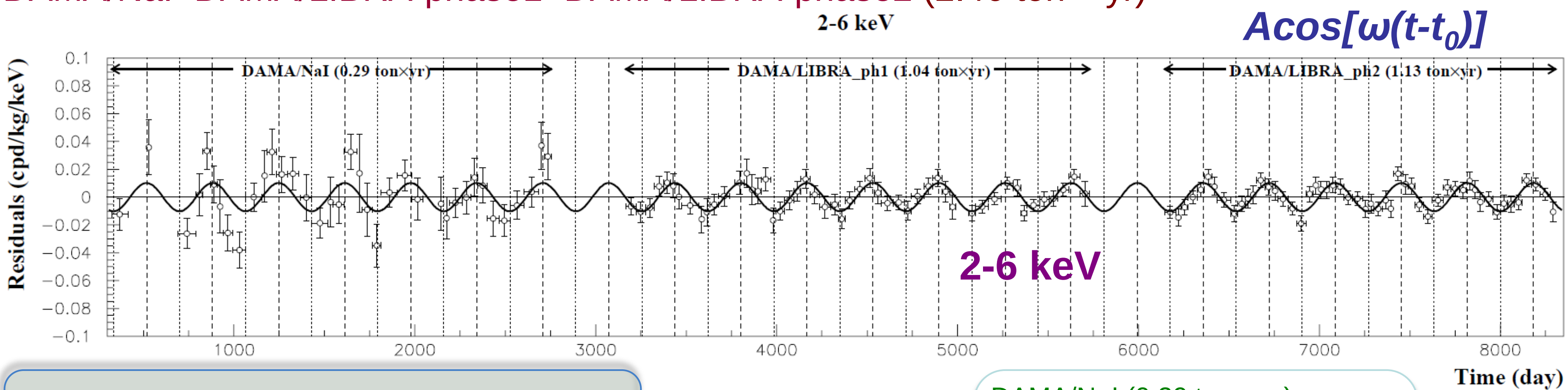
DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.46 ton × yr)



Absence of modulation? No

χ^2/dof=272.3/142 ⇒ P(A=0) =3.0×10^{-10}

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

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

A=(0.0102±0.0008) cpd/kg/keV

χ^2/dof = 113.8/138 **12.8 σ C.L.**

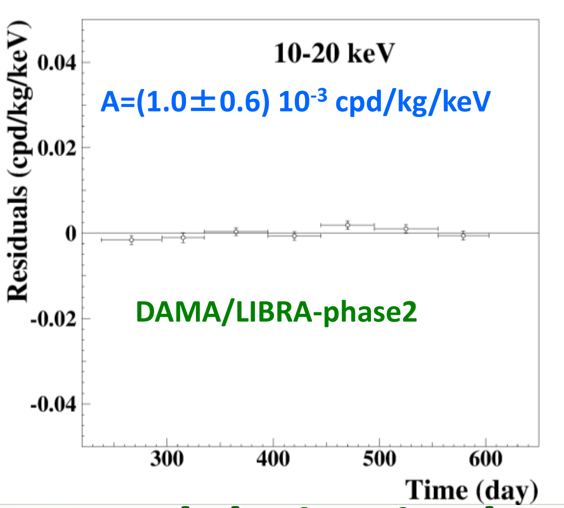
Releasing period (*T*) and phase (t_0) in the fit

	ΔE	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0184±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

The data of DAMA/NaI + DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 12.9 σ C.L.

Rate behaviour above 6 keV

• No Modulation above 6 keV

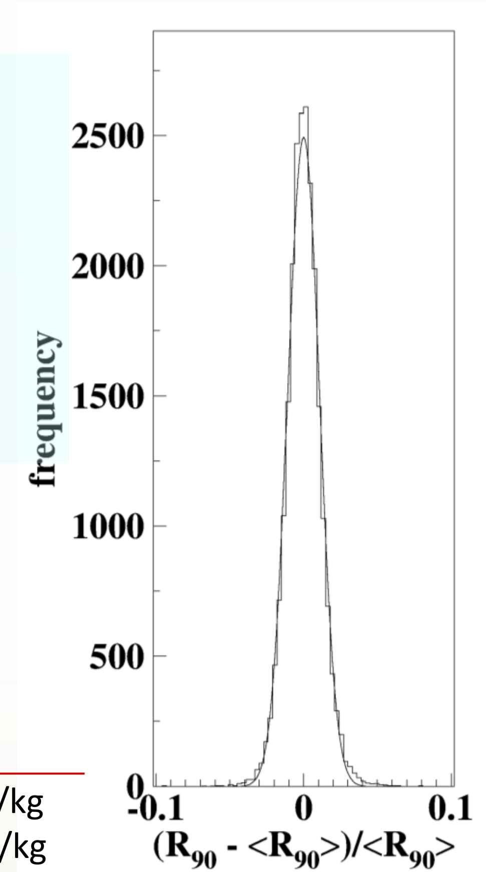


Mod. Ampl. (6-14 keV): cpd/kg/keV

(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

→ 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**

+ 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

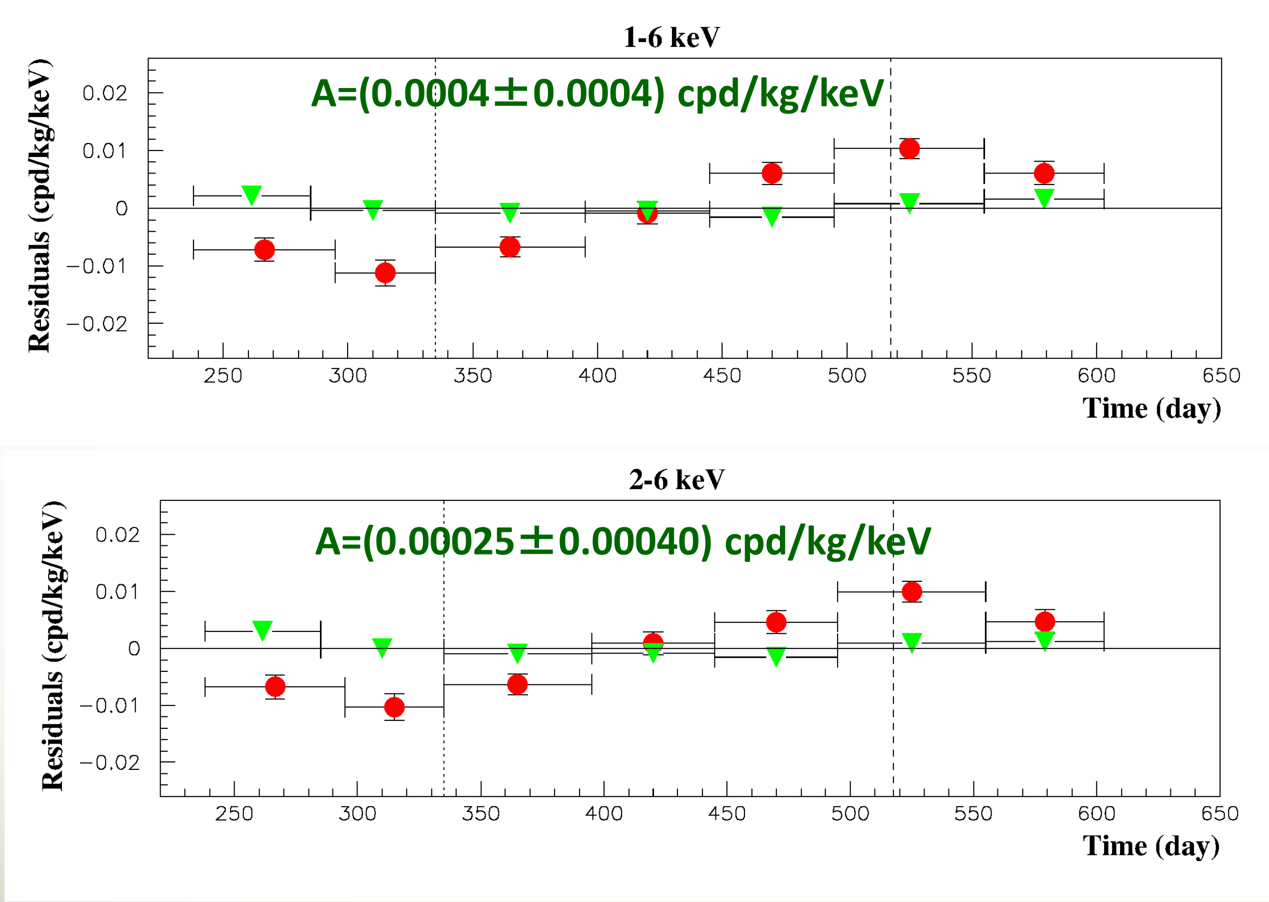
Period	Mod. Ampl.
DAMA/LIBRA-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg

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

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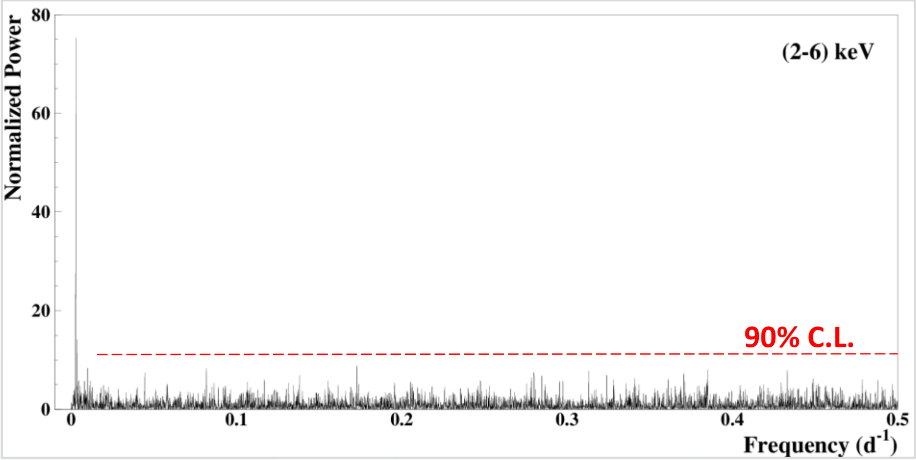
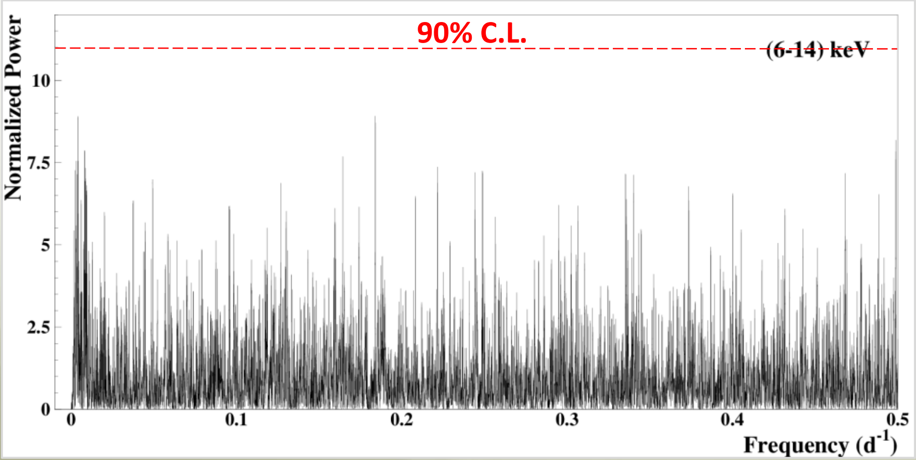
(according to PRD75 (2007) 013010)

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

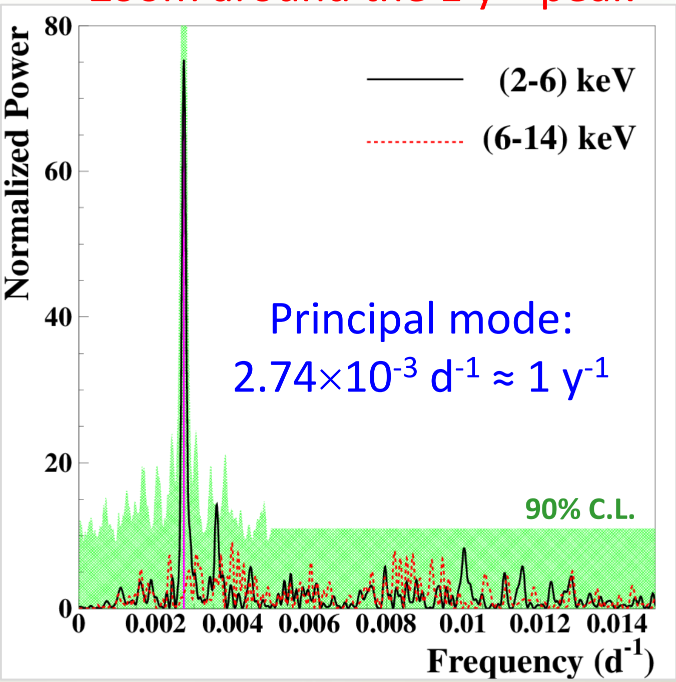
The whole power spectra up to the Nyquist





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
+ DAMA/LIBRA-phase2 (2.46 ton×yr)

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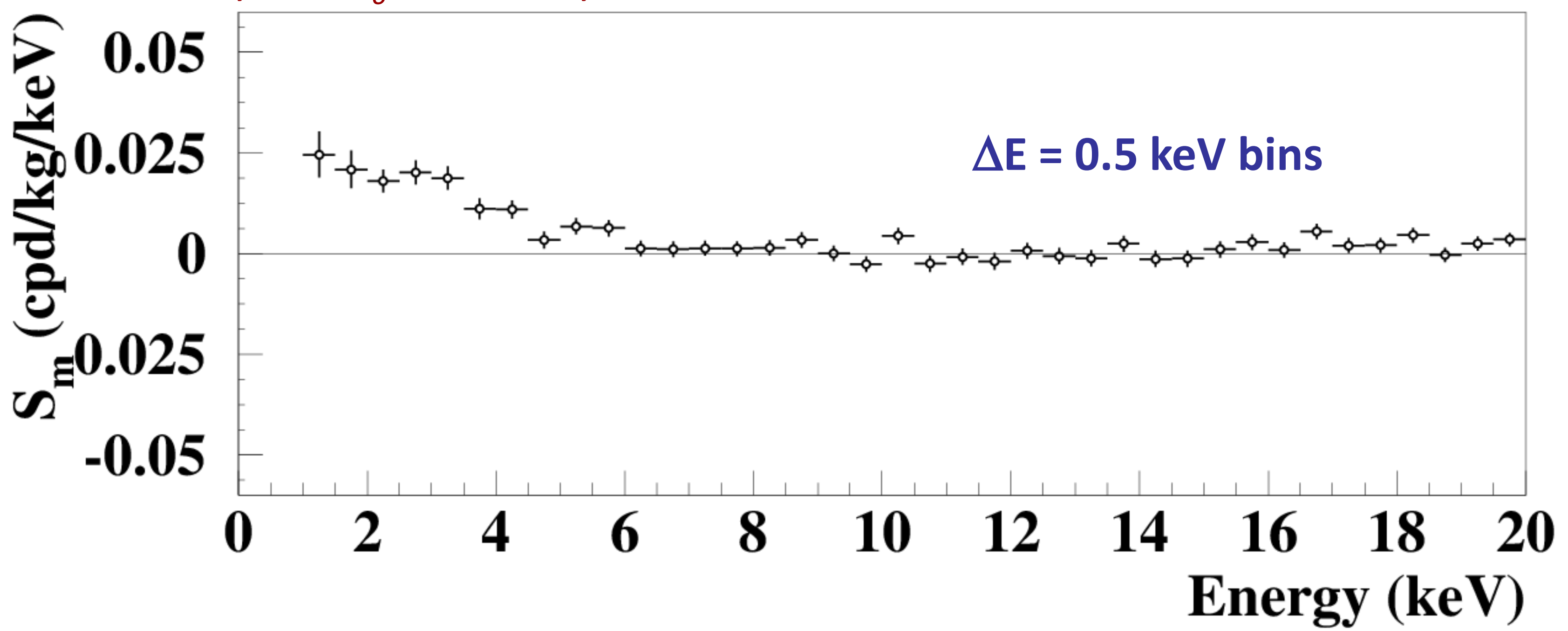

A clear modulation is present in the (1-6) keV energy interval, while S_m values compatible with zero are present just above

- 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

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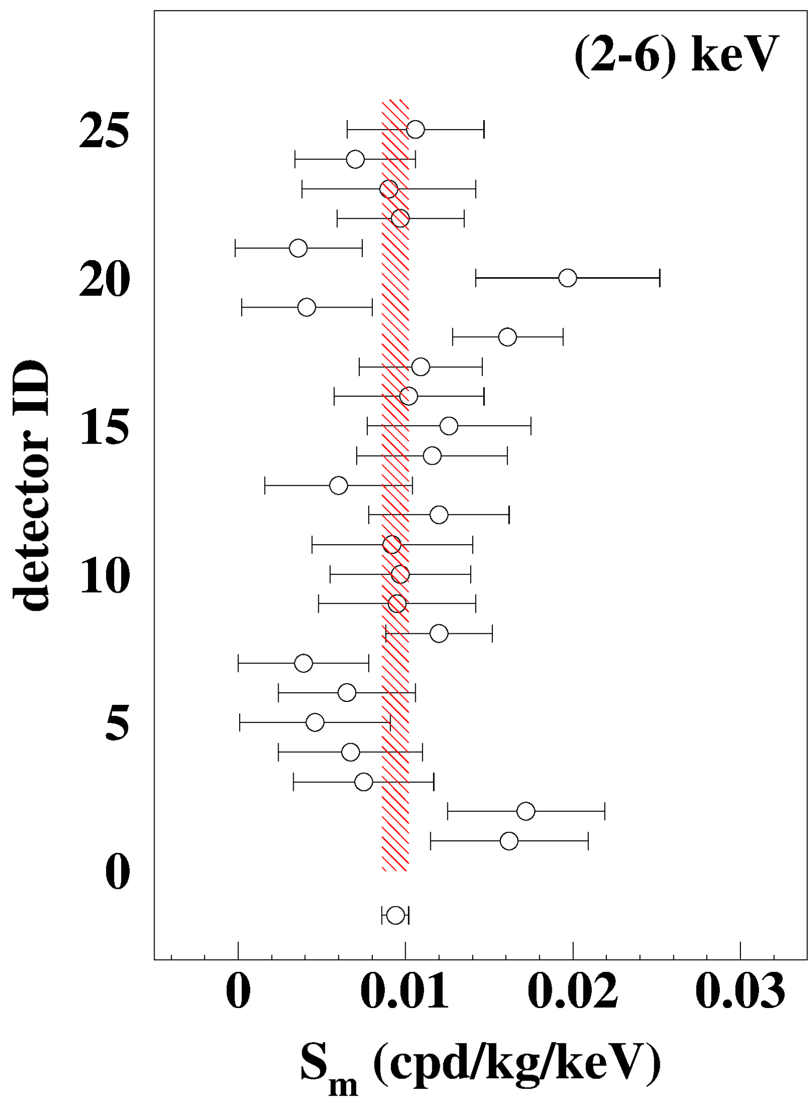

DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: **2.17 ton×yr**

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?

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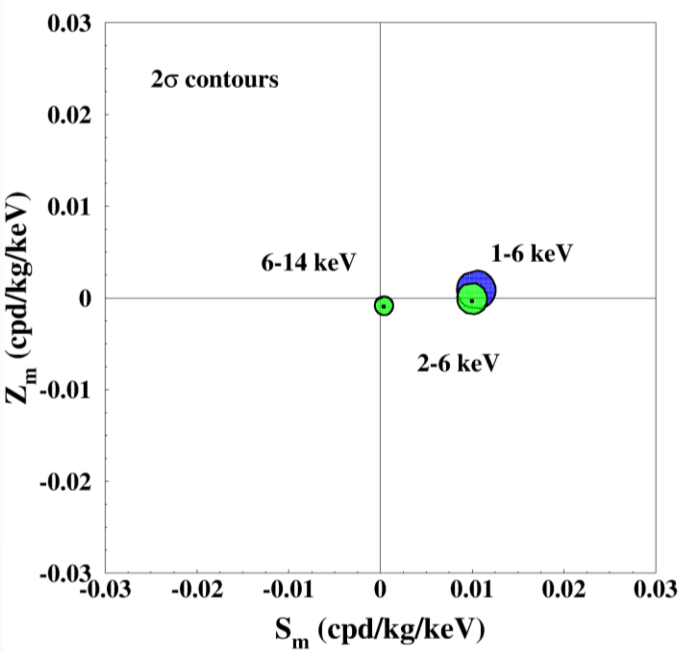
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

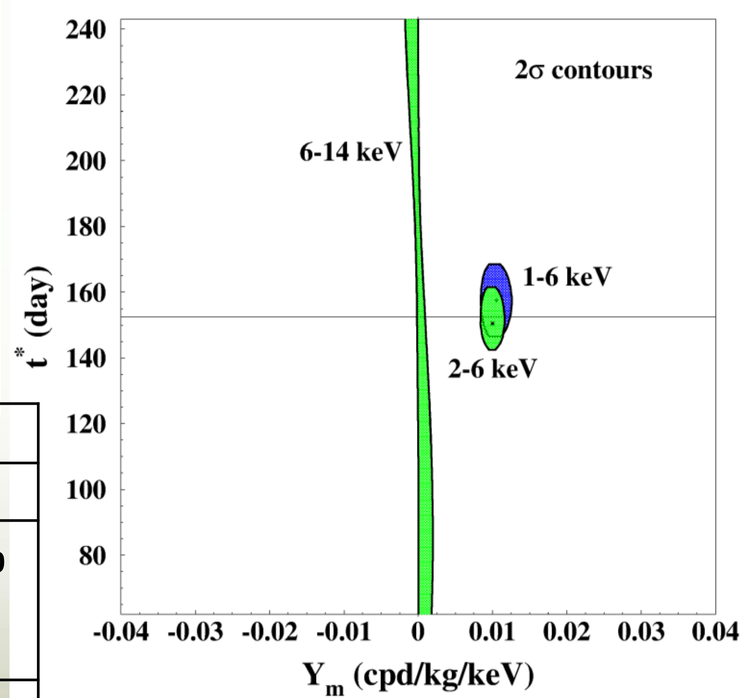
For Dark Matter signals:

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

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



Slight differences from 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

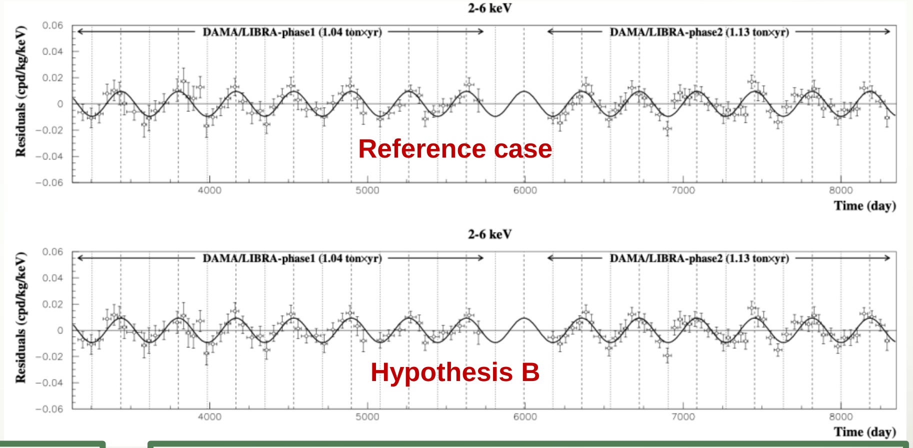
Any effect from long-term decay in DAMA/LIBRA?

- Adopted cautious procedure: each annual cycle starts from Sept./Autumn (when cos ω $(t-t_0) \simeq 0$) towards Summer → during the annual cycle the **minimum** (December) of the DM signal **occurs before** of the **maximum** (June).
- Any possible decay of **long–term–living isotopes** cannot simulate the observed positive signal.
- Assuming a constant background within each annual cycle, it may only lead to an **underestimate** of the observed S_m
- arXiv:2002.00459 claims that the DAMA annual modulation signal may be biased by a slow variation only in the (2-6) keV *single-hit* rate, possibly due to some background, even that the total rate at low energy in DAMA/LIBRA can have a odd behaviour, increasing with time.
- By the fact, this odd time behaviour of the counting rate was already **excluded**: the contaminants of the DAMA set-ups are reported in several papers; none of them increases with time. The stability with time of the running parameters is well verified.

The assumptions in arXiv:2002.00459 are **untenable** and the conclusions are **valueless**.

1) The case of (2–6) keV *single-hit* residual rates.

- We recalculate the (2–6) keV *single-hit* residual rates by considering a possible time behaviour given by the signal searched for and by **different straight lines**, one for each annual cycle, simulating the time–varying background (hereafter, **hypothesis B**).
- The residuals, once subtracting the so-obtained background, are reported in figure.



Period and phase fixed in the fit

- Reference case: A = (0.0095 ± 0.0008) cpd/kg/keV (χ^2/dof = 71.8/101)
- Hypothesis B: A = (0.0093 ± 0.0008) cpd/kg/keV (χ^2/dof = 60.4/75)
- $\Delta\chi^2$/dof = 11.4/26 → the hypothesis B is not favoured at 90% C.L. wrt the reference case: $P(\Delta\chi^2 < 11.4 | dof = 26) = 5.9 \times 10^{-3}$.

Period and phase released in the fit

- Reference case: A = (0.0096 ± 0.0008) cpd/kg/keV
  T = (0.9987 ± 0.0008) yr
  t_0 = (145 ± 5) days
- Hypothesis B: A = (0.0094 ± 0.0008) cpd/kg/keV
  T = (0.9985 ± 0.0009) yr
  t_0 = (143 ± 5) days

the effect of long–term time–varying background – if any – is negligible.

Any effect from long-term decay in DAMA/LIBRA?

2) The tail of the S_m distribution case.

- A possible long–term time–varying background can also induce a (either positive or negative) **fake modulation amplitudes (Σ)** on the tail of the S_m distribution above the energy region where the signal has been observed.
- For example, taking as reference the (6–14) keV energy interval:

  $\langle S_m \rangle_{(6\text{-}14)}$ = (0.00028 ± 0.00075) cpd/kg/keV, for DAMA/LIBRA–phase1

  $\langle S_m \rangle_{(6\text{-}14)}$ = (0.0006 ± 0.0006) cpd/kg/keV for DAMA/LIBRA–phase2
- They are both **compatible with zero** → one can obtain an upper limit on the absolute value of Σ:

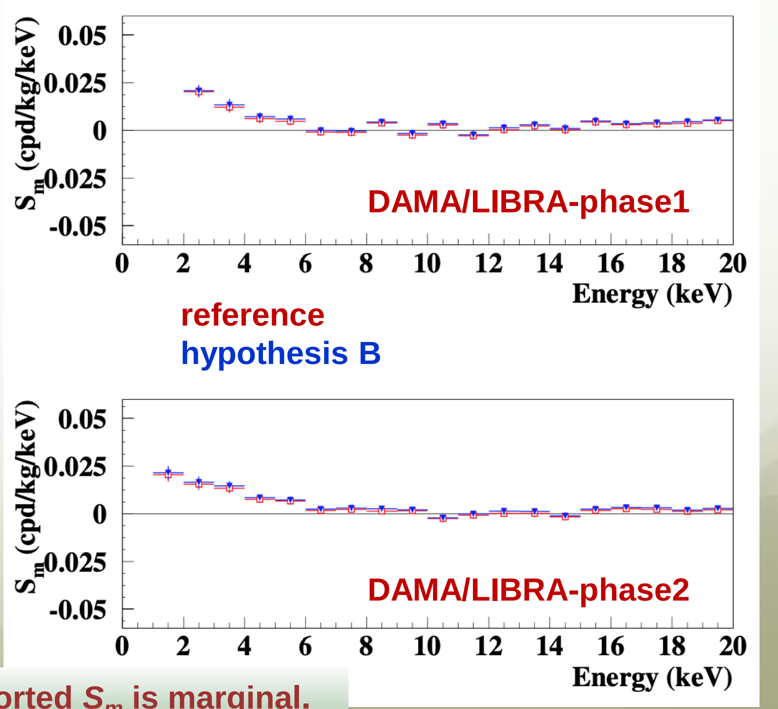
  $|\Sigma| < 1.5 \times 10^{-3}$ cpd/kg/keV (90% C.L.) for DAMA/LIBRA–phase1

  $|\Sigma| < 1.6 \times 10^{-3}$ cpd/kg/keV (90% C.L.) for DAMA/LIBRA–phase2
- The observed $S_m \sim 10^{-2}$ cpd/kg/keV → **the possible effect of long–term time–varying background – if any – is negligible.**

3) The maximum likelihood analysis.

- The maximum likelihood analysis has been repeated by replacing the b_{jk} constant in each annual cycle with a **linear behaviour decreasing with time** (**hypothesis B**).

	S_m (cpd/kg/keV) Reference case	Hypothesis B
DAMA/LIBRA–phase1		
2–6 keV	0.0093±0.0013	0.0103±0.0013
DAMA/LIBRA–phase2		
1–6 keV	0.0105±0.0011	0.0114±0.0011
2–6 keV	0.0095±0.0011	0.0103±0.0011



Possibly the systematic error on the determination of the previously-reported S_m is marginal.

- Contributions to the total neutron flux at LNGS; → $\Phi_k = \Phi_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by: → $R_k = R_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$
    - neutrons,
    - muons,
    - solar neutrinos.

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

Modulation amplitudes

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

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

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

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

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

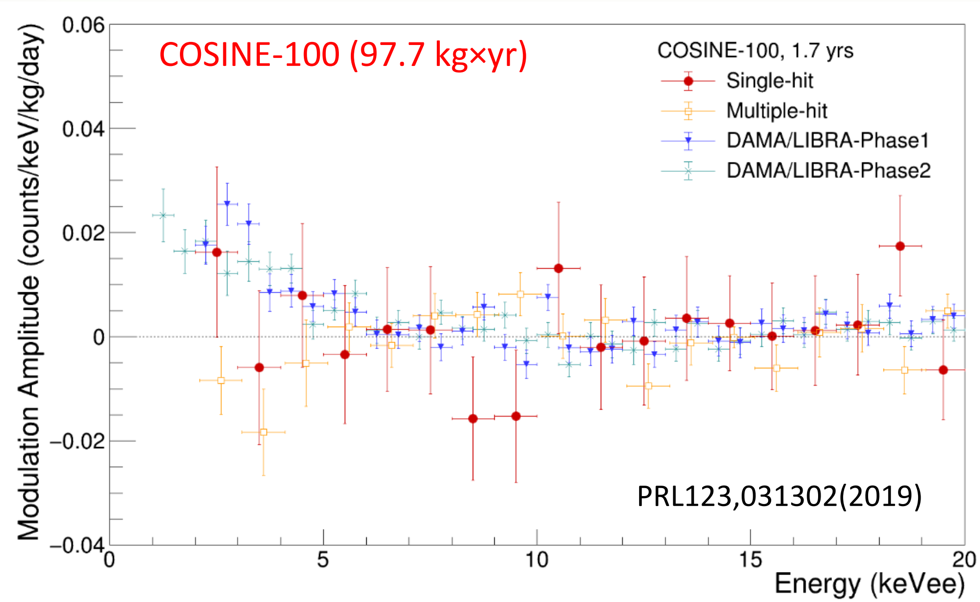
NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196, IJMPA31(2017)issue31, Universe4(2018)116, Bled19(2018)27,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

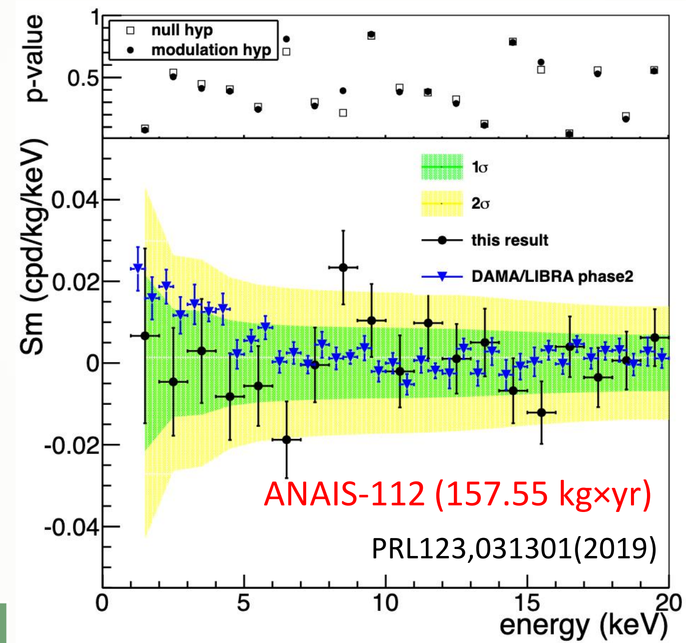
Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<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

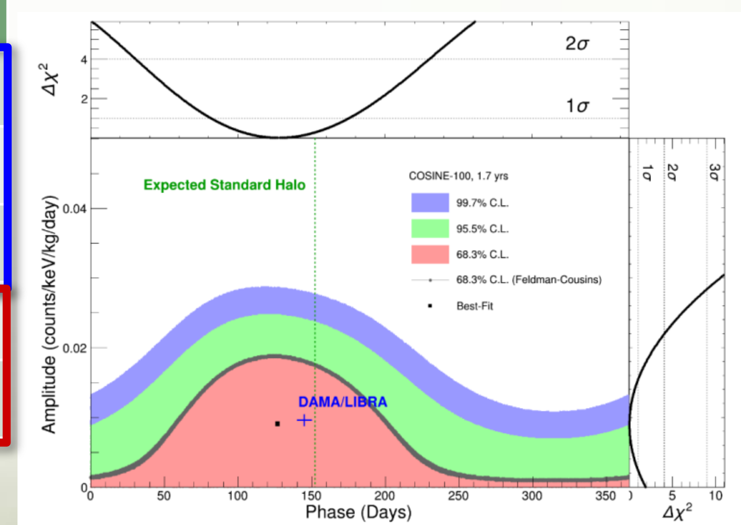
→ **Thus, they cannot mimic the observed annual modulation effect**

Other annual modulation results with NaI(Tl)





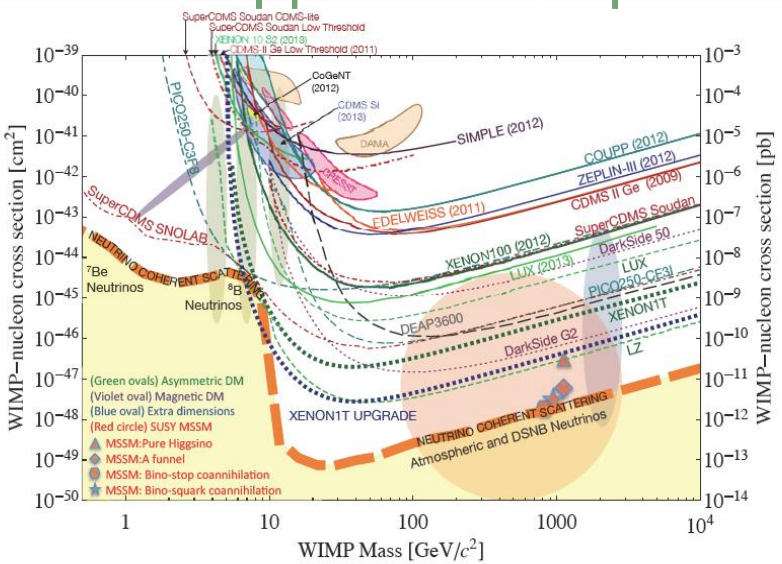
Energy interval	Experiment	Exposure ton x yr	Rate (cpd/kg/keV)	Amplitude (cpd/kg/keV)
(2,6) keV	DAMA/LIBRA (ph1 + ph2)	2.17	0.8	0.0095 ± 0.0008
	COSINE-100	0.098	3.0	0.0083 ± 0.0068
	ANAIS-112	0.16	3.2	- 0.0044 ± 0.0058
(1,6) keV	DAMA/LIBRA-phase2	1.13	0.7	0.0105 ± 0.0011
	ANAIS-112	0.16	3.6	- 0.0015 ± 0.0063



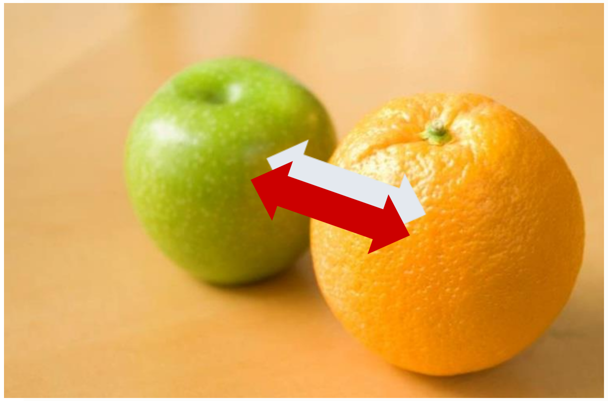
DAMA-LIBRA is still much better than any other NaI experiment for exposure time, for exposed mass, for background, and for energy threshold and control of all the experimental parameters

COSINE & ANAIS have not sufficient sensitivity to DAMA signal

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, IJMPD 13 (2004) 2127, EPJC 47 (2006) 263, IJMPA 21 (2006) 1445, EPJC 56 (2008) 333, PRD 84 (2011) 055014, IJMPA 28 (2013) 1330022, arXiv:1907.06405

...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, ...
- ...

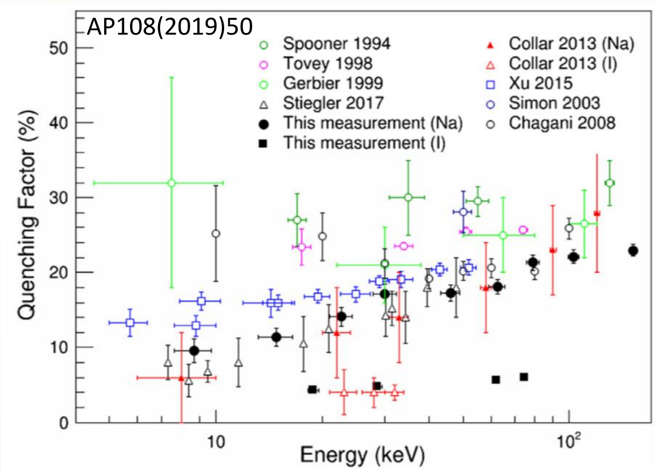
Uncertainty in experimental parameters, and necessary **assumptions** on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with **a fixed set** of assumptions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

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

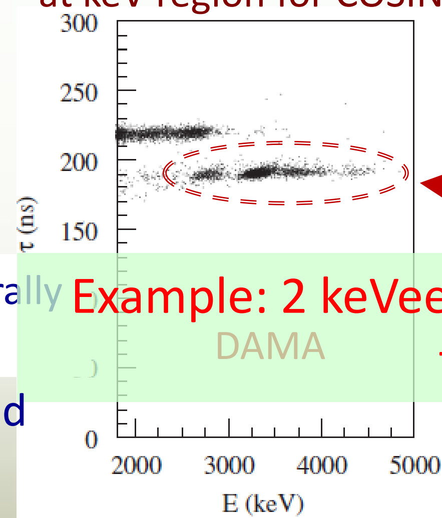
The case of the NaI(Tl) quenching factors (QF)

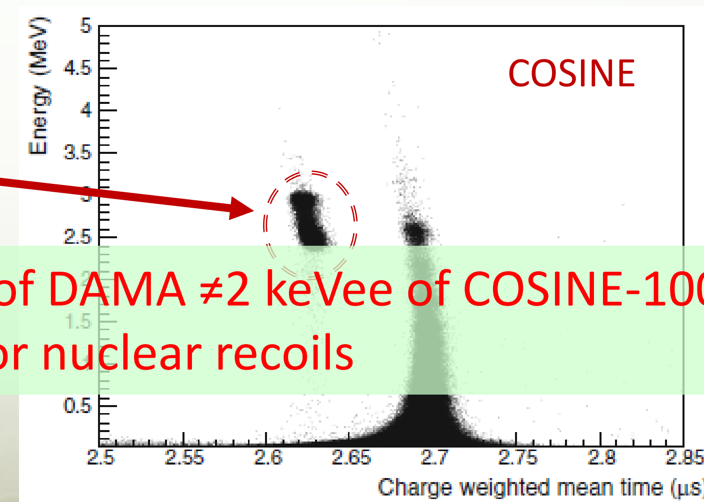
- ✓ The QFs are a property of the specific detector and not general property, particularly in the very low energy range.
- ✓ For example in NaI(Tl), QFs depend on the adopted growing procedures, on Tl concentration and uniformity in the detector, on the specific materials added in the growth, on the mono-crystalline or poly-crystalline nature of the detector, etc.
- ✓ Their measurements are difficult and always affected by significant experimental uncertainties.
- ✓ All these aspects are always relevant sources of uncertainties when comparing whatever results in terms of DM candidates inducing nuclear recoils.

+ QF depending on energy + channeling effects
+ Migdal effect



- A wide spread existing in literature for different NaI(Tl) productions
- This is also confirmed by the different α/β light ratio measured with DAMA and COSINE crystals. This implies much lower QFs at keV region for COSINE than DAMA.





CURIOSITY: Recent productions (generally by Bridgman growth) yields low QF…

Example: 2 keVee of DAMA ≠2 keVee of COSINE-100 for nuclear recoils

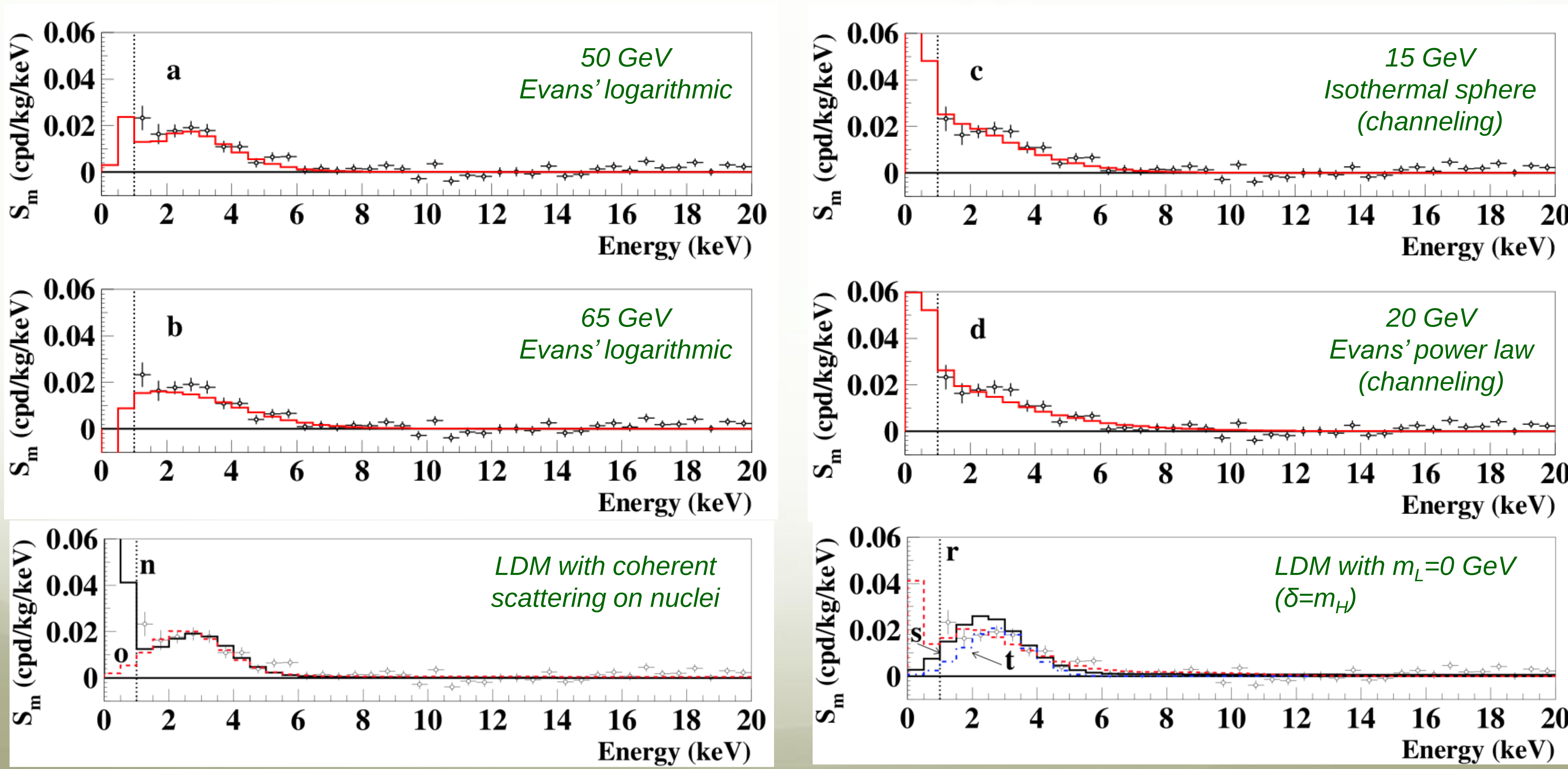
The model dependent analyses and comparisons must be performed using the QF **measured** for each detector.

Alphas from ^{238}U and ^{232}Th chains span from 2.6 to 4.5 MeVee in DAMA, while from 2.3 to 3.0 MeVee in COSINE

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

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

Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios



Examples of model-dependent analyses

DM particles elastically interacting with target nuclei – SI interaction

DAMA/NaI, DAMA/LIBRA-ph1 and ph2

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arXiv:1907.06405

- A large (but not exhaustive) class of halo models is considered;
- Local velocity v_0 in the range [170,270] km/s;
- Halo density ρ depending on the halo model;
- v_{esc} = 550 km/s (no sizable differences if v_{esc} in the range [550, 650]km/s);
- For DM candidates inducing nuclear recoils: three different sets of values for the nuclear form factor and quenching factor parameters.

σ_{SI} SI point-like DM-nucleon cross section

ξ fractional amount of local density in terms of the considered DM candidate

The point-like SI cross section of DM particles scattering off (A,Z) nucleus:

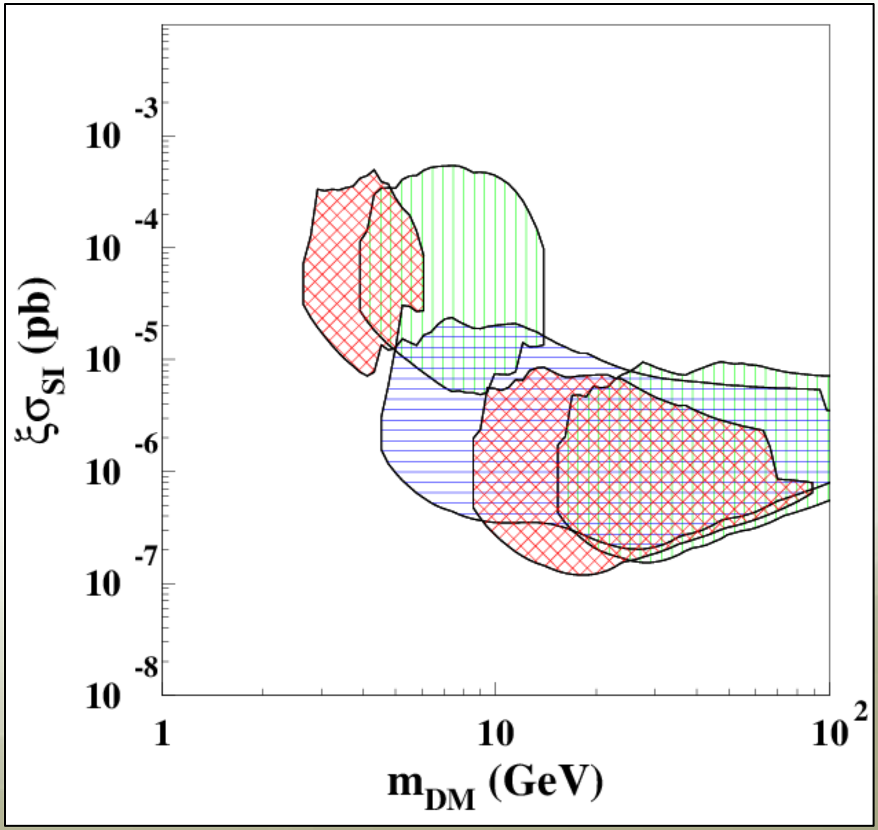
$$\sigma_{SI}(A,Z) \propto m_{red}^2(A,DM)\left[f_p Z + f_n(A-Z)\right]^2$$

where f_p, f_n are the effective DM particle couplings to protons and neutrons.

If $f_p = f_n$: $$\sigma_{SI}(A,Z) = \frac{m_{red}^2(A,DM)}{m_{red}^2(1,DM)} A^2 \sigma_{SI}$$

$\xi\sigma_{SI}$ vs m_{DM}

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



Allowed DAMA regions:
Domains where the likelihood-function values differ more than 10σ from absence of signal

Model-dependent analyses

DM particles elastically interacting with target nuclei SI-IV interaction

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DAMA/NaI, DAMA/LIBRA-ph1 and ph2

Case of isospin violating SI coupling:

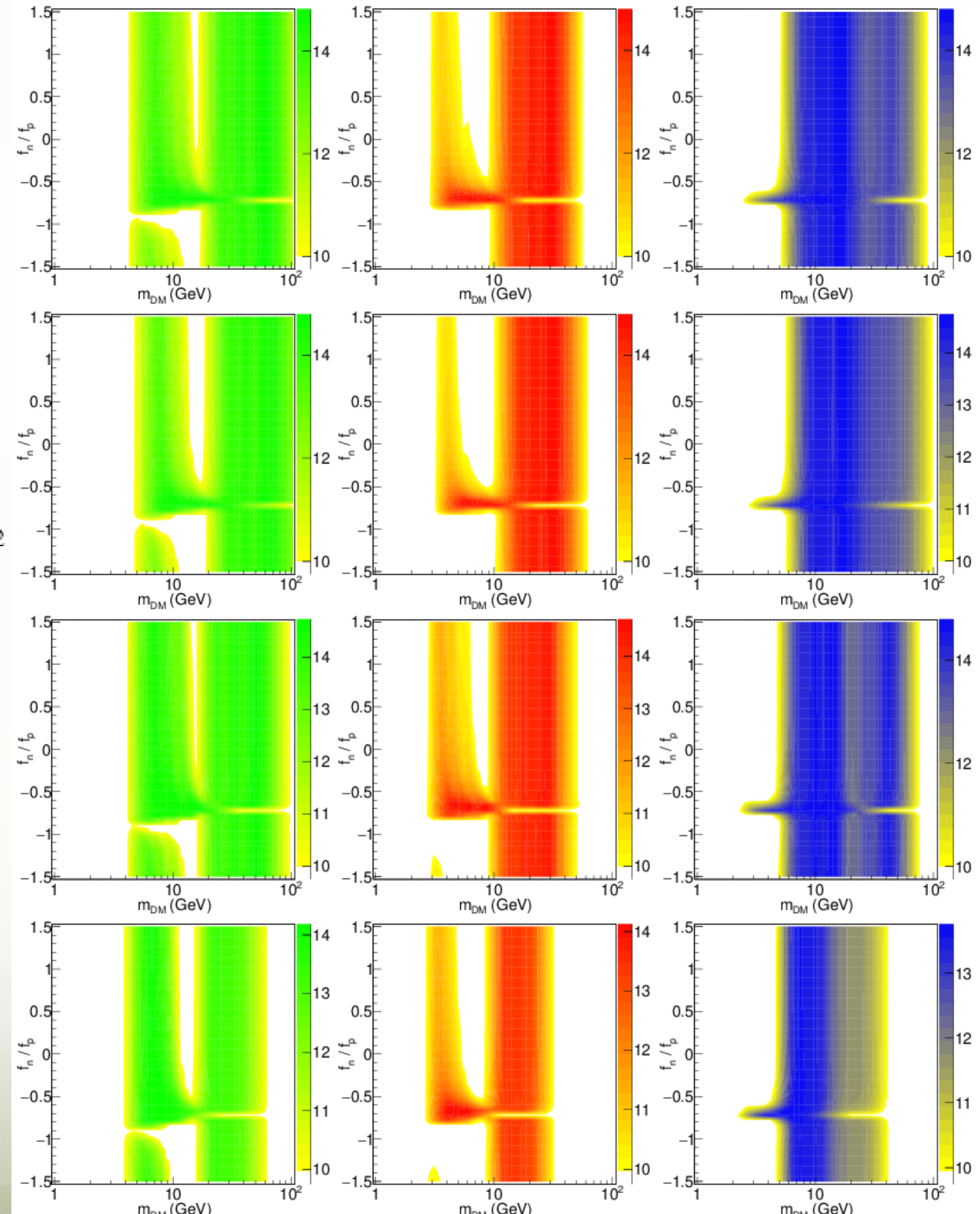
$$f_p \neq f_n$$

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

f_n/f_p vs m_{DM}
marginalizing on $\xi\sigma_{SI}$

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

Allowed DAMA regions for A0 (isothermal sphere), B1, C1, D3 halo models (top to bottom)



Model-dependent analyses

DM particles elastically interacting with target nuclei SI-IV interaction

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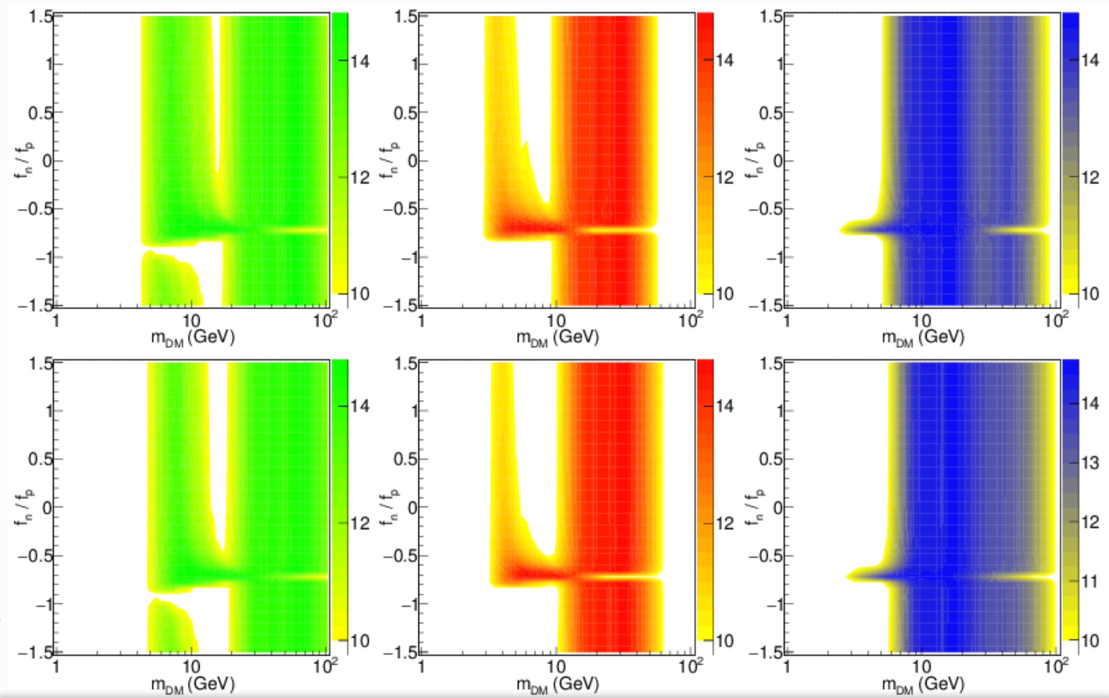
DAMA/NaI, DAMA/LIBRA-ph1 and ph2



Case of isospin violating SI coupling:

$$f_p \neq f_n$$

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

f_n/f_p vs m_{DM}

marginalizing on $\xi\sigma_{SI}$

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

Allowed DAMA regions for A0 (isothermal sphere), B1, C1, D3 halo models (top to bottom)

- 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).
- Contrary to what was stated in Ref. [PLB789,262(2019), JCAP07,016(2018), JCAP05,074(2018)] where the low mass DM candidates were disfavored for $f_n/f_p = 1$ by DAMA data, the inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support 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.

Model-dependent analyses: other examples

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DM particles elastically interacting with target nuclei – purely SD interaction

Only possible for target nuclei with spin≠0

$$\tan\vartheta = \frac{a_n}{a_p}, \quad \vartheta \ \text{in} \left[0, \pi\right]$$

a_p and a_n are the effective DM-nucleon coupling strengths for SD int.

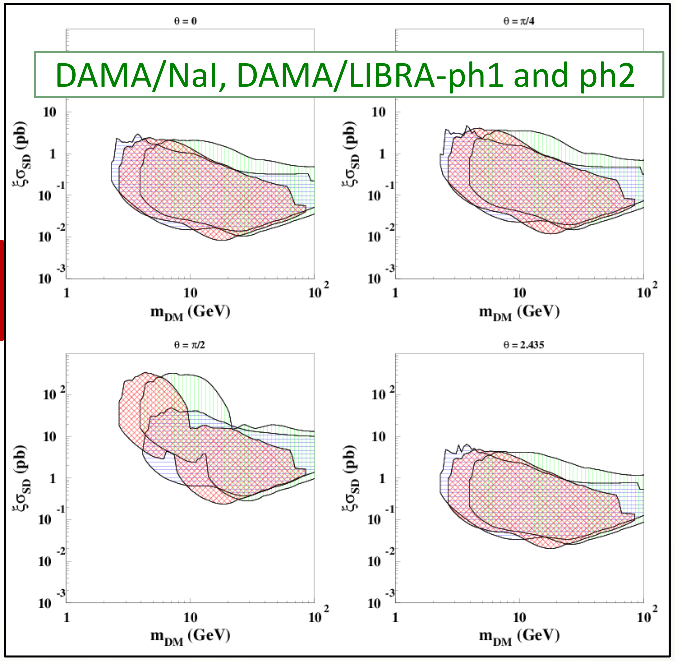
$\theta = 0 \Rightarrow a_n=0,\ a_p\neq 0$ or $|a_p|>>|a_n|$;

$\theta = \pi/4 \Rightarrow a_n=a_p$;

$\theta = \pi/2 \Rightarrow a_p=0,\ a_n\neq 0$ or $|a_n|>>|a_p|$;

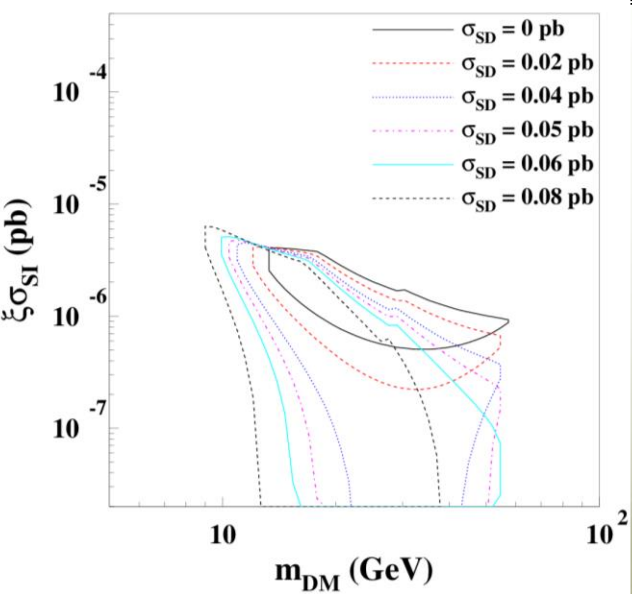
$\theta = 2.435\text{rad} \Rightarrow a_n/a_p=-0.85$, pure Z_0 coupling

$\xi\sigma_{SD}$ vs m_{DM}



Effect induced by the inclusion of a SD component on allowed regions in the plane $\xi\sigma_{SI}$ vs m_{DM}

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;
- The model-dependent comparison plots between exclusion limits at a given C.L. and regions of allowed parameter space do not hold e.g. for mixed scenarios when comparing experiments with and without sensitivity to the SD component of the interaction.
- The same happens when comparing regions allowed by experiments whose target-nuclei have unpaired proton with exclusion plots quoted by experiments using target-nuclei with unpaired neutron when the SD component of the interaction would correspond either to $\theta\approx 0$ or $\theta\approx\pi$

Model-dependent analyses: other examples

Inelastic DM in the scenario of Smith and Weiner [Phys. Rev. D 64, 043502 (2001)]

W + N → W* + N

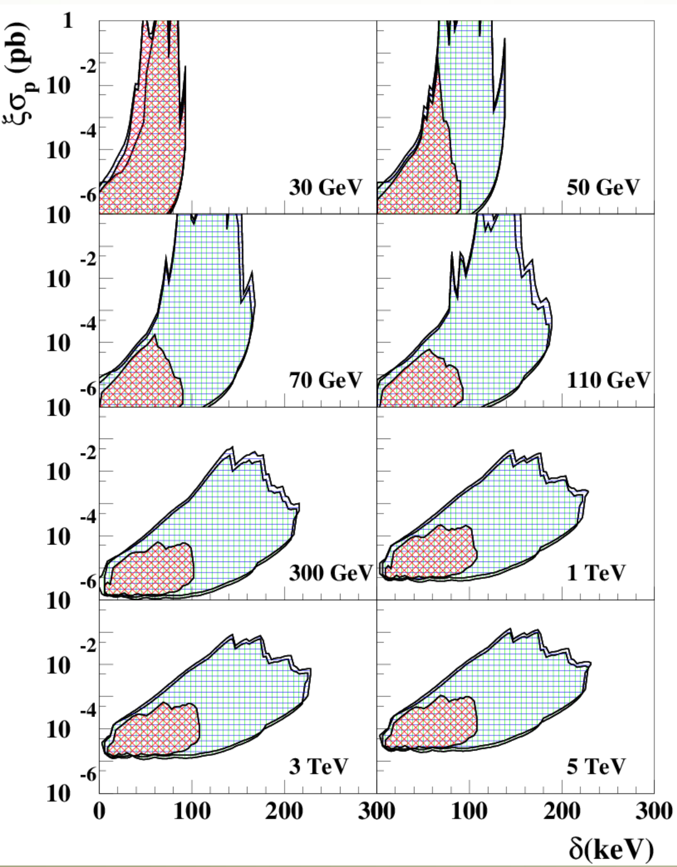
DAMA/NaI, DAMA/LIBRA-ph1 and ph2

→ W has 2 mass states χ+ , χ- with δ mass splitting

→ Kinematical constraint for the inelastic scattering of χ- on a nucleus (μ: χ-nucleus reduced mass)

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

- Higher mass target-nuclei are favourites
- Enhanced S_m with respect to S_0

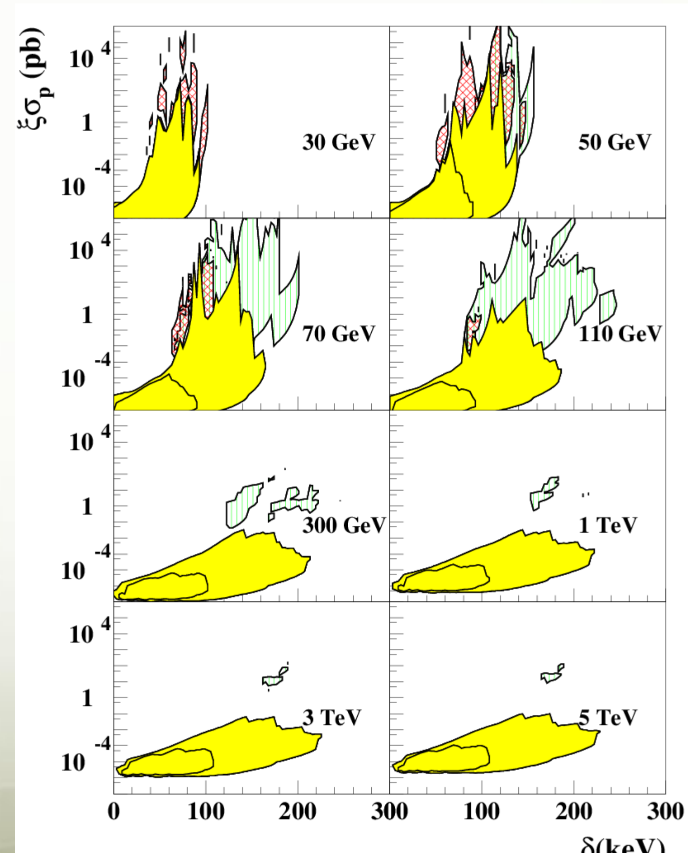


Slices of the 3-dim allowed volume

$(\xi\sigma_p, m_{DM}, \delta)$

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

Including Thallium: new allowed regions



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Model-dependent analyses: other examples

Inelastic DM in the scenario of Smith and Weiner [Phys. Rev. D 64, 043502 (2001)]

W + N → W* + N

DAMA/NaI, DAMA/LIBRA-ph1 and ph2

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

→ Kinematical constraint for the inelastic scattering of $\chi-$ on a nucleus (μ: χ-nucleus reduced mass)

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

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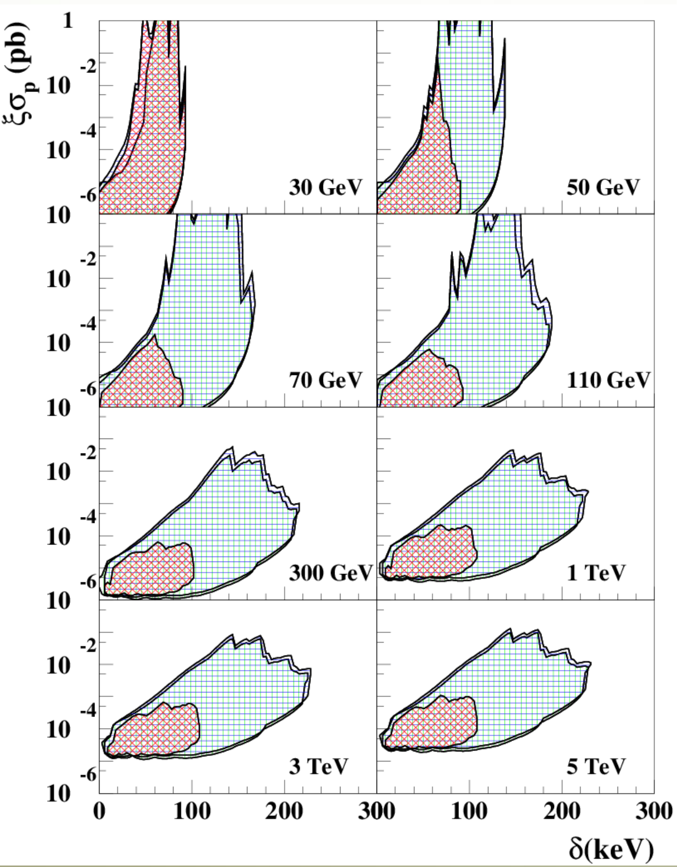
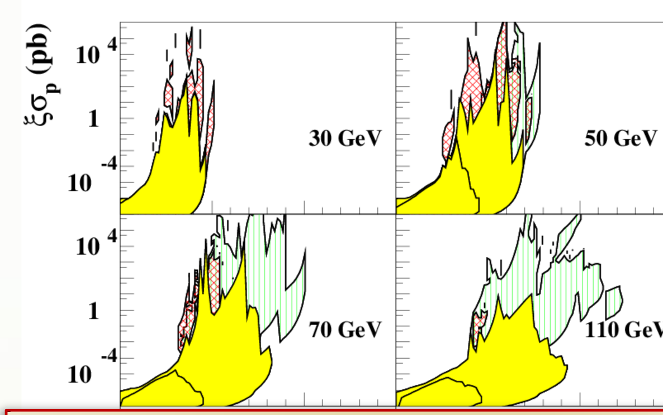
- Enhanced S_m with respect to S_0



Slices of the 3-dim allowed volume
($\xi\sigma_p$, m_{DM}, δ)

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

Including Thallium: new allowed regions



- New regions with $\xi\sigma_p > 1$ pb and $\delta > 100$ keV are allowed by DAMA after the inclusion of the inelastic scattering off Thallium nuclei.
- Such regions are not fully accessible to detectors with target nuclei having mass lower than Thallium.

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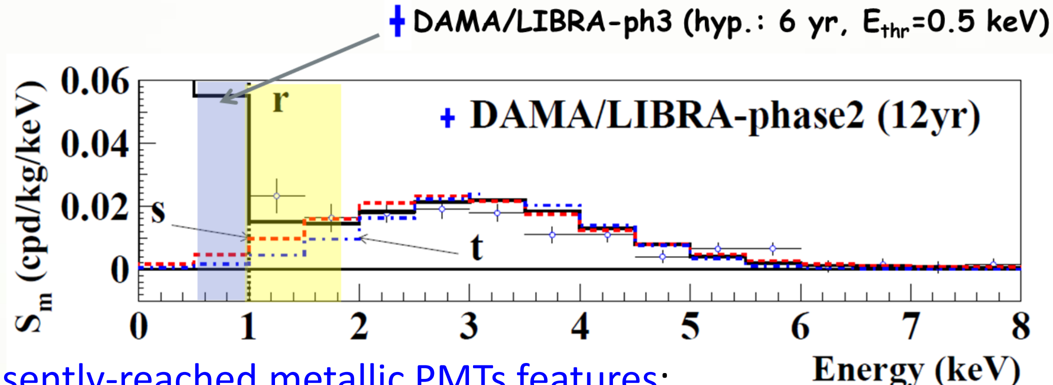
Toward DAMA/LIBRA-phase3

updating hardware to lower the software energy threshold below 1 keV

new miniaturized low background **pre-amps** directly installed on the low-background supports of the **voltage dividers** of the new lower background high Q.E. **PMTs**

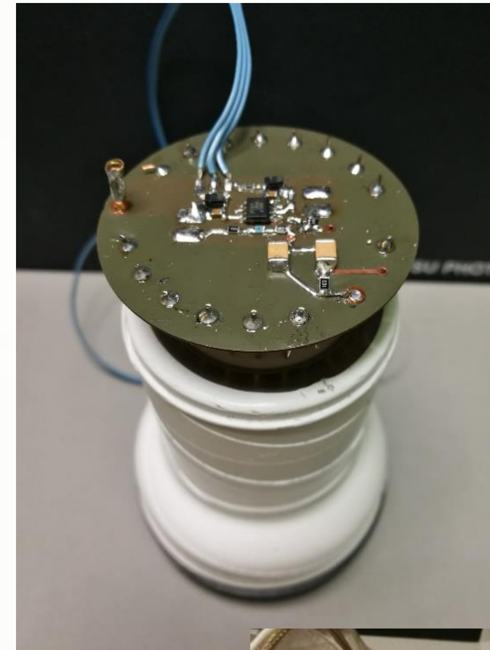


The presently-reached metallic PMTs features:

- 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).
- Dark counts < 100 Hz

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 much lower than that of the single PMT



- several prototypes from a dedicated R&D with HAMAMATSU at hand
- 4 DAMA/LIBRA detectors already equipped with the new PMTs

Features of the DM signal

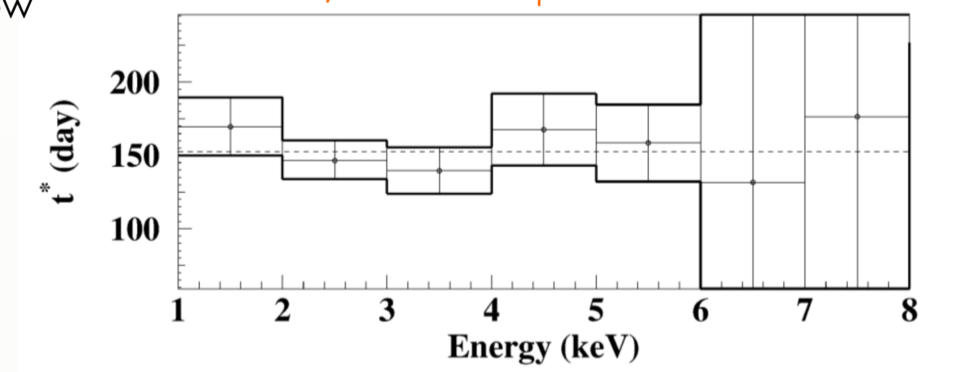
Investigated by the different stages of DAMA; improvements foreseen with DAMA/LIBRA-phase3

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

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

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

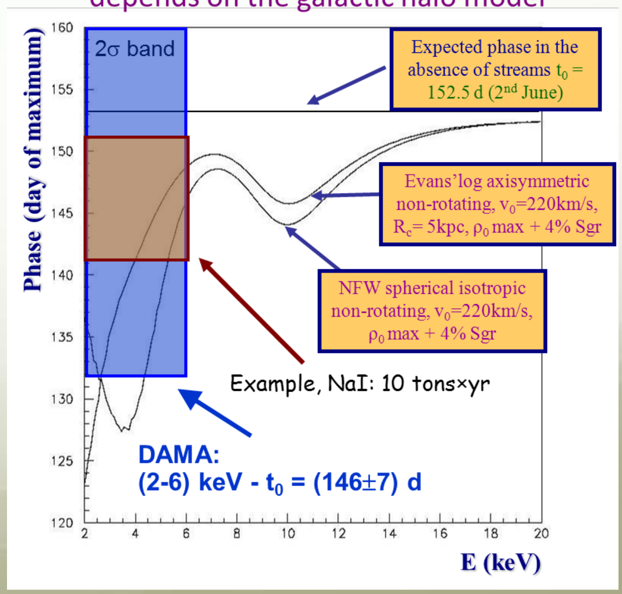
DAMA/NaI+LIBRA-phase2



The annual modulation phase depends on :

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

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



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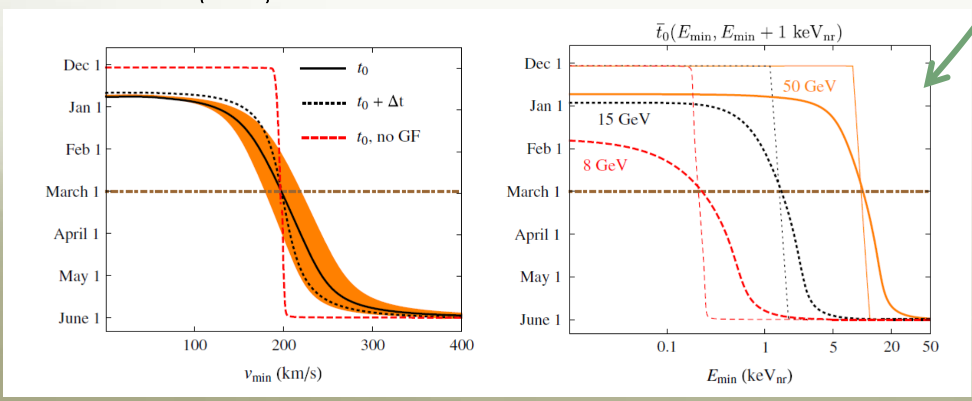

Conclusions

- **Model-independent** evidence for a signal that satisfies all the requirements of the DM annual modulation signature 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 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 wrt previous DAMA results
- DAMA/LIBRA–phase2 **continuing data taking**
- DAMA/LIBRA–phase3 **R&D almost concluded;** 4 detectors already equipped with the new PMT/divider/amp systems
- Continuing investigations of **rare processes** other than DM
- Other pursued ideas: **$ZnWO_4$ anisotropic scintillator** for DM **directionality**. Response to nuclear recoils measured.