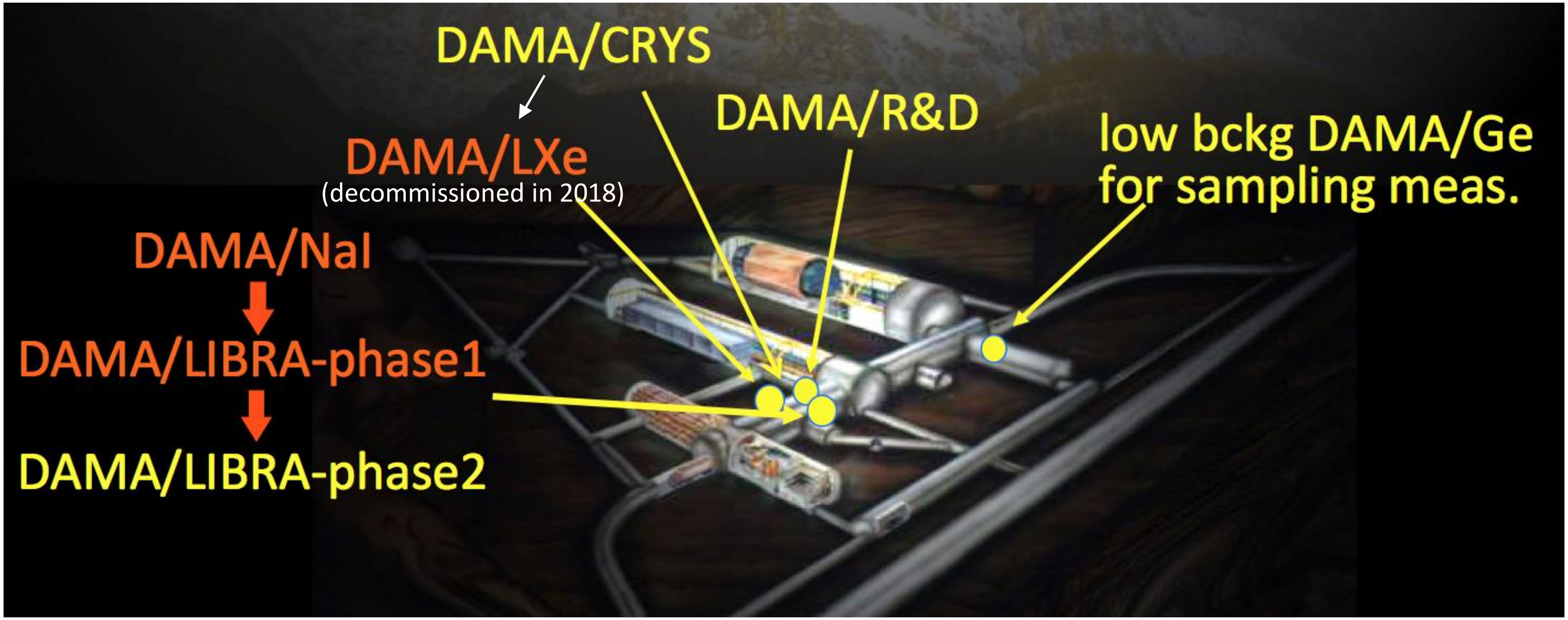
DAMA/LIBRA–phase2 Results and Implications on Several Dark Matter Scenarios

8th **I**nternational **C**onference on **N**ew **F**rontiers in **P**hysics
August 21-30, 2019, Crete

Vincenzo Caracciolo (University of Roma “Tor Vergata” and INFN)
on behalf of DAMA collaboration

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

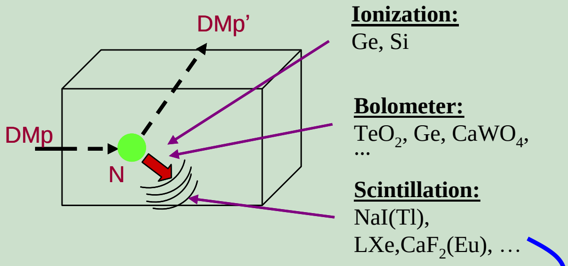
+ in some studies on ββ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

See Belli's talk (Aug, 29th): "Direct Detection of Dark Matter Particles"

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

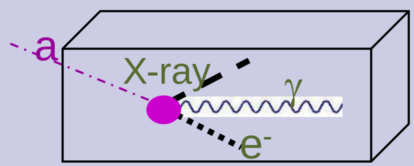
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

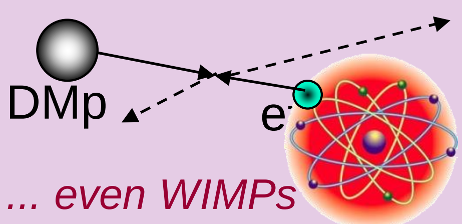
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

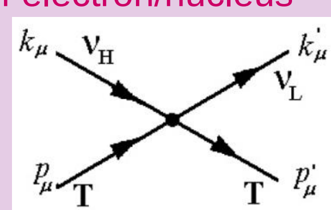


… even WIMPs

- 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

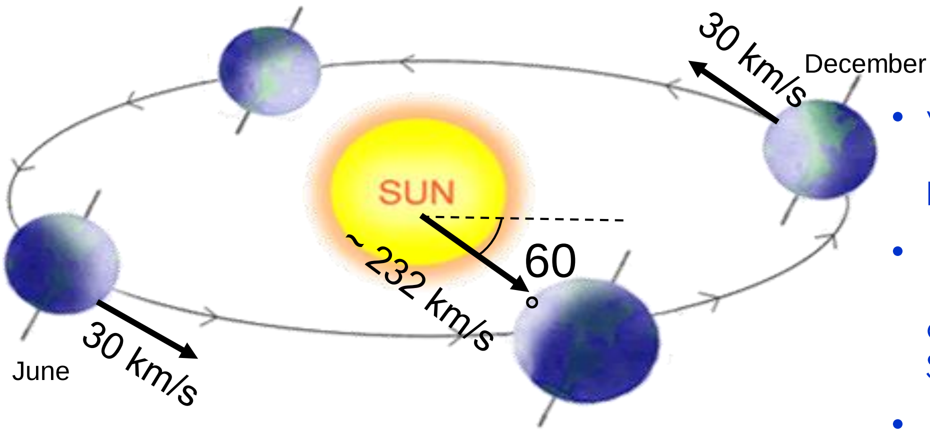
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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 June 2)
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)

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

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

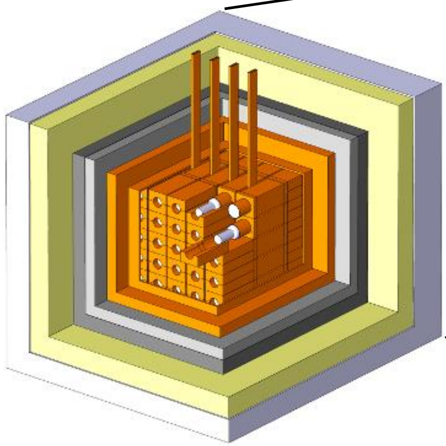
the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

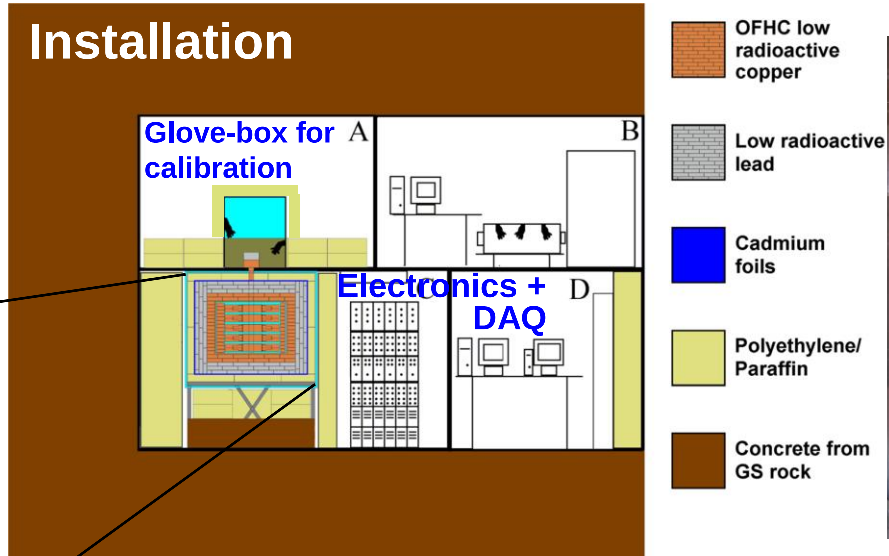
To mimic this signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

The DAMA/LIBRA–phase2 set-up

NIMA592(2008)297, JINST 7(2012)03009, IJMPA31(2017)issue31

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two new high Q.E. PMTs for each crystal working in coincidence at the single ph. el. threshold
- **6-10 phe/keV; 1 keV software energy threshold**





- Multiton-multicomponent passive shield (>10 cm OFHC Cu, 15 cm boliden Pb + Cd foils, 10/40 cm polyethylene/paraffin, ~1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as prod runs
- Never neutron source in DAMA installations
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data

- Whole setup decoupled from ground
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- Dismounting/Installing protocol in HP N_2
- All the materials selected for low radioactivity
- Pulse shape recorded by Waweform Analyzer Acqiris DC270 (2chs per detector), 1 *Gs/s,* 8 bit, bandwidth 250 MHz both for single-hit and multiple-hit events
- Data collected from low energy up to MeV region, despite the hardware optimization for low energy
- DAQ with optical readout
- New electronic modules

DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled W. in Phys.19 (2018) 27
arXiv:1907.06405

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

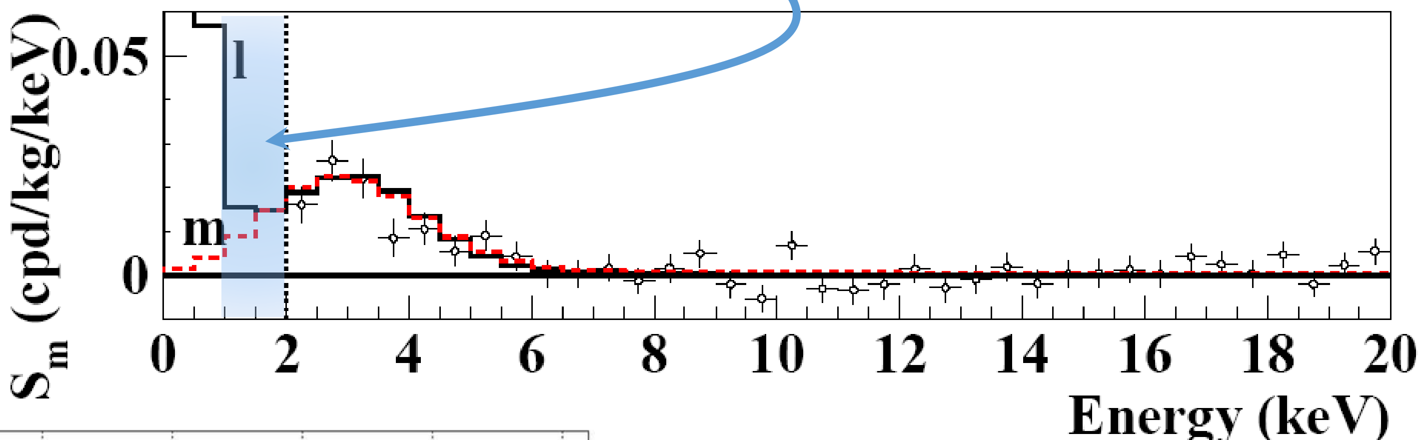
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak

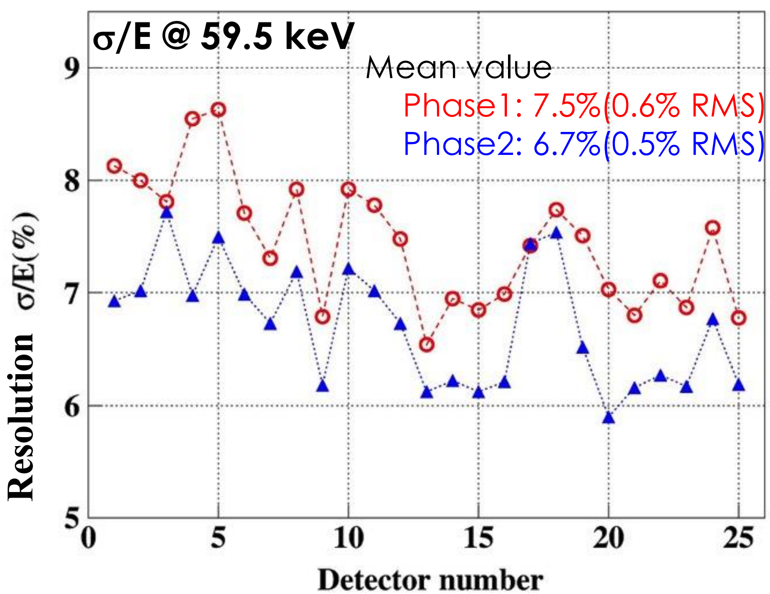
DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 207
Bled W. in Phys.19 (2018) 27
arXiv:1907.06405

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

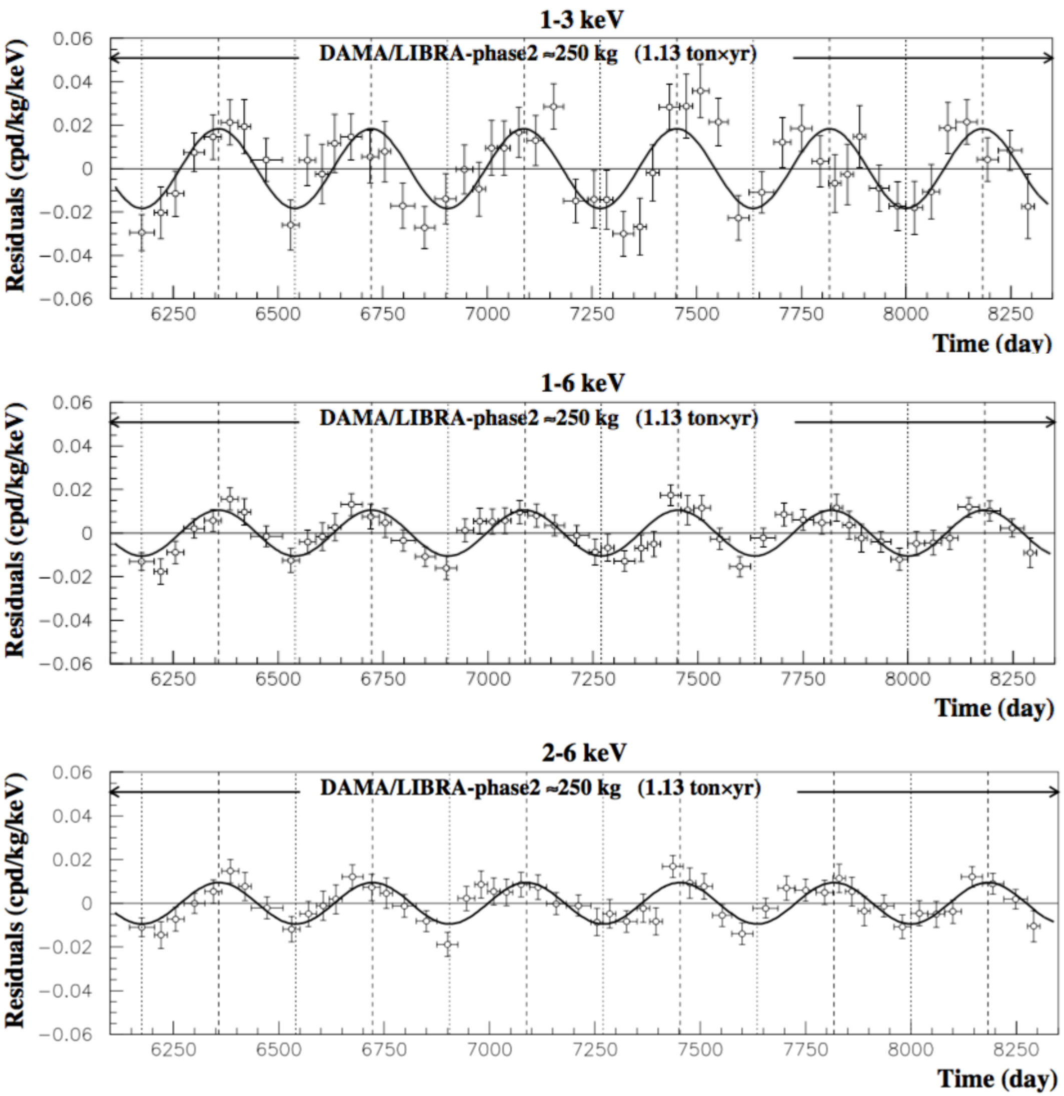
Annual Cycles	Period	Mass (kg)	Exposure (kg×day)	$(\alpha-\beta^2)$
I	Dec 23, 2010 – Sept. 9, 2011	commissioning		
II	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 – Sept. 9, 2015	242.5	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 × yr**
Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.46 ton × yr**

DM model-independent Annual Modulation Result

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

DAMA/LIBRA-phase2 (1.13 ton×yr)



Absence of modulation? No

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

Fit on DAMA/LIBRA-phase2

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

1-3 keV

A=(0.0184±0.0023) cpd/kg/keV

χ^2/dof = 61.3/51 **8.0 σ C.L.**

1-6 keV

A=(0.0105±0.0011) cpd/kg/keV

χ^2/dof = 50.0/51 **9.5 σ C.L.**

2-6 keV

A=(0.0095±0.0011) cpd/kg/keV

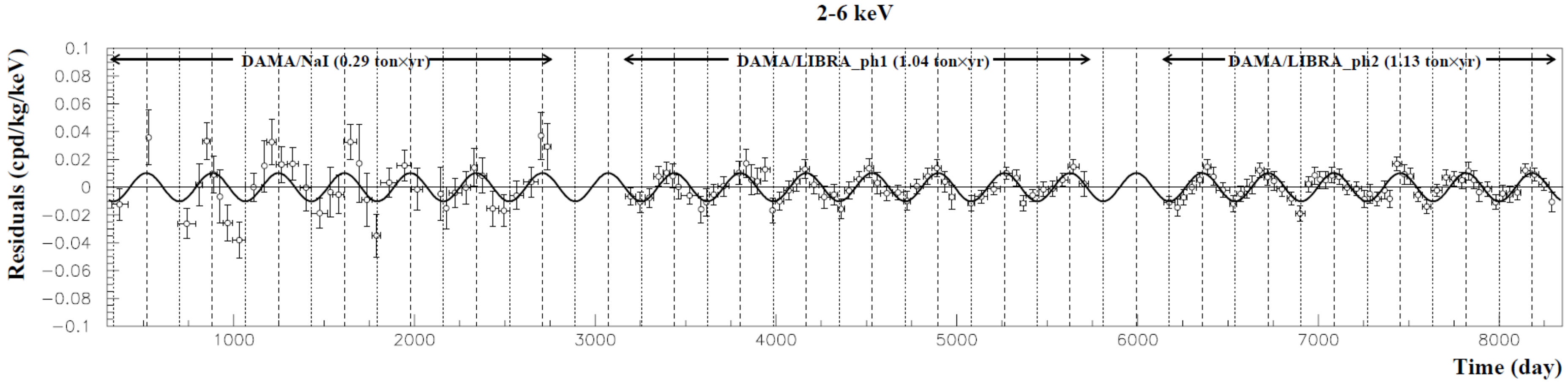
χ^2/dof = 42.5/51 **8.6 σ C.L.**

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

DM model-independent Annual Modulation Result

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

DAMA/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)

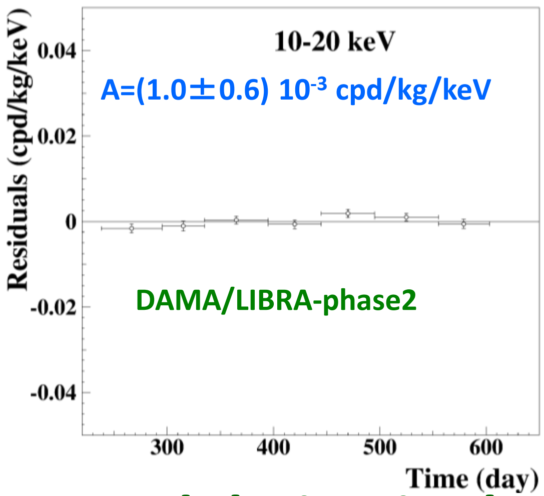
DAMA/LIBRA-ph1 (1.04 ton x yr)

DAMA/LIBRA-ph2 (1.13 ton x yr)

total exposure = 2.46 ton×yr

Rate behaviour above 6 keV

• No Modulation above 6 keV

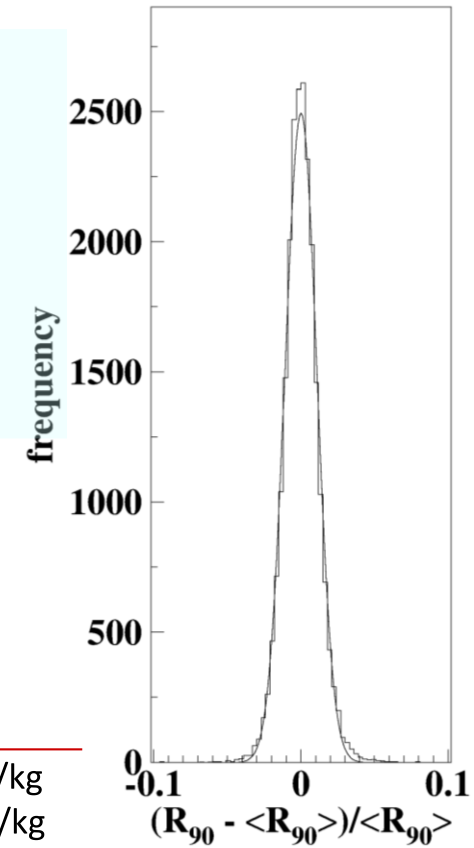


Mod. Ampl. (6-14 keV): cpd/kg/keV

- (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**

+ 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

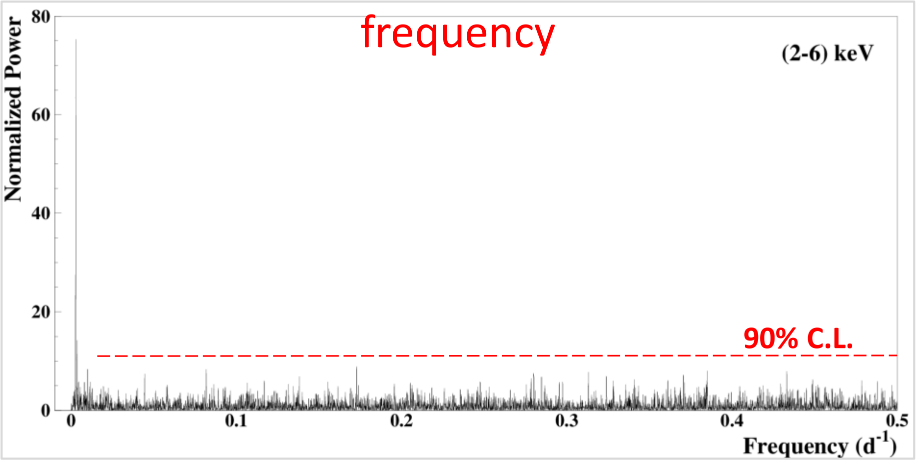
No modulation above 6 keV
This accounts for all sources of background and is consistent with the studies on the various components

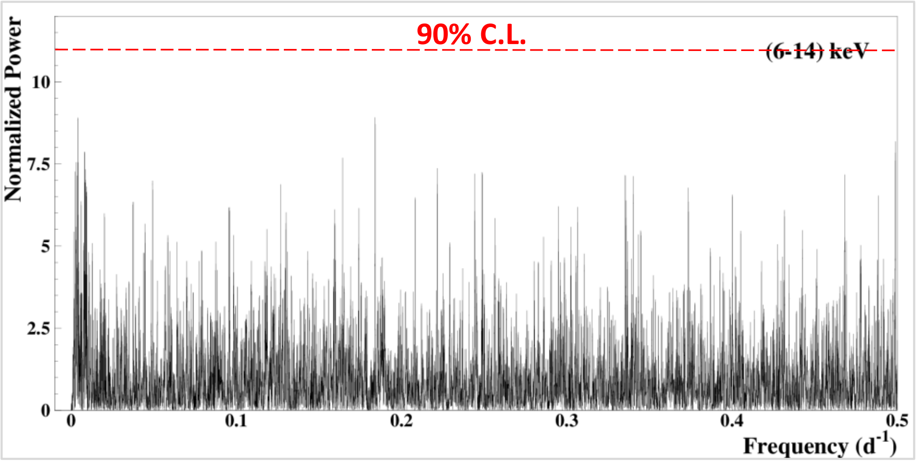
The analysis in frequency

(according to PRD75 (2007) 013010)

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

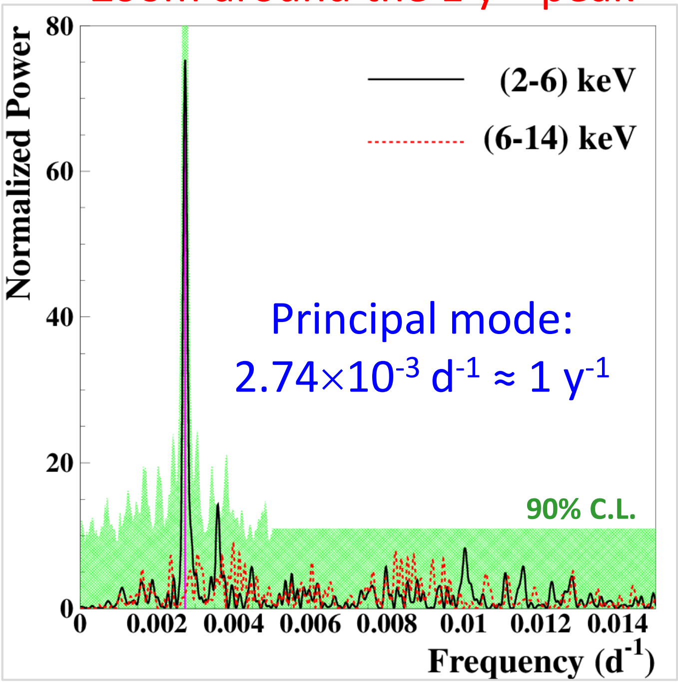
The whole power spectra up to the Nyquist frequency





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

- 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	$\Phi^{(\mu)}_0 \simeq 20\ \mu$ m^{-2}d^{-1} [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}\ \nu$ cm^{-2}s^{-1} [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

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

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

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

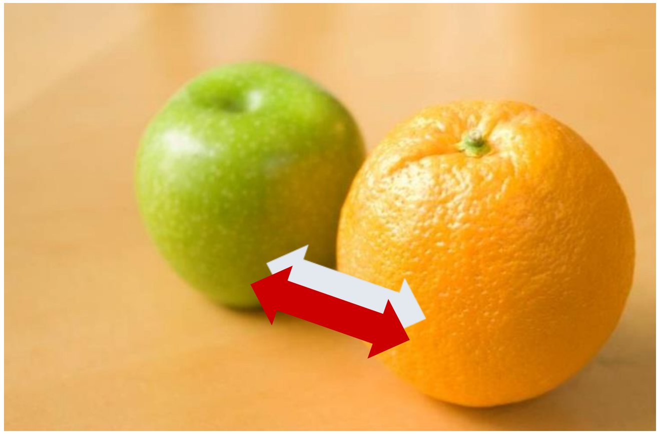
Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA

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

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

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect



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 direct model-independent comparison among experiments with different target-detectors and different approaches.

arXiv:1907.06405

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 $\rho_{\rm dm}$, 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 $\rho_{\rm dm}$, 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 $\rho_{\rm dm}$		
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 $\rho_{\rm dm}$ (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.	$\delta = 16$

arXiv:1907.06405

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

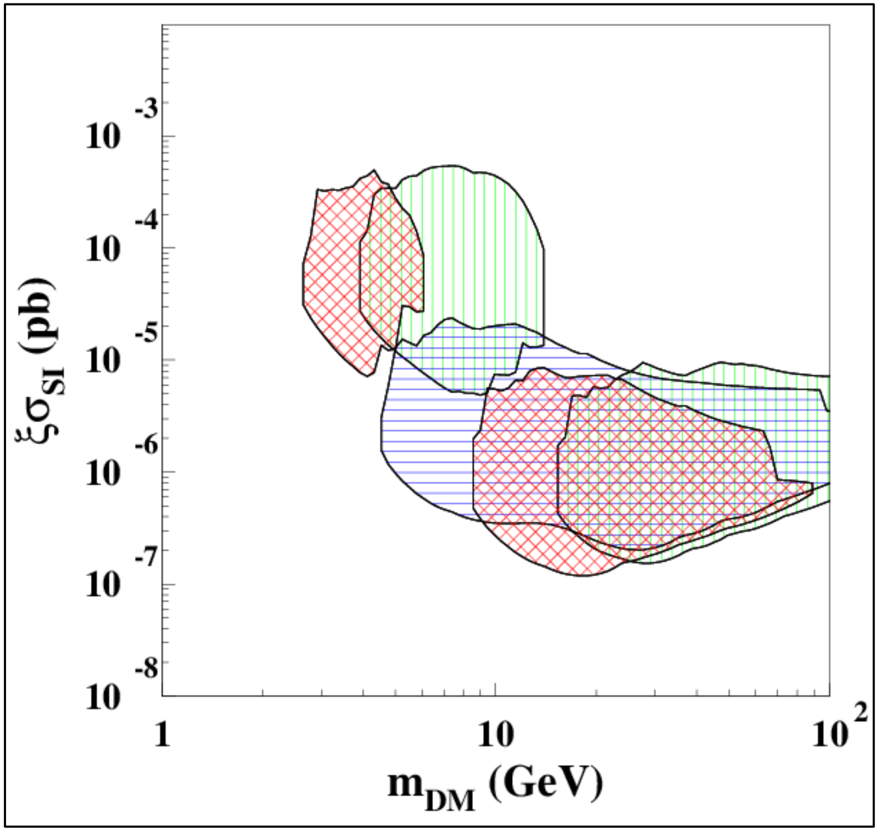
If $f_p=f_n$: $$\sigma_{SI}(A,Z) = \frac{m_{red}^2(A,DM)}{m_{red}^2(1,DM)} A^2 \sigma_{SI}$$

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

arXiv:1907.06405

Model-dependent analyses

DM particles elastically interacting with target nuclei

SI-IV interaction

Including DAMA/LIBRA/phase2

Case of isospin violating SI coupling:

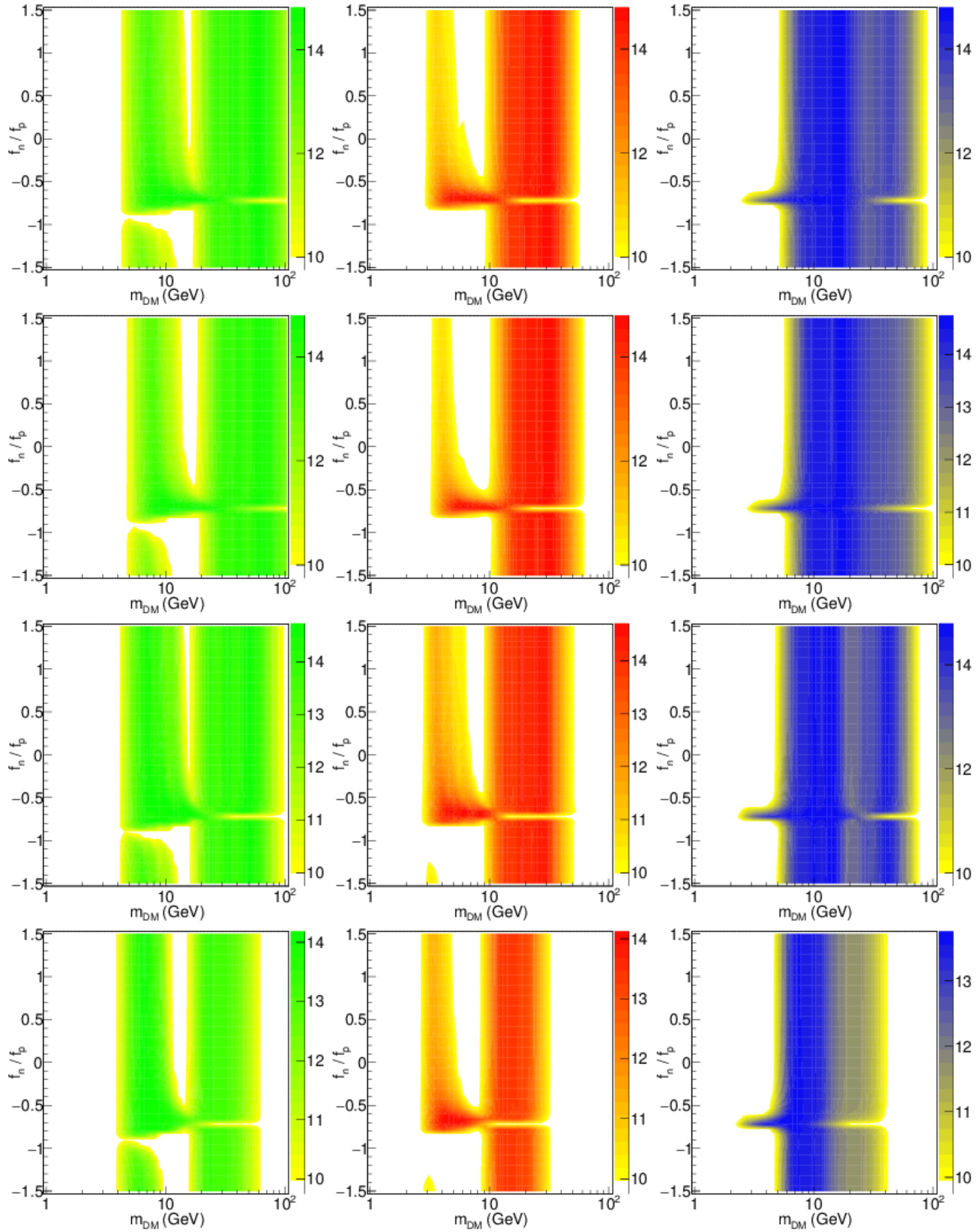
$f_p \neq f_n$

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

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)

arXiv:1907.06405

Model-dependent analyses

DM particles elastically interacting with target nuclei

SI-IV interaction

Including DAMA/LIBRA/phase2

Case of isospin violating SI coupling:

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f_n/f_p vs m_{DM}

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1. Constants q.f.
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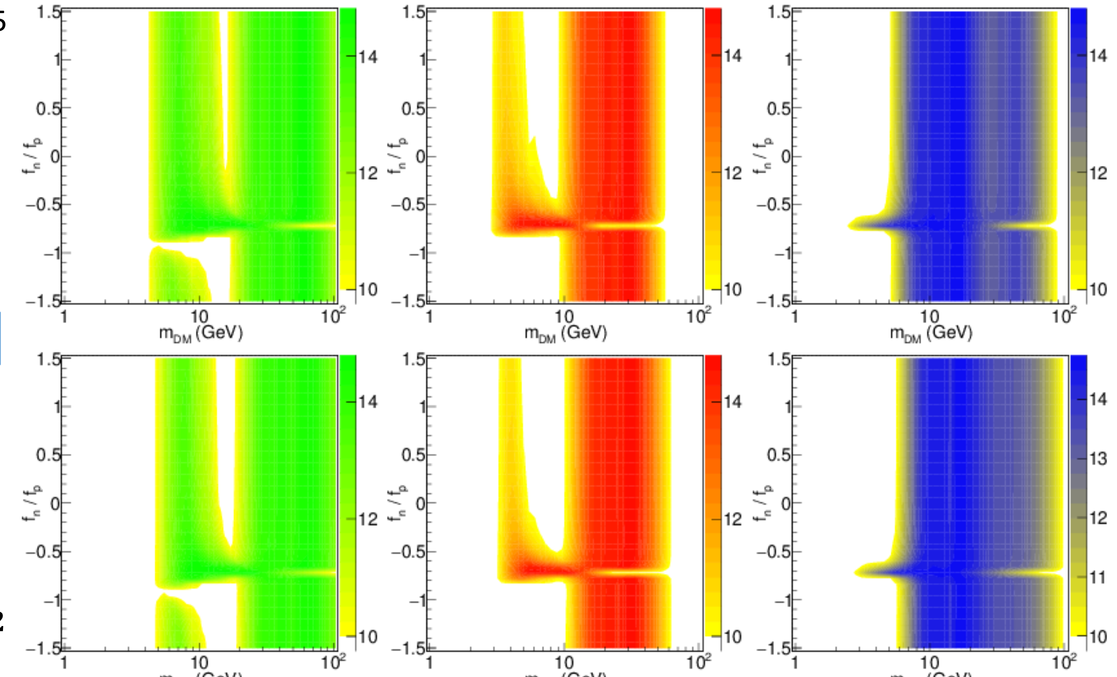
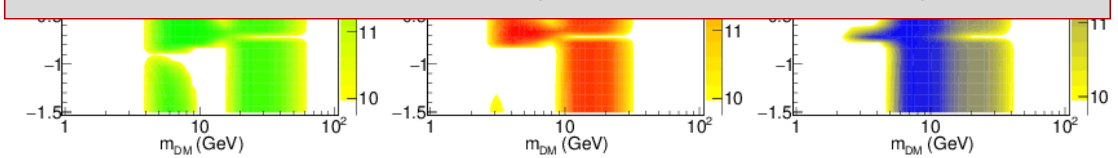
3. With channeling effect



- 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.



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

arXiv:1907.06405

Model-dependent analyses

DM particles elastically interacting with target nuclei – purely SD interaction

Including DAMA/LIBRA/phase2

Possible only for target nuclei with spin≠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, $a_p \neq 0$ or $|a_p| >> |a_n|$;

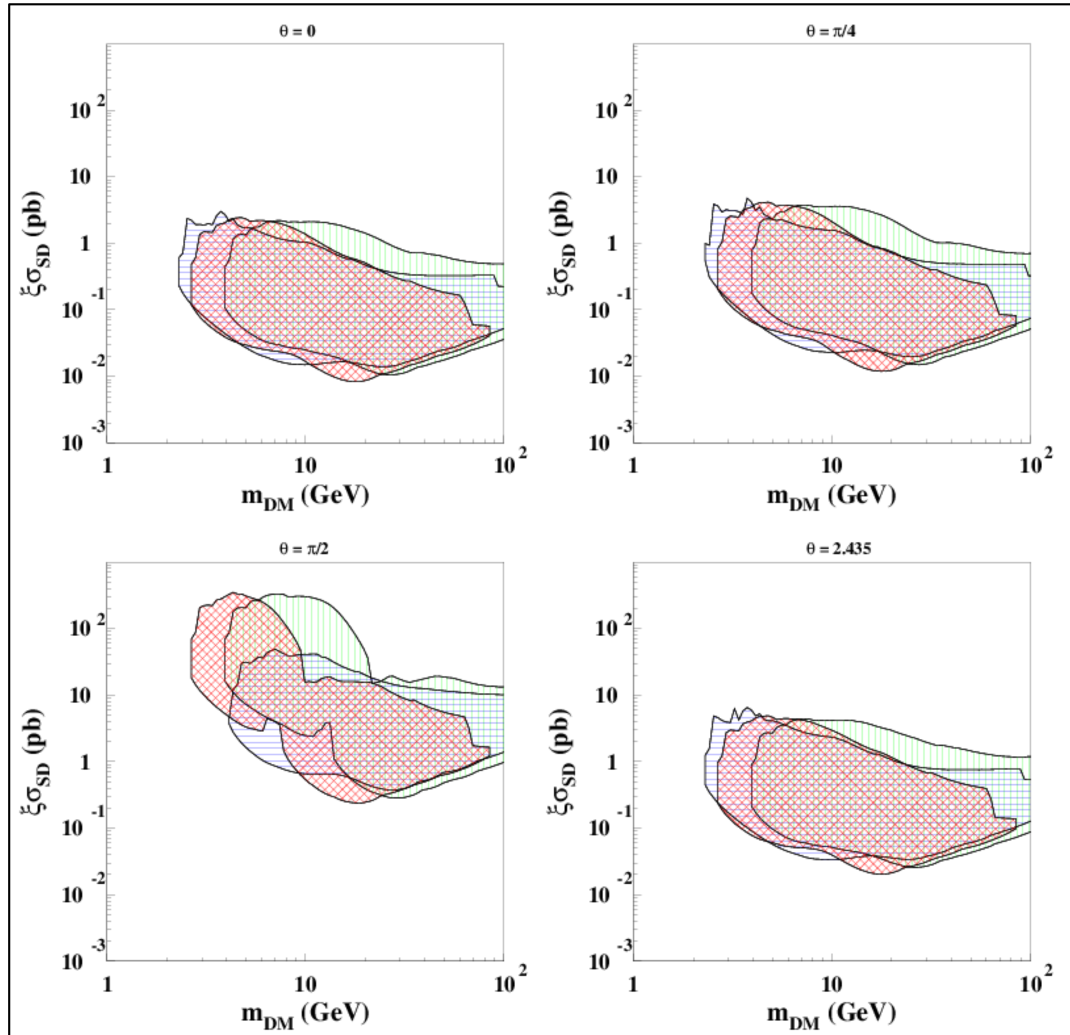
$\theta = \pi/4$ $\Rightarrow$ $a_n = a_p$;

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

θ=2.435rad $\Rightarrow$ 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

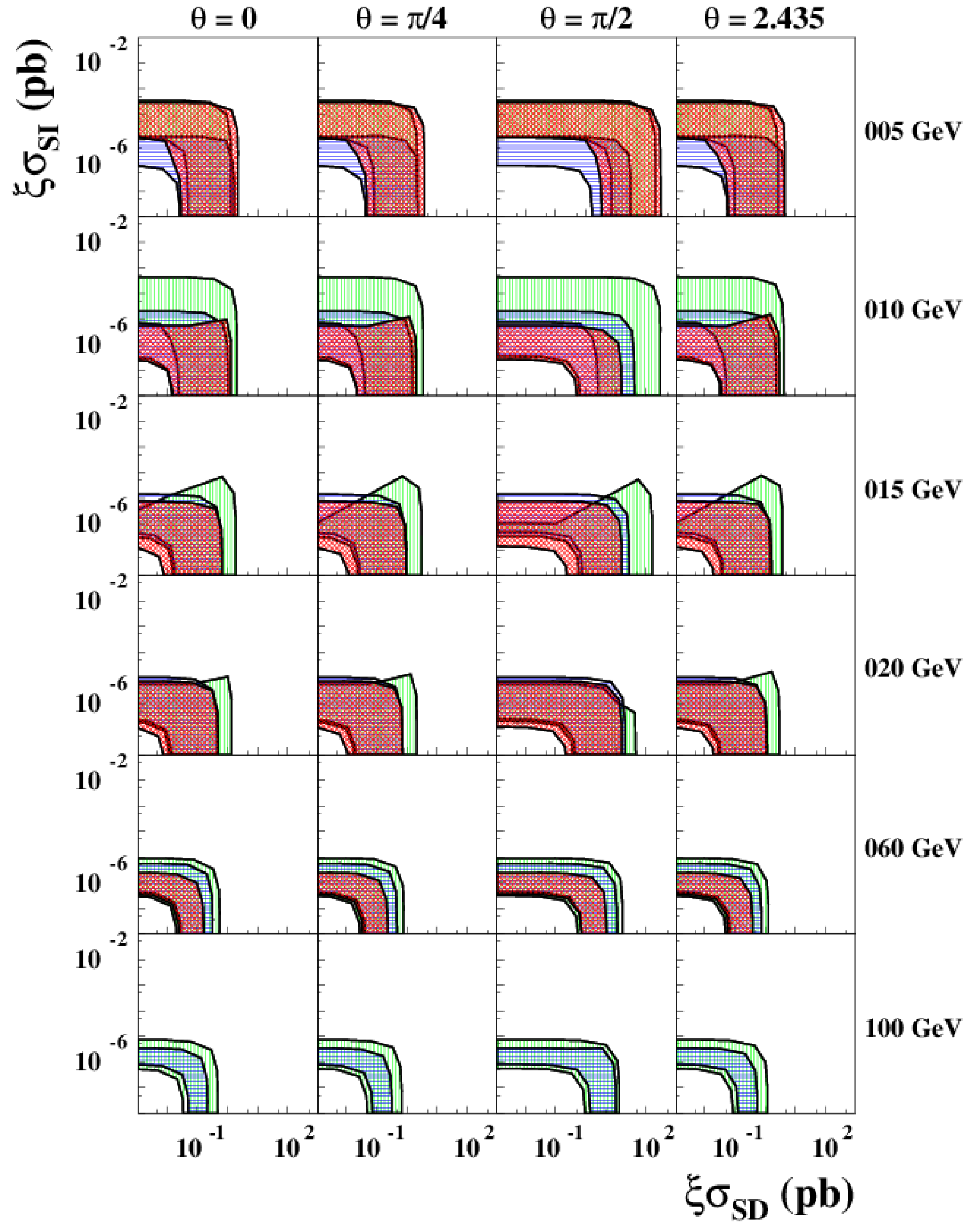
DM particles elastically interacting with target nuclei

Mixed SI-SD interaction

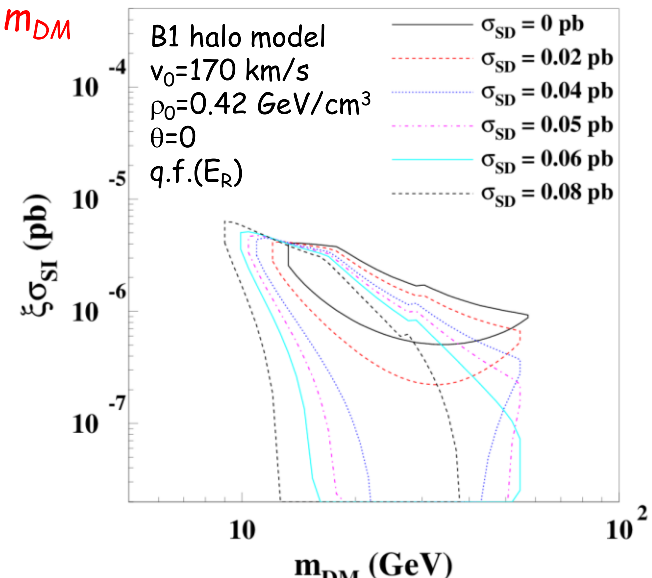
Including DAMA/LIBRA/phase2

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}



arXiv:1907.06405

Model-dependent analyses

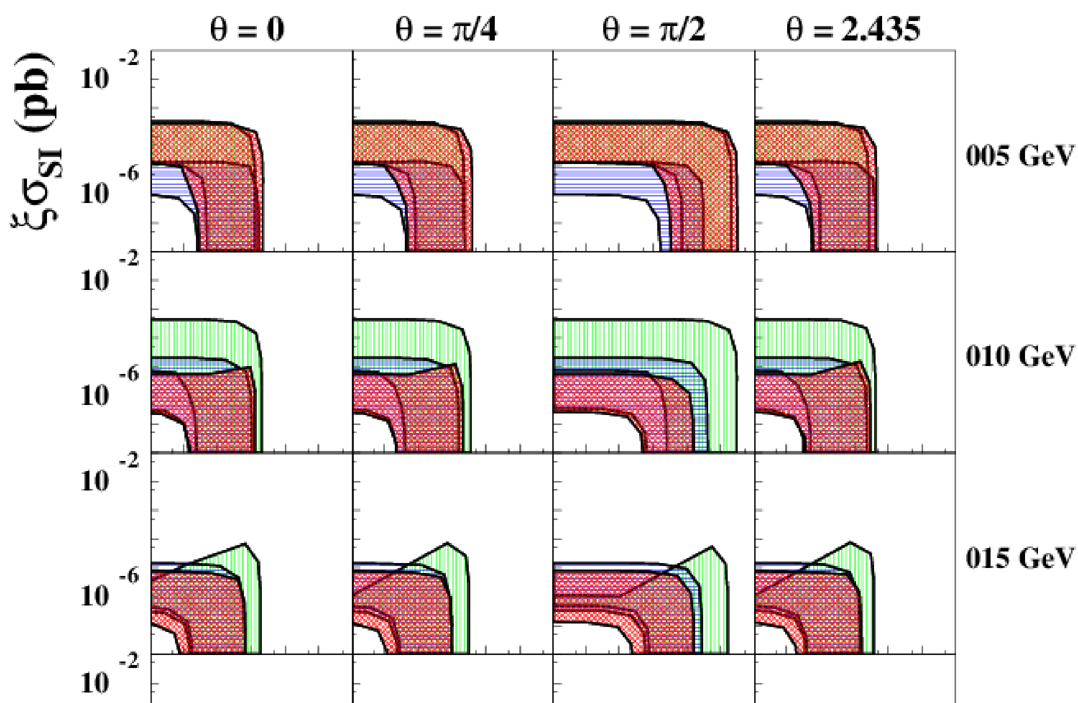
DM particles elastically interacting with target nuclei

Mixed SI-SD interaction

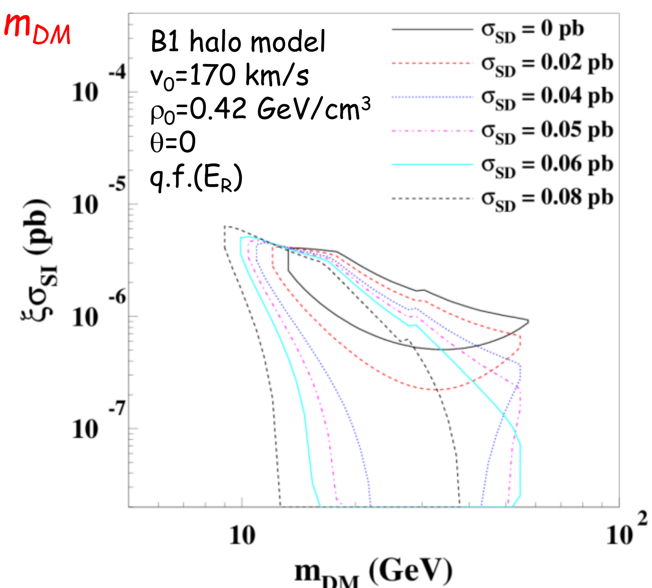
Including DAMA/LIBRA/phase2

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}



- 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 $\theta \approx \pi$

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Model-dependent analyses

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

Including DAMA/LIBRA/phase2

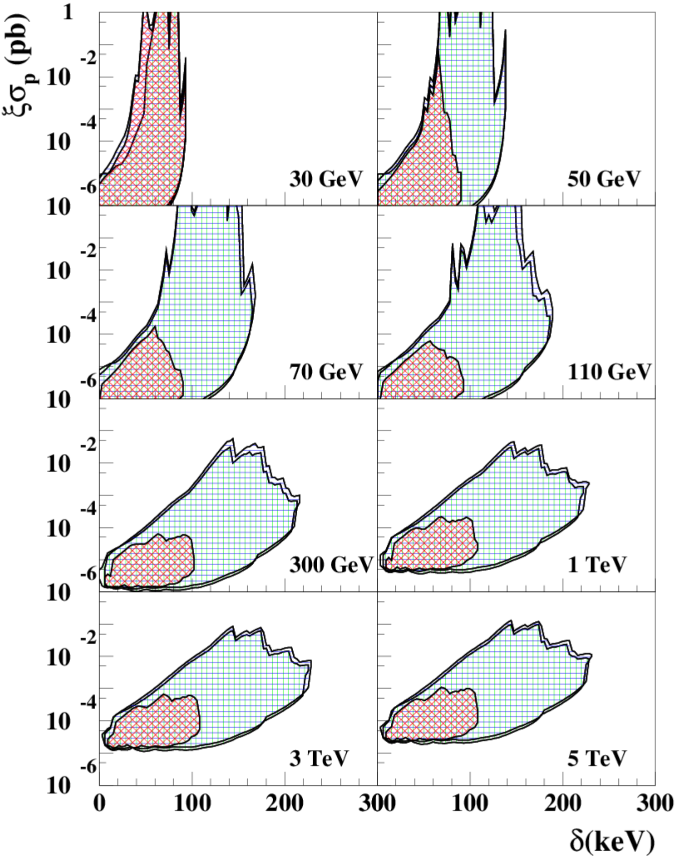
W + N → W* + N

→ 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)

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

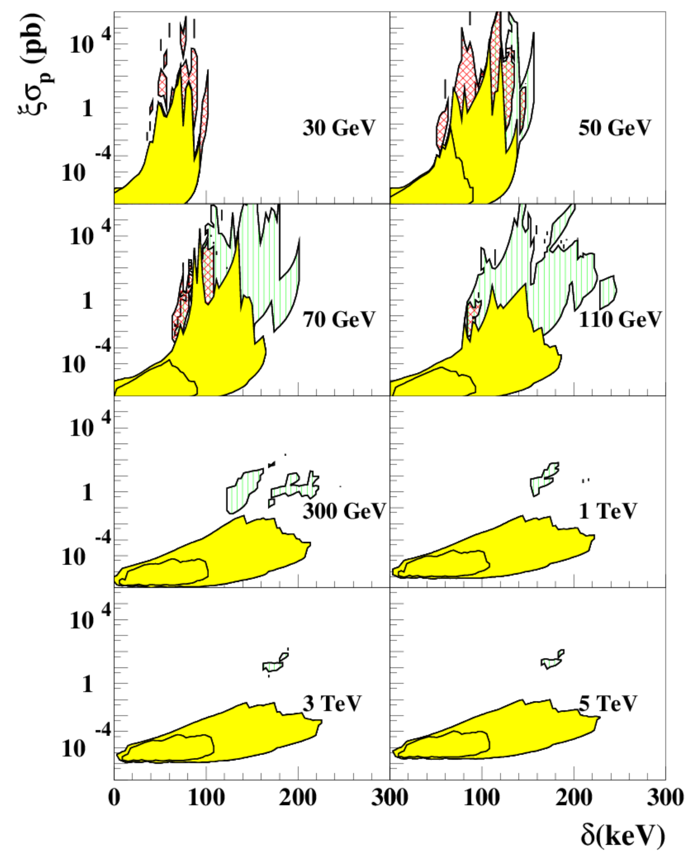
- Higher mass target-nuclei are favourites
- Enhanced S_m with respect to S_0



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



arXiv:1907.06405

Model-dependent analyses

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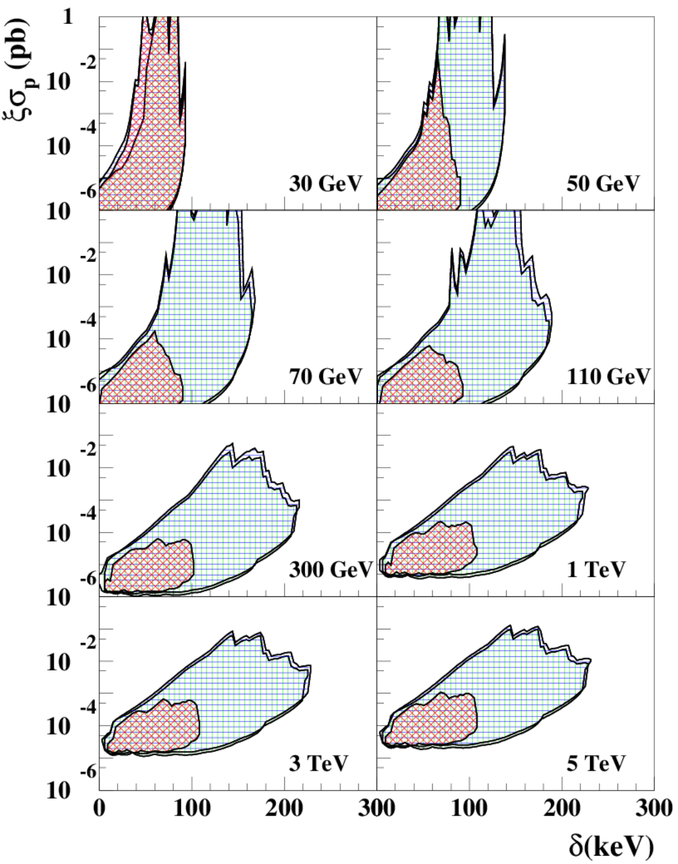

Slices of the 3-dim allowed volume ($\xi\sigma_p$, m_{DM}, δ)

1. Constants q.f.
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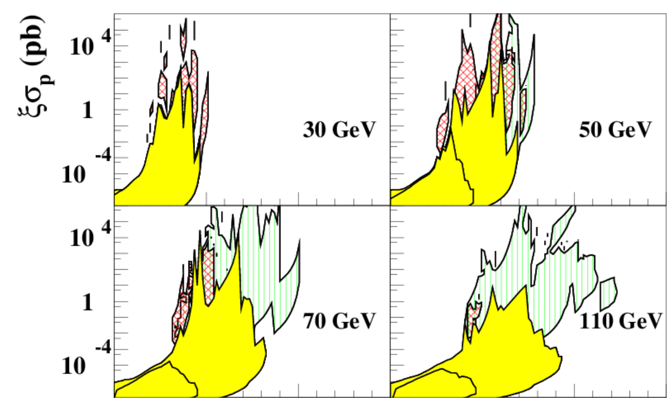


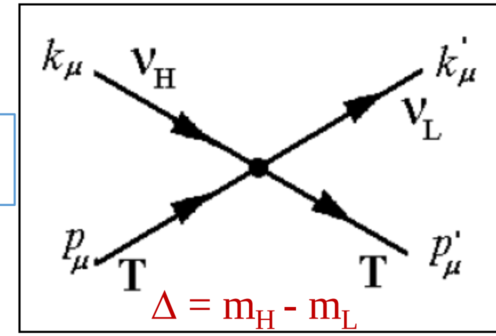
- New regions with $\xi\sigma_p$ > 1 pb and δ > 100 keV are allowed by DAMA after the inclusion of the inelastic scattering off Thallium nuclei.
- Such regions are not fully accessible to detectors with target nuclei having mass lower than Thallium.

arXiv:1907.06405

Model-dependent analyses

Light Dark Matter

Including DAMA/LIBRA/phase2



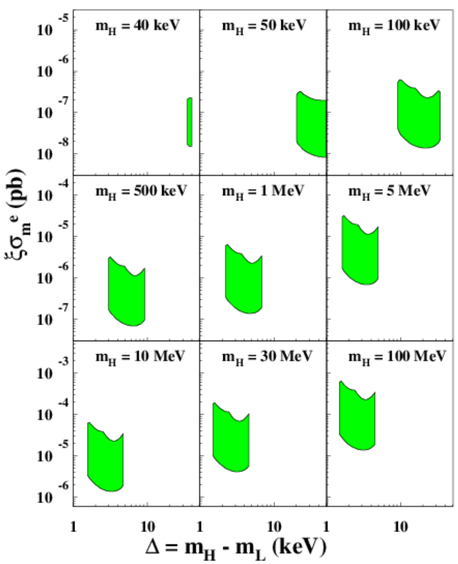
ν_L is neutral, weakly interacting and can escape the detector

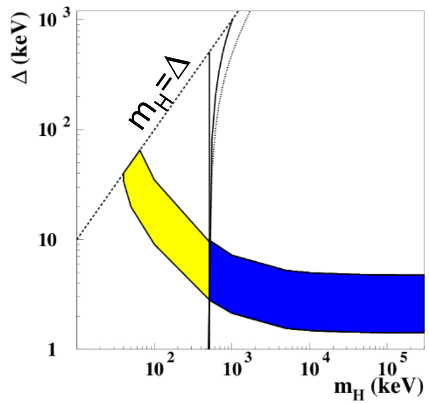
Elastic scattering of LDM (sub-GeV mass) particles both off electrons and off nuclei yields energy releases hardly detectable by the detectors

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

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

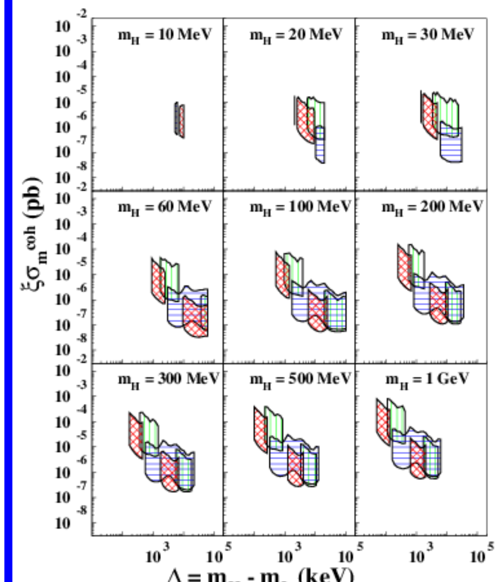
$\nu_H\bar{\nu}_H \to e^+e^-$, $\nu_H\bar{\nu}_L \to e^+e^-$, $\nu_L\bar{\nu}_H \to e^+e^-$, $\nu_L\bar{\nu}_L \to e^+e^-$

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

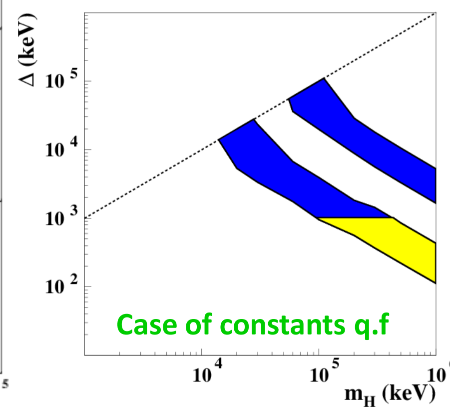
Example of slices (coherent case) of the 3-dim allowed volume (m_H, $\xi\sigma_m^{nucleus}$, Δ) and their projection on the plane (m_H, Δ)



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

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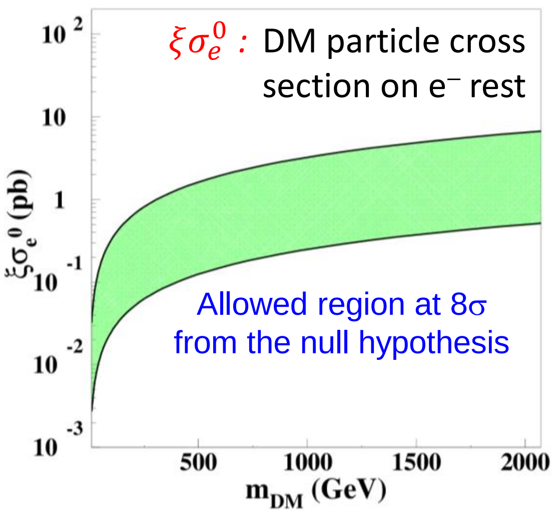
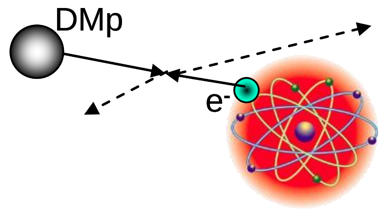
Other model-dependent analyses

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





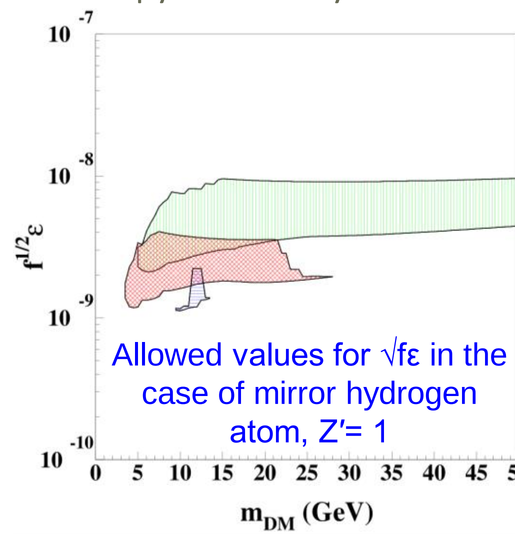
DM candidate particles with mass ≈ few GeV can interact on bound electrons with p ≈ few MeV/c and provide signals in the keV region

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.

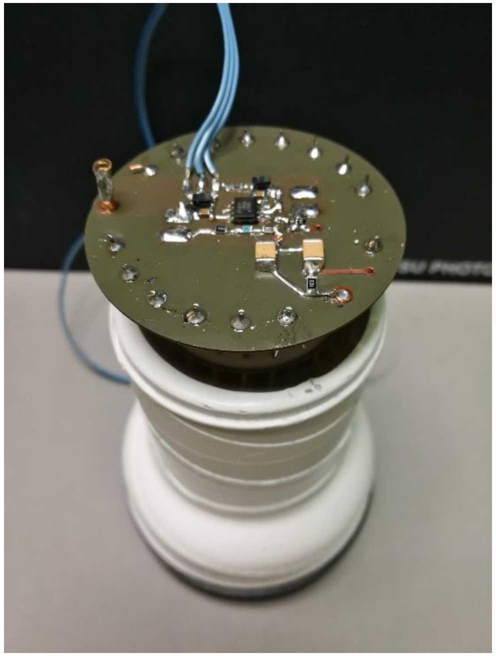
$\sqrt{f}\cdot\epsilon$ coupling const. and fraction of mirror atom

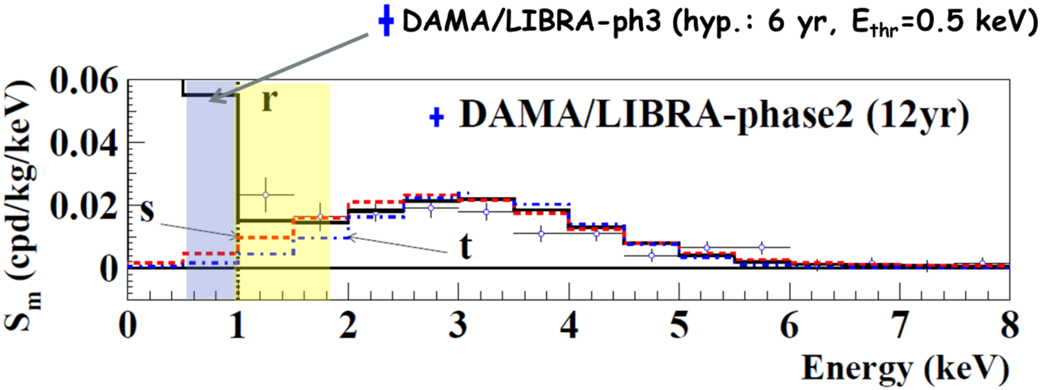


Toward DAMA/LIBRA-phase3

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?

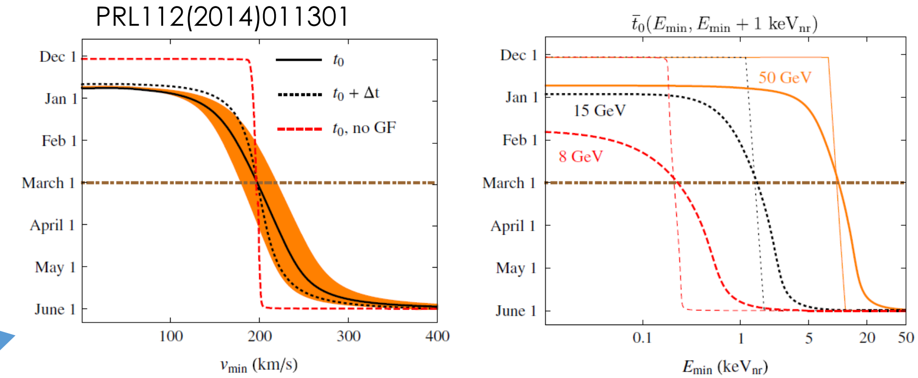
- possible diurnal effects on the sidereal time

- ✓ 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

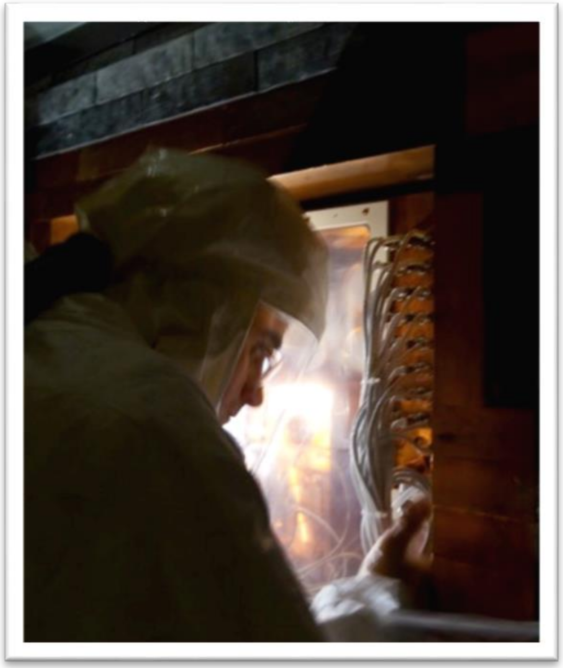
PRL112(2014)011301



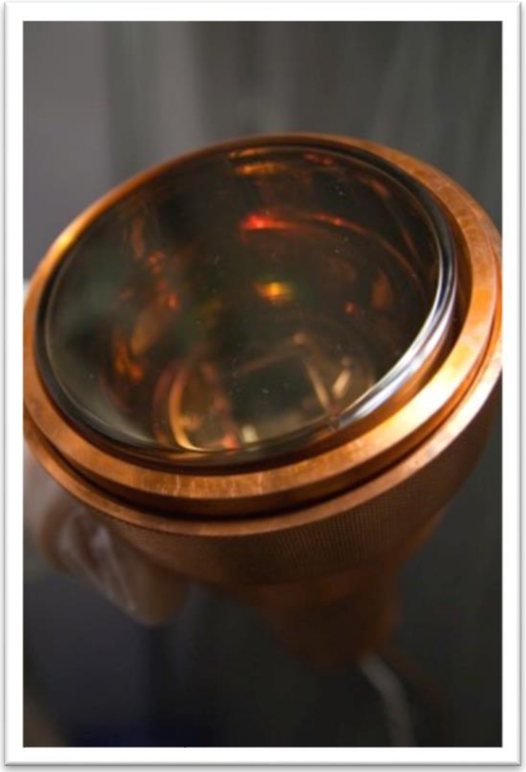
The annual modulation phase depends on :

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

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 × 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 almost concluded**
- Continuing investigations of **rare processes** other than DM