Recent Results from DAMA/LIBRA and Perspectives

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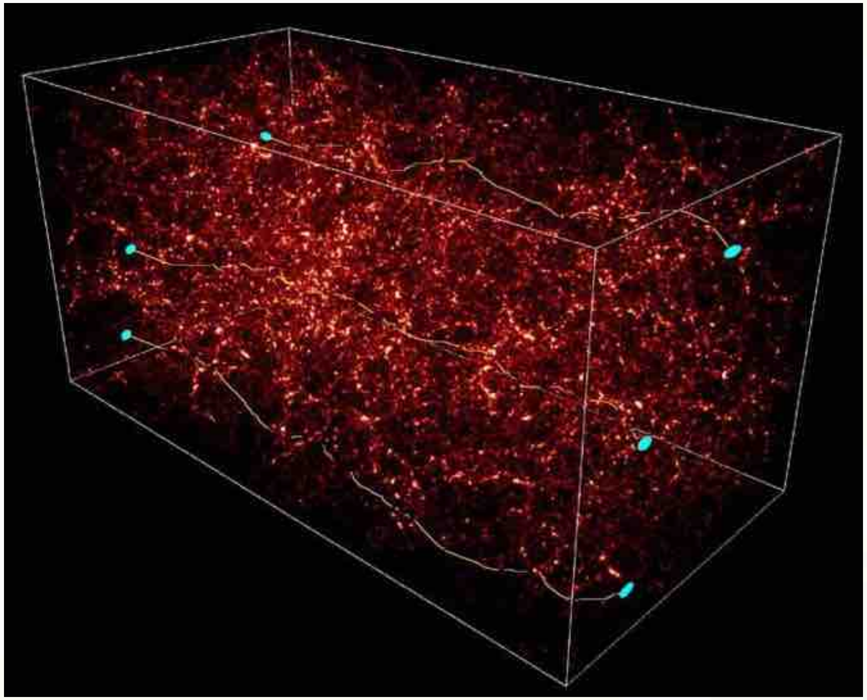
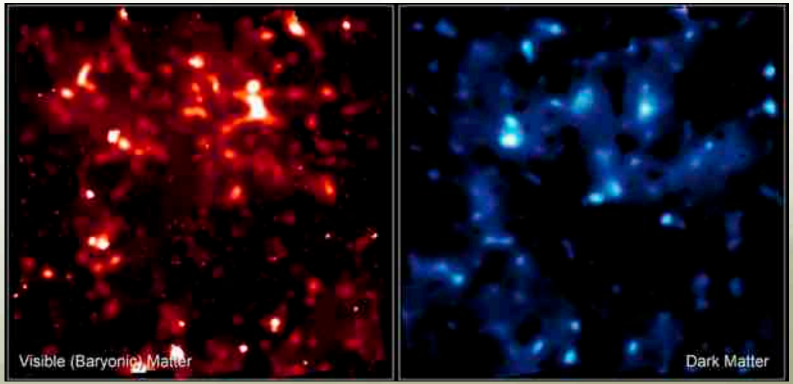
The Dark Matter in the Universe

- A large part of the Universe is made of Dark Matter and Dark Energy
- The so-called "baryonic" matter is only ≈5% of the total budget
- (Concordance) ΛCDM model and precision cosmology
- The Dark Matter is fundamental for the formation of the structures and galaxies in the Universe
- Non-baryonic Cold Dark Matter is the dominant component (≈27%) among the matter.
- CDM particles, possibly relics from Big Bang, with no em and color charges → beyond the SM





Relic DM particles from primordial Universe

SUSY
(as neutralino or sneutrino
in various scenarios)

the sneutrino in the Smith
and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not
yet foreseen by theories

etc...

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects, Daemons

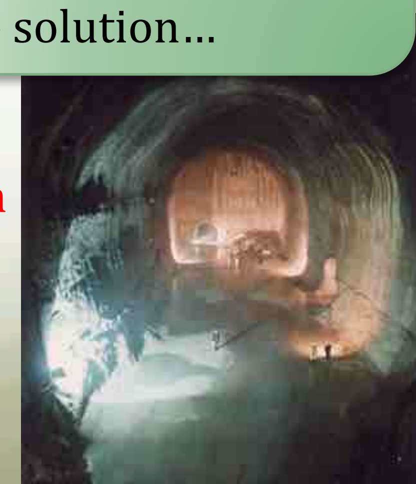
invisible axions, ν's

What accelerators can do:
to demostrate the existence of
some of the possible DM candidates

What accelerators cannot do:
to credit that a certain particle is the
Dark Matter solution or the "single"
Dark Matter particle solution…

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

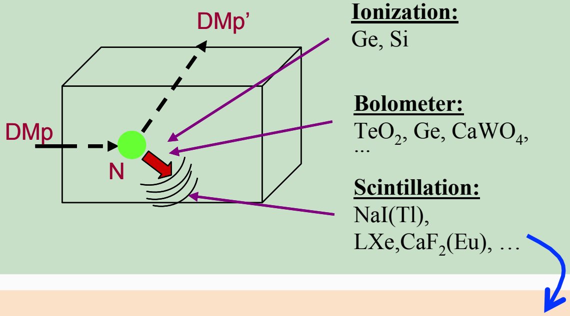
DM direct detection method using a model independent approach and a low-background widely-sensitive target material



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

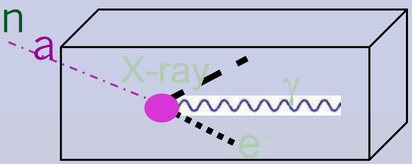
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

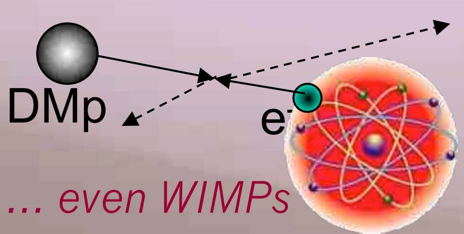
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

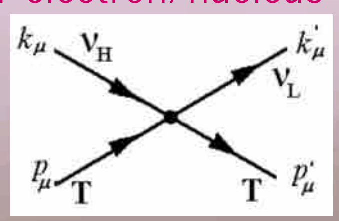


… even WIMPs

- 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

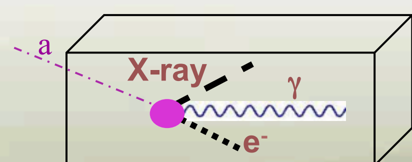
… also other ideas …

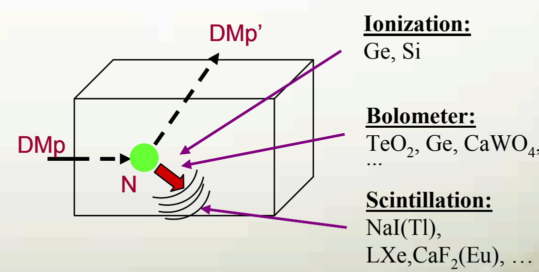
Direct detection experiments

The direct detection experiments can be classified in **two classes**, depending on what they are based:

1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a ***model-independent* signature**

2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)





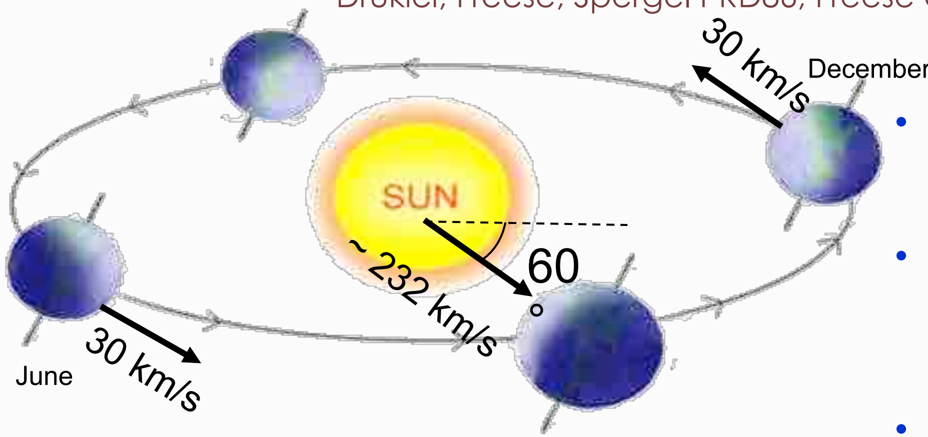
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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)

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

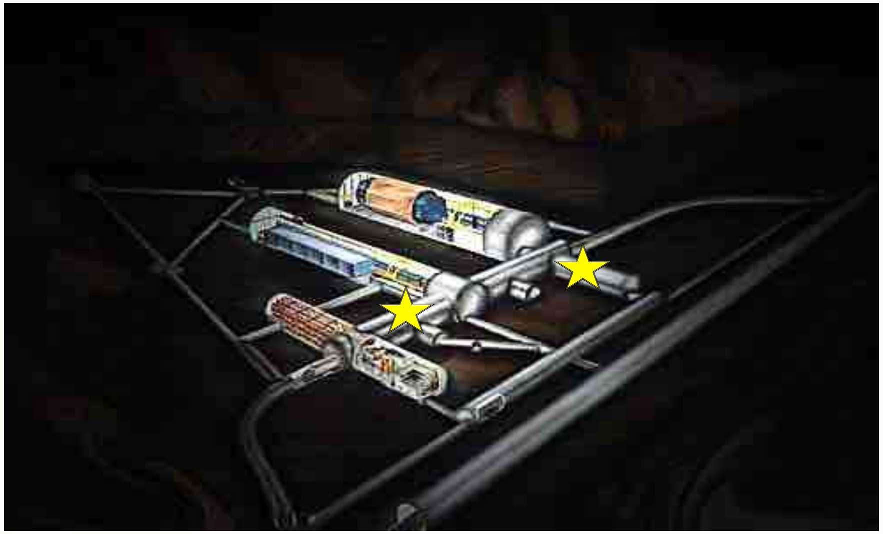
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

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 - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

DAMA set-ups

an observatory for rare processes @ LNGS



- DAMA/LIBRA (DAMA/NaI)
- DAMA/LXe
- DAMA/R&D
- DAMA/Crys
- DAMA/Ge

Collaboration:

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

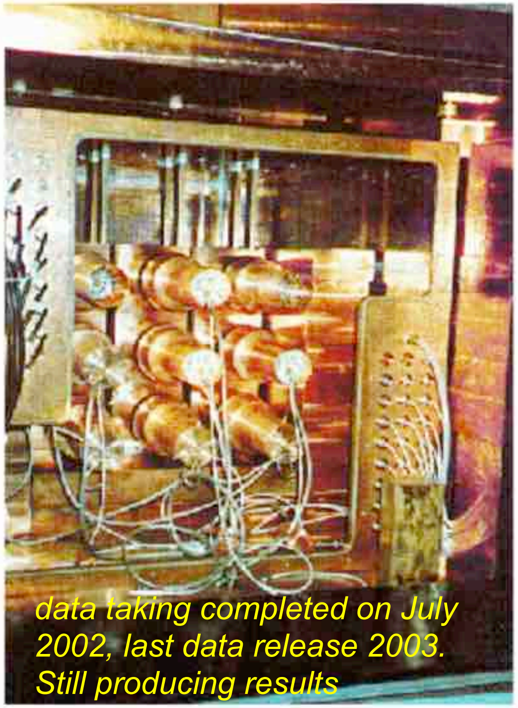
+ by-products and small scale expts.: INR-Kiev

+ neutron meas.: ENEA-Frascati

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

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

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



Performances:

N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

Results on rare processes:

- Possible Pauli exclusion principle violation — PLB408(1997)439
- CNC processes — PRC60(1999)065501
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) — PLB460(1999)235
- Search for solar axions — PLB515(2001)6
- Exotic Matter search — EPJdirect C14(2002)1
- Search for superdense nuclear matter — EPJA23(2005)7
- Search for heavy clusters decays — EPJA24(2005)51

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- **Annual Modulation Signature** — PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

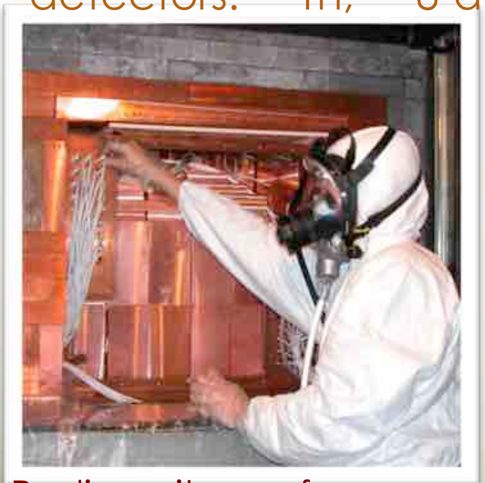
Model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

total exposure (7 annual cycles) 0.29 ton×yr

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

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving - including photos - in HP Nitrogen atmosphere)

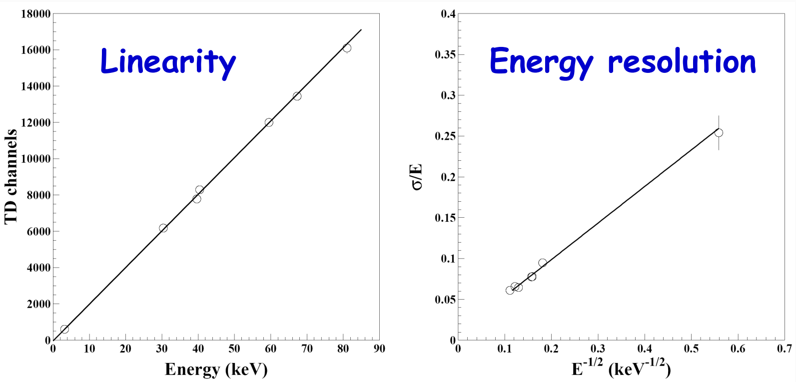
Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g



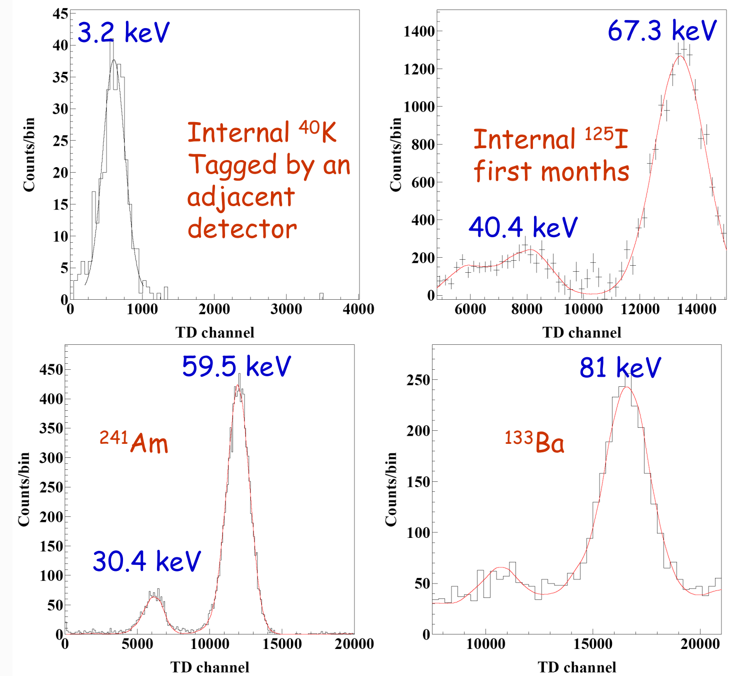
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, arXiv:1507.04317
- Results on rare processes: PEPv: EPJC62(2009)327; CNC: EPJC72(2012)1920; IPP in ^{241}Am: EPJA49(2013)64

DAMA/LIBRA calibrations

Low energy: various external gamma sources (^{241}Am, ^{133}Ba) and internal X-rays or gamma's (^{40}K, ^{125}I, ^{129}I), routine calibrations with ^{241}Am

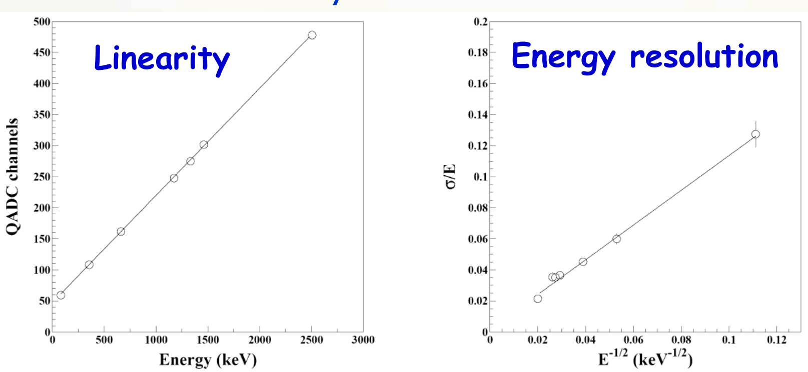


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1)\cdot 10^{-3}$$



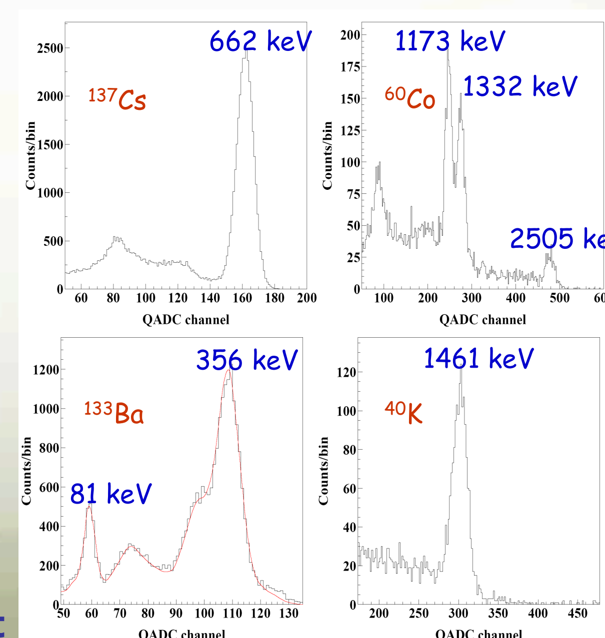
The curves superimposed to the experimental data have been obtained by simulations

High energy: external sources of gamma rays (e.g. ^{137}Cs, ^{60}Co and ^{133}Ba) and gamma rays of 1461 keV due to ^{40}K decays in an adjacent detector, tagged by the 3.2 keV X-rays



The signals (unlike low energy events) for high energy events are taken only from one PMT

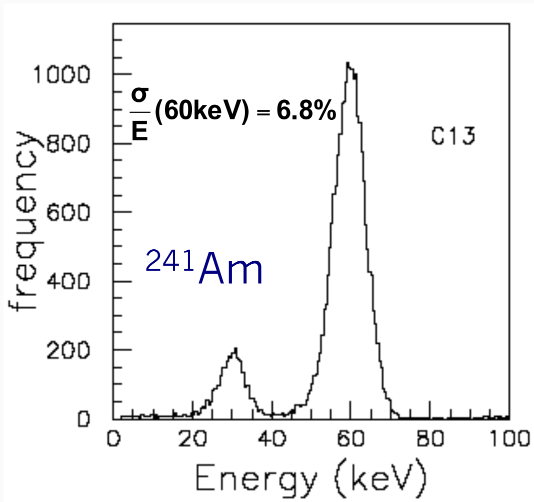
$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23)\cdot 10^{-4}$$



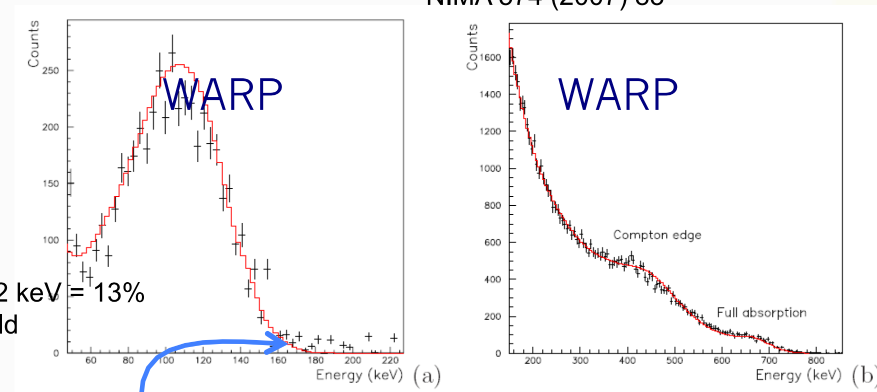
Thus, here and hereafter keV means keV electron equivalent

Examples of energy resolutions

DAMA/LIBRA ULB NaI(Tl)



NIMA 574 (2007) 83



σ/E @ 122 keV = 13%
at zero field

Fig. 2. Energy spectra taken with external γ-ray sources, superimposed with the corresponding Monte Carlo simulations. (a) ^{57}Co source ($E = 122$ keV, B.R. 85.6%, and 136 keV, B.R. 10.7%), (b) ^{137}Cs source ($E = 662$ keV).

subtraction of the spectrum ?

ZEPLIN-II

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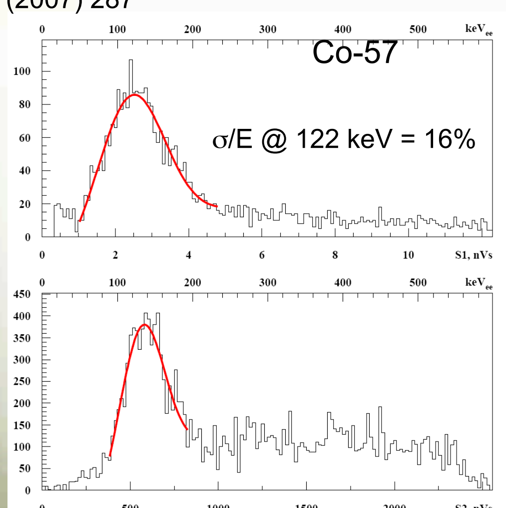


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.

XENON10 XENON10

σ/E @ 122 keV = 17%

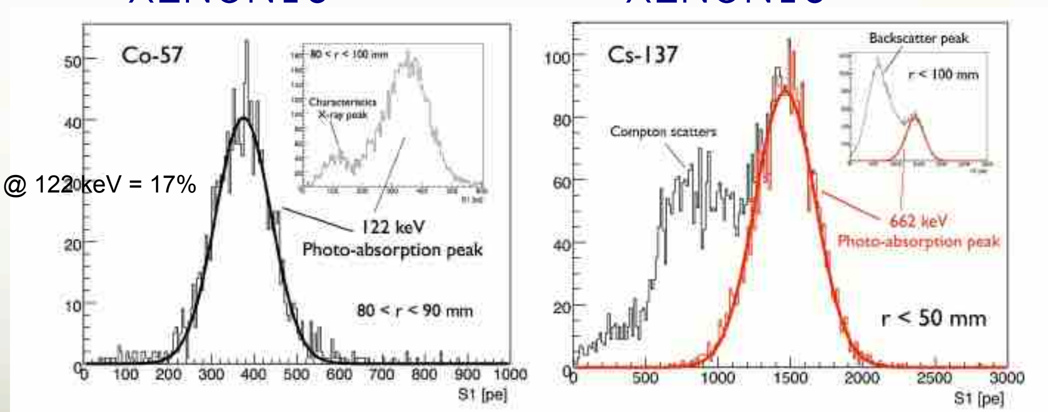
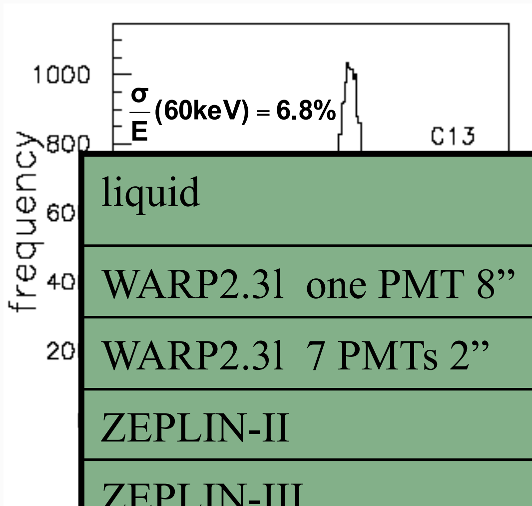


Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

JoP: Conf. Ser. 65 (2007) 012015

Examples of energy resolutions

DAMA/LIBRA ULB NaI(Tl)



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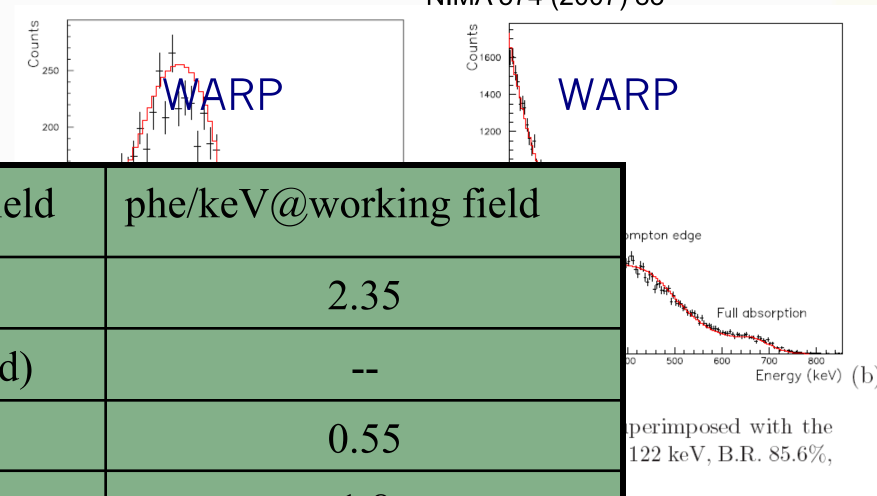

liquid	phe/keV@zero field	phe/keV@working field
WARP2.31 one PMT 8”	--	2.35
WARP2.31 7 PMTs 2”	0.5-1 (deduced)	--
ZEPLIN-II	1.1	0.55
ZEPLIN-III		1.8
XENON10	--	2.2 (^{137}Cs), 3.1 (^{57}Co)
XENON100	2.7	1.57 (^{137}Cs), 2.2 (^{57}Co)
Neon	0.93	field not foreseen

DAMA/LIBRA : 5.5 – 7.5 phe/keV

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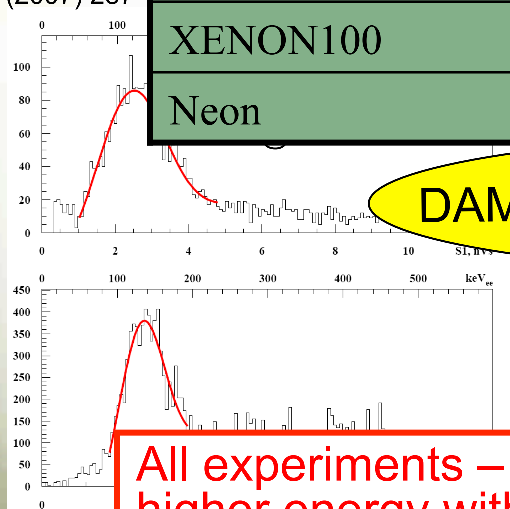
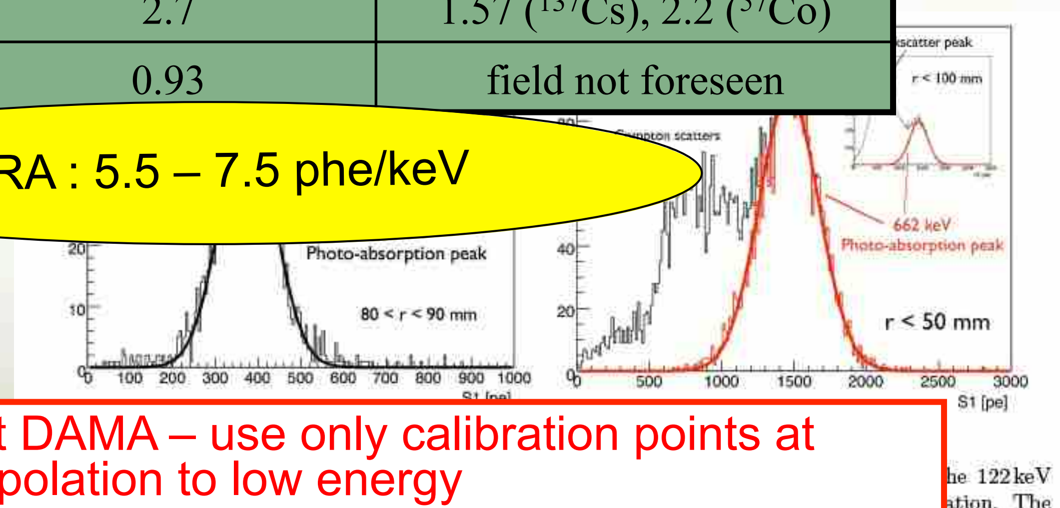


Fig. 5. Typical energy (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.



light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

All experiments – except DAMA – use only calibration points at higher energy with extrapolation to low energy

JoP: Conf. Ser. 65 (2007) 012015

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	

a ton × yr experiment? done

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

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

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 on Oct./Nov. 2010: replacement of all the PMTs with higher Q.E. ones from dedicated developments

Goal: lowering the software energy threshold

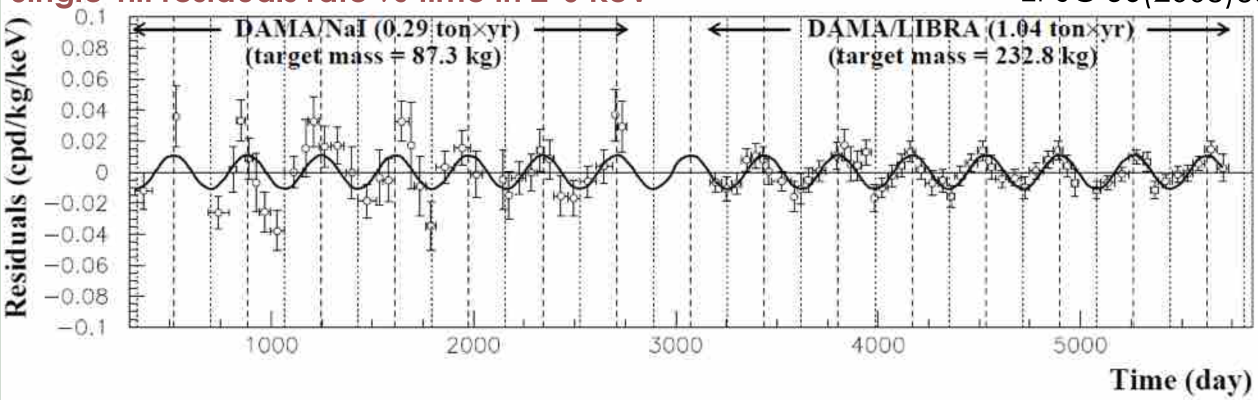
- Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

Model Independent Annual Modulation Result

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

Single-hit residuals rate *vs* time in 2-6 keV

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



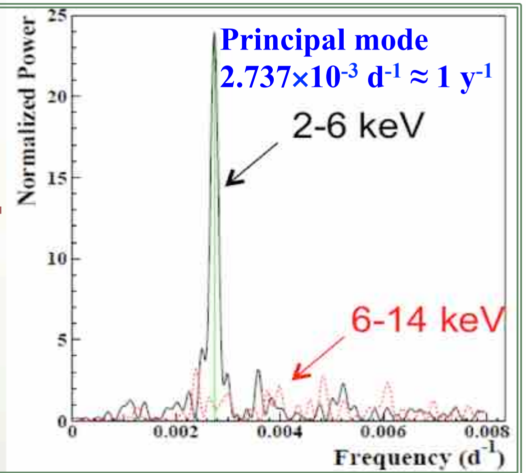
continuous line: t_0 = 152.5 d, T =1.0 y

A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

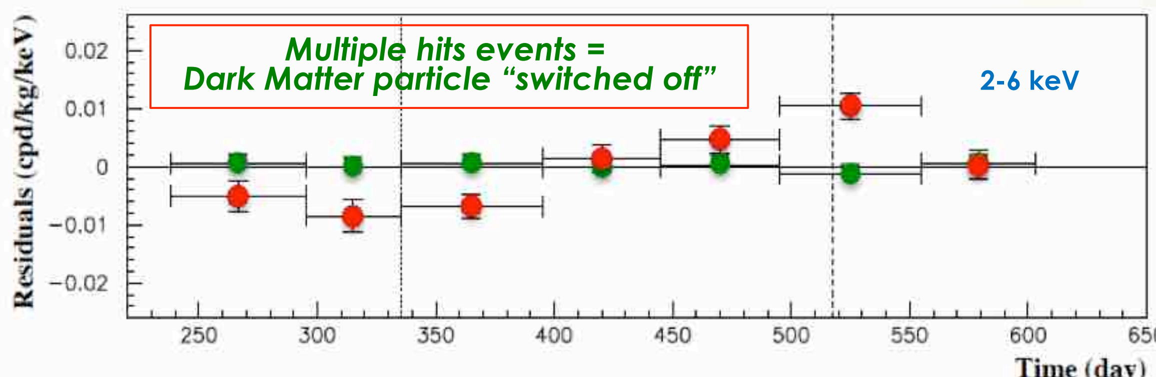
Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y

Power spectrum



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**

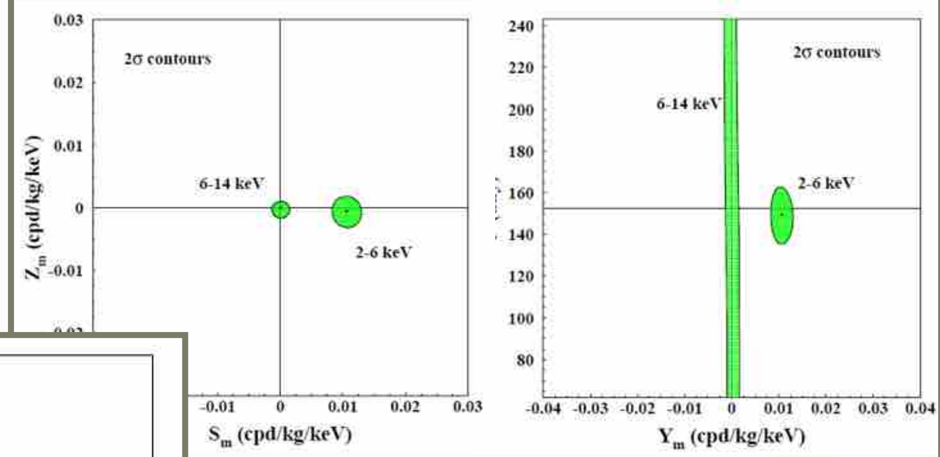
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

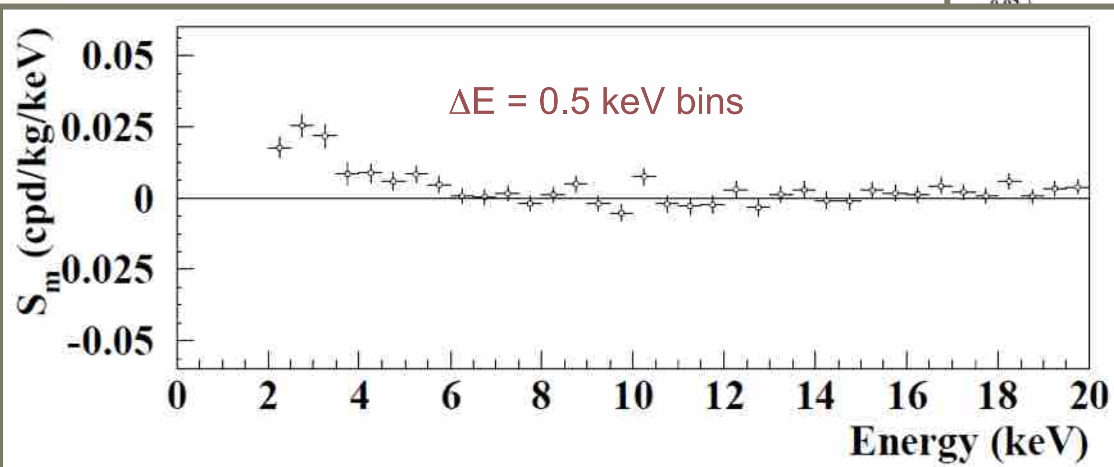
- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

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

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

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





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

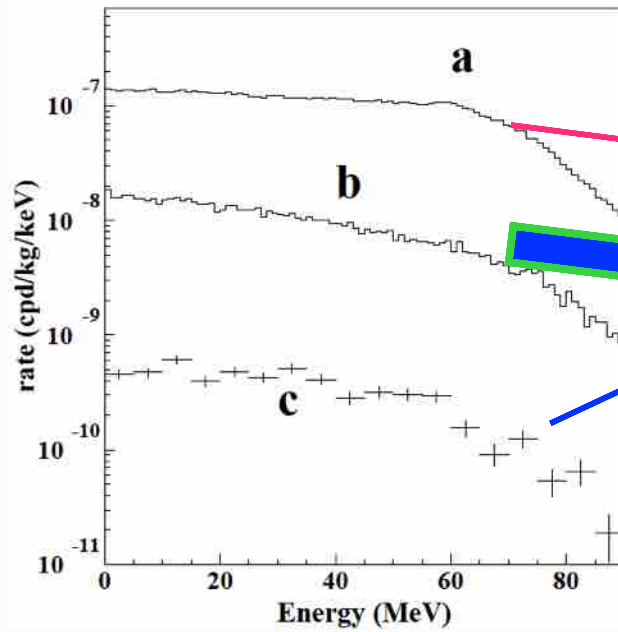
No role for μ in DAMA annual modulation result

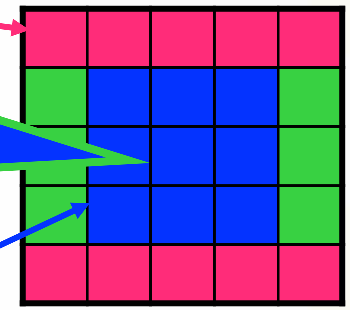
Much more in EPJC72(2012)2064

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

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

MonteCarlo simulation:
- muon intensity distribution
- Gran Sasso rock overburden map
- Single hit events





Detector's matrix

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

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

R_n = (fast n by μ)/(time unit) = $\Phi_\mu \, Y \, M_{eff}$

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Measured neutron Yield @ LNGS:

  Y=1÷7 10^{-4} n/μ/(g/cm^2)

g = geometrical factor;
ε = detection eff. by elastic scattering
f_{DE} = energy window (E>2keV) effic.;
f_{single} = single hit effic.

Annual modulation amplitude at low energy due to μ modulation:

$S_m^{(\mu)} = R_n \, g \, \varepsilon \, f_{\Delta E} \, f_{single} \, 2\% / (M_{setup} \, \Delta E)$

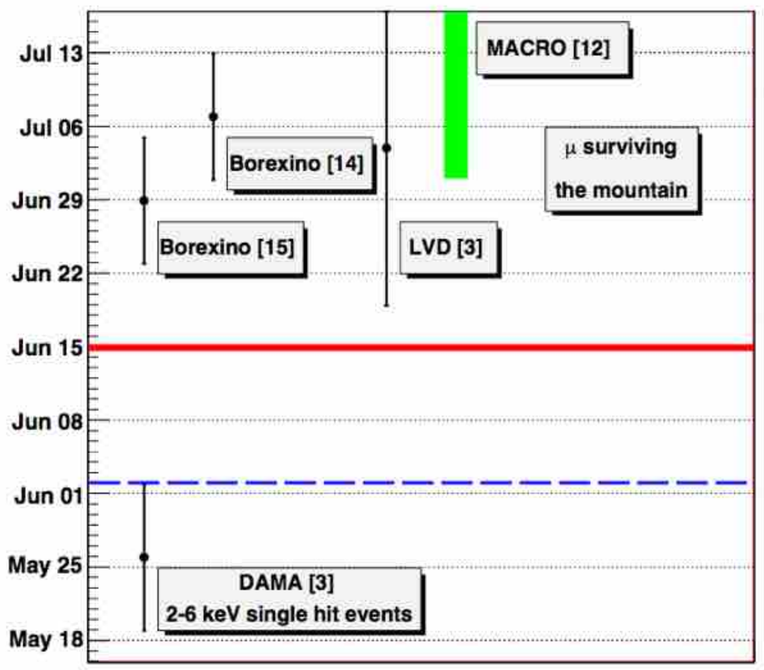
Hyp.: M_{eff} = 15 tons; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)
Knowing that: M_{setup} ≈ 250 kg and ΔE=4keV

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

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

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

Inconsistency of the phase between DAMA signal and μ 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)

but

- the muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a "mean" of the muon phase of each year
- The DAMA: modulation amplitude 10^{-2} cpd/kg/keV, in 2-6 keV energy range for single hit events; phase: May 26 ± 7 days (stable over 13 years)

considering the seasonal weather al LNGS, quite impossible that the max. temperature of the outer atmosphere (on which μ flux variation is dependent) is observed e.g. in June 15 which is 3 σ from DAMA

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

Similar for the whole DAMA/LIBRA-phase1

✓ Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:

- only events at low energy,
- only *single-hit* events,
- no sizable effect in the *multiple-hit* counting rate
- pulses with time structure as scintillation light

But, its phase should be (much) larger than μ phase, t_μ :

- if $\tau \ll T/2\pi$: $t_{side} = t_\mu + \tau$
- if $\tau \gg T/2\pi$: $t_{side} = t_\mu + T/4$

Also this cannot mimic the signature: different phase

... and for many others arguments and details EPJC72(2012)2064

- 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		$\Phi_{0,k}^{(n)}$ (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, $(\alpha, n) \rightarrow$ 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]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \rightarrow$ 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])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \rightarrow$ 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)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \rightarrow$ 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-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→ 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**

Model-independent evidence by DAMA/NaI and DAMA/LIBRA

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

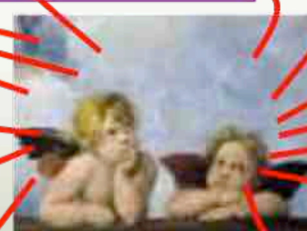
Light Dark Matter

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

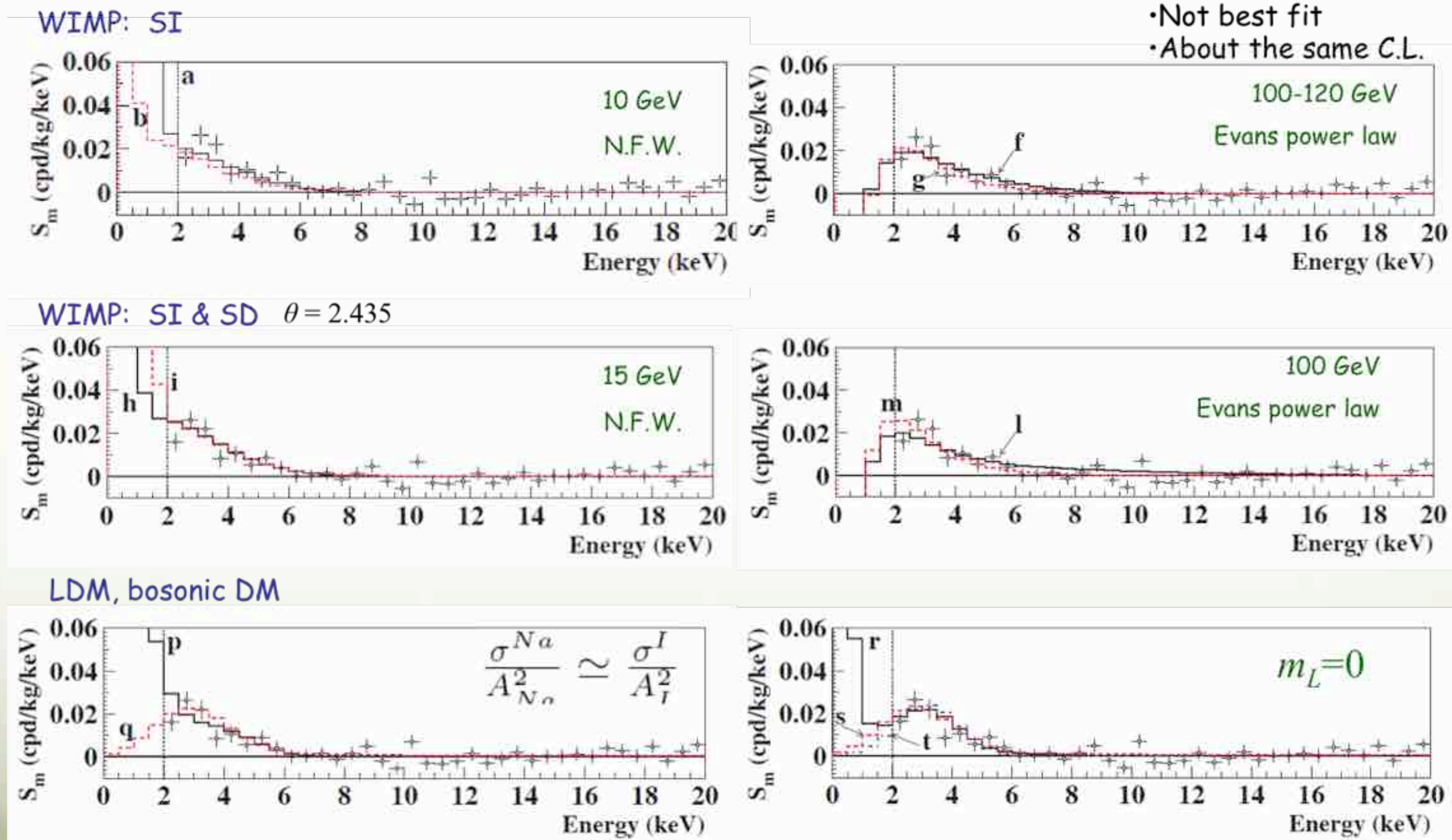
… and more

Model-independent evidence by DAMA/NaI and DAMA/LIBRA

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

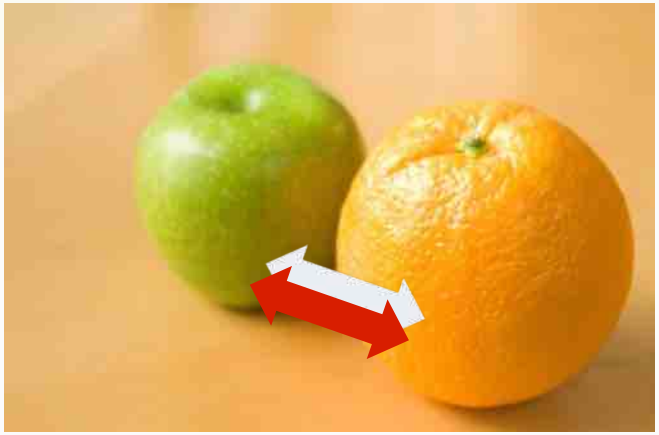
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

- Not best fit
- About the same C.L.



Compatibility with several candidates; other ones are open

EPJC56(2008)333
IJMPA28(2013)1330022



About interpretation

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…

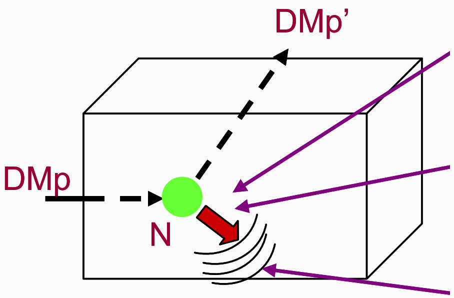
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- 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

... an example in literature...

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



Regions in the nucleon cross section vs DM particle mass plane

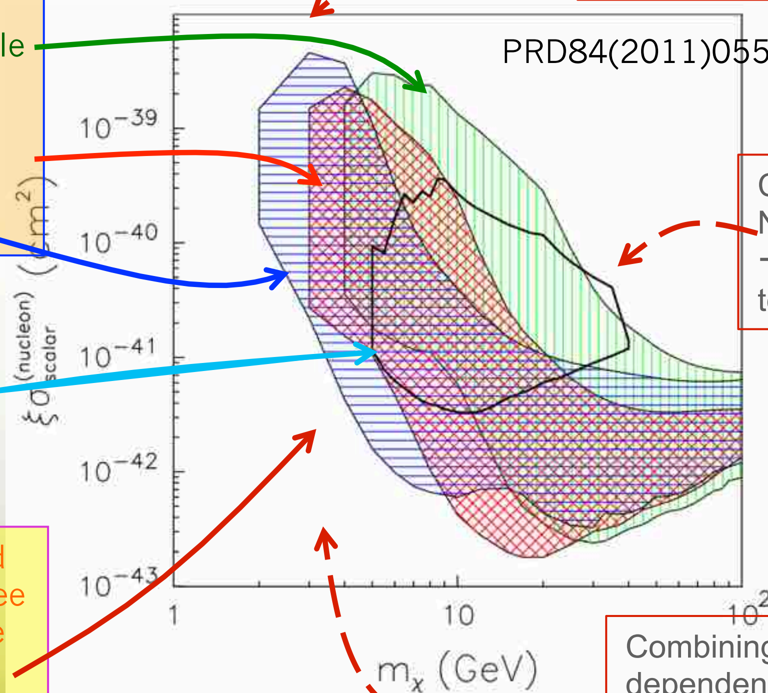
- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters 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 a particular set of astrophysical, nuclear and particle Physics assumptions 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 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

Scratching Below the Surface of the Most General Parameter Space (S. Scopel arXiv:1505.01926)

Most general approach: consider ALL possible NR couplings, including those depending on velocity and momentum

- A much wider parameter space opens up
- First explorations show that indeed large rooms for compatibility can be achieved

$$\mathcal{O}_1 = 1_\chi 1_N,$$
$$\mathcal{O}_2 = (v^\perp)^2,$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N,$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp,$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N},$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}.$$

… and much more considering experimental and theoretical uncertainties

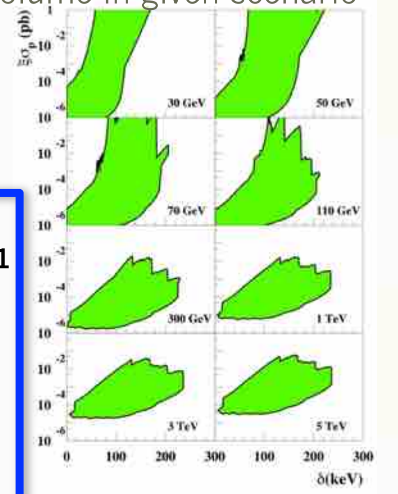
Other examples

DMp with preferred inelastic interaction:
$\chi^- + N \rightarrow \chi^+ + N$

- iDM mass states χ^+, χ^- with δ mass splitting
- Kinematic constraint for iDM:

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

DAMA/NaI+DAMA/LIBRA
Slices from the 3d allowed volume in given scenario



Fund. Phys. 40(2010)900

iDM interaction on Tl nuclei of the NaI(Tl) dopant?
PRL106(2011)011301

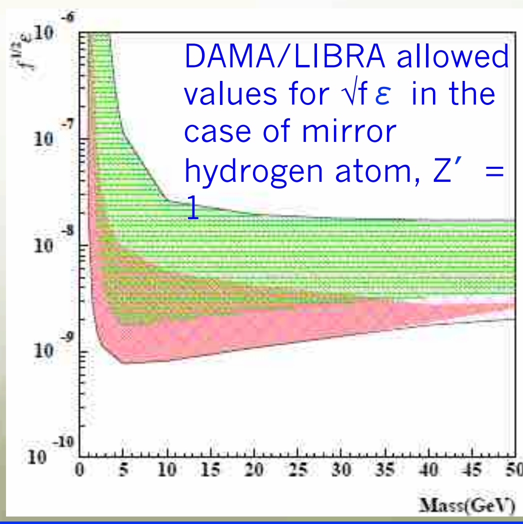
- For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with A~205, which are present as a dopant at the 10^{-3} level in NaI(Tl) crystals.
- large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

Mirror Dark Matter

Asymmetric mirror matter: mirror parity spontaneously broken ⇒ mirror sector becomes a heavier and deformed copy of ordinary sector
(See arXiv:1507.04317)

- 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



- *Other signatures?*
- *Diurnal effects*
- *Shadow effects*
- *Second order effects*
- *Directionality*
- *…*

Diurnal effects

EPJC 74 (2014) 2827

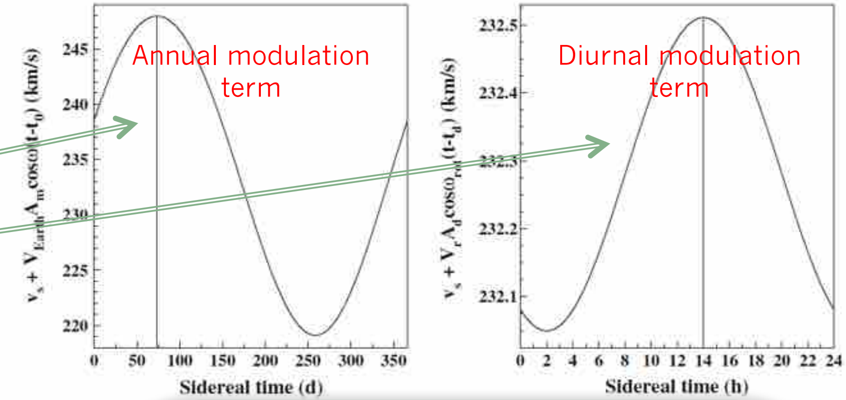
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

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:

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

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

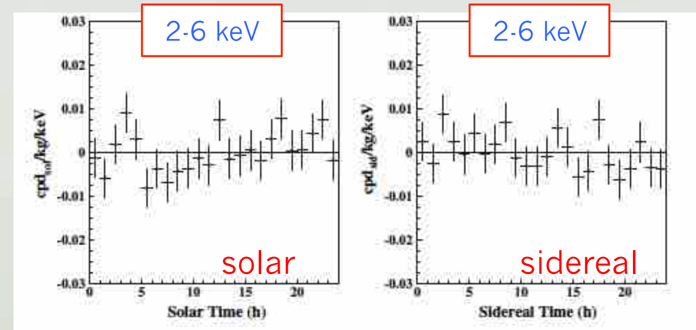
The ratio R_{dy} is a model independent constant:

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$ 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 period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes A_d are compatible with zero within the present sensitivity.

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

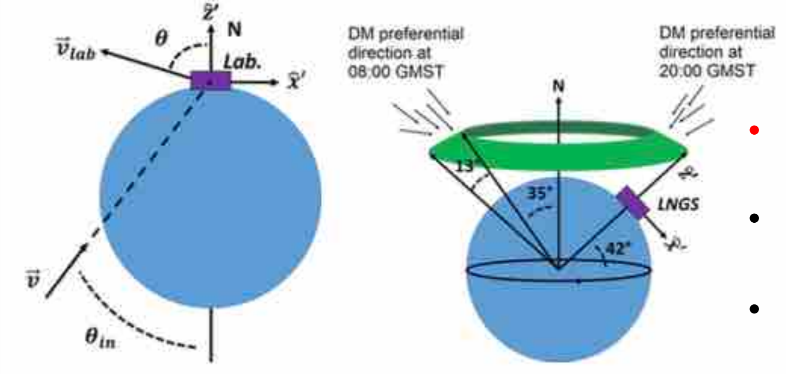


Present experimental sensitivity is not yet enough for the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect.

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

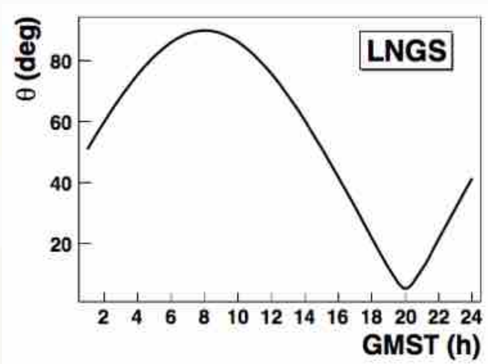
- *Other signatures?*
- *Diurnal effects*
- *Shadow effects*
- *Second order effects*
- *Directionality*
- *...*

Investigation of Earth Shadow Effect

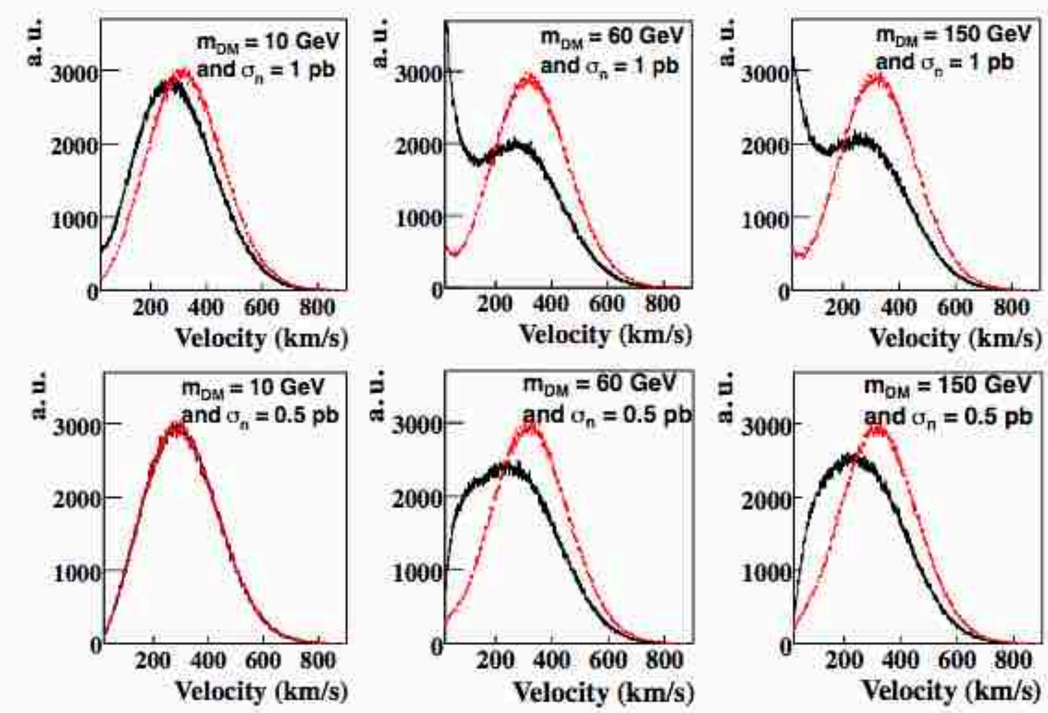


EPJC75 (2015) 239

- **Earth Shadow Effect** expected for DM candidate particles inducing 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



At LNGS:

GMST 20:00 red
→ Minimum thickness crossed
→ Maximum counting rate

GMST 08:00 black
→ maximum thickness crossed
→ Minimum counting rate

Investigation of Earth Shadow Effect

→ DAMA/LIBRA–phase1

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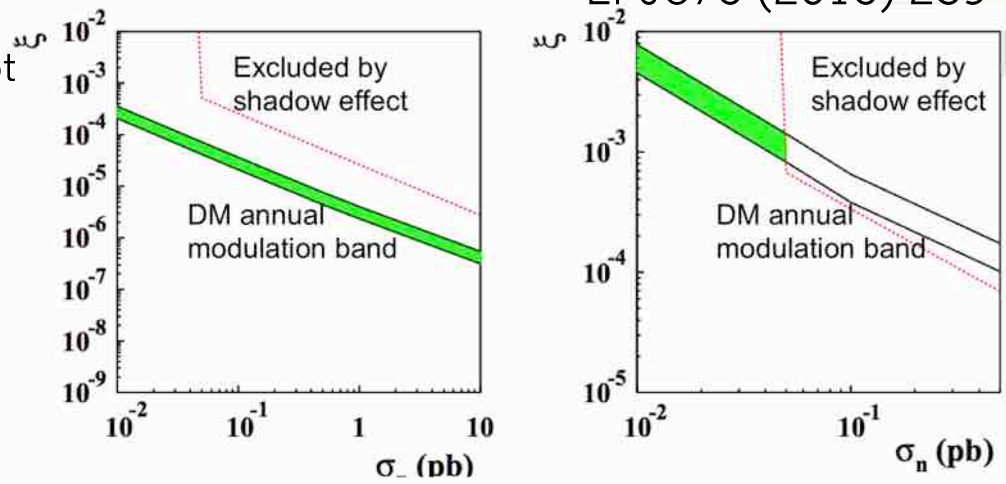
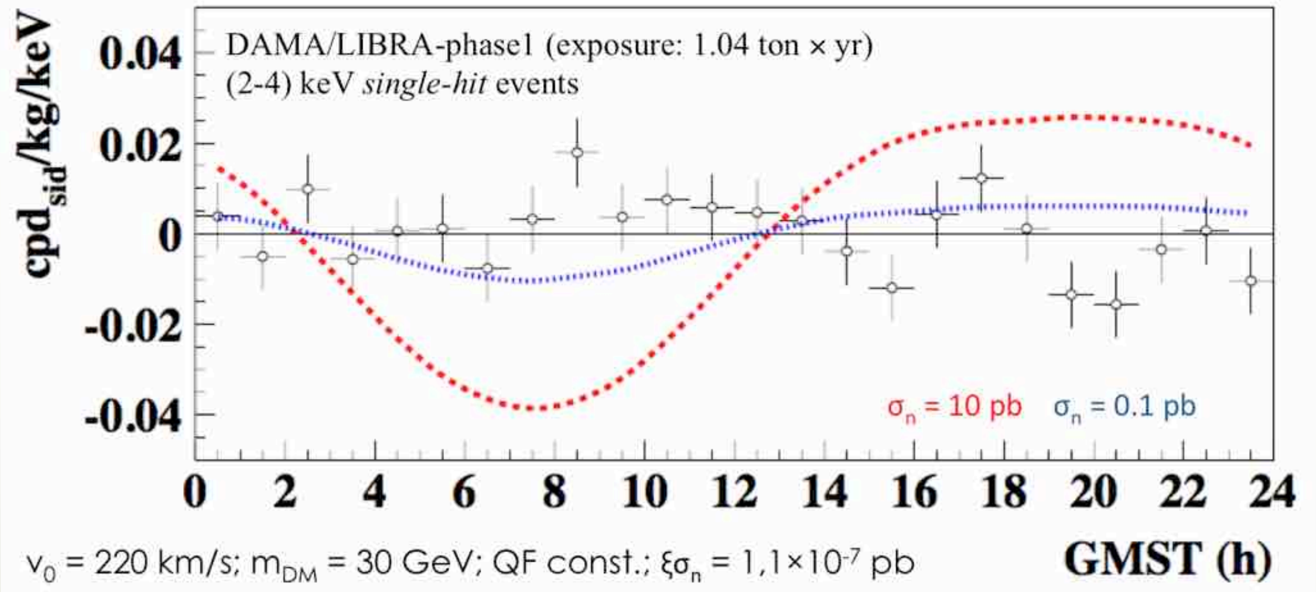
Two examples for a given model:

- *Left* m_{DM}=10 GeV, the upper limits on ξ do not constrain the results of annual modulation.
- *Right* m_{DM}=60 GeV, the upper limits on ξ do exclude the band with $\sigma_n > 0.05$ pb and $\xi > 10^{-3}$ for the considered model framework.

The combined allowed regions are reported as *shaded–green on-line–area*





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

Investigation of Earth Shadow Effect

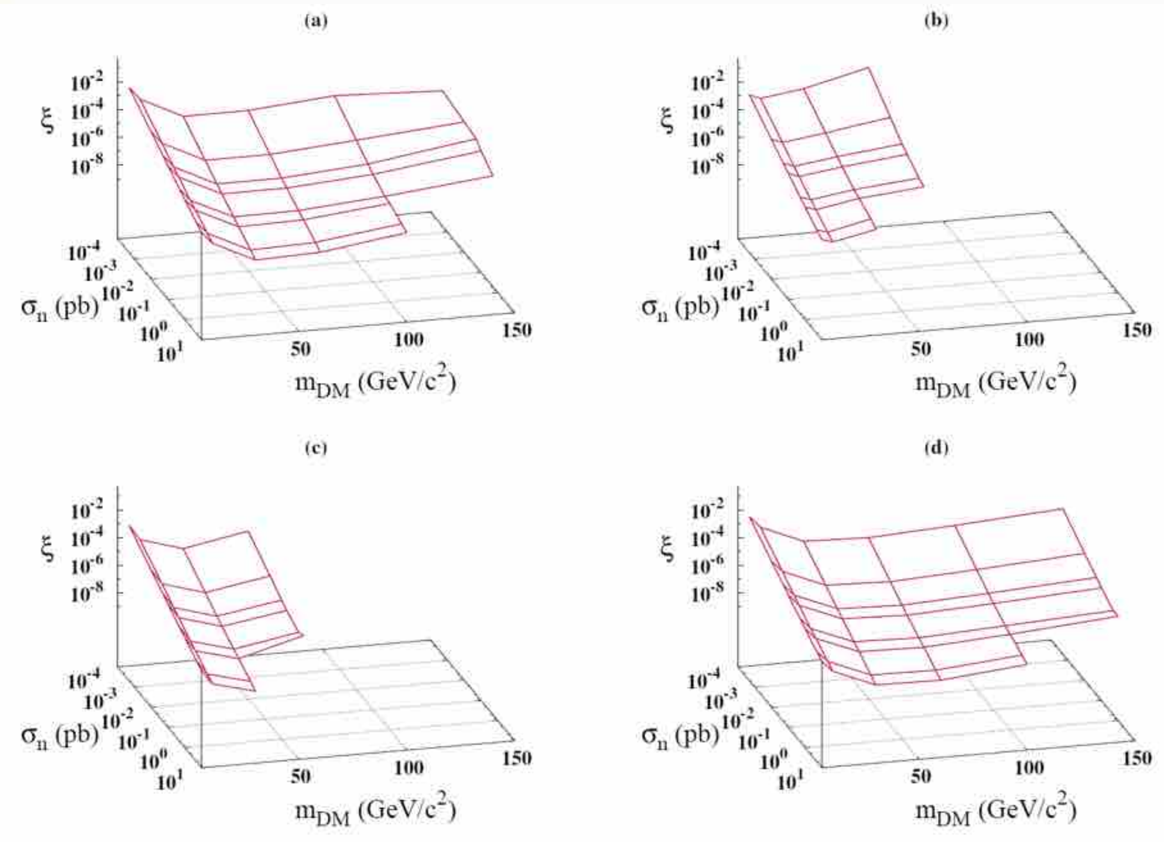
Expected counting rate for a given mass, cross section and scenario by MC:

EPJC75 (2015) 239

$$S_{d,sh}(t) = \xi \, \sigma_n \, S'_{d,sh}(t)$$

Expectations compared with diurnal residual rate of the *single-hit* events of DAMA/LIBRA-phase1 in (2-4) keV

Minimizing χ^2, upper limits on ξ can be evaluated



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

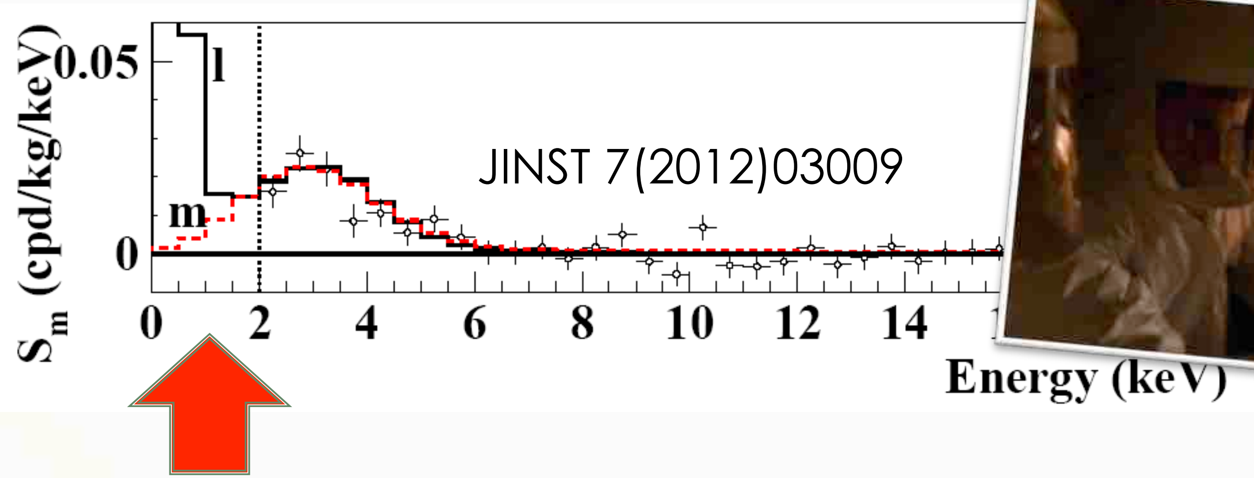
In these examples:
Isothermal halo model with v_0=220 km/s and v_{esc}=650 km/s

a) QF const. without channeling
b) QF const. including channeling
c) QF depending on energy
d) QF depending on energy renormalized to DAMA/LIBRA values

Red surface: 95% C.L. allowed mean value for ξ (surface thickness ± 30%)

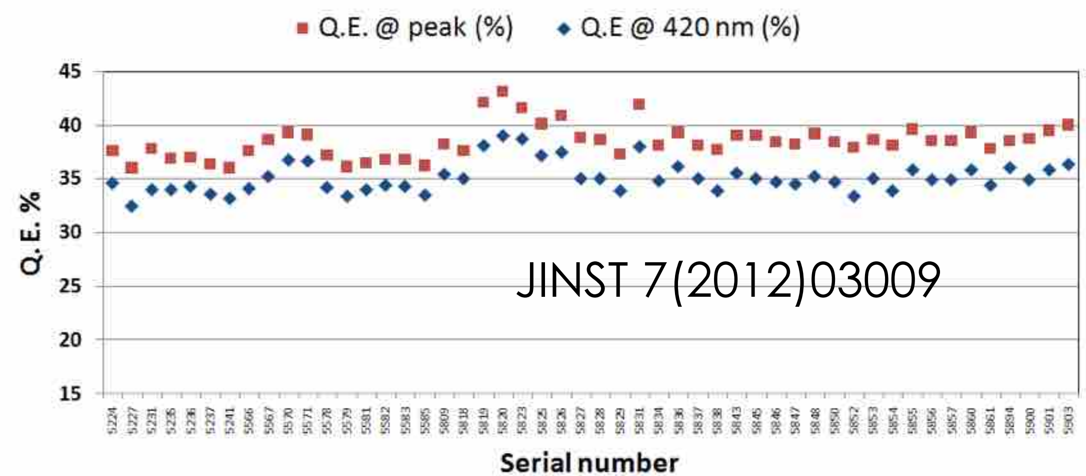
DAMA/LIBRA phase2 - running

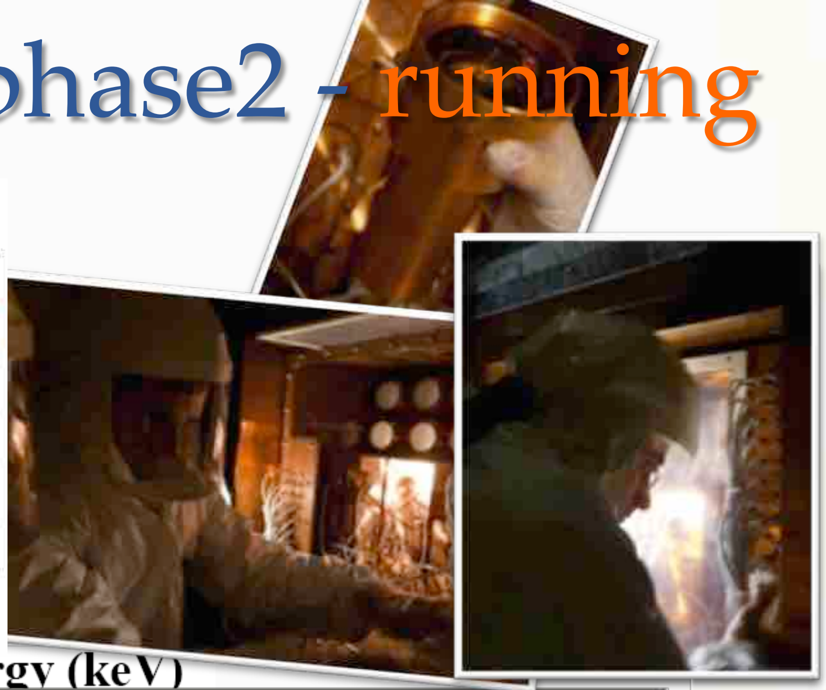
Second upgrade on end of 2010:
all PMTs replaced with new ones of higher Q.E.



DAMA/LIBRA phase2 - running

Quantum Efficiency features





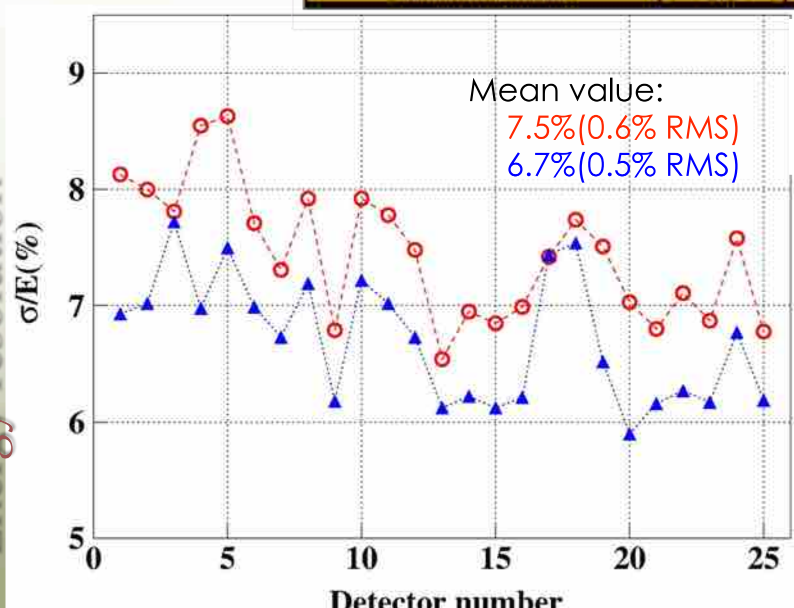
Residual Contamination

The limits are at 90% C.L.

Energy (keV)

PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{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)
Average			*0.43*	-	*47*	*0.12*	*83*	*0.54*	-	-
Standard deviation			*0.06*	-	*10*	*0.02*	*17*	*0.16*	-	-

Energy resolution



σ/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blu points) and with previous PMT EMI-Electron Tube (red points).

The light responses

Previous PMTs:	5.5-7.5 ph.e./keV
New PMTs:	up to 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*

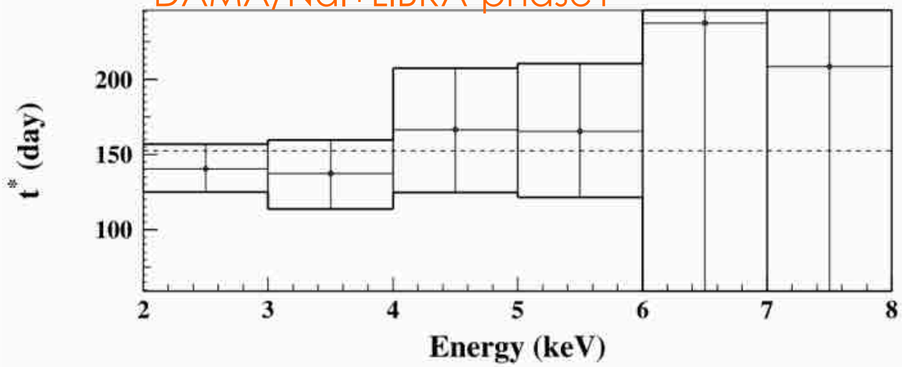
Features of the DM signal

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

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

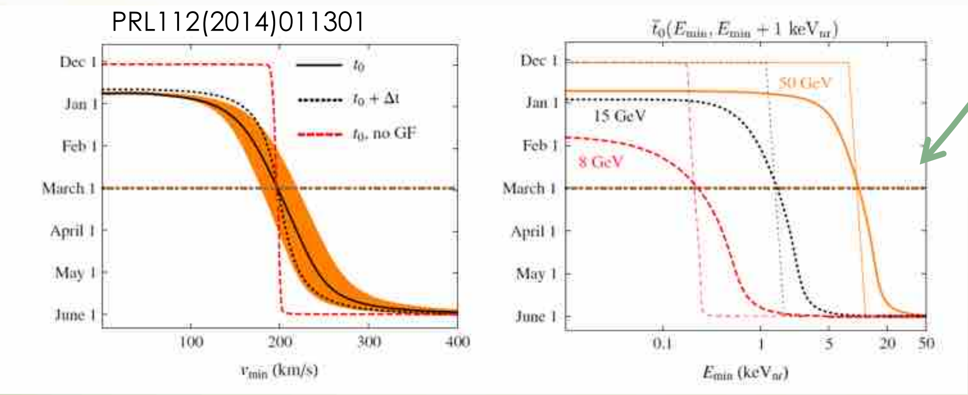
- the nature of the DM candidates
- possible diurnal effects on the sidereal time
- astrophysical models

DAMA/NaI+LIBRA-phase1

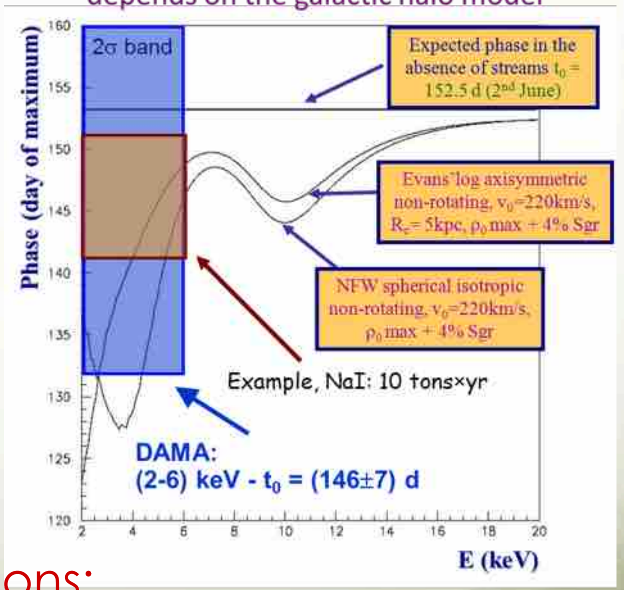


The annual modulation phase depends on :
- Presence of **streams** (as SagDEG and Canis Major) in the Galaxy
- Presence of **caustics**
- Effects of gravitational **focusing of the Sun**

PRL112(2014)011301



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



A step towards such investigations:

➔**DAMA/LIBRA-phase2**

with lower energy threshold and larger exposure

+ further possible improvements (DAMA/LIBRA-phase3) and DAMA/1ton

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, but not for the same PMT mod.:

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

Directionality technique

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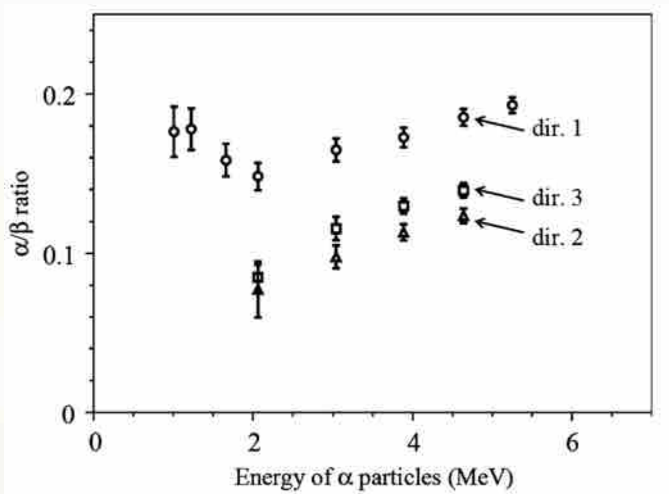
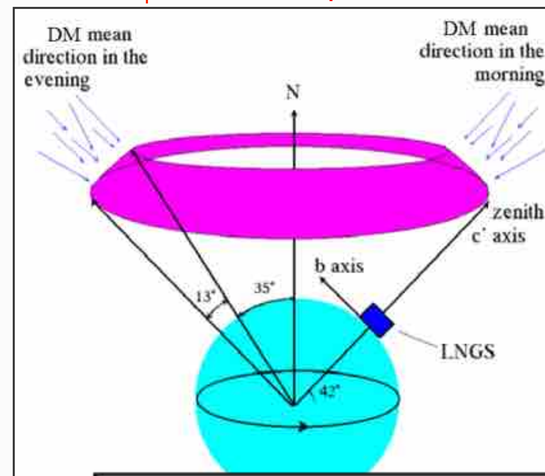
- Only for candidates inducing just recoils
- Identification of the Dark Matter particles by exploiting the non-isotropic recoil distribution correlated to the Earth velocity

The ADAMO project: Study of the directionality approach with $ZnWO_4$ anisotropic detectors



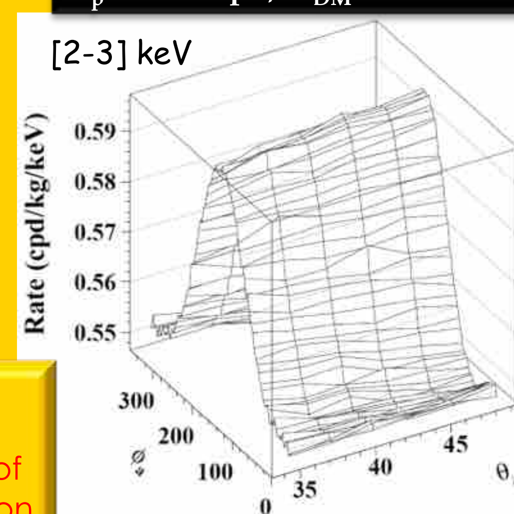
Nuclear recoils are expected to be strongly correlated with the DM impinging direction
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day



The light output and the pulse shape of $ZnWO_4$ detectors depend on the direction of the impinging particles with respect to the crystal axes

Both these anisotropic features can provide two independent ways to exploit the directionality approach

$\sigma_p = 5\times10^{-5}$ pb, $m_{DM} = 50$ GeV



These and others competitive characteristics of $ZnWO_4$ detectors could permit to reach sensitivity comparable with that of the DAMA/LIBRA positive result

Example (for a given model framework) of the expected counting rate as a function of the detector velocity direction

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo supported at **9.3σ** C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: 1.33 ton × yr)
- Modulation parameters determined with high precision
- New investigation on different peculiarities of the DM signal exploited (**Diurnal Modulation** and **Earth Shadow Effect**)
- 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) to investigate further features of DM signals and second order effects
- Continuing investigations of rare processes other than DM as well as further developments
- **DAMA/LIBRA – phase3 under study**
- R&D for a possible DAMA/1ton set-up in progress
- Study of $ZnWO_4$ scintillator for exploiting directionality technique in progress