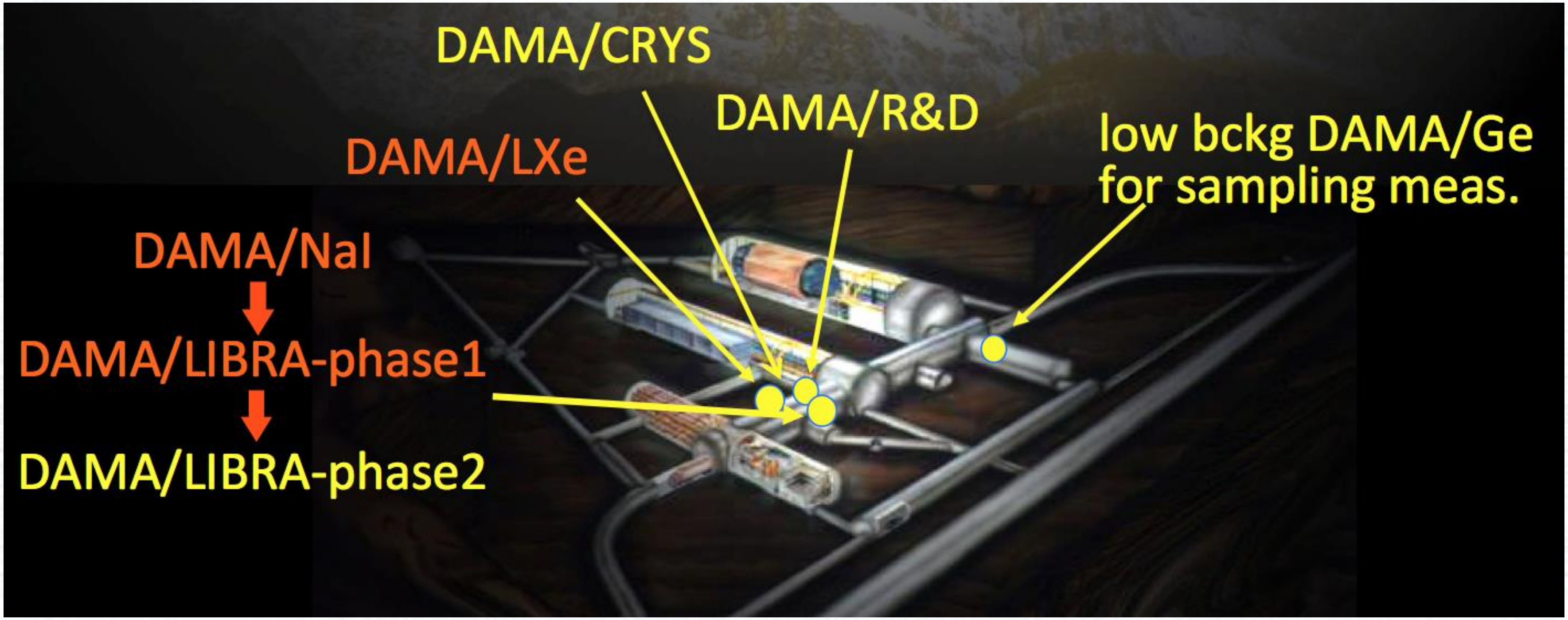
DAMA/LIBRA-phase2 model independent results and corollary analyses in various frameworks

22st Bled Workshop
"What comes beyond the standard models?"
Bled, Slovenia
July 6-14, 2019

F. Cappella
INFN – Roma

DAMA set-ups

an observatory for rare processes @ LNGS



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

Collaboration:

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

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

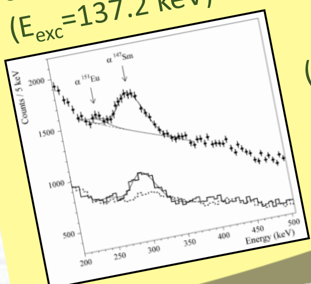
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

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

Main results obtained by DAMA in the search for rare processes

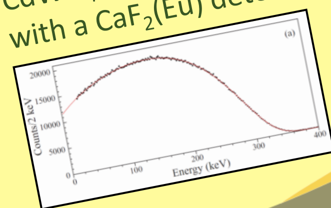
- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40,46,48}Ca, ^{64,70}Zn, ^{100}Mo, ^{96,104}Ru, ^{106,108,114,116}Cd, ^{112,124}Sn, ^{134,136}Xe, ^{130}Ba, ^{136,138,142}Ce, ^{150}Nd, ^{156,158}Dy, ^{162,170}Er, ^{180,186}W, ^{184,192}Os, ^{190,198}Pt (observed 2ν2β decay in ^{100}Mo, ^{116}Cd , ^{150}Nd)
- The best experimental sensitivities in the field for 2β decays with positron emission (^{106}Cd)

First observation of α decays of ^{151}Eu with a CaF_2(Eu) scintillator and of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os



($T_{1/2}=5\times10^{18}$yr)

Investigations of rare β decays of ^{113}Cd ($T_{1/2}=8\times10^{15}$yr), ^{113m}Cd with $CdWO_4$ scintillator and ^{48}Ca with a CaF_2(Eu) detector



Observation of correlated e^+e^- pairs emission in α decay of ^{241}Am ($A_{e+e-}/A_\alpha \approx 5\times10^{-9}$)

Search for cluster decays of ^{127}I, ^{138}La and ^{139}La

CNC processes, e.g. in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La

Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

Search for PEP violating processes in Sodium and in Iodine

Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state

Search for ^{7}Li solar axions using resonant absorption in LiF crystal

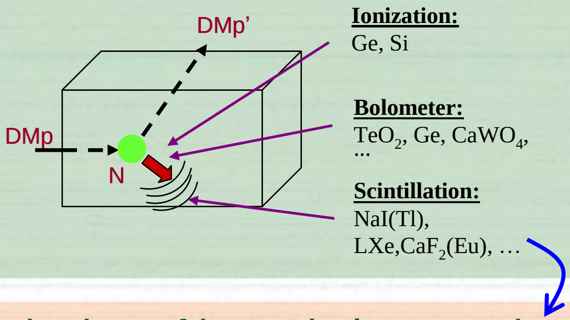
Dark Matter investigation

… many others are in progress

Some direct detection processes:

- 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

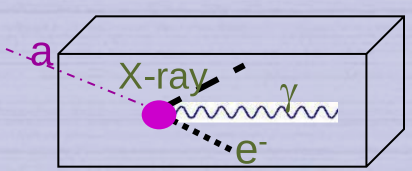
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

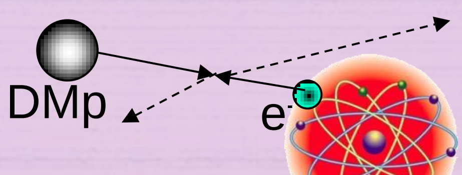
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

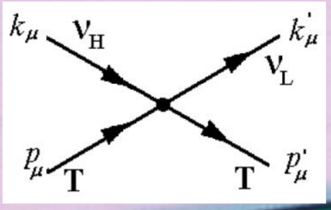


... even WIMPs

- 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



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

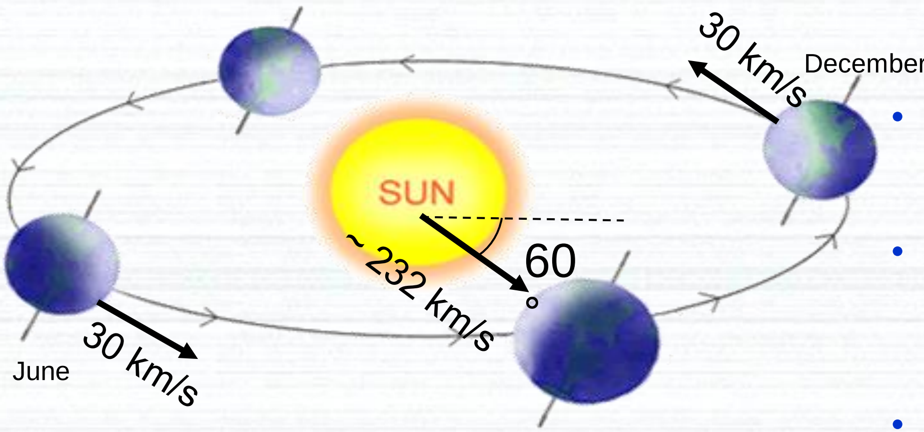
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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 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)

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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)

- 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

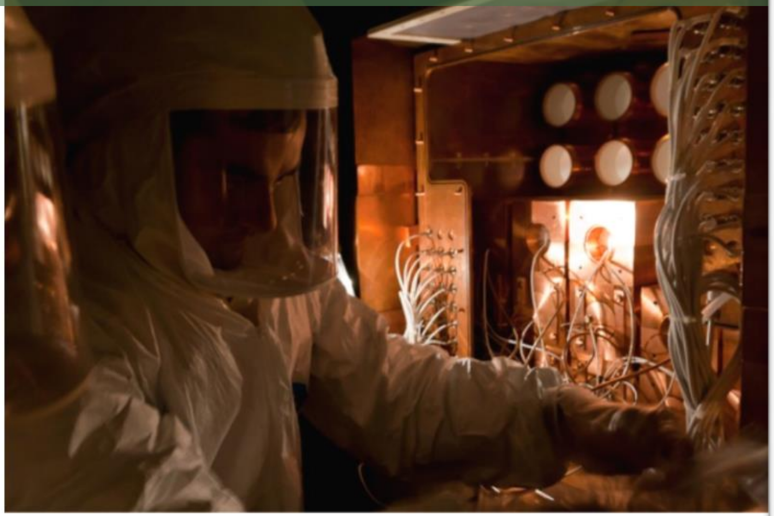
Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

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 W. in Phys.19 (2018) 27

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



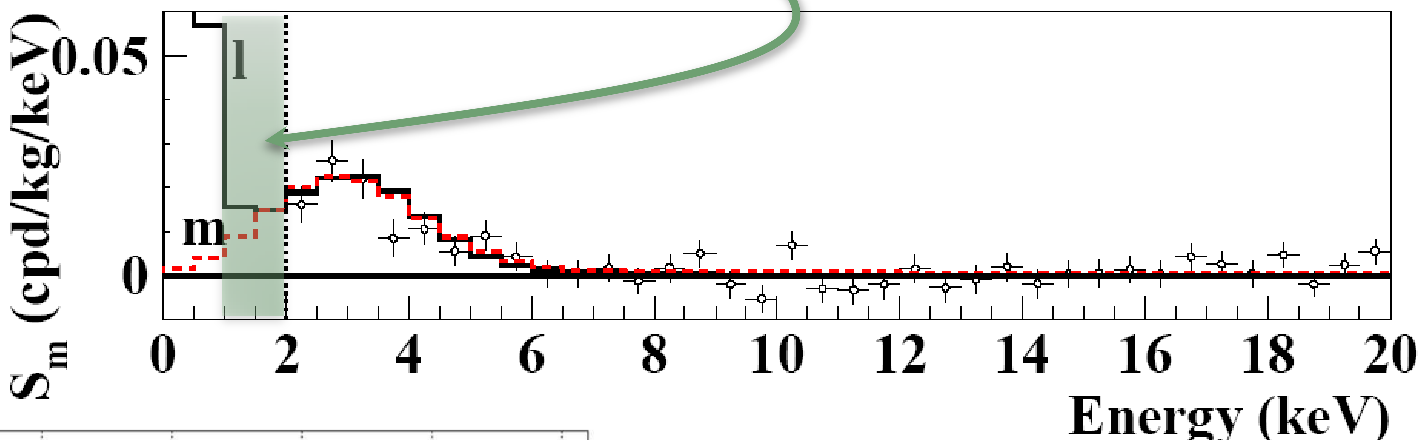
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak

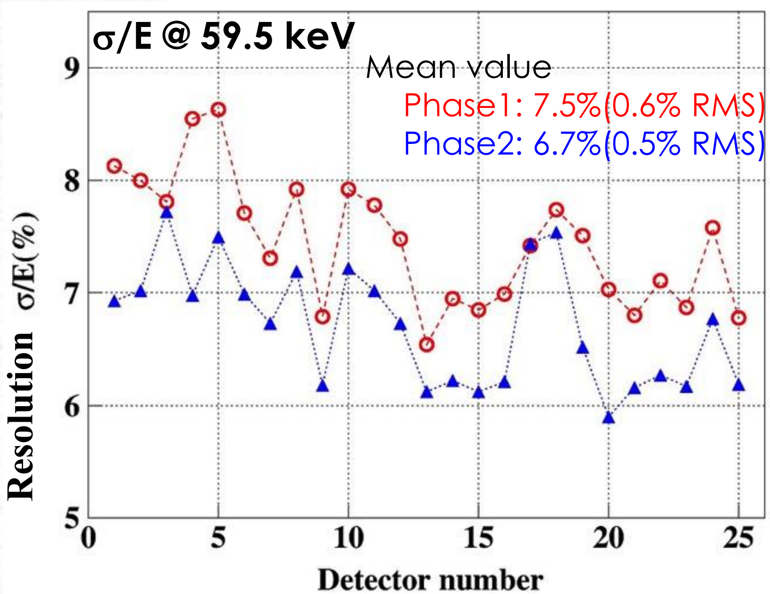
DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 207
Bled W. in Phys.19 (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*





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.

JINST 7(2012)03009

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

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

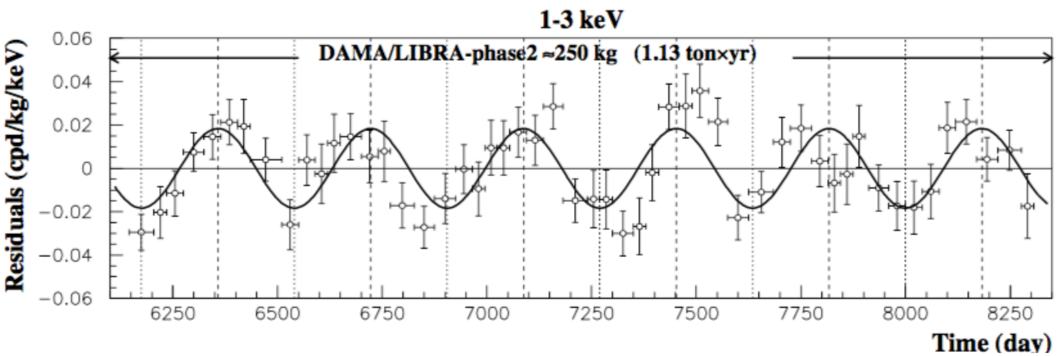
Annual Cycles	Period	Mass (kg)	Exposure (kg×day)	$(\alpha-\beta^2)$
I	Dec 23, 2010 – Sept. 9, 2011	commissioning		
II	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
VI	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527	0.522
VII	Sept. 7, 2016 – Sept. 25, 2017	242.5	75135	0.480

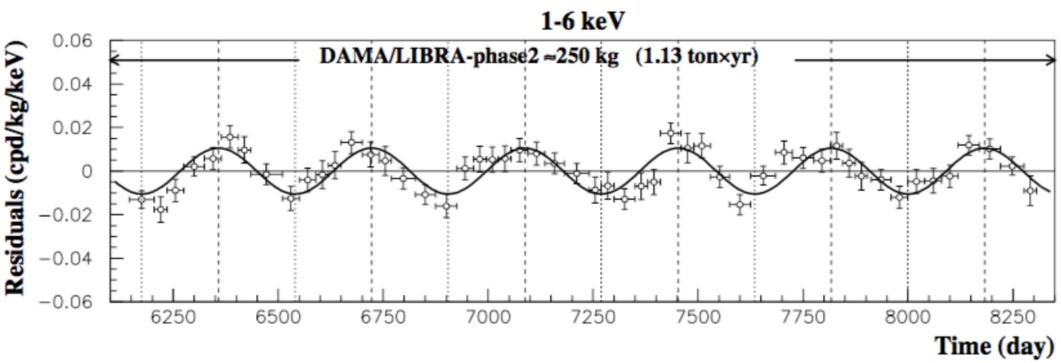
Exposure first data release of DAMA/LIBRA-phase2: **1.13 ton x yr**
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.46 ton x yr**

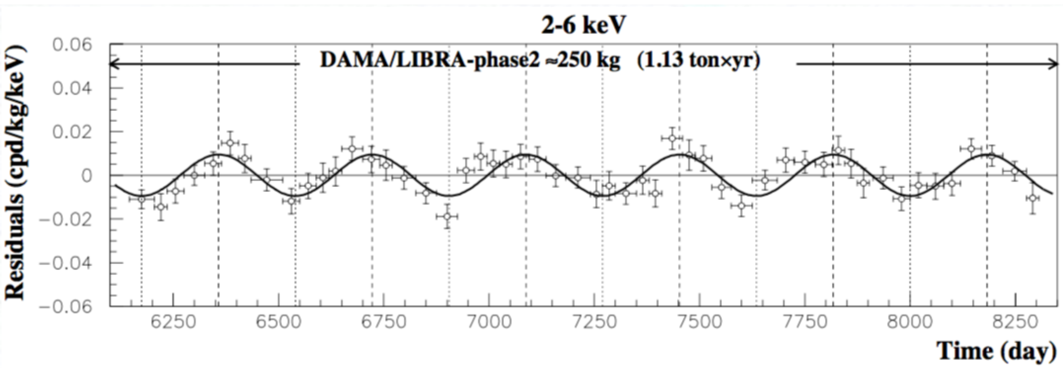
DM model-independent Annual Modulation Result

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

DAMA/LIBRA-phase2 (1.13 ton×yr)







Absence of modulation? No

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

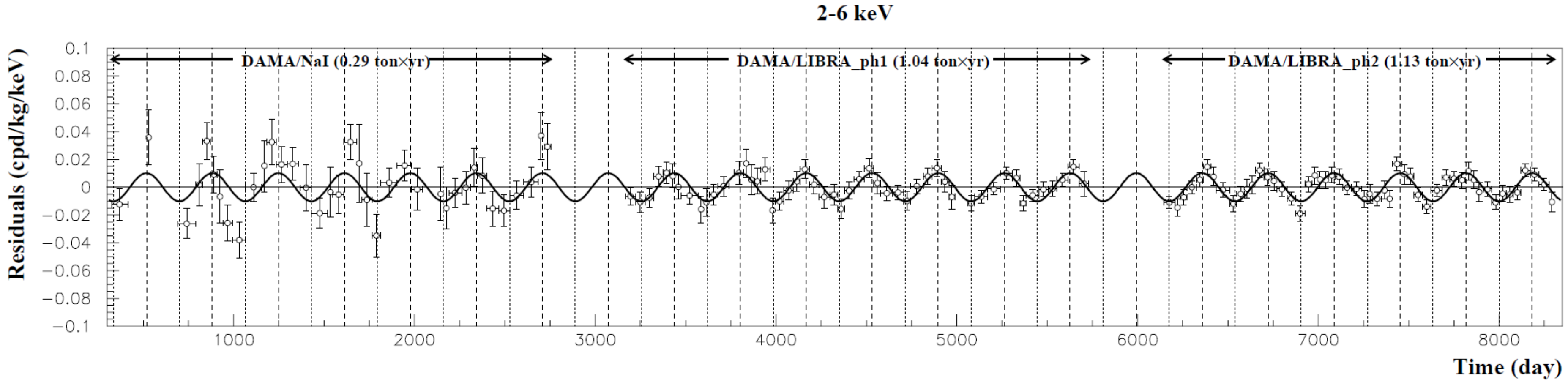
χ^2/dof = 42.5/51 **8.6 σ C.L.**

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



Absence of modulation? No

- 2-6 keV: χ^2/dof=272.3/142 $\Rightarrow$ P(A=0) =3.0×10^{-10}

Fit on DAMA/NaI+ DAMA/LIBRA-ph1+ DAMA/LIBRA-ph2

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

2-6 keV

A=(0.0102±0.0008) cpd/kg/keV

χ^2/dof = 113.8/138 **12.8 σ C.L.**

The data of DAMA/NaI + DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 12.8 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

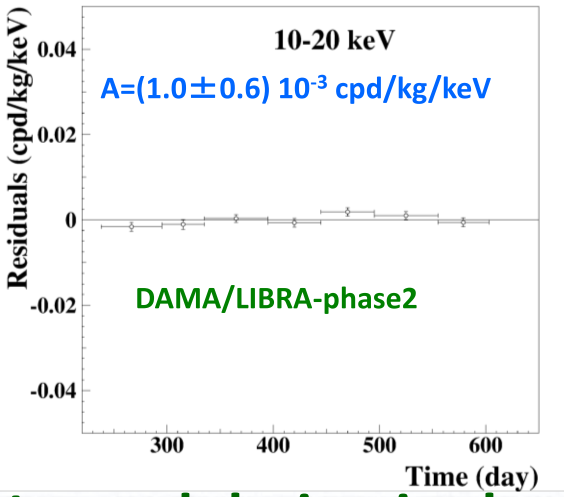
$A\cos[\omega(t-t_0)]$

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

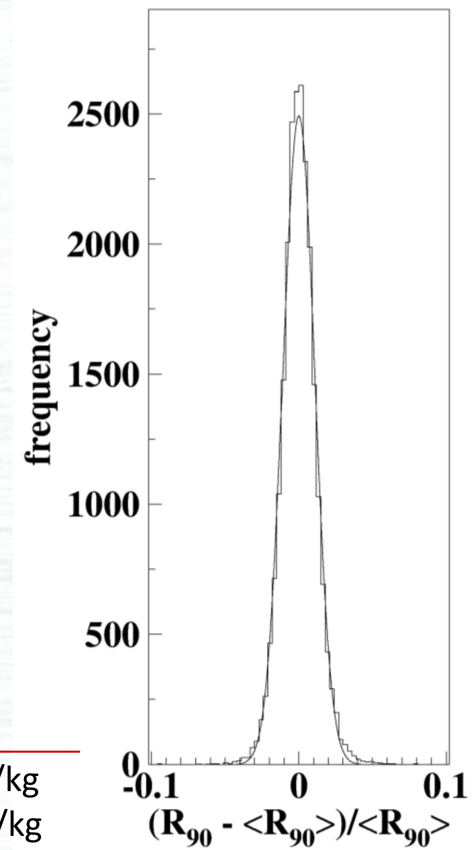
Rate behaviour above 6 keV

- **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
- 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

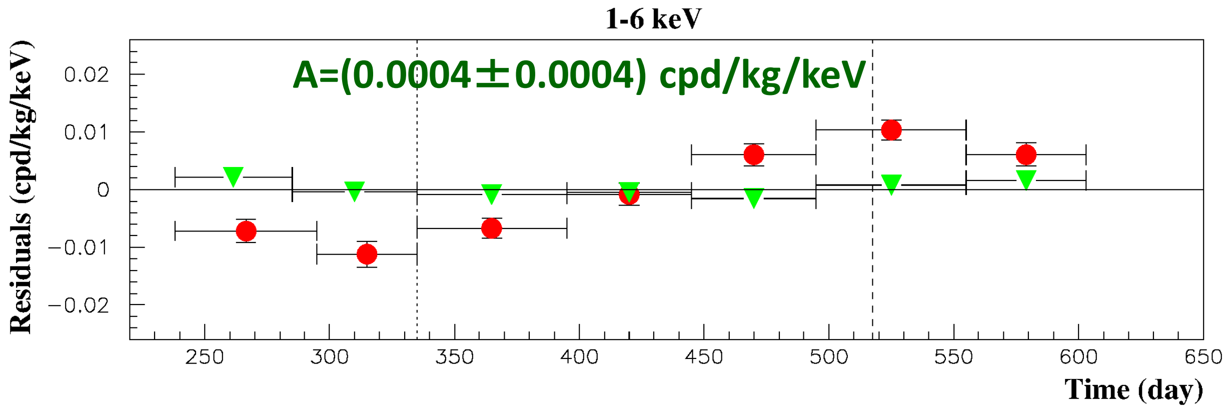
+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

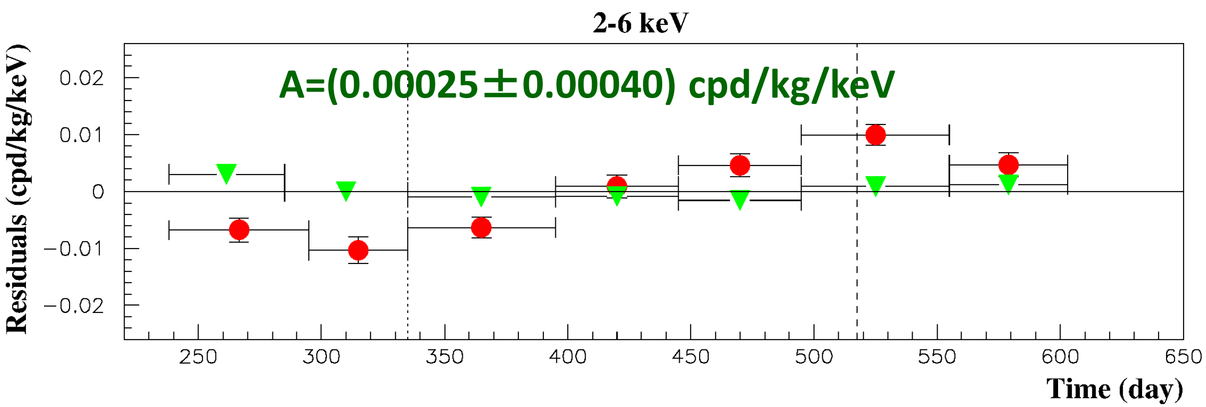
No modulation above 6 keV
This accounts for all sources of background and is consistent with the studies on the various components

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 furthermore rules out any side effect either from hardware or from software procedures or from background

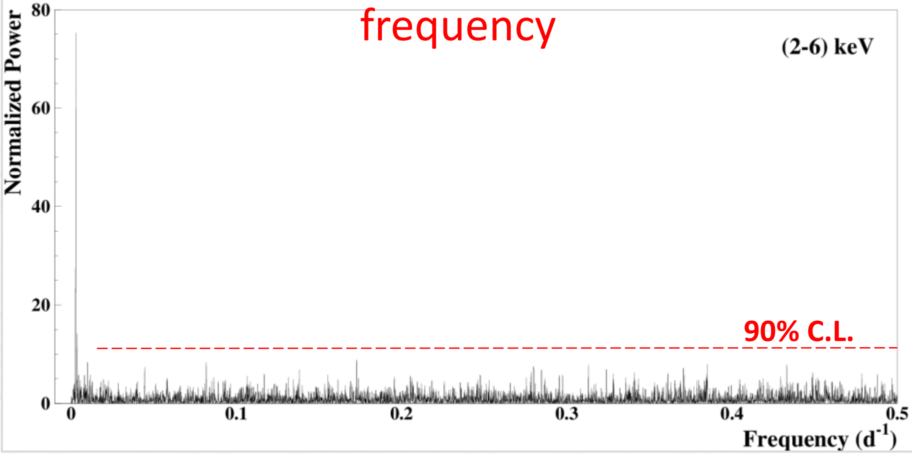
The analysis in frequency

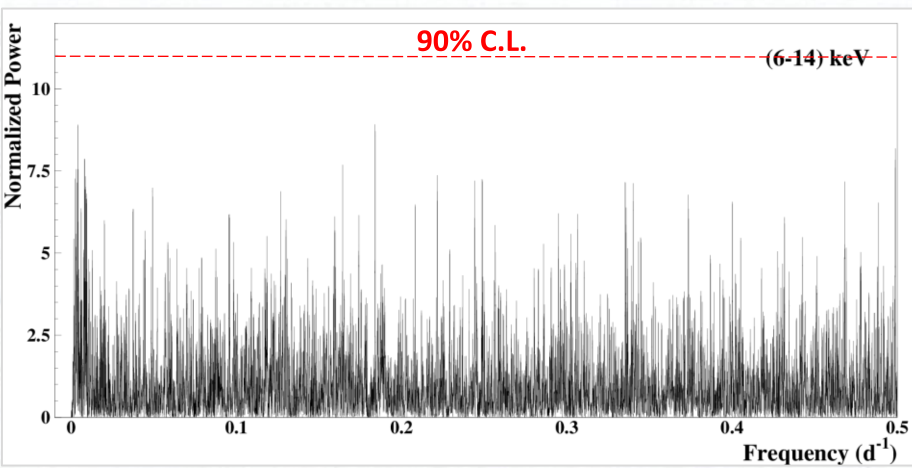
(according to PRD75 (2007) 013010)

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

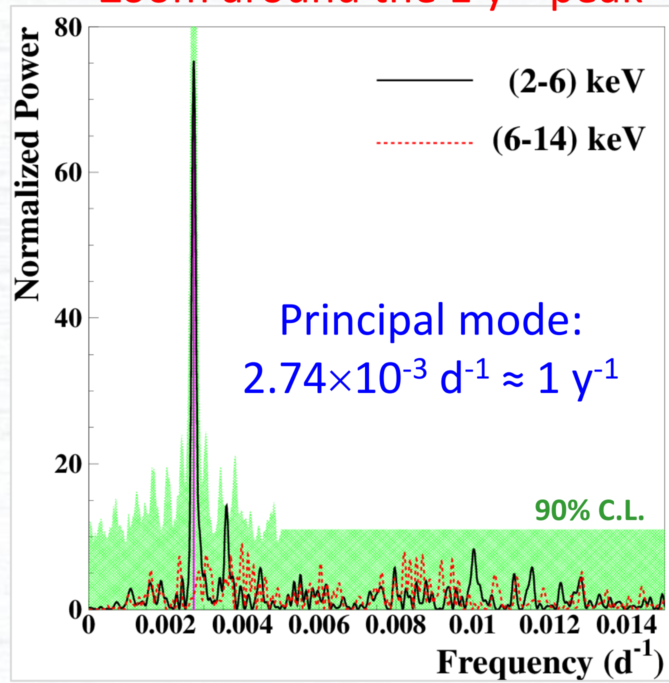
DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (20 yr)
total exposure: 2.46 ton×yr

The whole power spectra up to the Nyquist frequency





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

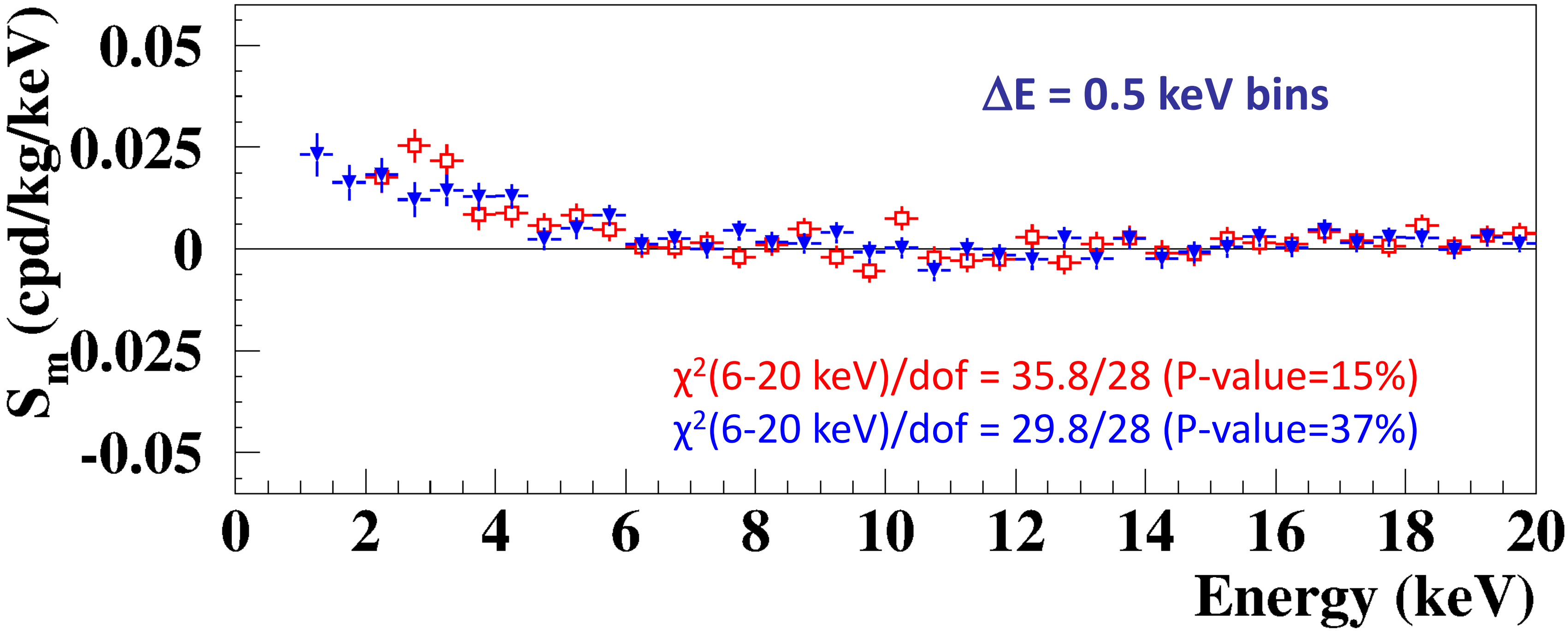
Energy distribution of the modulation amplitudes

Max-likelihood analysis

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

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%)

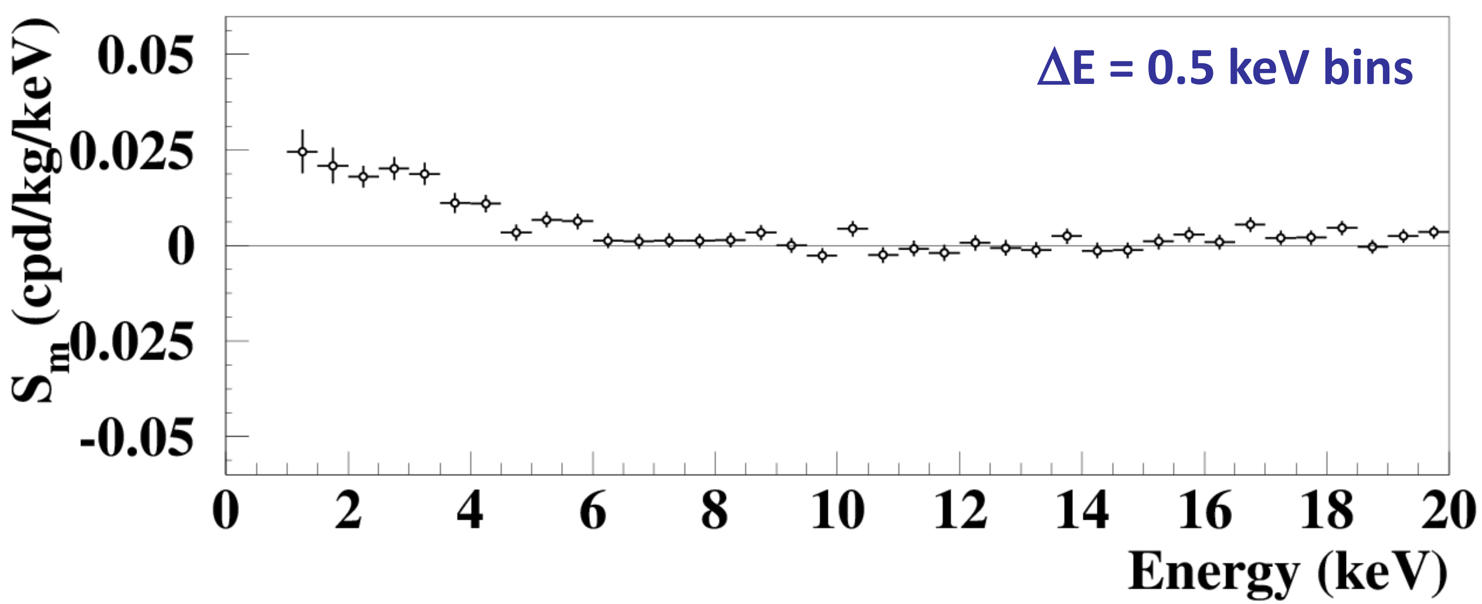
Energy distribution of the modulation amplitudes

Max-likelihood analysis

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

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

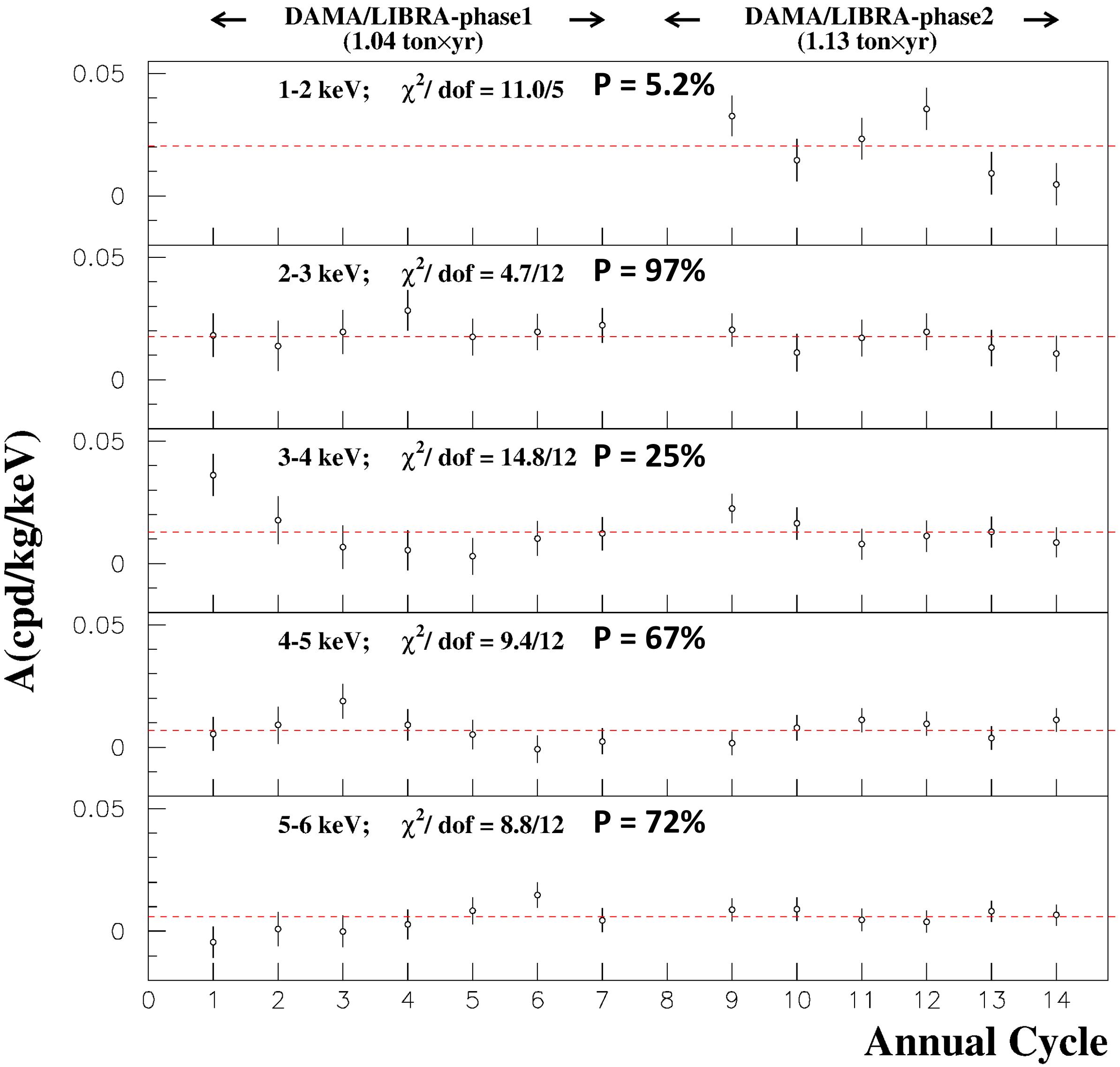
DAMA/NaI + DAMA/LIBRA-phase1 **+ DAMA/LIBRA-phase2 (2.46 ton×yr)**



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 annual cycle



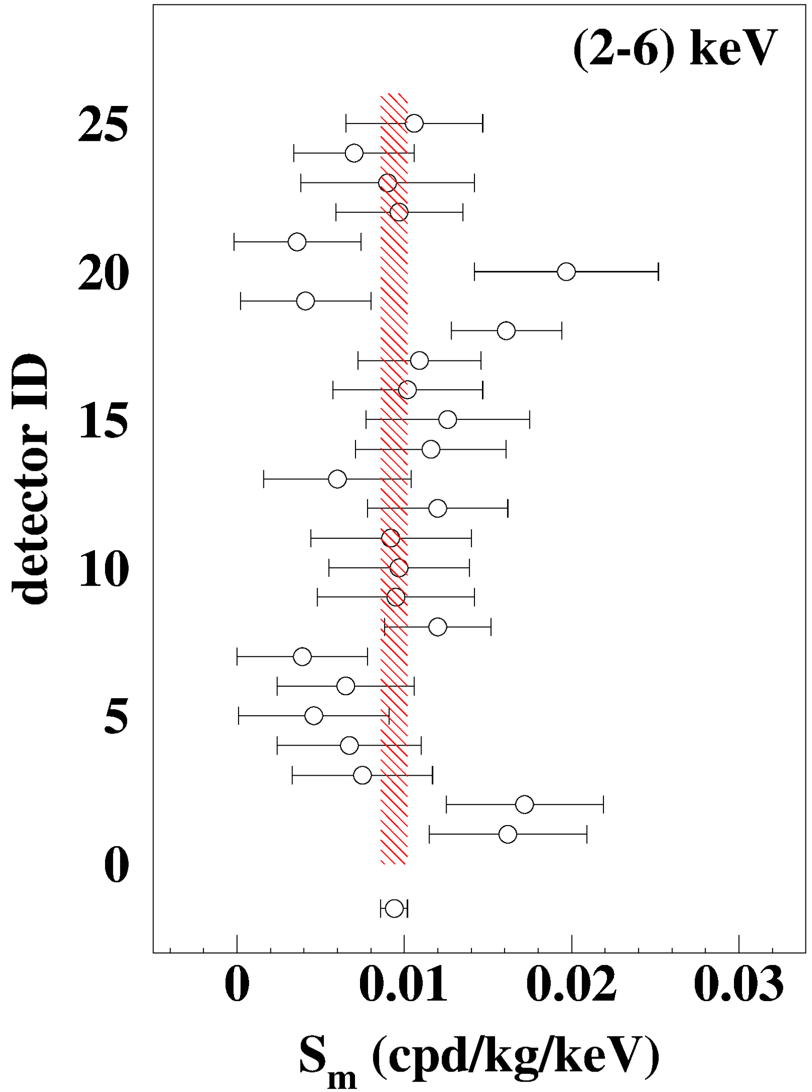
DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: 2.46 ton×yr

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

*it verifies the hypothesis that the positive (above the mean value) and negative (under the mean value) data points are randomly distributed

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

S_m for each detector



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

χ^2/dof = 23.9/24 d.o.f.

The signal is well distributed over all the 25 detectors

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)	$(1.1 \pm 0.9) \times 10^{-3}$	(0.2 ± 1.1)) $\times 10^{-3}$	$(2.4 \pm 5.4) \times 10^{-3}$	$(0.6 \pm 6.2) \times 10^{-3}$	$(1.5 \pm 6.3) \times 10^{-3}$	$(7.2 \pm 8.6) \times 10^{-3}$
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)	$-(0.12 \pm 0.16) \times 10^{-2}$	$(0.00 \pm 0.12) \times 10^{-2}$	$-(0.14 \pm 0.22) \times 10^{-2}$	$-(0.05 \pm 0.22) \times 10^{-2}$	$-(0.06 \pm 0.16) \times 10^{-2}$	$-(0.08 \pm 0.17) \times 10^{-2}$

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; → $\Phi_k = \Phi_{0,k}\,(1+\eta_k cos\omega\,(t-t_k))$
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by: → $R_k = R_{0,k}\,(1+\eta_k cos\omega\,(t-t_k))$
  - 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	$\Phi_0^{(\mu)} \simeq 20\ \mu$ 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	$\Phi_0^{(\nu)} \simeq 6 \times 10^{10}\ \nu$ 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

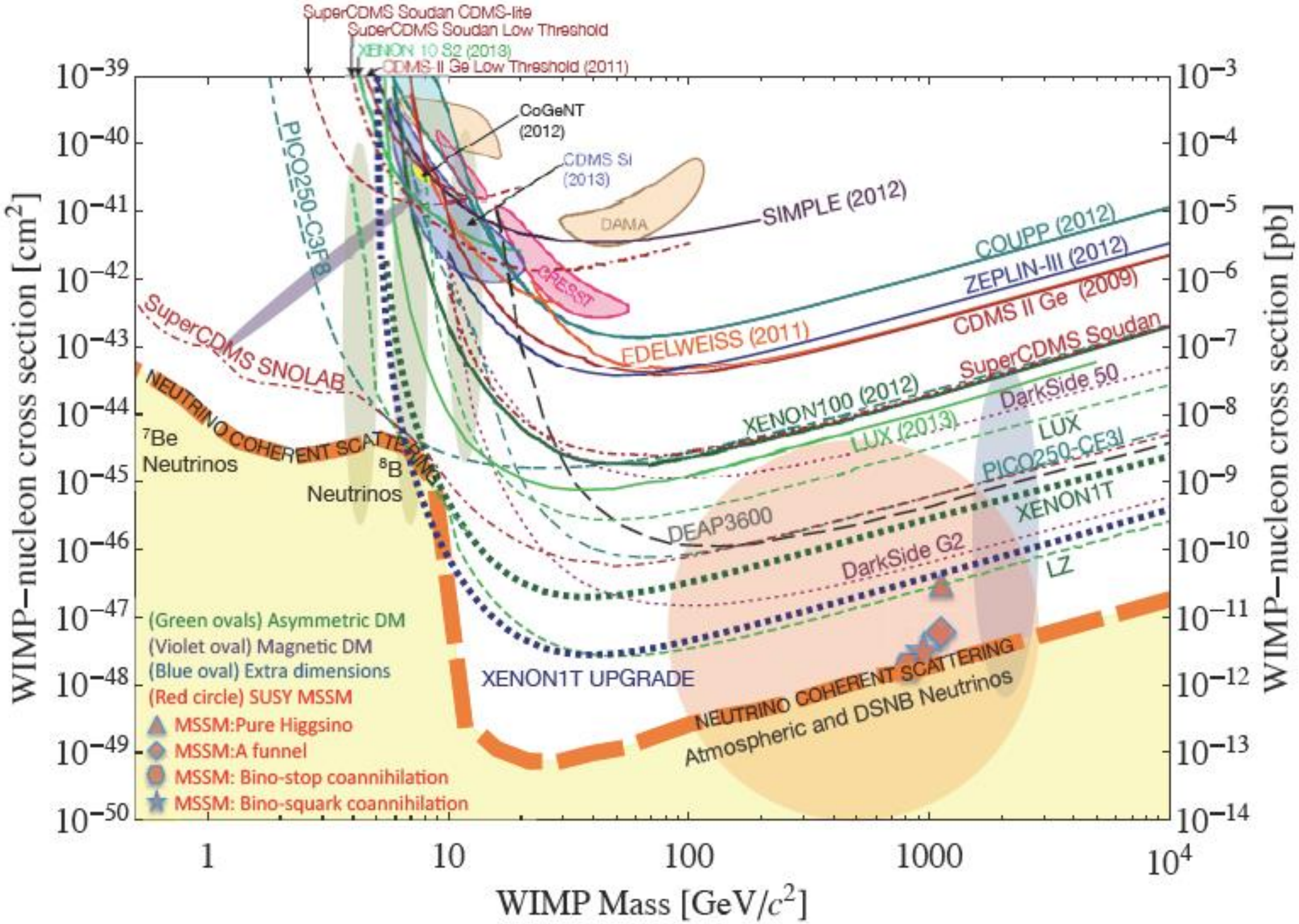
NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196, IJMPA31(2017)issue31, Universe4(2018)03009, Beld19,2(2018)27

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-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

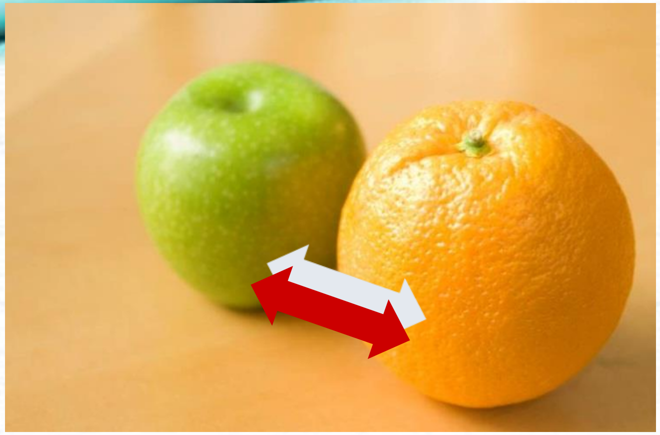
→ **Thus, they cannot mimic the observed annual modulation effect**

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

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

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

Neutralino as LSP in various SUSY theories

Various kinds of WIMP candidates with several different kind of interactions
Pure SI, pure SD, mixed + Migdal effect +channeling,… (from low to high mass)

a heavy ν of the 4-th family

Pseudoscalar, scalar or mixed light bosons with axion-like interactions

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

Self interacting Dark Matter

Dark Matter (including some scenarios for WIMP) electron-interacting

Sterile neutrino

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

Elementary Black holes such as the Daemons

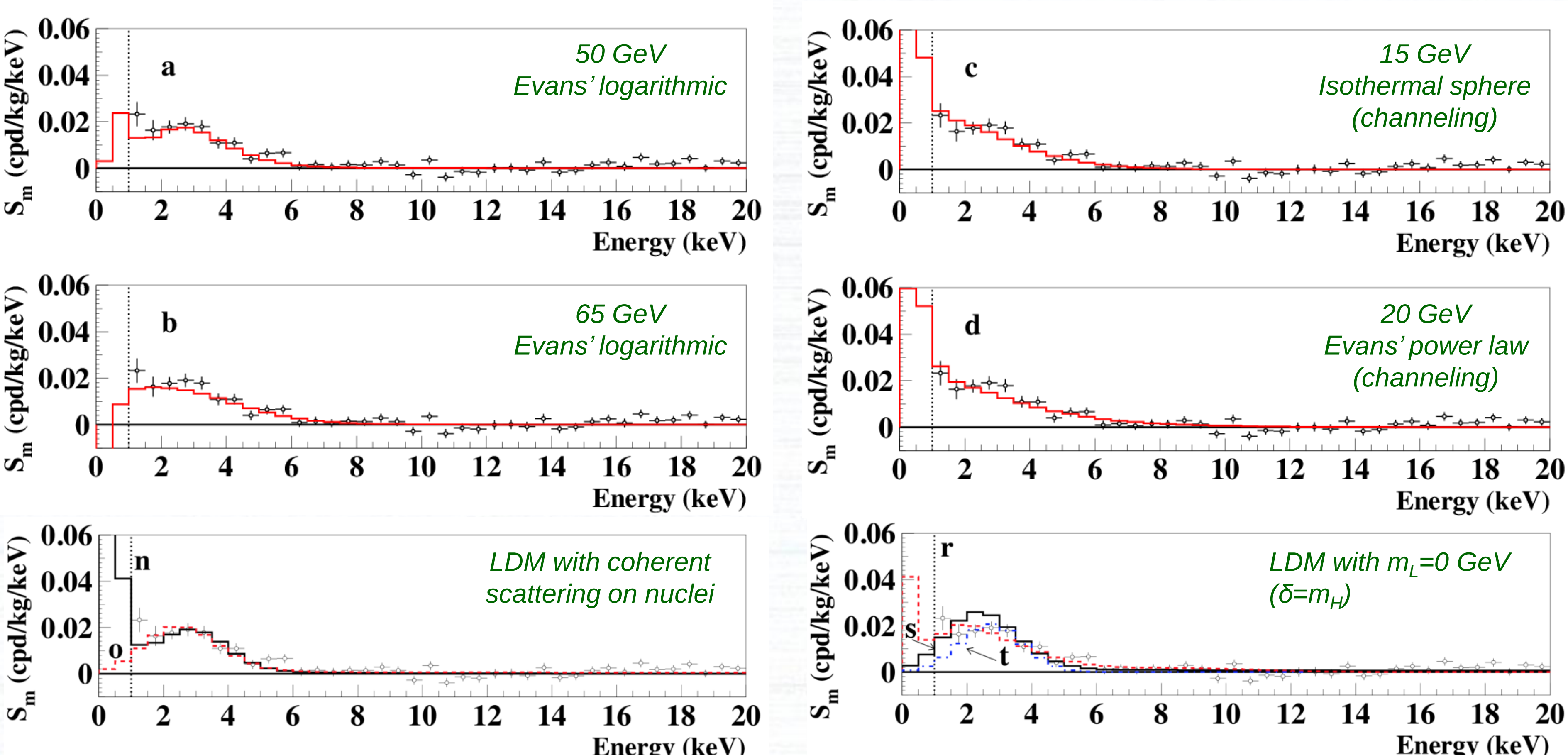
Kaluza Klein particles

… and more

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>



Model-dependent analyses for some DM candidates

Including DAMA/LIBRA/phase2

- 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_0 in the range:
  - [0.17, 0.67] GeV/cm^3 for v_0=170 km/s
  - [0.29, 1.11] GeV/cm^3 for v_0 = 220 km/s
  - [0.45, 1.68] GeV/cm^3 for v_0 = 270 km/s

  depending on the halo model
- v_{esc} = 550 km/s

  no sizable differences if v_{esc} in the range [550, 650]km/s
- And for DM candidates inducing nuclear recoils:
  - constants quenching factors, q.f., with respect to the recoil energy, E_R;
  - varying q.f. as a function of E_R [Astr.Phys.33, 40 (2010)];
  - channeling effect [EPJC 53, 205 (2008)]
  - Three different sets of values for the nuclear form factor and quenching factor parameters

Class A: spherical ρ_{dm}, isotropic velocity dispersion		
A0	Isothermal Sphere	
A1	Evans' logarithmic	$R_c = 5$ kpc
A2	Evans' power-law	$R_c = 16$ kpc, $\beta = 0.7$
A3	Evans' power-law	$R_c = 2$ kpc, $\beta = -0.1$
A4	Jaffe	$\alpha = 1, \beta = 4, \gamma = 2, a = 160$ kpc
A5	NFW	$\alpha = 1, \beta = 3, \gamma = 1, a = 20$ kpc
A6	Moore et al.	$\alpha = 1.5, \beta = 3, \gamma = 1.5, a = 28$ kpc
A7	Kravtsov et al.	$\alpha = 2, \beta = 3, \gamma = 0.4, a = 10$ kpc
Class B: spherical ρ_{dm}, non–isotropic velocity dispersion (Osipkov–Merrit, $\beta_0 = 0.4$)		
B1	Evans' logarithmic	$R_c = 5$ kpc
B2	Evans' power-law	$R_c = 16$ kpc, $\beta = 0.7$
B3	Evans' power-law	$R_c = 2$ kpc, $\beta = -0.1$
B4	Jaffe	$\alpha = 1, \beta = 4, \gamma = 2, a = 160$ kpc
B5	NFW	$\alpha = 1, \beta = 3, \gamma = 1, a = 20$ kpc
B6	Moore et al.	$\alpha = 1.5, \beta = 3, \gamma = 1.5, a = 28$ kpc
B7	Kravtsov et al.	$\alpha = 2, \beta = 3, \gamma = 0.4, a = 10$ kpc
Class C: Axisymmetric ρ_{dm}		
C1	Evans' logarithmic	$R_c = 0, q = 1/\sqrt{2}$
C2	Evans' logarithmic	$R_c = 5$ kpc, $q = 1/\sqrt{2}$
C3	Evans' power-law	$R_c = 16$ kpc, $q = 0.95, \beta = 0.9$
C4	Evans' power-law	$R_c = 2$ kpc, $q = 1/\sqrt{2}, \beta = -0.1$
Class D: Triaxial ρ_{dm} (q = 0.8, p = 0.9)		
D1	Earth on maj. axis, rad. anis.	$\delta = -1.78$
D2	Earth on maj. axis, tang. anis.	$\delta = 16$
D3	Earth on interm. axis, rad. anis.	$\delta = -1.78$
D4	Earth on interm. axis, tang. anis.	$\delta = 16$

Model-dependent analyses: the analysis procedure

Including DAMA/LIBRA/phase2

The allowed regions in the parameters' space of each considered scenario are derived by comparing, for each k-th energy bin of 1 keV:

- $S_{m,k}^{exp}$, the measured DM annual modulation amplitude with
- $S_{m,k}^{th}(\bar{\theta})$, the theoretical expectation in each considered framework ($\bar{\theta}$ are the free parameters of the model)

A cautious prior on $S_{0,k}^{th}$ (the un-modulated part of the expected signal) is worked out from the measured counting rate in the cumulative energy spectrum:

$$\chi^2(\bar{\theta}) = \sum_k \frac{\left(S_{m,k}^{exp} - S_{m,k}^{th}(\bar{\theta})\right)^2}{\sigma_k^2} + \sum_{k'} \frac{\left(S_{0,k'}^{max} - S_{0,k'}^{th}(\bar{\theta})\right)^2}{\sigma_{0,k'}^2} \Theta\left(S_{0,k'}^{th}(\bar{\theta}) - S_{0,k'}^{max}\right)$$

$\Delta\chi^2(\bar{\theta}) = \chi^2(\bar{\theta}) - \chi_0^2$, where χ_0^2 is the χ^2 calculated in absence of signal, is used to determine the allowed intervals of the model parameters at 10σ from the null signal hypothesis

Model-dependent analyses

DM particles elastically interacting with target nuclei – SI interaction

Including DAMA/LIBRA/phase2

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

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

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

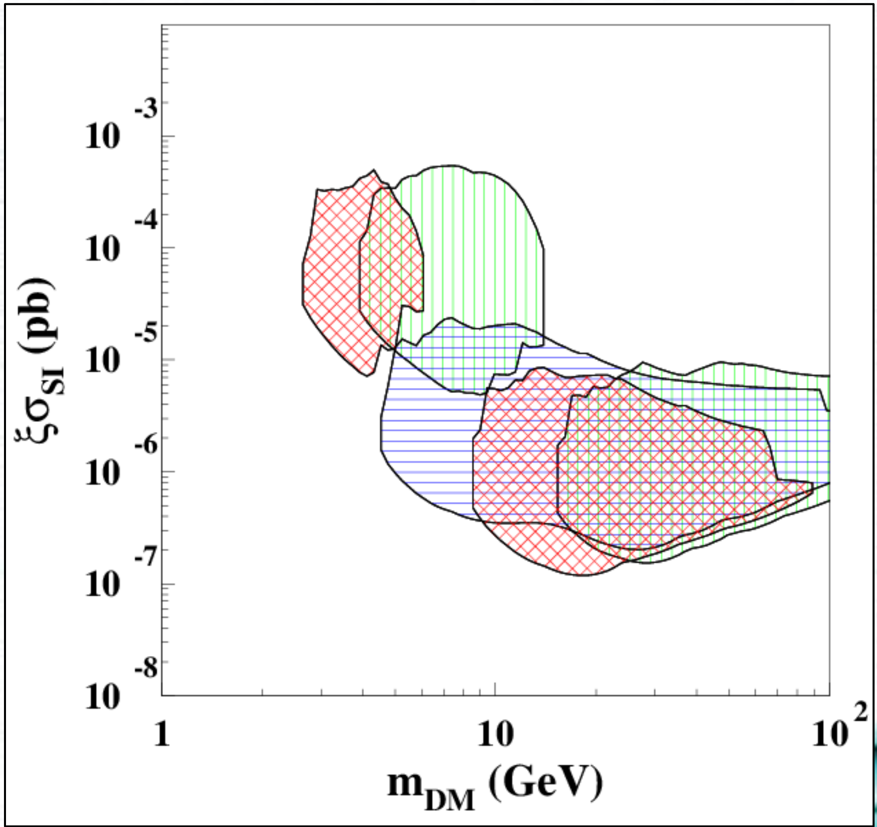
If $f_p = f_n$: $$\sigma_{SI}(A,Z) = \frac{m_{red}^2(A,DM)}{m_{red}^2(1,DM)} A^2 \sigma_{SI}$$

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

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

$\xi\sigma_{SI}$ 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

Including DAMA/LIBRA/phase2

Case of isospin violating SI coupling:

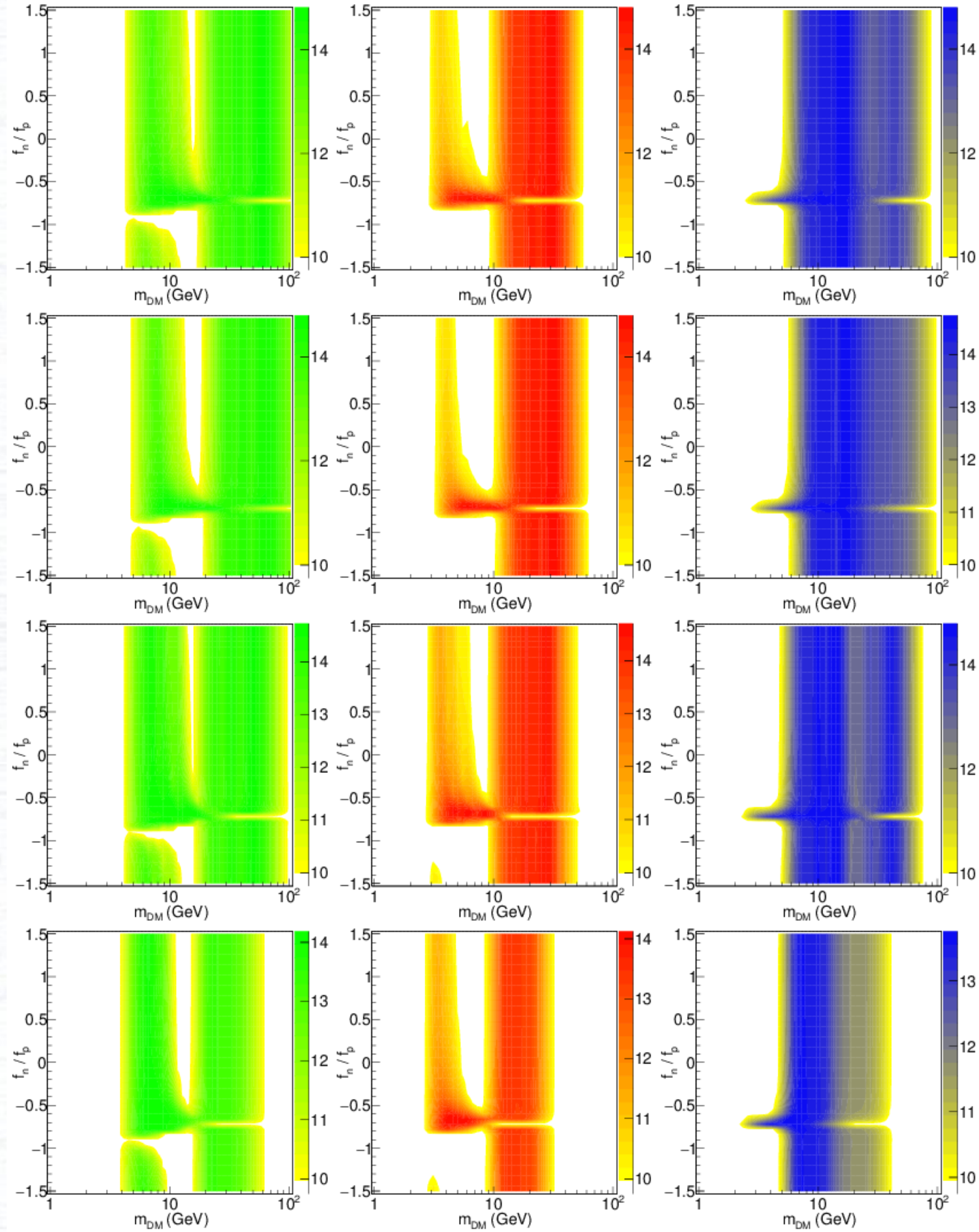
$f_p \neq f_n$

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

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

Including DAMA/LIBRA/phase2

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 $\xi\sigma_{SI}$

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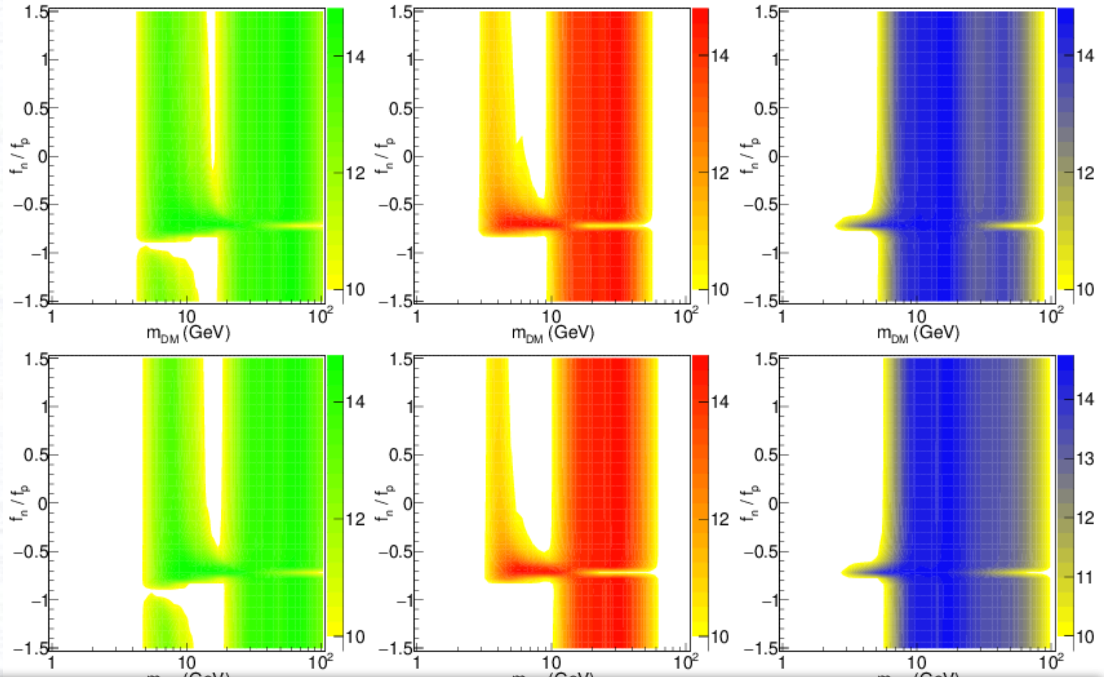
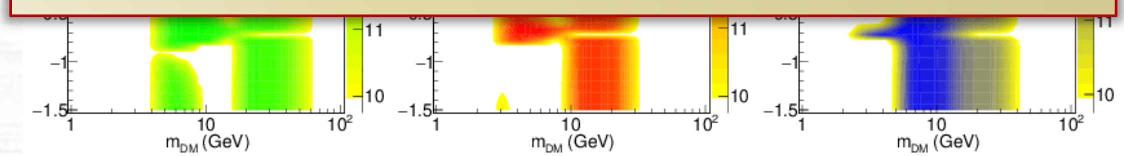
Allowed DAMA regions for A0 (isothermal sphere), B1, C1, D3 halo models (top to bottom)



- 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.



Model-dependent analyses

DM particles elastically interacting with target nuclei – purely SD interaction

Including DAMA/LIBRA/phase2

Possible only for target nuclei with spin$\neq$0

A further parameter, θ, is needed:

$$\tan\theta = \frac{a_n}{a_p}, \qquad \theta \text{ in } [0,\pi]$$

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

Slices at fixed θ values of the 3-dim allowed volume ($\xi\sigma_{SD}$, θ, m_{DM})

$\theta=0$ $\Rightarrow$ $a_n=0$, $a_p\neq0$ or $|a_p|>>|a_n|$;

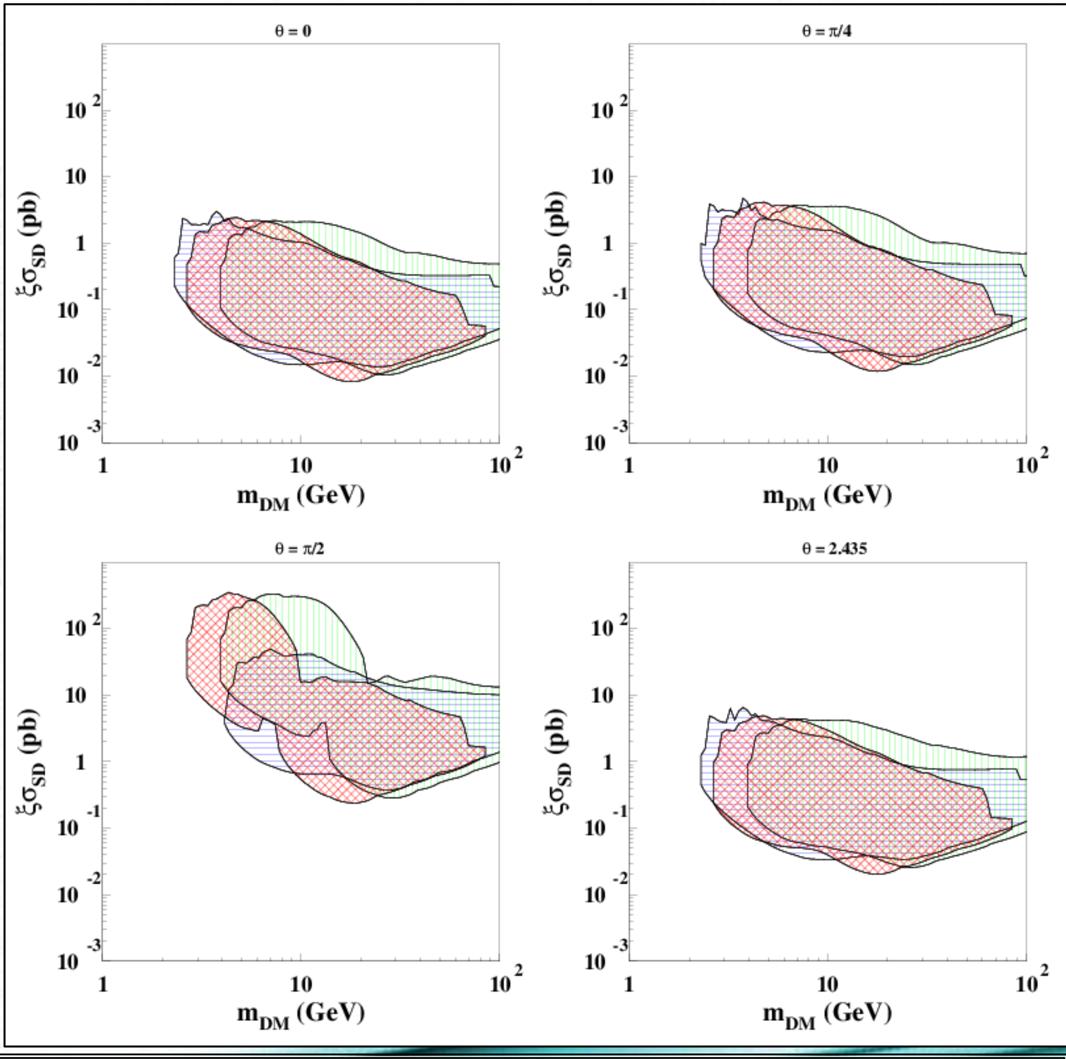
$\theta=\pi/4$ $\Rightarrow$ $a_n=a_p$;

$\theta=\pi/2$ $\Rightarrow$ $a_p=0$, $a_n\neq0$ or $|a_n|>>|a_p|$;

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

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

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



Model-dependent analyses

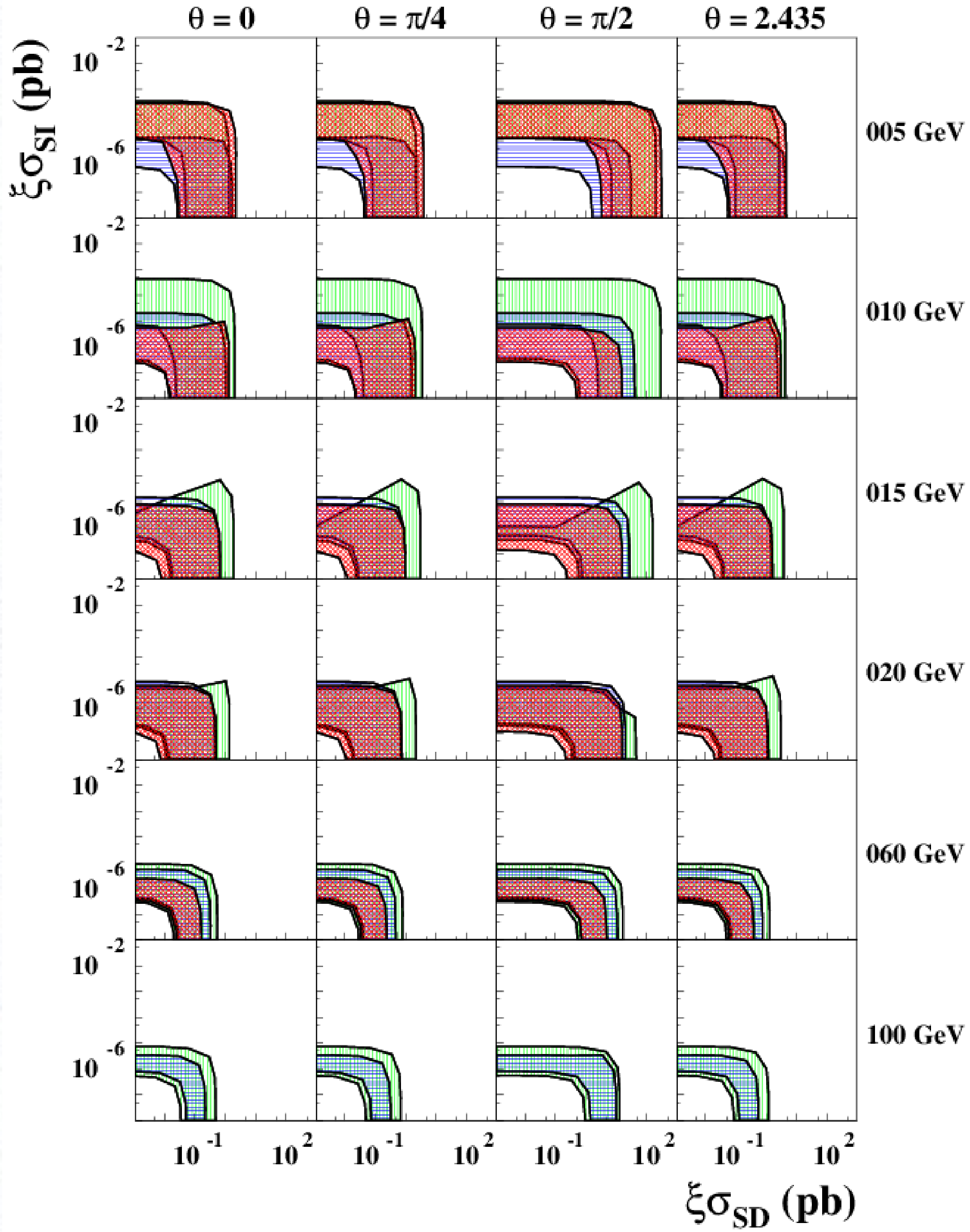
DM particles elastically interacting with target nuclei

Mixed SI-SD interaction

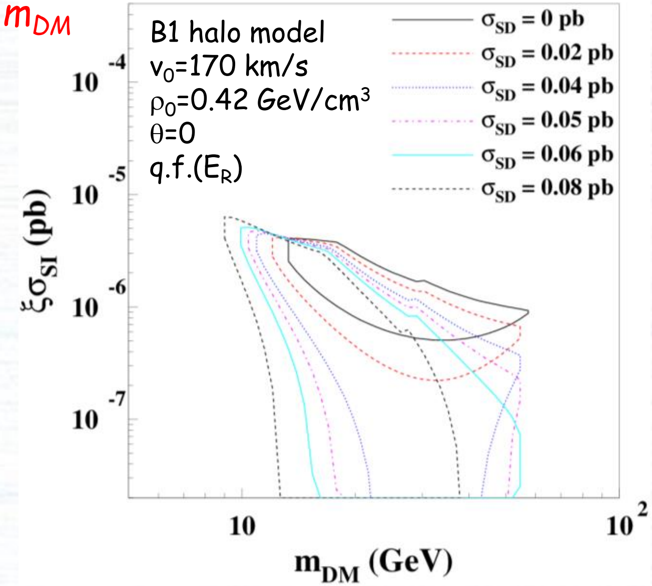
Including DAMA/LIBRA/phase2

Slices of the 4-dim allowed volume ($\xi\sigma_{SI}$, $\xi\sigma_{SD}$, θ, m_{DM})

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



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



Model-dependent analyses

DM particles elastically interacting with target nuclei

Mixed SI-SD interaction

Including DAMA/LIBRA/phase2

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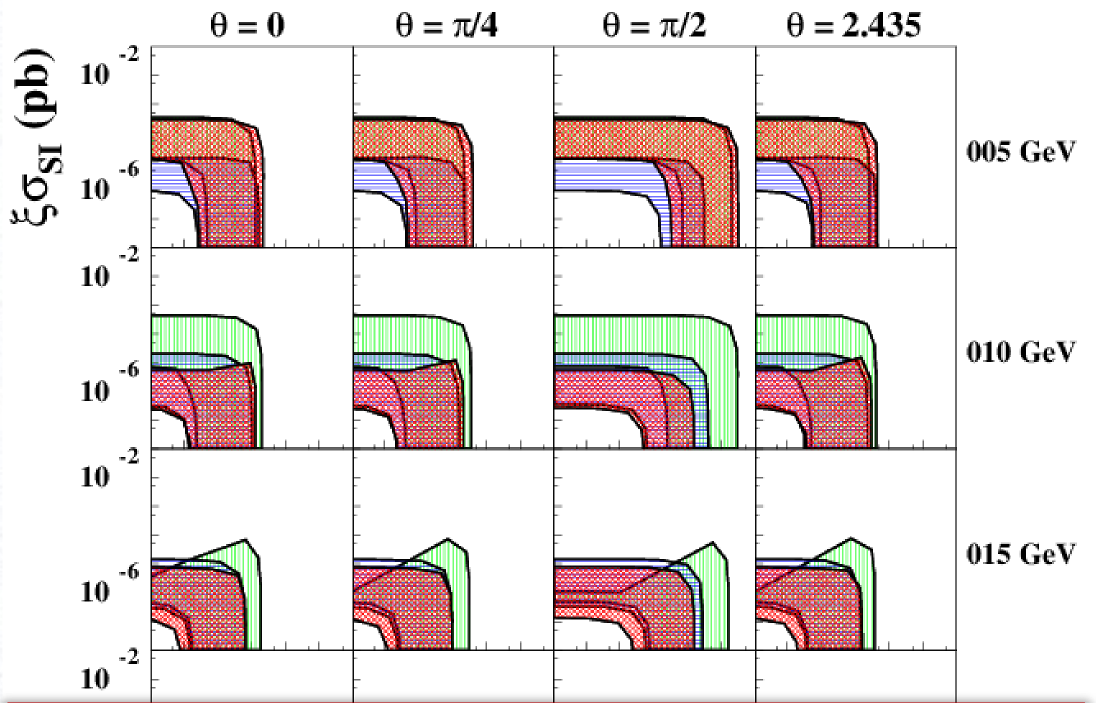
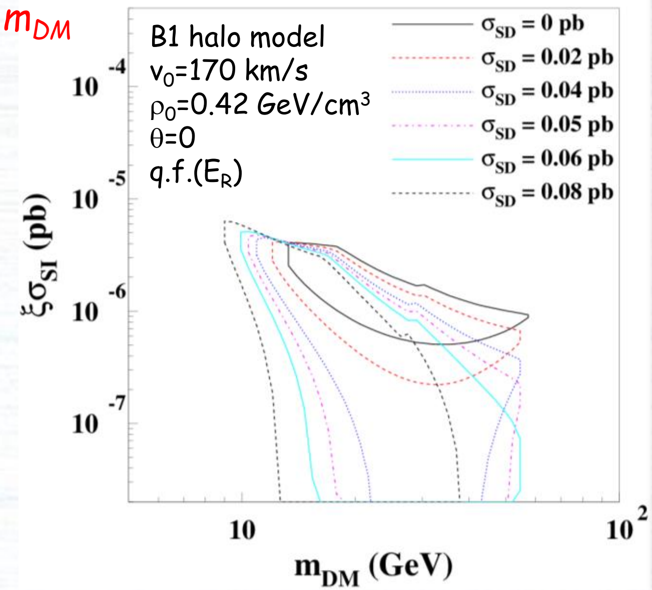


Effect induced by the inclusion of a SD component on allowed regions in the plane $\xi\sigma_{SI}$ vs m_{DM}



- 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

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

Including DAMA/LIBRA/phase2

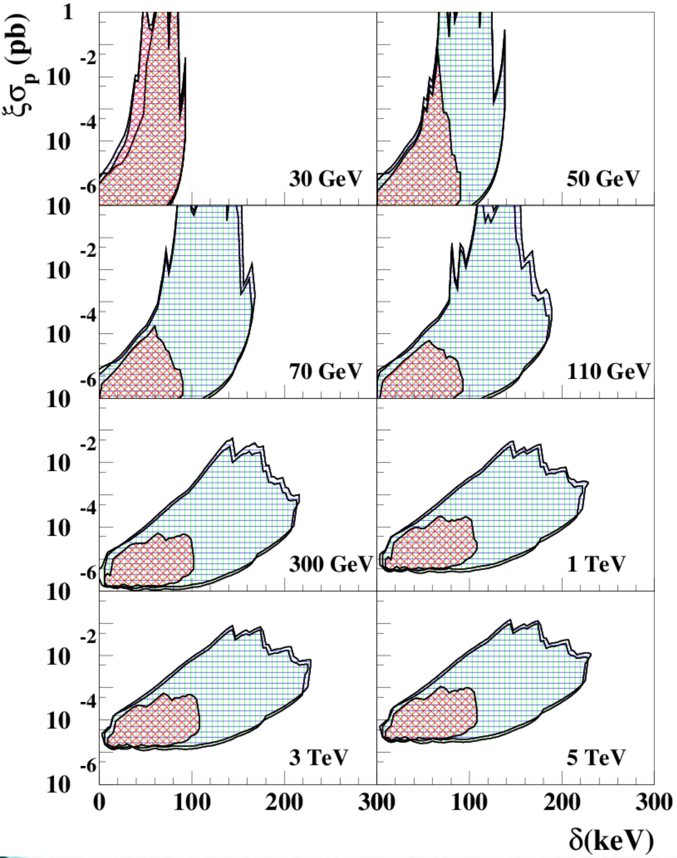
W + N → W* + N

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

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

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

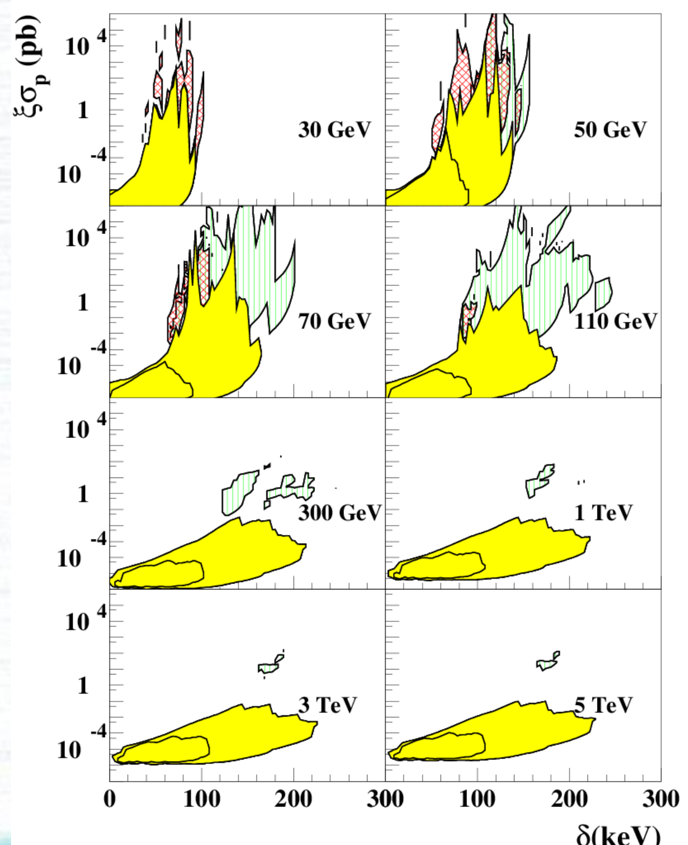
- Higher mass target-nuclei are favourites
- Enhanced S_m with respect to S_0



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

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

Including Thallium: new allowed regions



Model-dependent analyses

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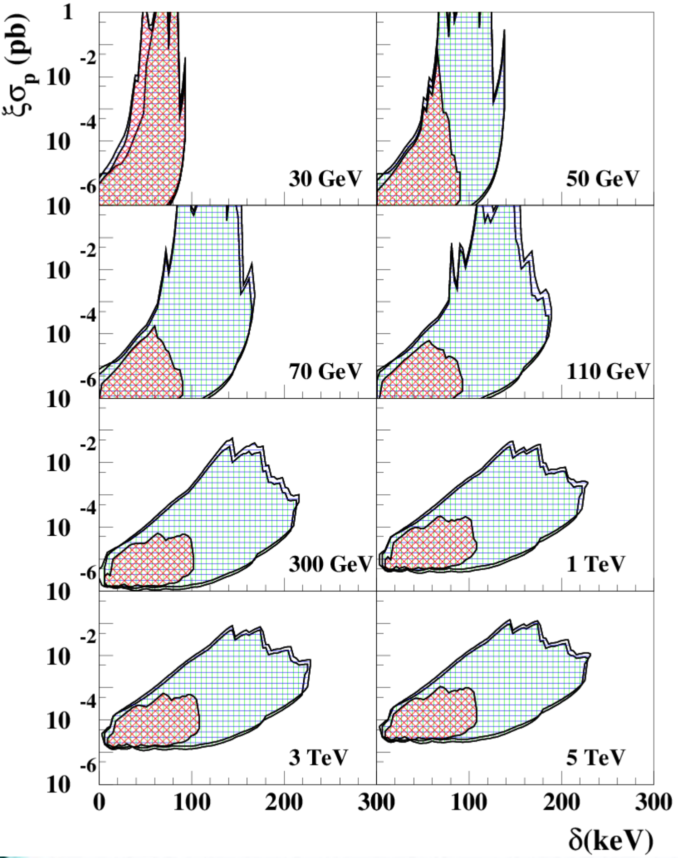

Slices of the 3-dim allowed volume ($\xi\sigma_p$, m_{DM}, δ)

1. Constants q.f.
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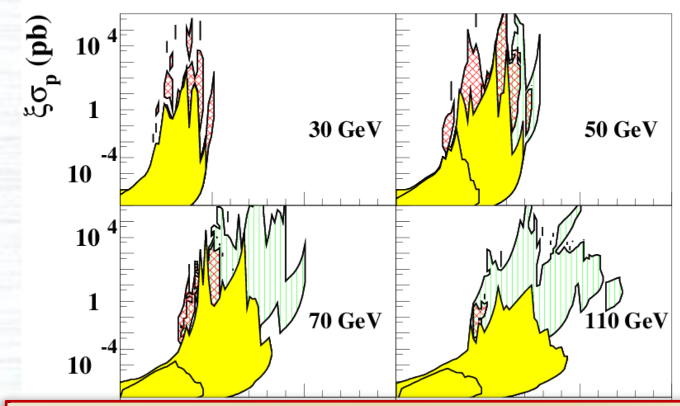
Including Thallium: new allowed regions

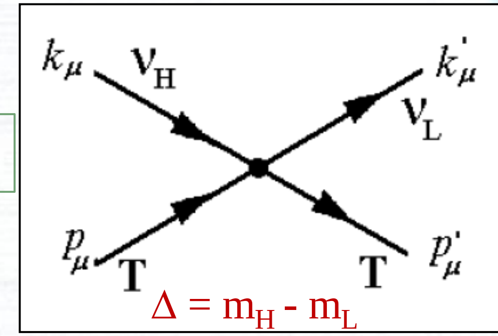


- New regions with $\xi\sigma_p > 1$ pb and $\delta > 100$ keV are allowed by DAMA after the inclusion of the inelastic scattering off Thallium nuclei.
- Such regions are not fully accessible to detectors with target nuclei having mass lower than Thallium.

Model-dependent analyses

Light Dark Matter

Including DAMA/LIBRA/phase2



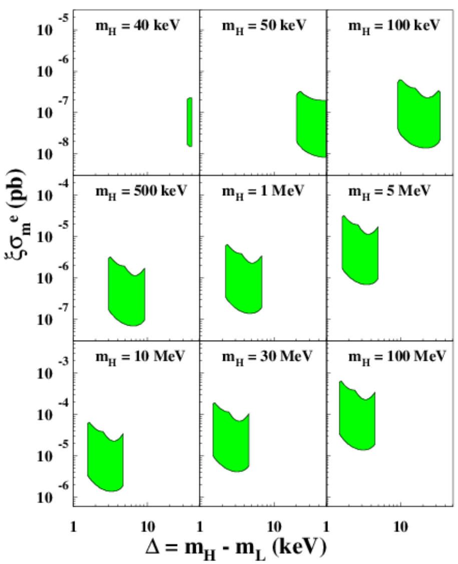
Elastic scattering of LDM (sub-GeV mass) particles both off electrons and off nuclei yields energy releases hardly detectable by the detectors

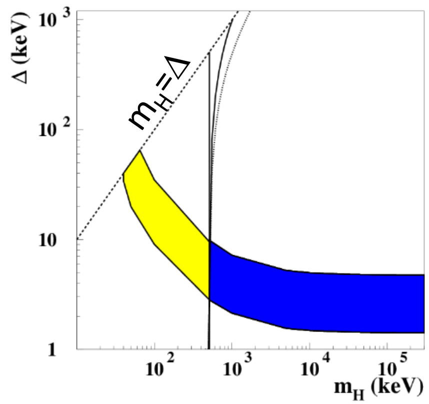
Investigation on the direct detection of LDM candidate particles by considering inelastic scattering channels on the electron or on the nucleus

ν_L is neutral, weakly interacting and can escape the detector

Electron interacting LDM

Examples of slices of the 3-dim allowed volume (m_H, $\xi\sigma_m^e$, Δ) and their projection on the plane (m_H, Δ)





$m_H > m_e$ (blue) interesting for the annihilation processes

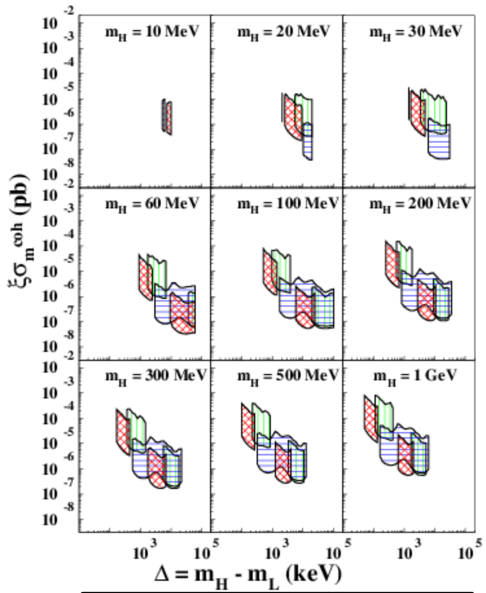
$\nu_H\bar{\nu}_H \to e^+e^-$, $\nu_H\bar{\nu}_L \to e^+e^-$, $\nu_L\bar{\nu}_H \to e^+e^-$, $\nu_L\bar{\nu}_L \to e^+e^-$

in the galactic centre

Electron interacting LDM in the few-tens-keV/sub-MeV range allowed by DAMA can be of interest, e.g., in the models of WDM particles (e.g. weakly sterile neutrino)

Nucleus interacting LDM

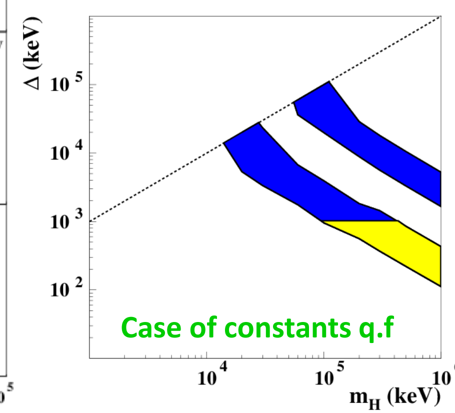
Example of slices (coherent case) of the 3-dim allowed volume (m_H, $\xi\sigma_m^{nucleus}$, Δ) and their projection on the plane (m_H, Δ)



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

Two volumes from inter. on:

- I (larger Δ at m_H fixed)
- Na (smaller Δ at m_H fixed)



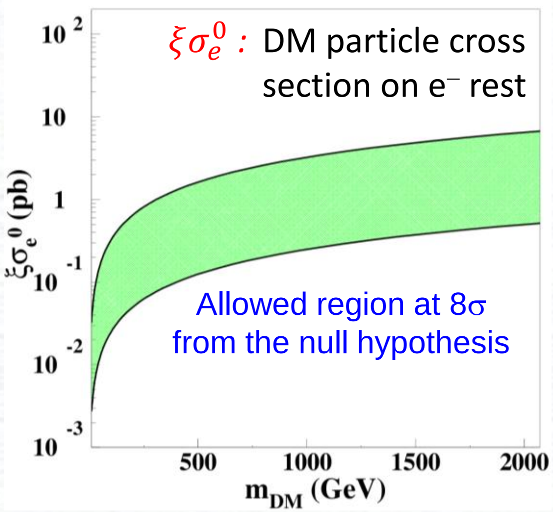
If $\Delta > 2m_e$ (blue): $\nu_H \to \nu_L e^+ e^-$ allowed

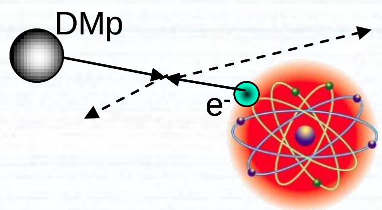
Other model-dependent analyses

Including DAMA/LIBRA/phase2

DM particles with preferred electron interaction

They offer a possible source of the 511 keV photons observed from the galactic bulge





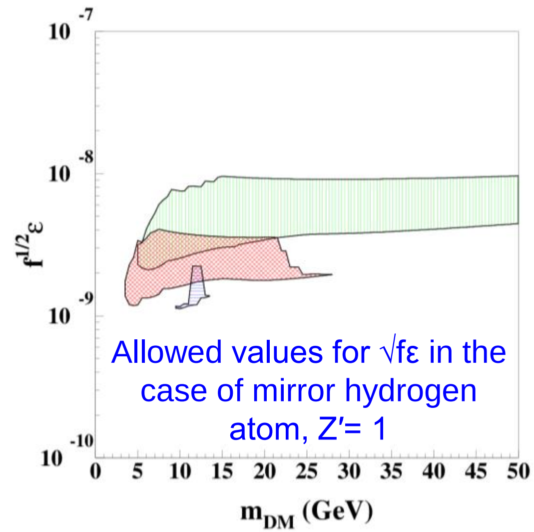
DM candidate particles with mass ≈ few GeV can interact on bound electrons with p ≈ few MeV/c and provide signals in the keV region

Mirror Dark Matter

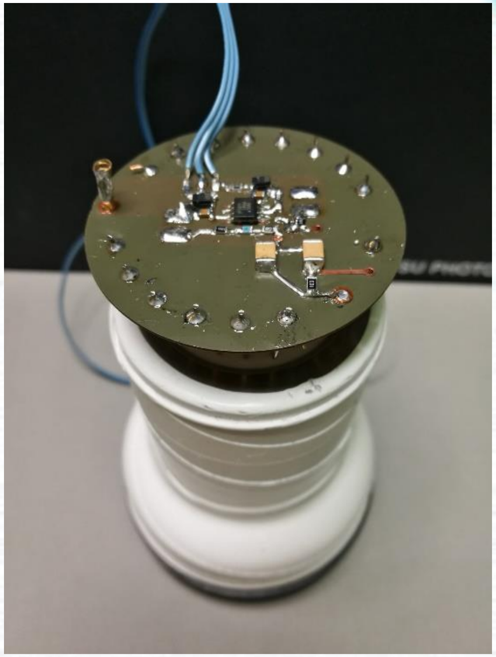
Asymmetric mirror matter: mirror parity spontaneously broken ⇒ mirror sector becomes a heavier and deformed copy of ordinary sector

- Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$
- mirror atom scattering of the ordinary target nuclei in the NaI(Tl) detectors of DAMA/LIBRA set-up with the Rutherford-like cross sections.

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

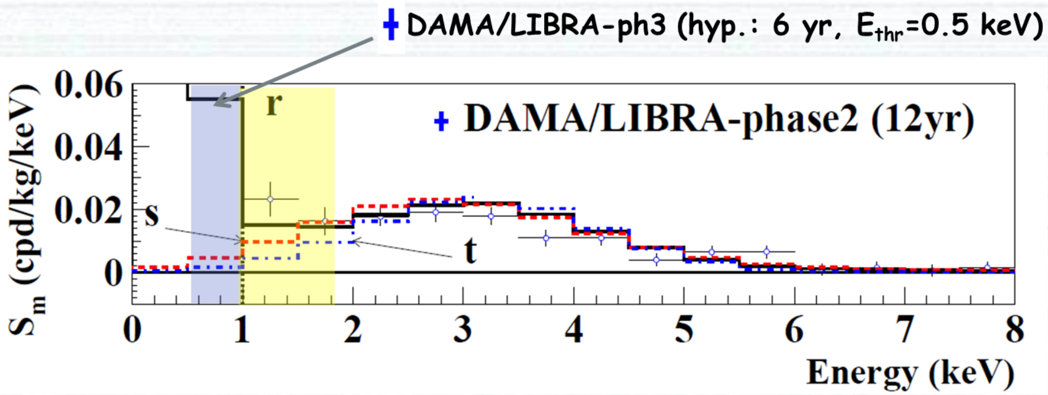


Toward DAMA/LIBRA-phase3



updating hardware to lower 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).

several prototypes from a dedicated R&D with HAMAMATSU at hand

Features of the DM signal investigated by DAMA at various levels; improvements foreseen with DAMA/LIBRA-phase3

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

High exposure and low energy threshold can allow investigation on:

- the nature of the DM candidates

- ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, form factors, spin-factors …)
- ✓ scaling laws and cross sections
- ✓ multi-component DM particles halo?

- possible diurnal effects on the sidereal time

- ✓ expected in case of high cross section DM candidates (shadow of the Earth)
- ✓ due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates)
- ✓ due to the channeling in case of DM candidates inducing nuclear recoils.

- astrophysical models

- ✓ velocity and position distribution of DM particles in the galactic halo, possibly due to:
  - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";
  - caustics in the halo;
  - gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");
  - possible structures as clumpiness with small scale size
  - Effects of gravitational focusing of the Sun

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**

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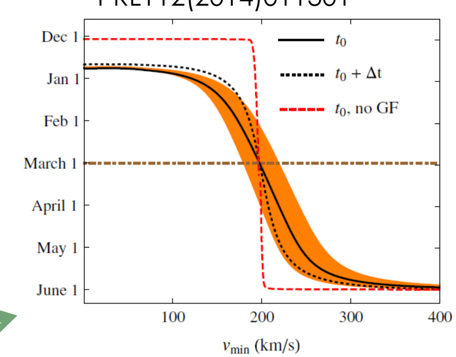
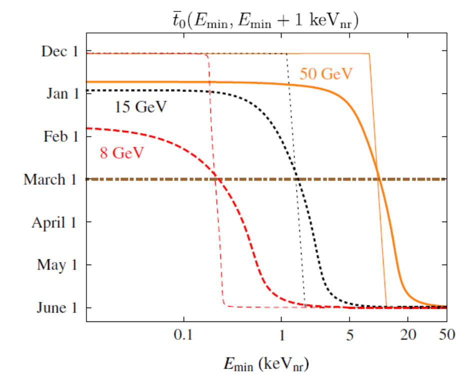
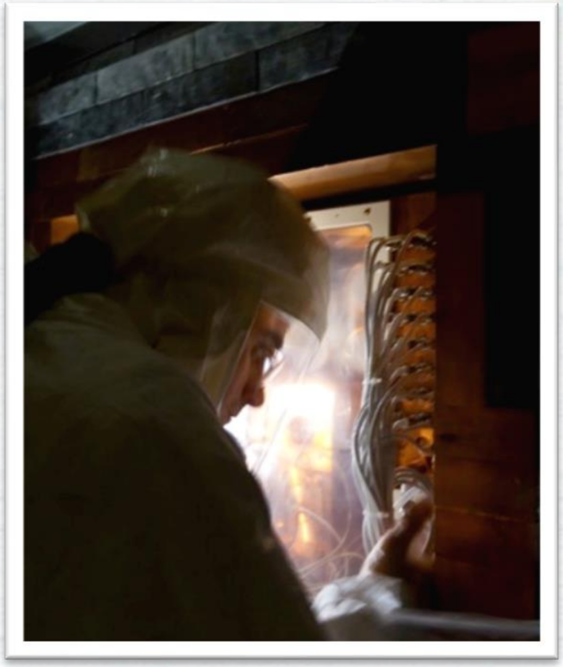
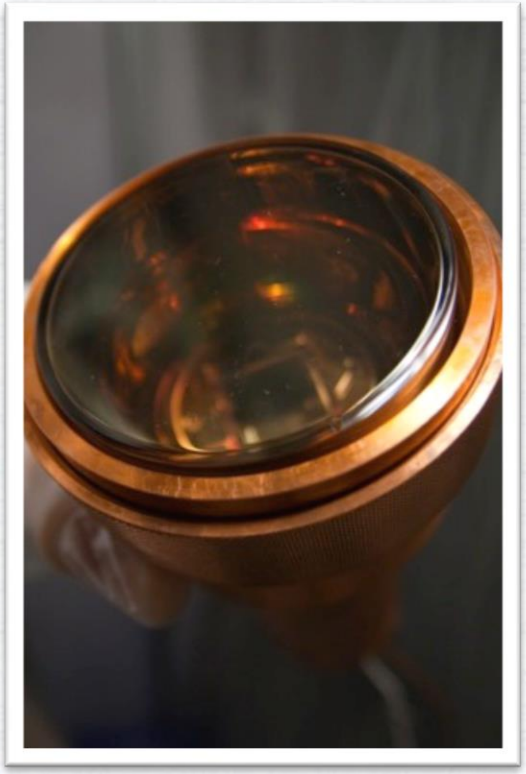




Conclusions



- Model-independent evidence for a signal that satisfies all the requirement of the DM annual modulation signature at **12.9σ** C.L. (20 independent annual cycles with 3 different set-ups: 2.46 ton $\times$ 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**
- Model dependent analyses on new data allowed significantly improving the C.L. and restricting the allowed parameters' space for the various scenarios with respect to previous DAMA analysis
- DAMA/LIBRA–phase2 **continuing data taking**
- DAMA/LIBRA–phase3 **R&D in progress**
- Continuing investigations of **rare processes** other than DM