DAMA/LIBRA Results and Perspectives

6th International Conference on New Frontiers in Physics (ICNFP 2017)

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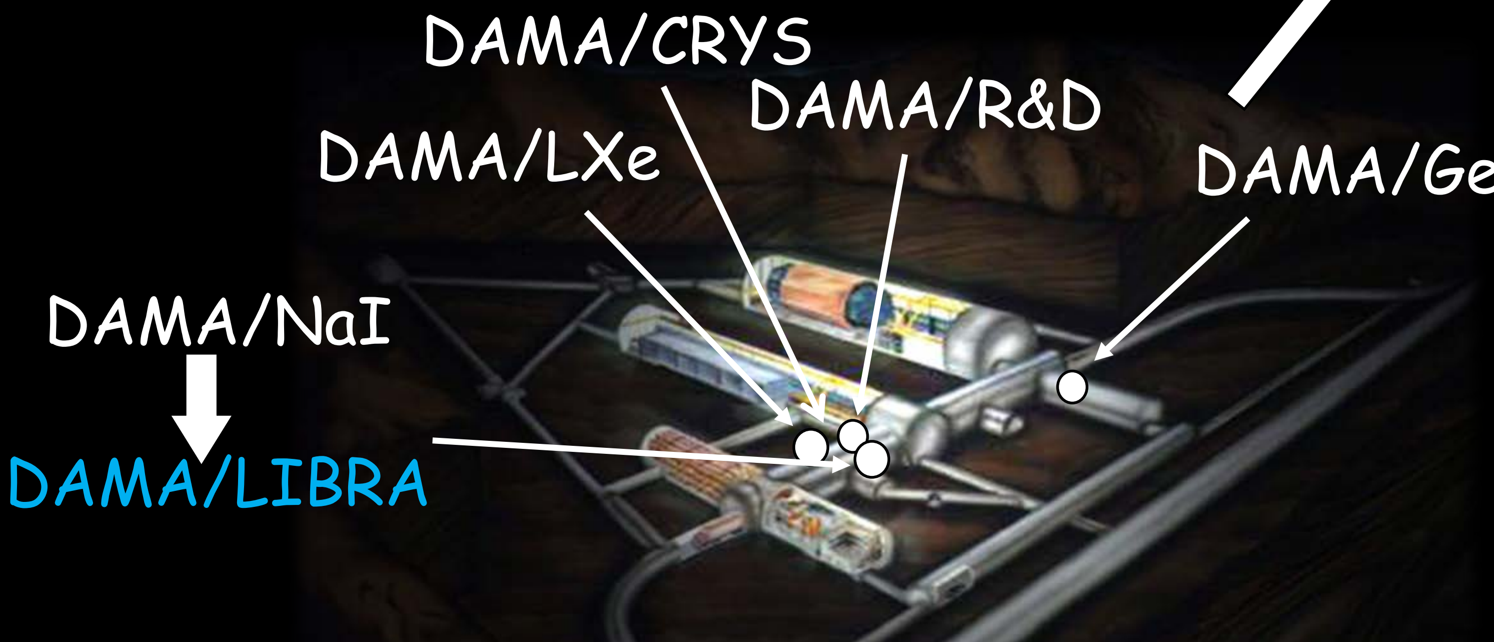
DAMA Experimental Activities

DAMA Collaboration:

Roma2 (spokesperson: prof. R. Bernabei), **Roma1, LNGS-INFN, IHEP/Beijing**
+ by-products and small scale expts.: INR-Kiev and others
+ neutron meas.: ENEA-Frascati e ENEA-Casaccia
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur/Ropar, India



DAMA: an observatory for rare processes @LNGS

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

Relic DM Particles from Primordial Universe

What Accelerators can do:
- to demonstrate the existence of some of the DM candidates

What Accelerators cannot do:
- to credit that a certain particle is a DM solution or the "only" DM particle solution…

\+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

SUSY (as neutralino or sneutrino In various scenarios)

the sneutrino in the Smith and Weiner scenario

sterile ν

mirror dark matter

invisible axions, n's

even a suitable particle not yet foreseen by theories

axion-like (light pseudoscalar and scalar candidate)

self-interacting dark matter

electron interacting dark matter

Kaluza-Klein particles (LKK)

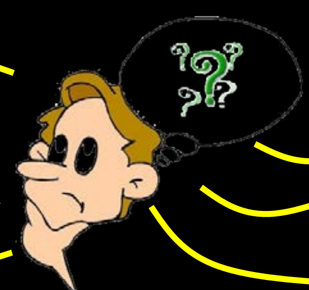
heavy exotic canditates, as "4th family atoms", ...

Elementary Black holes, Planckian objects, Daemons

etc…

a heavy n of the 4-th family

&



- Composition? DM multicomponent also in the particle part?
- Right related nuclear and particle physics?

etc… etc…

Right halo model and parameters?

Non thermalized components?

Caustics?

clumpiness?

Some Direct Detection Processes:

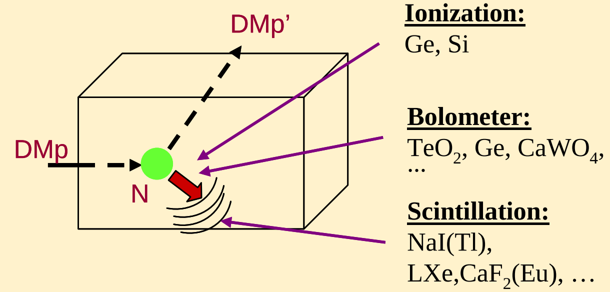
- Inelastic Dark Matter: W + N → W* + N

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

→ Kinematic constraint for the inelastic scattering of χ- on a nucleus

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

- Elastic scatterings on nuclei
→ detection of nuclear recoil energy

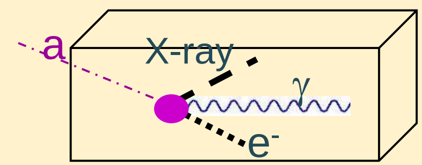


- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

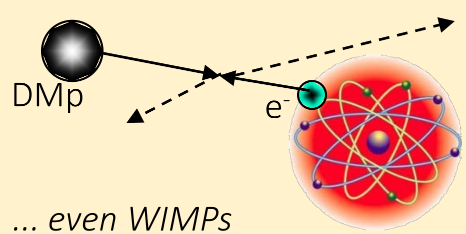
- **Conversion of particle into e.m. radiation**

→ detection of g, X-rays, e$^-$



- Interaction only on atomic electrons

→ detection of e.m. radiation

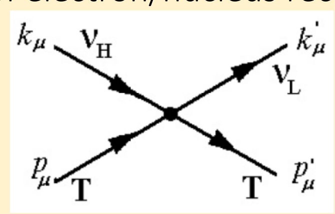


... even WIMPs

- Interaction of light DMp (LDM) on e$^-$ or nucleus with production of a lighter particle

→ detection of electron/nucleus recoil energy

e.g. sterile ν



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

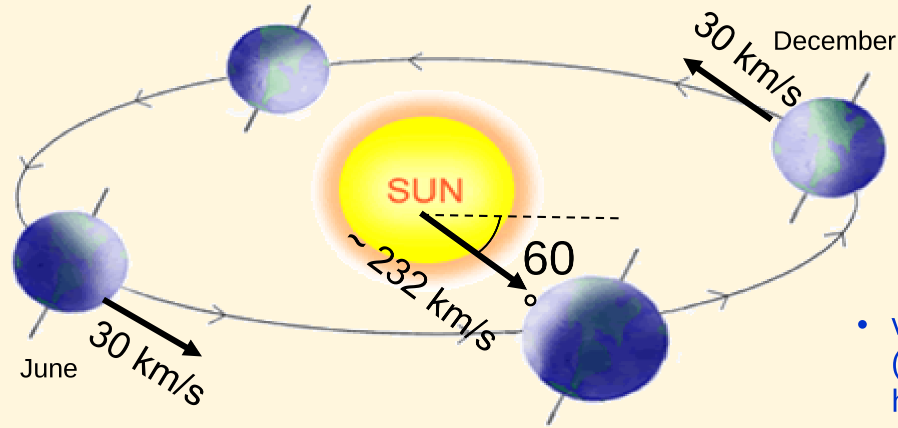
... also other ideas ...

- ... and more

The DM Annual Modulation: a Model Independent Signature to Investigate the 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



- 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)

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

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

Requirements of the DM annual modulation

1) Modulated rate according cosine
2) In a definite 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

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

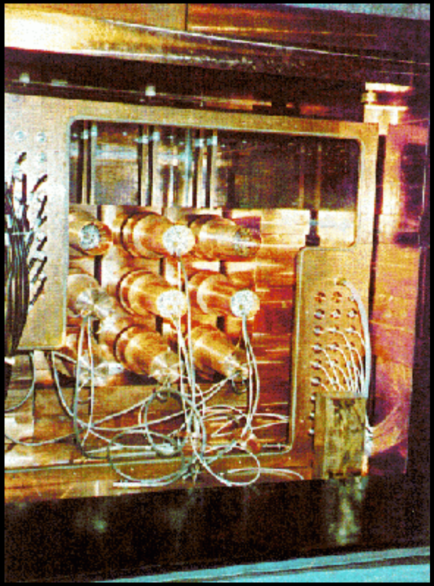
The pioneer DAMA/NaI: 100 kg highly radiopure NaI(Tl)

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



Data taking completed on July 2002, last data release 2003. Still producing results

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

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

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

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

- ***Radiopurity,performances, procedures, etc.:*** **NIMA592(2008)297, JINST 7 (2012) 03009**
- ***Results on DM particles:*** ***Ann. Mod. Signature:*** **EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648**
- ***related results:*** **PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022,EPJC74(2014)2827, EPJC75 (2015) 239, EPJC75(2015)400,IJMPA 31 (2016) dedicated issue, EPJC77(2017)83**
- ***Results on rare processes:*** ***PEP violation in Na, I:*** **EPJC62(2009)327,** ***CNC in I:*** **EPJC72(2012)1920**
  IPP in ^{241}Am: **EPJA49(2013)64**

Complete DAMA/LIBRA-phase1

	Period	Mass (kg)	Exposure (kg×day)	$(\alpha - \beta^2)$
DAMA/LIBRA-1	Sept. 9, 2003 - July 21, 2004	232.8	51405	0.562
DAMA/LIBRA-2	July 21, 2004 - Oct. 28, 2005	232.8	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 - July 18, 2006	232.8	39445	0.591
DAMA/LIBRA-4	July 19, 2006 - July 17, 2007	232.8	49377	0.541
DAMA/LIBRA-5	July 17, 2007 - Aug. 29, 2008	232.8	66105	0.468
DAMA/LIBRA-6	Nov. 12, 2008 - Sept. 1, 2009	242.5	58768	0.519
DAMA/LIBRA-7	Sep. 1, 2009 - Sept. 8, 2010	242.5	62098	0.515
DAMA/LIBRA–phase1	Sept. 9, 2003 - Sept. 8, 2010		379795 ≃ 1.04 ton×yr	0.518
DAMA/NaI + DAMA/LIBRA–phase1:			1.33 ton×yr	

- EPJC56(2008)333
- EPJC67(2010)39
- EPJC73(2013)2648

- calibrations: ≈96 Mevents from sources
- acceptance window eff: 95 Mevents (≈3.5 Mevents/keV)

a ton × yr experiment? done

DAMA/LIBRA-phase1:

- First upgrade on Sept 2008: replacement of some PMTs in HP N_2 atmosphere, new Digitizers (U1063A Acqiris 1GS/s 8-bit High-speed cPCI), new DAQ system with optical read-out installed

DAMA/LIBRA-phase2 (running):

- Second upgrade at end 2010: replacement of all the PMTs with higher Q.E. ones from dedicated developments
- commissioning on 2011

Goal: lowering the software energy threshold

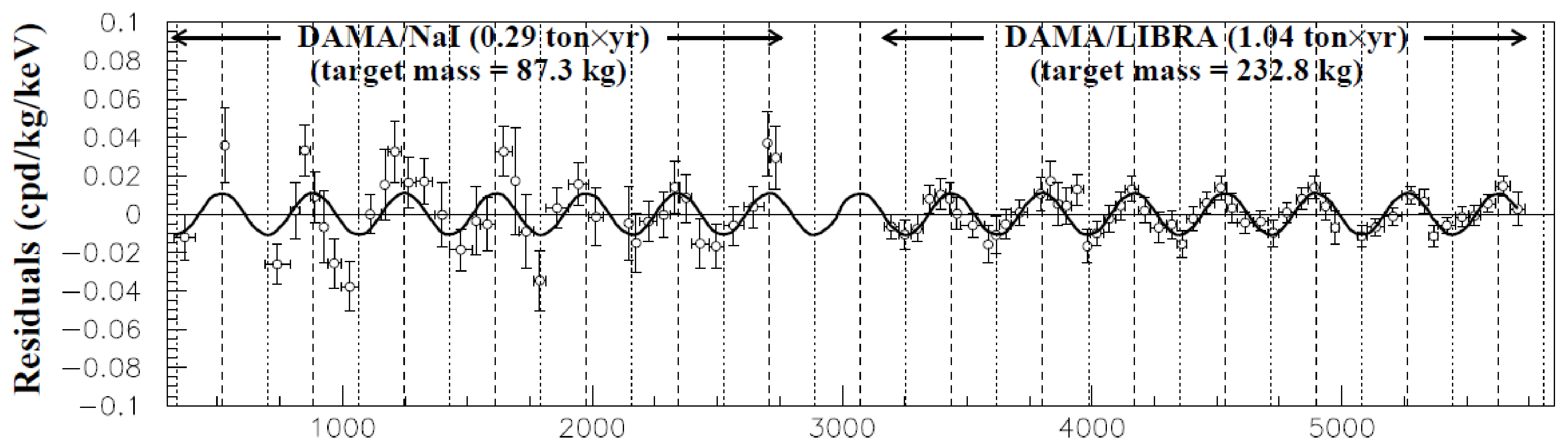
- Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: **1.33 ton×yr**

EPJC 56(2008)333,
EPJC 67(2010)39,
EPJC 73(2013)2648

Residual rate of the 2-6 keV single-hit scintillation events *vs* time



continuous line: t_0 = 152.5 d, T =1.0 y

Absence of modulation? No

χ^2/dof=154/87

P(A=0) = 1.3×10^{-5}

Fit with all the parameters free:

A = (0.0112 ± 0.0012) cpd/kg/keV

t_0 = (144±7) d - T = (0.998±0.002) y

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.

Model Independent Annual Modulation Result

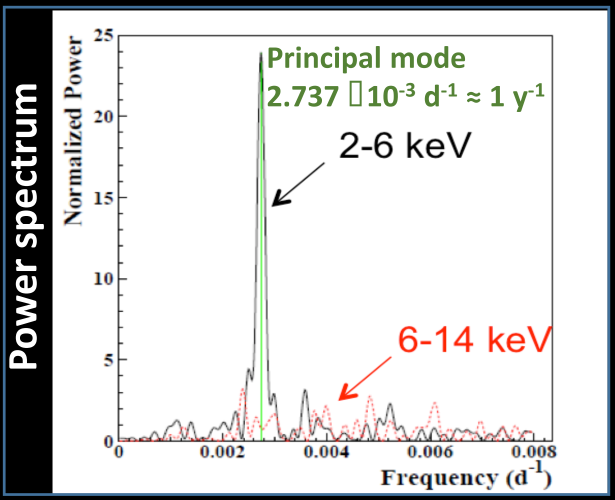
DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

The measured modulation amplitudes (A), period (T) and phase (t_0) from the single-hit residual rate vs time

DAMA/NaI+DAMA/LIBRA-phase1	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
(2-4) keV	0.0190 ±0.0020	0.996 ±0.002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.002	144 ± 7	9.3σ

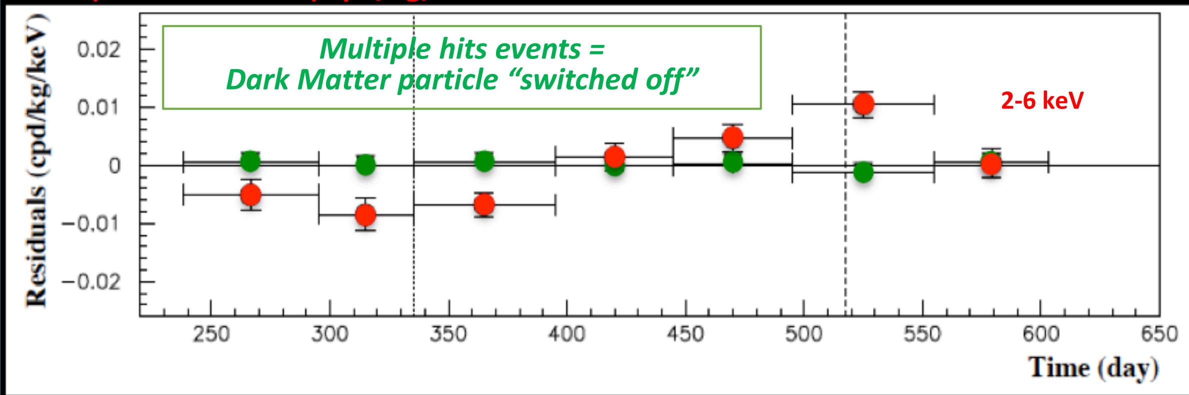
$A\cos[w(t-t_0)]$



No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events

A=-(0.0005±0.0004) cpd/kg/keV



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 data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

Max-lik analysis of single hit events

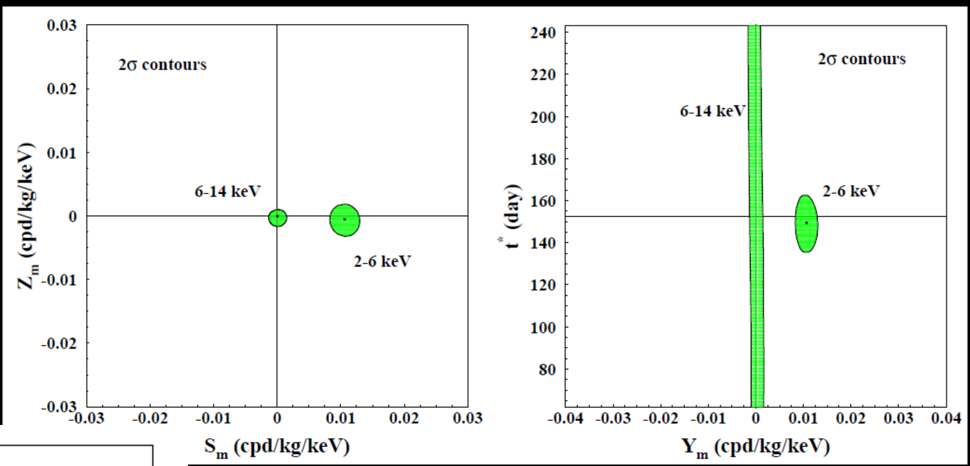
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

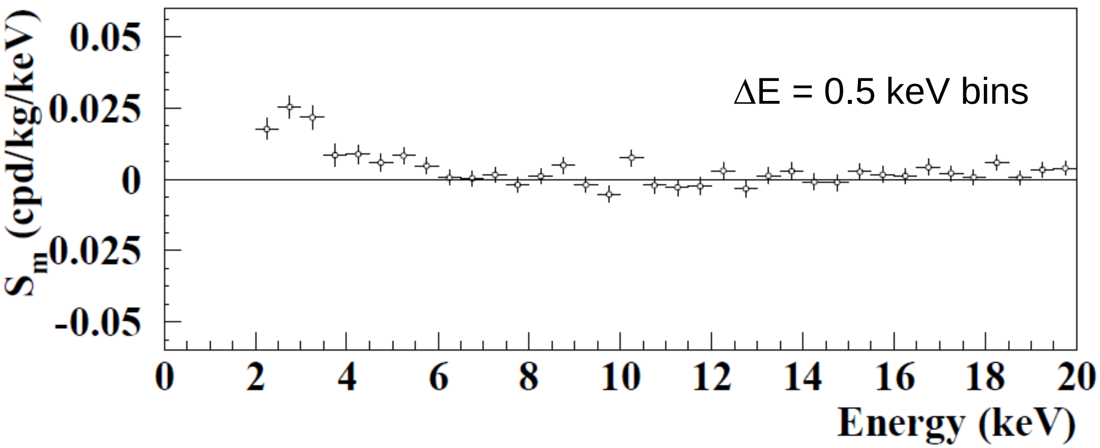
- **No modulation above 6 keV**
- **No modulation in the whole energy spectrum**
- **No modulation in the 2-6 keV multiple-hit events**

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

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

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

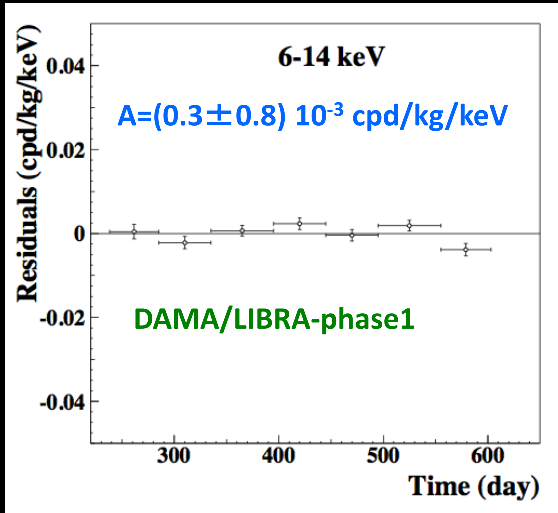




No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy all the many peculiarities of the signature are available.

Rate behaviour above 6 keV

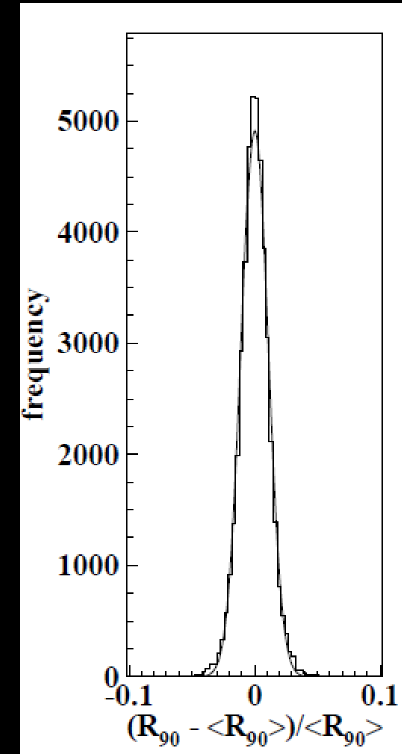
- **No Modulation above 6 keV**



Mod. Ampl. (6-10 keV): cpd/kg/keV

(0.0016 ± 0.0031) DAMA/LIBRA-1
-(0.0010 ± 0.0034) DAMA/LIBRA-2
-(0.0001 ± 0.0031) DAMA/LIBRA-3
-(0.0006 ± 0.0029) DAMA/LIBRA-4
-(0.0021 ± 0.0026) DAMA/LIBRA-5
(0.0029 ± 0.0025) DAMA/LIBRA-6
-(0.0023 ± 0.0024) DAMA/LIBRA-7
→ statistically consistent with zero

DAMA/LIBRA-phase1



- **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

s ≈ 1%, fully accounted by statistical considerations

- 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-1	-(0.05±0.19) cpd/kg
DAMA/LIBRA-2	-(0.12±0.19) cpd/kg
DAMA/LIBRA-3	-(0.13±0.18) cpd/kg
DAMA/LIBRA-4	(0.15±0.17) cpd/kg
DAMA/LIBRA-5	(0.20±0.18) cpd/kg
DAMA/LIBRA-6	-(0.20±0.16) cpd/kg
DAMA/LIBRA-7	-(0.28±0.18) 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 s far away

No modulation above 6 keV, no modulation in the whole energy spectrum, no modulation in the 2-6 keV multiple-hit events → This accounts for all sources of bckg and is consistent with the studies on the various components

Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

(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)

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$\rightarrow$ 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

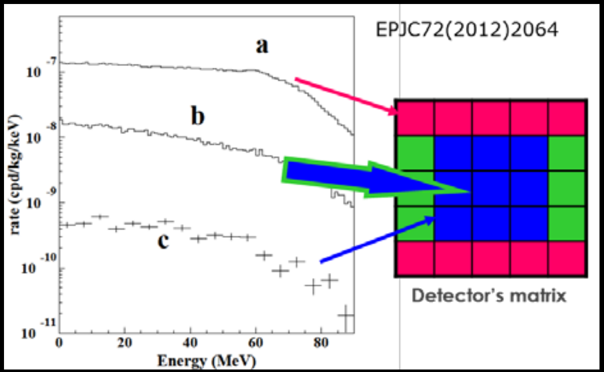
Thus, they cannot mimic the observed annual modulation effect

No role for μ in DAMA annual modulation result

✓ **Direct μ interaction in DAMA/LIBRA set-up:**

DAMA/LIBRA surface ≈0.13 m^2
m flux @ DAMA/LIBRA ≈2.5 μ/day

It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.



$S_m^{(m)} < (0.3\text{-}2.4) \times 10^{-5}$ cpd/kg/keV

✓ **Rate, R_n, of fast neutrons produced by μ:**

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Annual modulation amplitude at low energy due to **m modulation**:

$$S_m^{(m)} = R_n\ g\ e\ f_{DE}\ f_{single}\ 2\% / (M_{setup}\ DE)$$

Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events

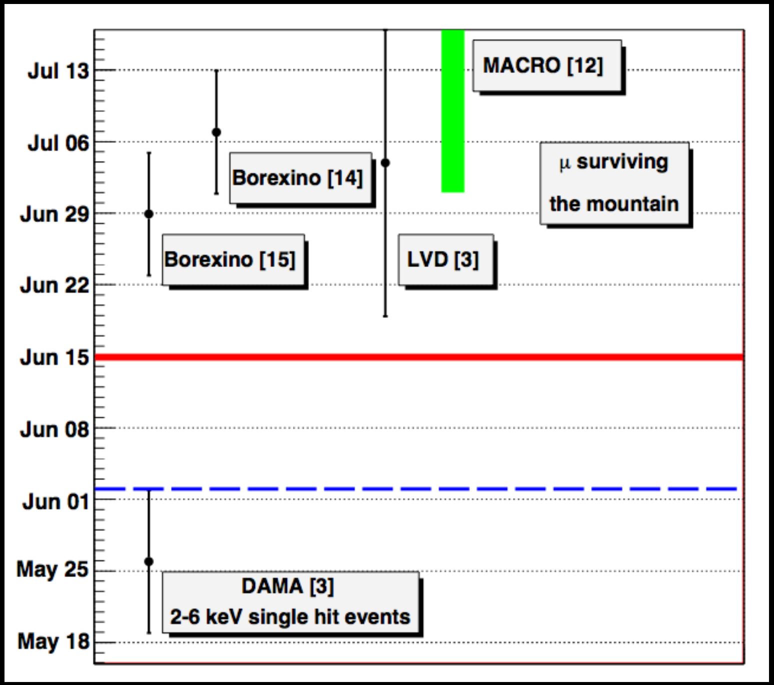
✓ **Inconsistency of the phase between DAMA signal and m modulation**

μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈$3 \cdot 10^{-4}\ m^{-2}s^{-1}$; modulation amplitude 1.5%; **phase**: July 7 ± 6 d, June 29 ± 6 d (Borexino)

The DAMA phase: May 26 ± 7 days (stable over 14 years)

The DAMA phase is 5.7σ far from the LVD/BOREXINO phases of muons (7.1 σ far from MACRO measured phase)

It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.



… many others arguments EPJC72(2012)2064, EPJC74(2014)3196

No role for n/μ/ν in DAMA annual modulation result

- 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.

(See e.g. also EPJC 56 (2008) 333, EPJC 72(2012) 2064, IJMPA 28 (2013) 1330022) EPJC74(2014)3196

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.

+ In no case neutrons (of whatever origin), muon or muon induced events, solar ν can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail (and – in addition - quantitatively negligible amplitude with respect to the measured effect).

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

About Interpretation and Comparisons

See e.g.: Riv.N.Cim.26 ono.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022

…models…

- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- 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…

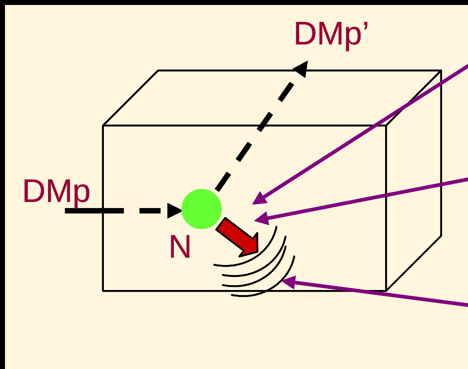
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- 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 – at least in principle - be directly compared in a model independent way with DAMA

... an example in literature...

Case of DM particles inducing elastic scatterings on target-nuclei, Spin-Independent case



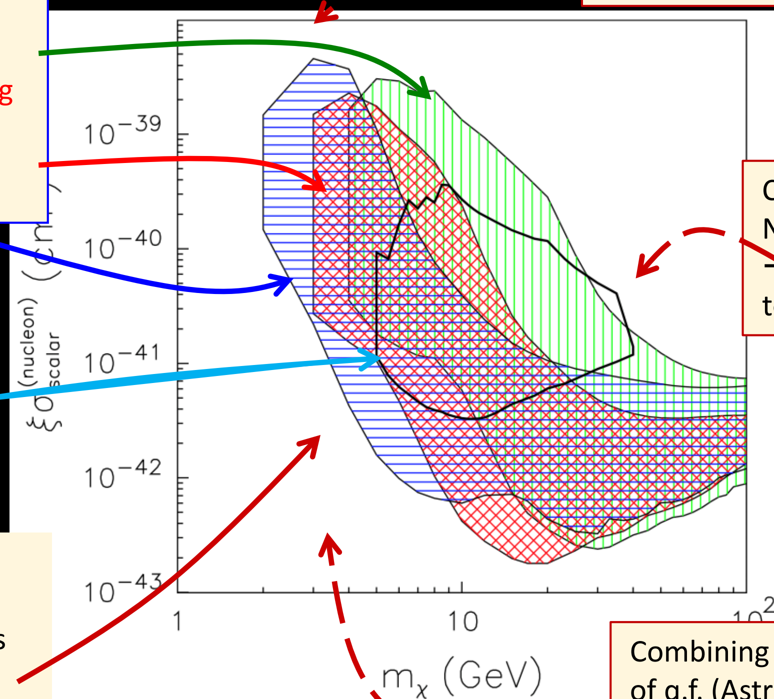
Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

Including the Migdal effect
→Towards lower mass/higher σ

DAMA allowed regions for the considered scenario without (green), with (blue) channeling, with energy-dependent Quenching Factors (red);

7.5 σ C.L.



PRD84(2011)055014,
IJMPA28(2013)1330022

Co-rotating halo,
Non thermalized component
→ Enlarge allowed region towards larger mass

CoGeNT; qf at fixed assumed value

1.64 σ C.L.

Compatibility also with first CRESST and CDMS, if the two CDMS-Ge, the three CDMS-Si and the CRESST recoil-like events are interpreted as relic DM interactions

Combining channeling and energy dependence of q.f. (AstrPhys33 (2010) 40) →Towards lower σ

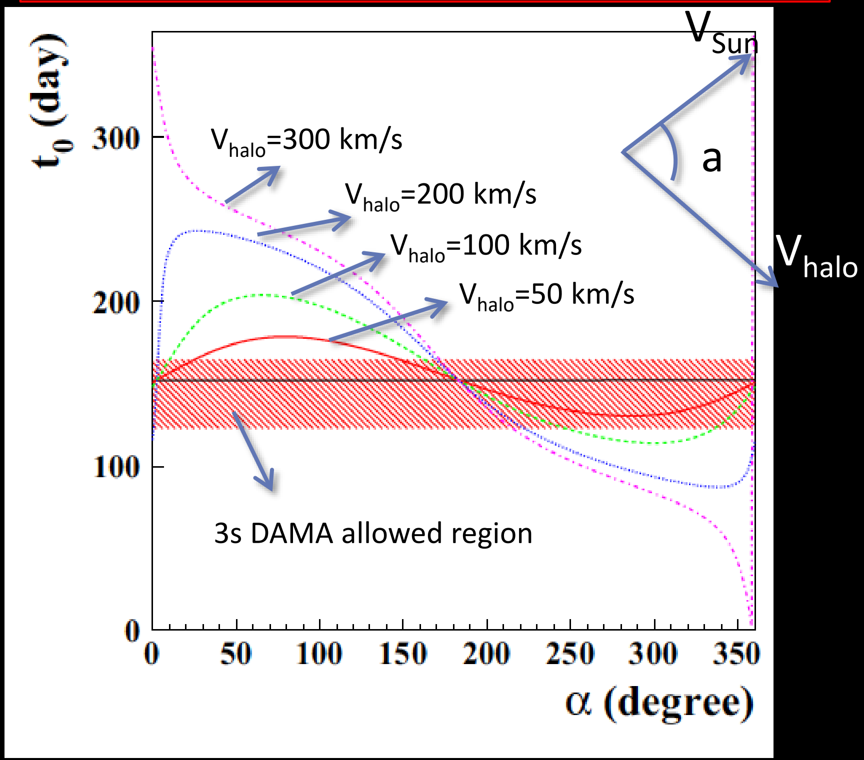
DAMA annual modulation effect and Symmetric mirror matter

Eur. Phys. J. C (2017) 77

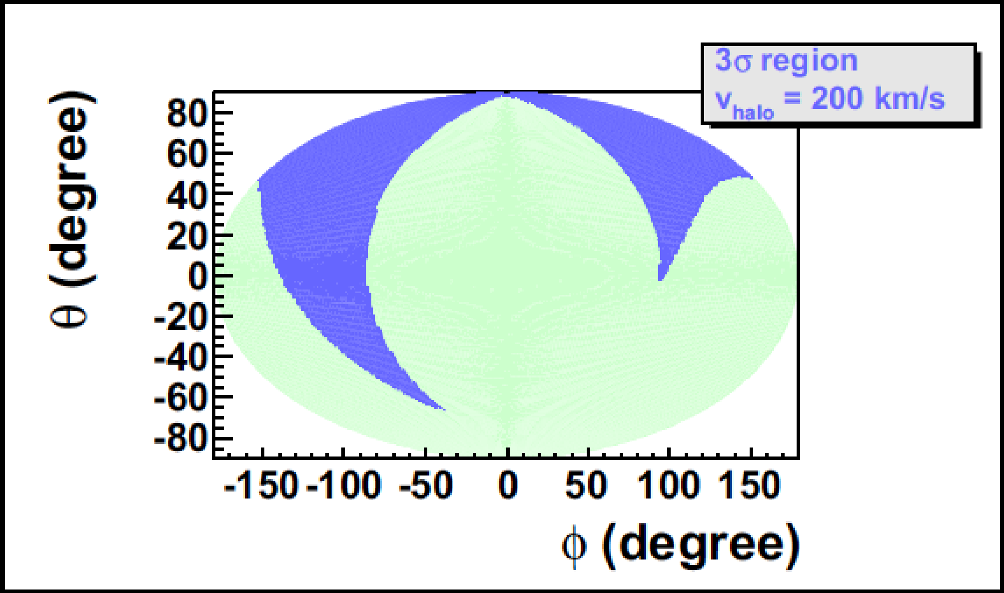
Symmetric mirror matter:

- halo composed by a bubble of Mirror particles of different species; Sun is travelling across the bubble which is moving in the Galactic Frame (GF);
- the mirror particles in the bubble have Maxwellian velocity distribution in a frame where the bubble is at rest; cold and hot bubble with temp from 10^4 K to 10^8 K
- interaction via photon - mirror photon kinetic mixing

Examples of expected phase of the annual modulation signal



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



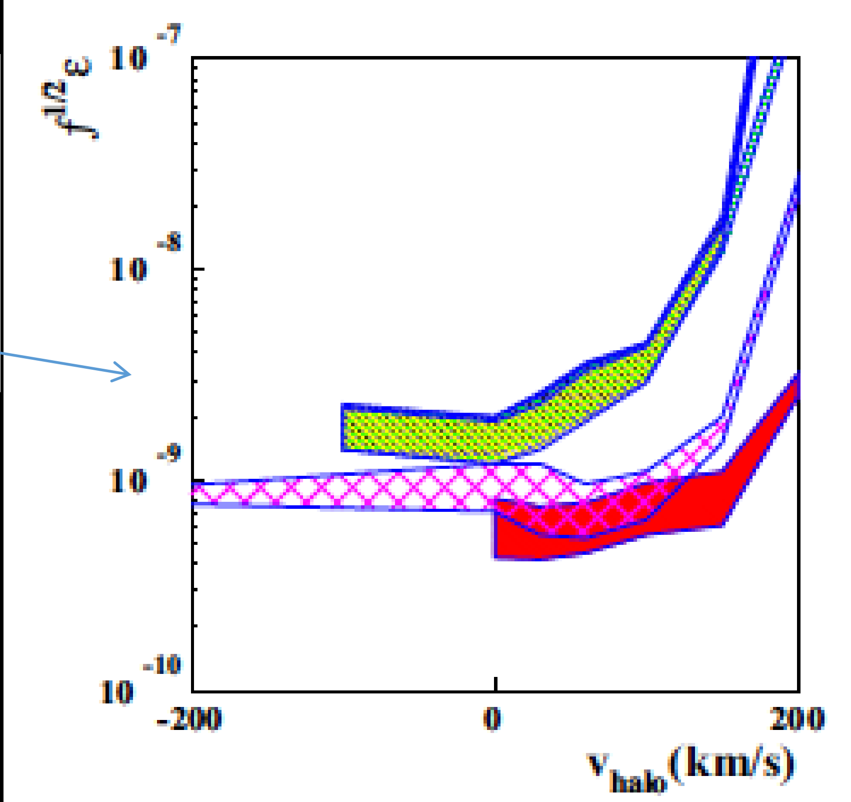
DAMA annual modulation effect and Symmetric mirror matter

Symmetric mirror matter:

Eur. Phys. J. C (2017) 77

- Results refers to halo velocities parallel or anti-parallel to the Sun ($\alpha = 0, \pi$). For these configurations the expected phase is June 2
- The only parameter whose value will be varied in the analysis is the V_{halo} module (positive velocity will correspond to halo moving in the same direction of the Sun while negative velocity will correspond to opposite direction)

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



DAMA/LIBRA allowed values for √fε in different scenarios

coupling const. and DM fraction as mirror atom

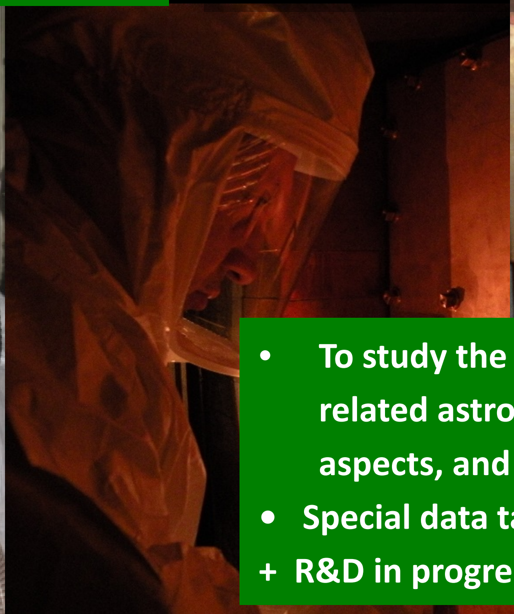
Many configurations and halo models favoured by the DAMA annual modulation effect corresponds to couplings values well compatible with cosmological bounds.

DAMA/LIBRA – phase2

After a period of tests and optimizations in data taking in this new configuration

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

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



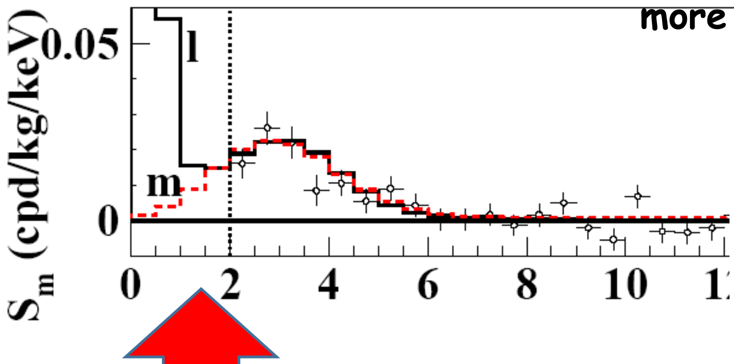
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes

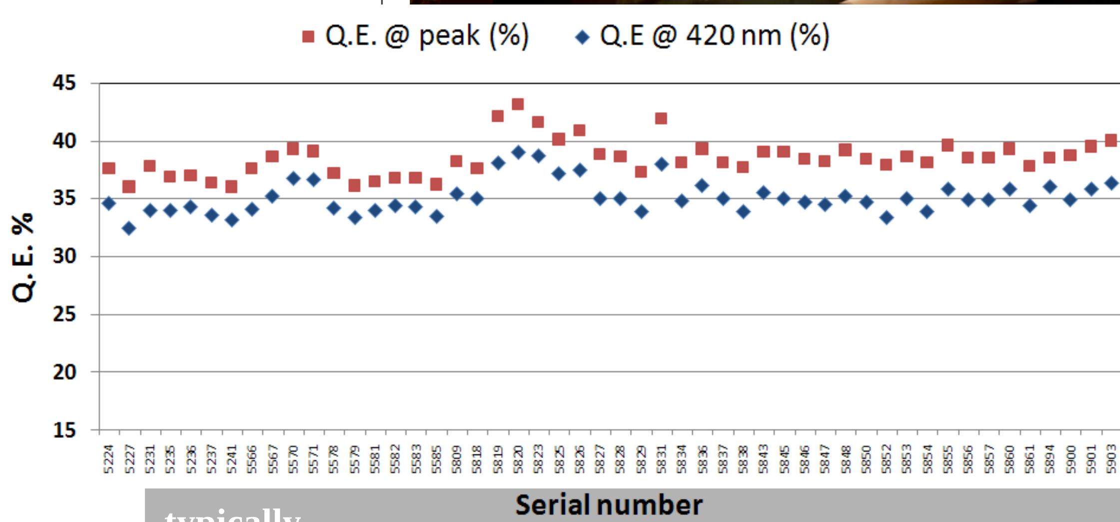
\+ R&D in progress towards more future phase3

DAMA/LIBRA – phase2

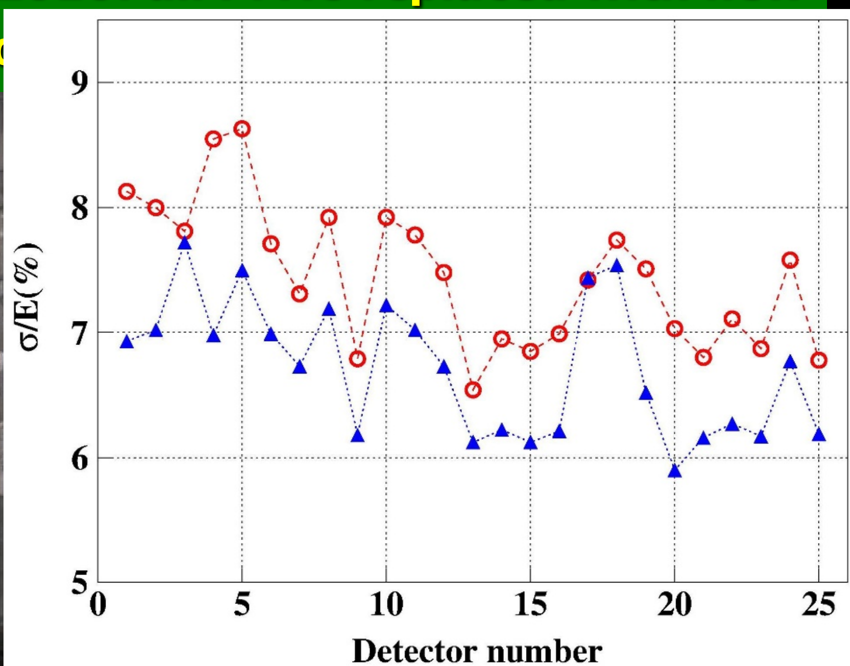
After a period of tests and optimizations in data taking in this new configuration

more IJMPA28(2013)1330022





Second upgrade on Nov/Dec 2010: all PMTs replaced with new



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

^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
-	47	0.12	83	0.54	-	-
-	10	0,02	17	0.16	-	-

- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes

\+ R&D in progress towards more future phase3

DAMA/LIBRA phase 2 – data taking

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

JINST 7(2012)03009

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

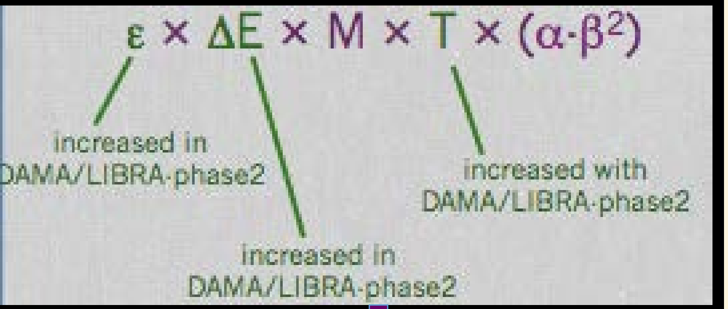
- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 5 a.c.: ~ 1.03×10^8 events from sources
- ✓ Acceptance window eff. 5 a.c.: ~ 7×10^7 events (~ 2.8×10^6 events/keV)
- ✓ Exposure collected in the first 5 a.c. of DAMA/LIBRA-phase2: **0.92 ton x yr**

Annual Cycles	Period	Mass (kg)	Exposure (kg · day)	$(\alpha-\beta^2)$
1	Dec 2010 – Sept. 2011		Commissioning	
2	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
3	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
4	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
5	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
6	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527	0.522
7	Sept 2016 –	242.5	running	

PRELIMINARY

Exposure expected for the first data release of DAMA/LIBRA-phase2, 6 a.c.: ≈ 1.1 ton x yr

The sensitivity of the DM annual modulation signature depends – apart from the counting rate – on the product:



→ DAMA/LIBRA-phase2 also equivalent to have enlarged the exposed mass

&: DM annual modulation signature acts itself as a strong bckg reduction strategy as already pointed out in the original paper by Freese et al.

&: No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

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

Higher exposure and lower threshold can allow further investigation on:

- <u>the nature of the DMp</u>
  - ✓ to disentangle among different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, form factors, spin-factors …)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DMp halo?
- <u>possible diurnal effects in sidereal time</u>
  - ✓ 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.
- <u>astrophysical models</u>
  - ✓ velocity and position distribution of DMp 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

A step towards such investigations:

→DAMA/LIBRA-phase2 with lower energy threshold

Possible DAMA/LIBRA-phase3

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

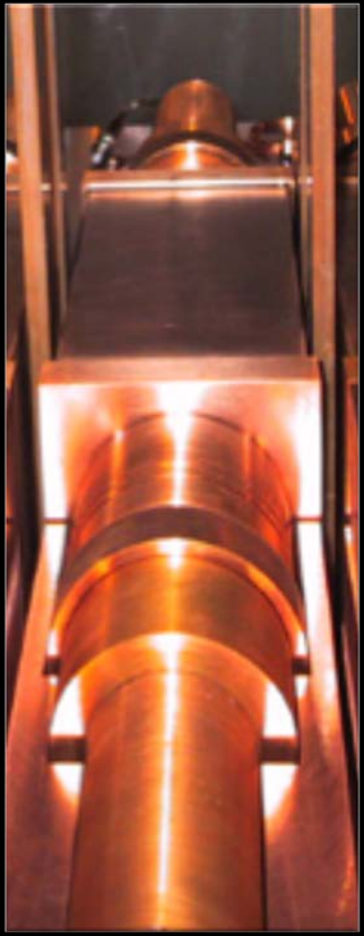
The strong interest in the low energy range suggests the possibility of a new development of **high Q.E. PMTs** with **increased radiopurity** to directly couple them to the DAMA/LIBRA crystals, **removing** the special radio-pure quartz (Suprasil B) light guides (10 cm long), which act also as optical window.

The presently-reached PMTs features:

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

R&D efforts to obtain PMTs matching the best performances… feasible

No longer need for light guides (a 30-40% improvement in the light collection is expected)



Other signatures?

- *Second order effects*
- *Diurnal effects*
- *Shadow effects*
- *Directionality*
- *…*

Diurnal effects

A diurnal effect with the sidereal time is expected for DM because of Earth rotation

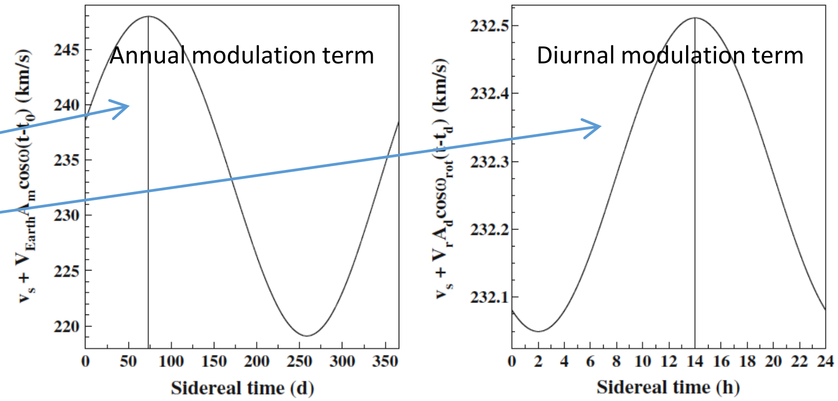
EPJC 74 (2014) 2827

Velocity of the detector in the terrestrial laboratory: $\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t),$

Since:

- $|\vec{v}_s| = |\vec{v}_{LSR} + \vec{v}_{\odot}| \approx 232 \pm 50$ km/s,
- $|\vec{v}_{rev}(t)| \approx 30$ km/s
- $|\vec{v}_{rot}(t)| \approx 0.34$ km/s at LNGS

$$v_{lab}(t) \simeq v_s + \hat{v}_s \cdot \vec{v}_{rev}(t) + \hat{v}_s \cdot \vec{v}_{rot}(t).$$



Expected signal counting rate in a given k−th energy bin:

$$S_k\left[v_{lab}(t)\right] \simeq S_k\left[v_s\right] + \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} \left[V_{Earth} B_m \cos\omega(t-t_0) + V_r B_d \cos\omega_{rot}(t-t_d)\right]$$

The ratio R_{dy} is a model independent constant:

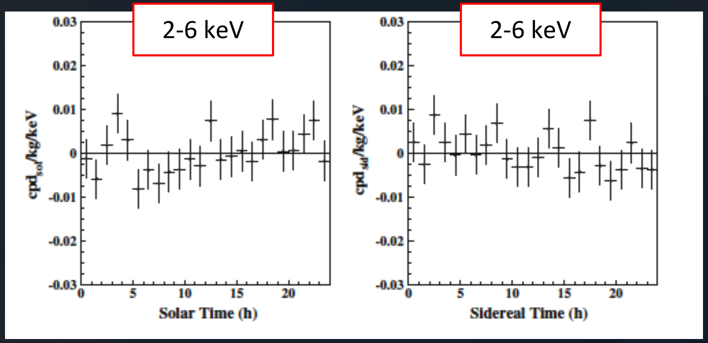
$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$

at LNGS latitude

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval: (0.0097 ± 0.0013) cpd/kg/keV
- Thus, the expected value of the diurnal modulation amplitude is ≃1.5 × 10^{-4} cpd/kg/keV.
- When fitting the *single-hit* residuals with a cosine function with amplitude A_d as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.

A_d (2-6 keV) < 1.2 × 10^{-3} cpd/kg/keV (90%CL)

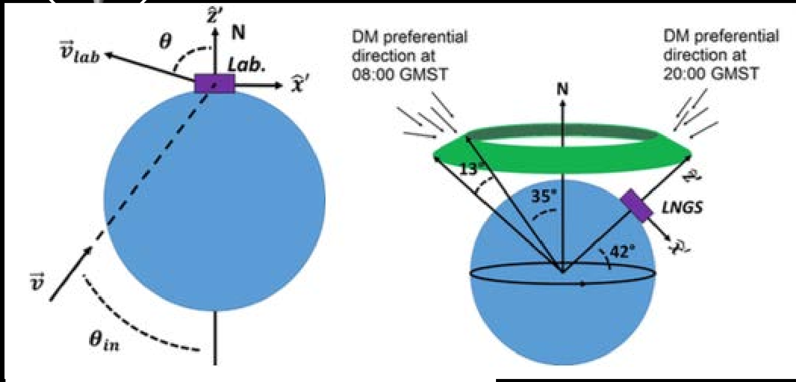
Model-independent result on possible diurnal effect in DAMA/LIBRA–phase1



Present experimental sensitivity more modest than the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect.

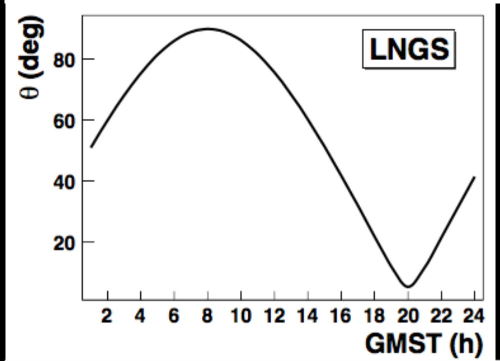
larger exposure DAMA/LIBRA–phase2 with lower energy threshold offers increased sensitivity to such an effect

Earth shadowing effect with DAMA/LIBRA–phase1

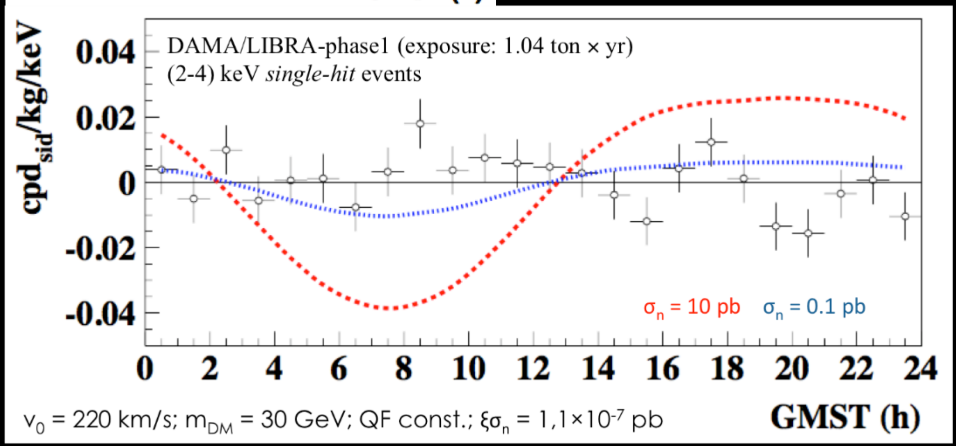


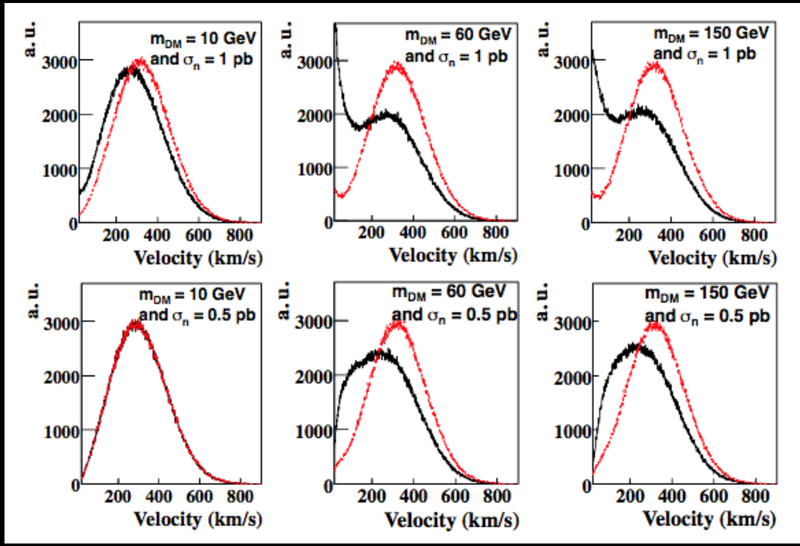
EPJC75 (2015) 239

- **Earth Shadow Effect** could be expected for DM candidate particles inducing just nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM particle in order to reach the experimental set-up



- DM particles crossing Earth lose their energy
- DM velocity distribution observed in the laboratory frame is modified as function of time (**GMST 8:00 black**; **GMST 20:00 red**)





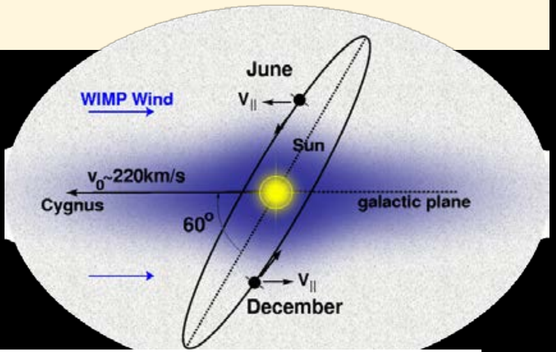
Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the ξ vs σ_n plane for each m_{DM}.

Development of detectors with anisotropic response

Eur. Phys. J. C 73 (2013) 2276

Anisotropic detectors are of great interest for many applicative fields, e.g.:
⇒ they can offer a unique way to study directionality for Dark Matter candidates that induce just nuclear recoils

Taking into account:
- the correlation between the direction of the nuclear recoils and the Earth motion in the galactic rest frame;
- the peculiar features of anisotropic detectors;



The detector response is expected to vary as a function of the sidereal time

See the F. Cappella Talk @ ICNFP17 on August 21th

Development of $ZnWO_4$ scintillators

✓ Both light output and pulse shape have anisotropic behavior and can provide two independent ways to study directionality

✓ Very high reachable radio-purity;

✓ Threshold at keV feasible;

O → light masses
Zn, W → high masses

Presently running at ENEA-Casaccia with neutron generator to measure anisotropy in keV range

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo at **9.3σ** C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: 1.33 ton × yr)
- Modulation parameters determined with higher precision
- New investigations on different peculiarities of the DM signal exploited (**Diurnal Modulation** and **Earth Shadow Effect**)
- New corollary analysis on **Mirror Dark Matter**
- 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**

- **DAMA/LIBRA – phase2 in data taking** at lower software energy threshold (below 2 keV)
- Continuing investigations of rare processes other than DM
- **DAMA/LIBRA – phase3 R&D in progress**
- R&D for a possible DAMA/1ton set-up, proposed by DAMA since 1996, **continuing** as well as **some other R&Ds**