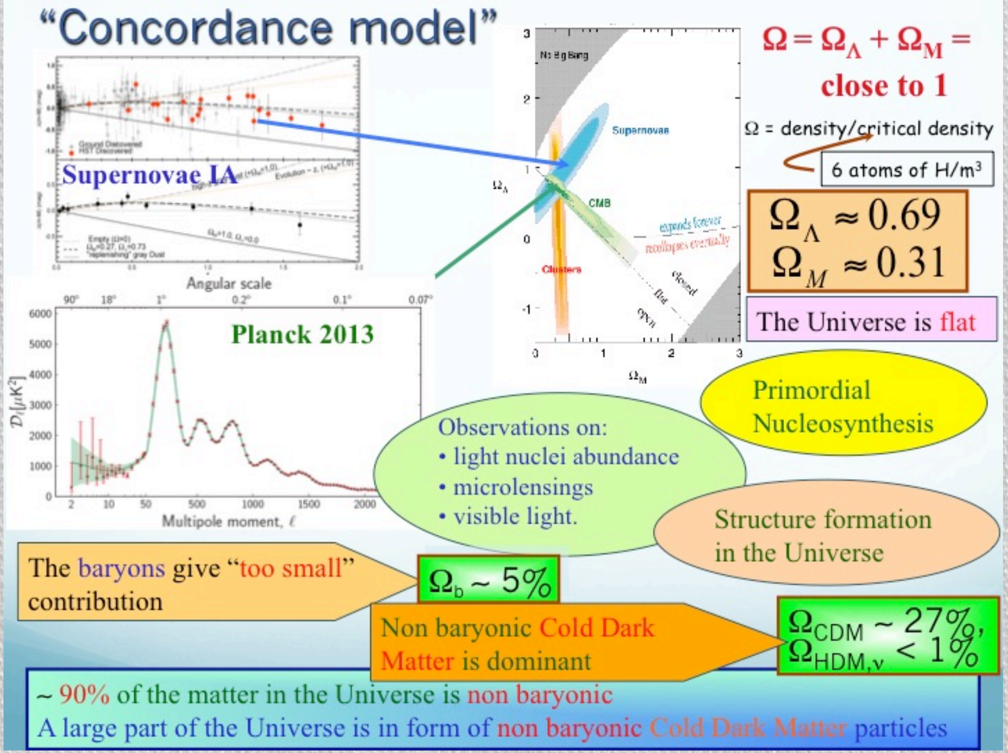
Dark Matter Particles in the Galactic Halo

R. Bernabei
University and INFN
Roma Tor Vergata

Dark Matter in the Universe

- A large part of the Universe is made of Dark Matter and Dark Energy
- The Dark Matter is fundamental for the formation of the structures and galaxies in the Universe
- The "baryonic" matter is only ≈5% of the total budget
- Concordance model and precision cosmology
- Non-baryonic Dark Matter is the dominant component (≈27%) in the matter.
- DM particles → beyond the SM



"Concordance model"

$\Omega = \Omega_\Lambda + \Omega_M =$ close to 1

Ω = density/critical density

6 atoms of H/m³

$\Omega_\Lambda \approx 0.69$
$\Omega_M \approx 0.31$

The Universe is flat

Primordial Nucleosynthesis

Observations on:
- light nuclei abundance
- microlensings
- visible light.

Structure formation in the Universe

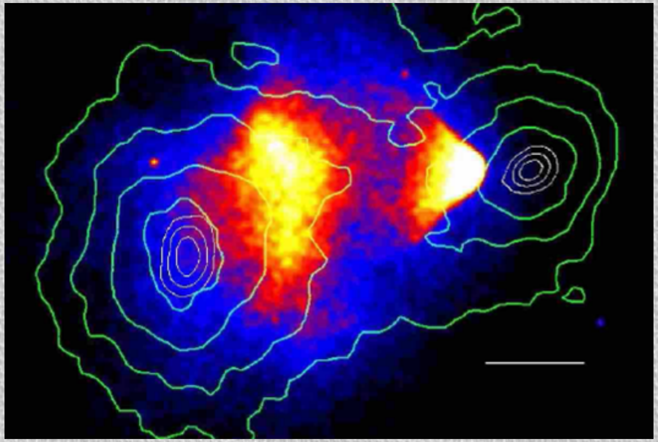
The baryons give "too small" contribution

$\Omega_b \sim 5\%$

Non baryonic Cold Dark Matter is dominant

$\Omega_{CDM} \sim 27\%,$
$\Omega_{HDM,\nu} < 1\%$

~ 90% of the matter in the Universe is non baryonic
A large part of the Universe is in form of non baryonic Cold Dark Matter particles



Relic DM particles from primordial Universe

What accelerators can do:
to demostrate 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

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

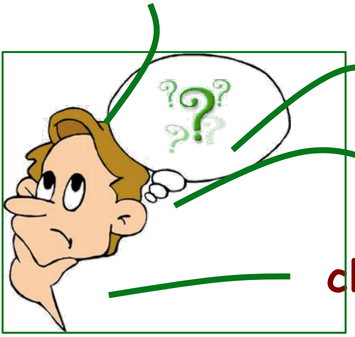
mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν's



Right halo model and parameters?

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

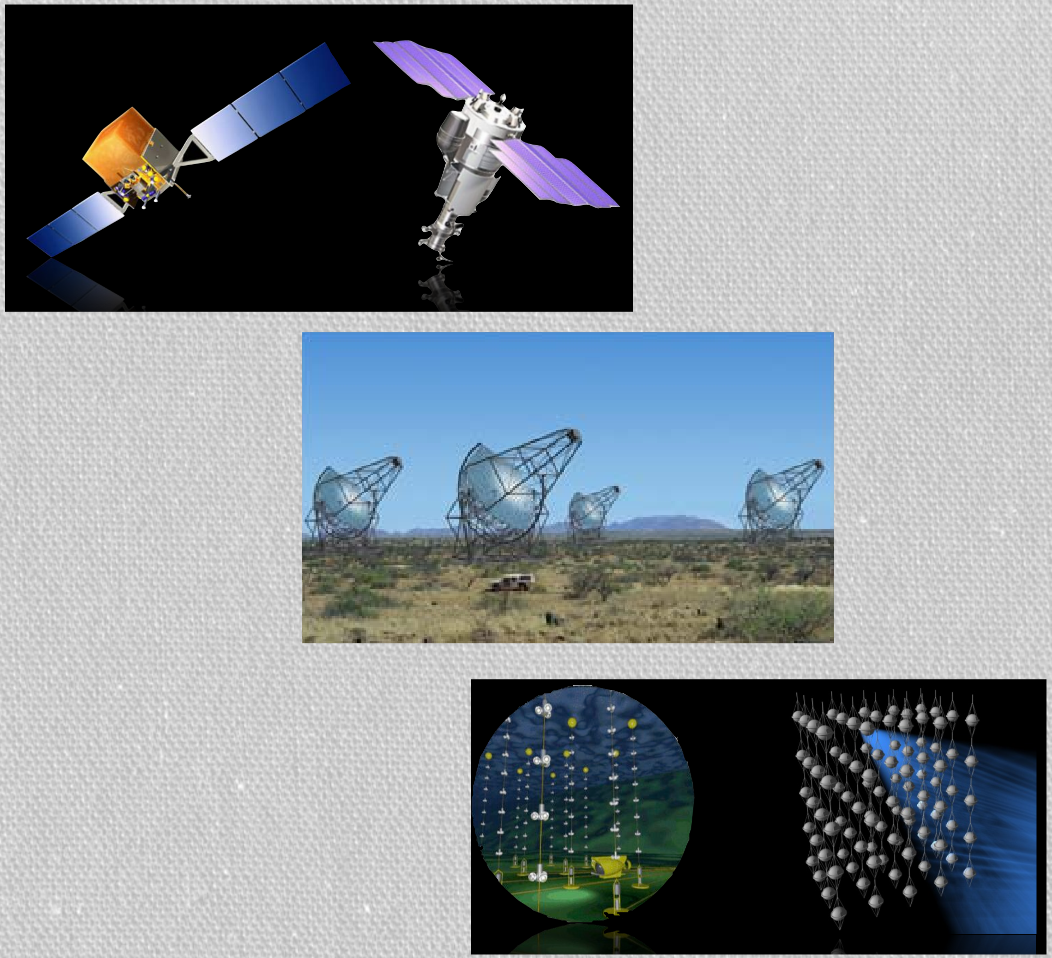
etc

Non thermalized components?

Caustics?

clumpiness?

Indirect detection: measurement of secondary particles (ν’s, γ’s, antiparticles,…) occasionally produced by annihilation of some particular DM candidate in celestial bodies provided several assumptions are fulfilled (approach: continuous radiation damage + subtraction of unknown competing background + strongly model dependent + can require very high boost factor, …)



No direct model independent comparison possible with direct detection and accelerators

MULTI-MESSENGER? ONLY FOR SOME PARTICULAR CASES

Some direct detection processes:

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

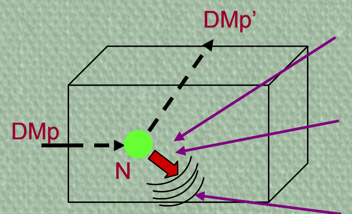
→ W has 2 mass states χ+ , χ- with δ mass splitting

→ 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



Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, ...

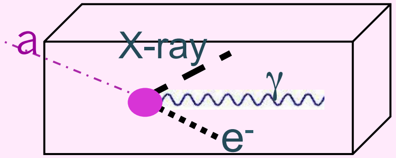
Scintillation:
NaI(Tl),
LXe,CaF_2(Eu), …

- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

- Conversion of particle into e.m. radiation

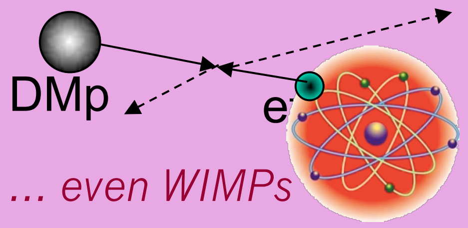
→ detection of γ, X-rays, e^-



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

- Interaction only on atomic electrons

→ detection of e.m. radiation

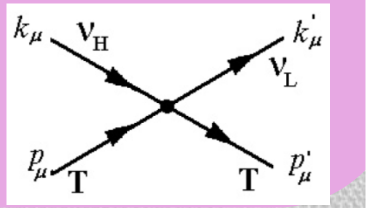


… even WIMPs

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

→ detection of electron/nucleus recoil energy

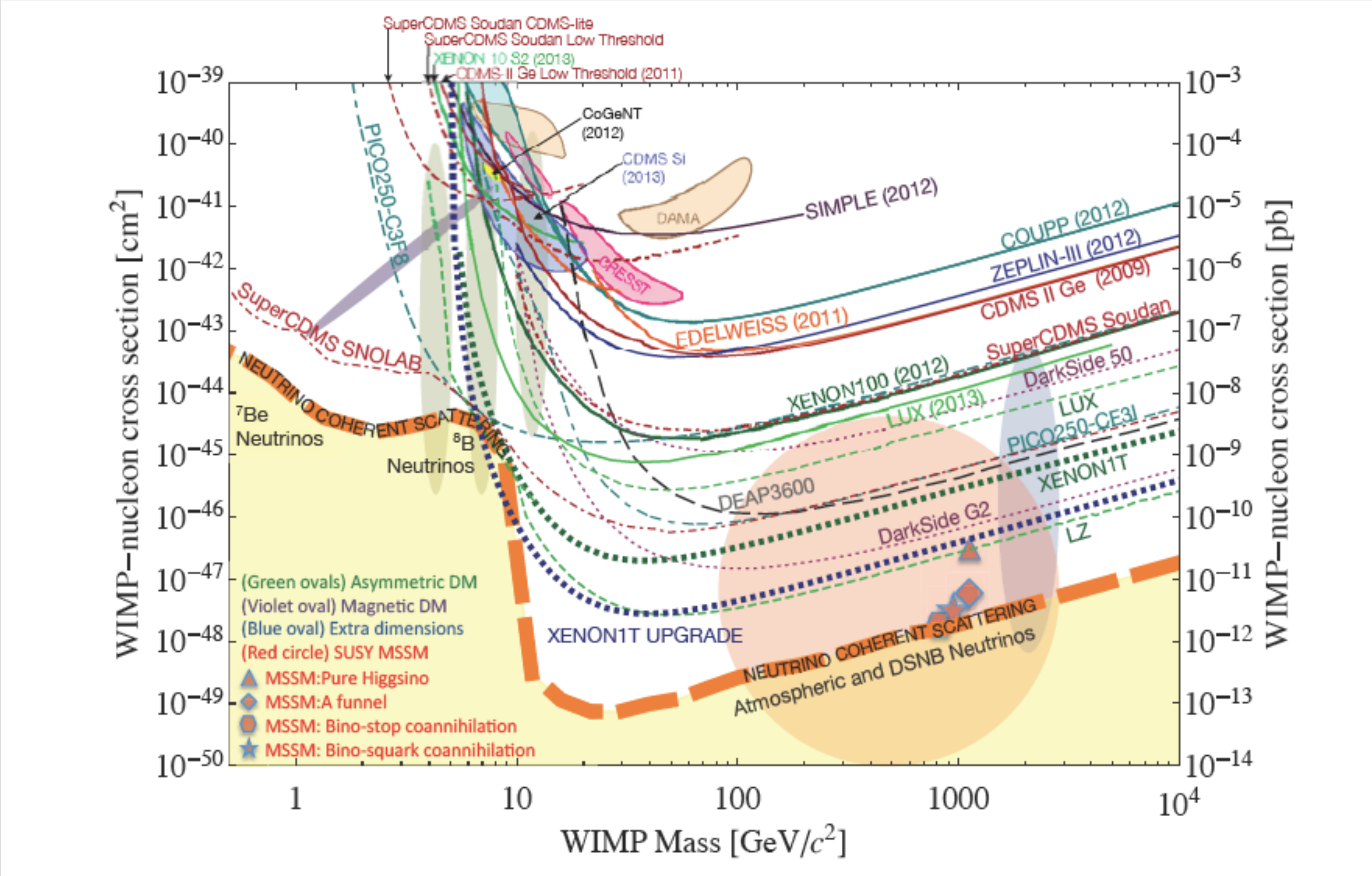
e.g. sterile ν



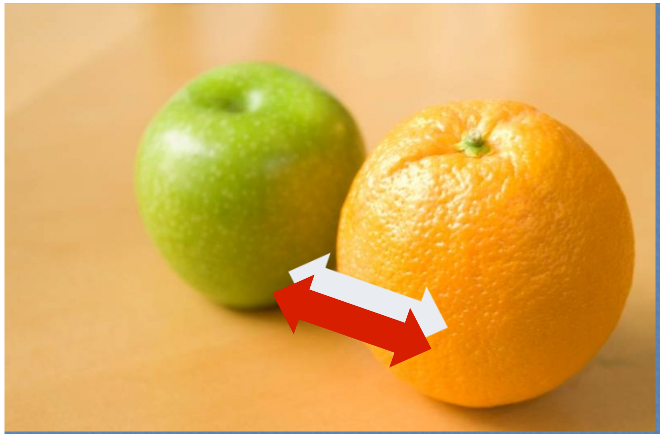
… also other ideas …

- … and more

Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



No, it isn't. This is just a largely arbitrary/partial/incorrect exercise



…models…

- Which particle?
- Which interaction?
- 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 possible among experiments using different target materials and/or approaches

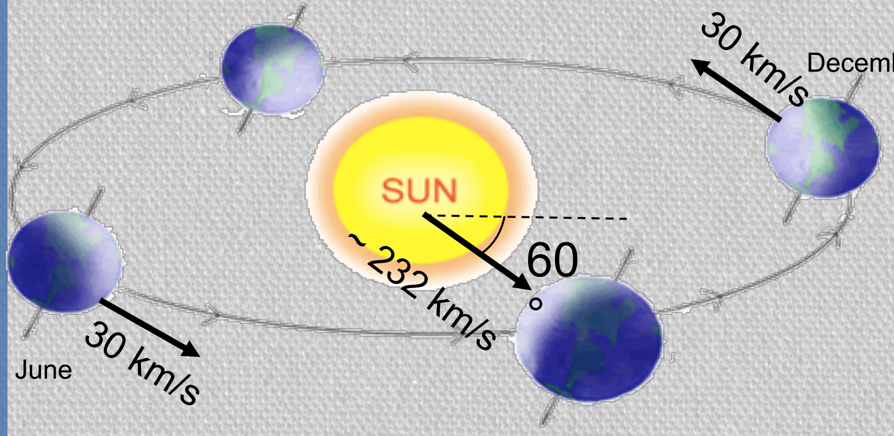
The DM annual modulation: a model independent signature to investigate the DM particles component in the galactic halo

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.

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

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 = 2nd June (when $v_\oplus$ is maximum)

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

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

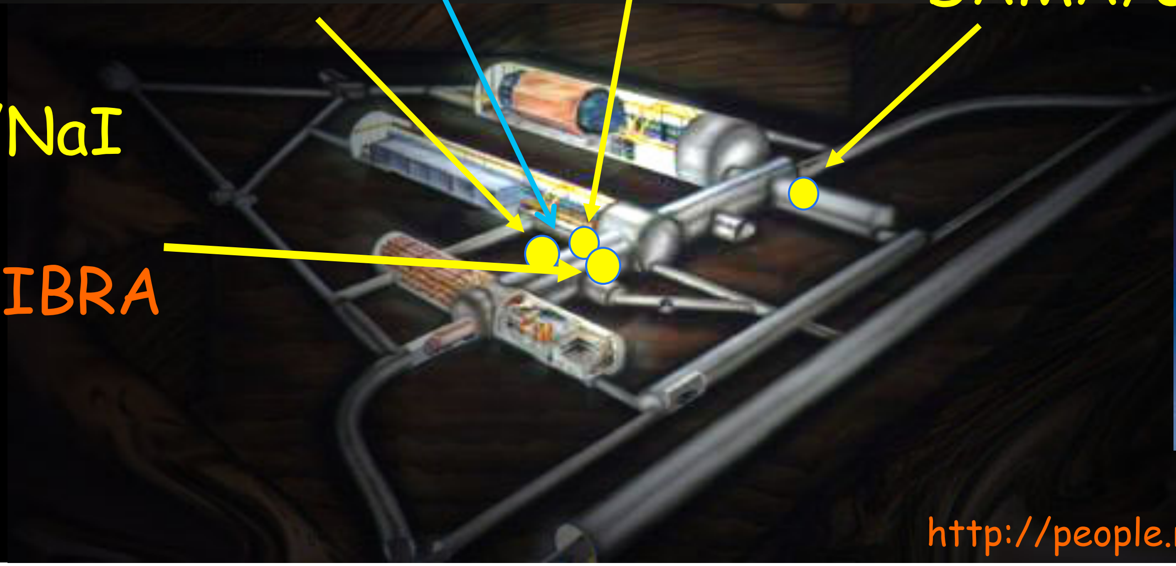
the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

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

Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev and others
+ neutron meas.: ENEA-Frascati
+ in some studies on $\beta\beta$ decays (DST-MAE project): IIT Kharagpur, India

DAMA: an observatory for rare processes @LNGS



DAMA/CRYS

DAMA/R&D

DAMA/LXe

DAMA/Ge

DAMA/NaI

DAMA/LIBRA

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

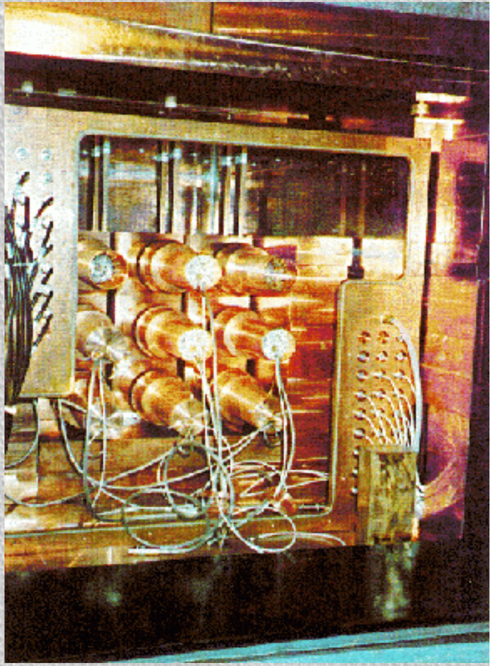
The pioneer DAMA/NaI: ≈100 kg highly radiopure NaI(Tl)

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



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

The 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

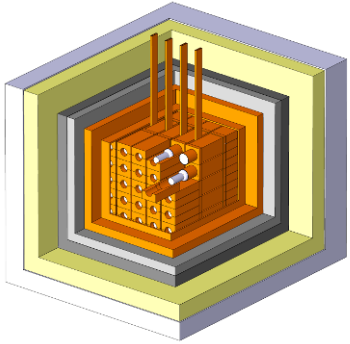
- *Radiopurity,performances, procedures, etc.:* NIMA592(2008)297, JINST 7 (2012) 03009
- *Results on DM particles: Ann. Mod. Signature:* EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648
- *related results:* PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC75 (2015) 239, EPJC75(2015)400
- *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

The DAMA/LIBRA set-up

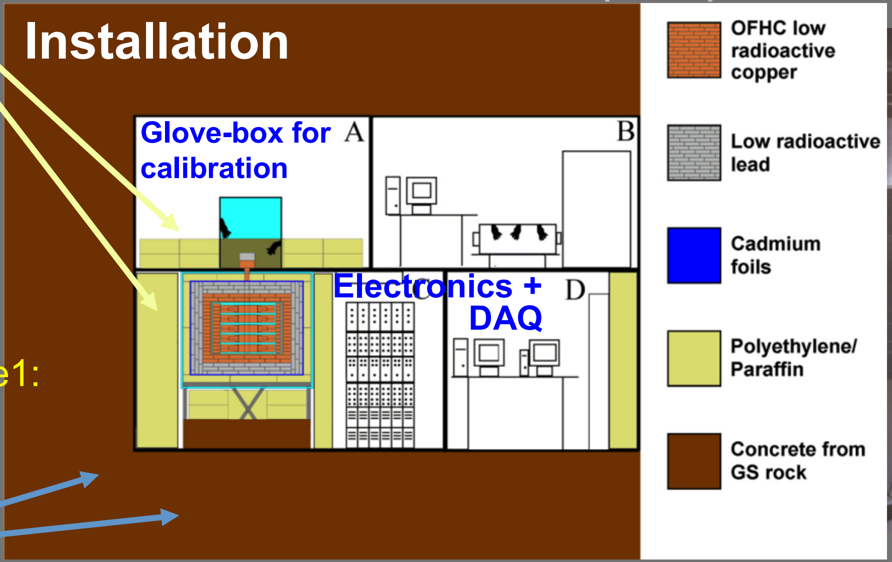
For details, radiopurity, performances, procedures, etc.
NIMA592(2008)297, JINST 7(2012)03009

Polyethylene/paraffin

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold



DAMA/LIBRA-phase1:
5.5-7.5 phe/keV

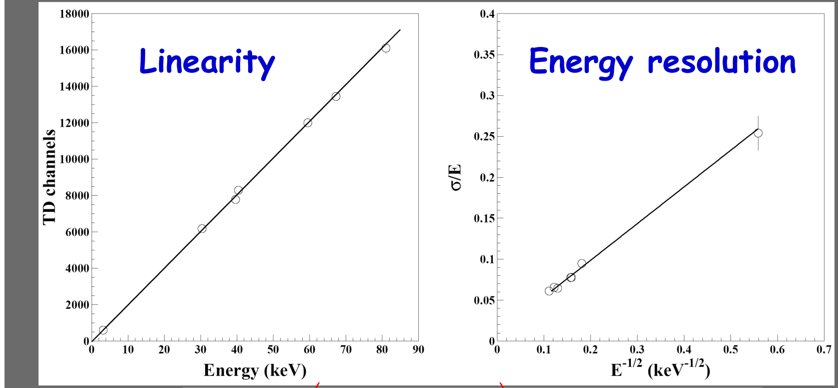


~ 1m concrete from GS rock

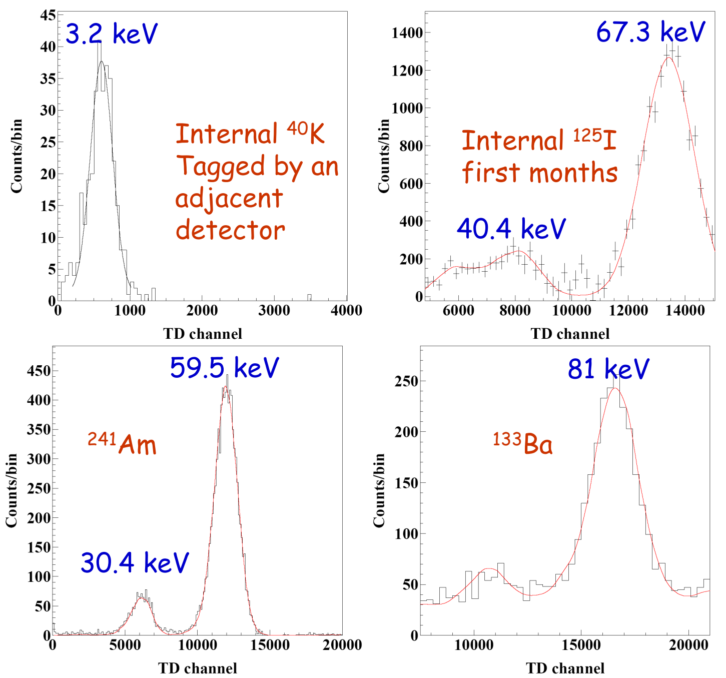
- Dismounting/Installing protocol in HPN_2
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of OFHC Cu, 15 cm of boliden Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waweform Analyzer Acqiris DC270 (2chs per detector), 1 *Gsample/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 was done for the low energy

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

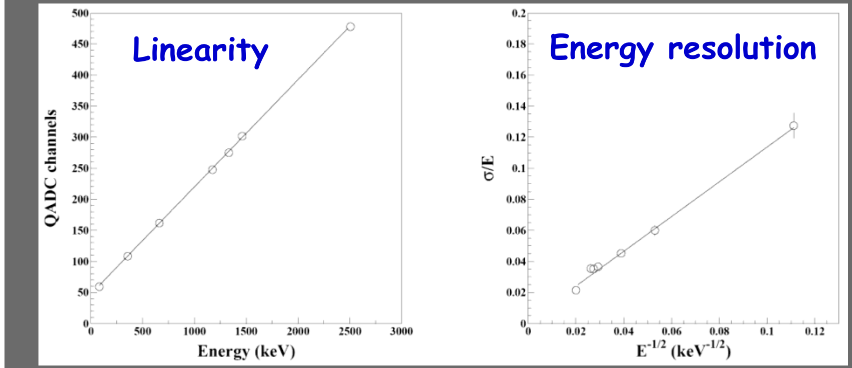


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1)\cdot 10^{-3}$$



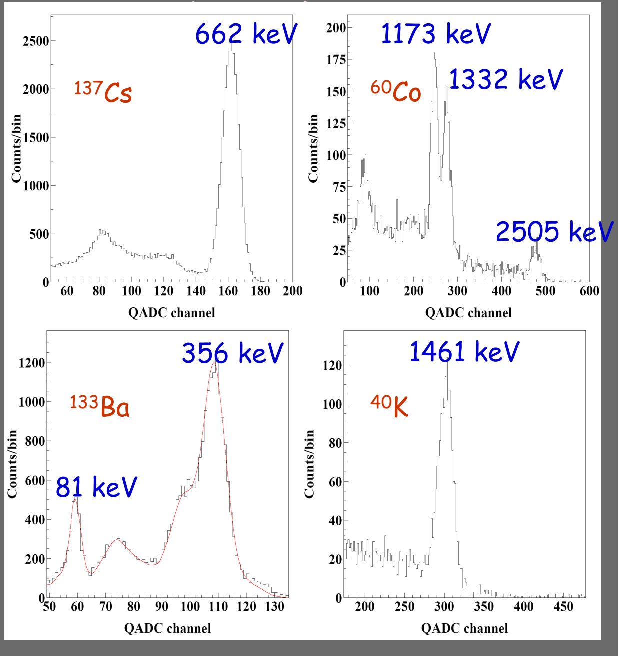
The curves superimposed to the experimental data have been obtained

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



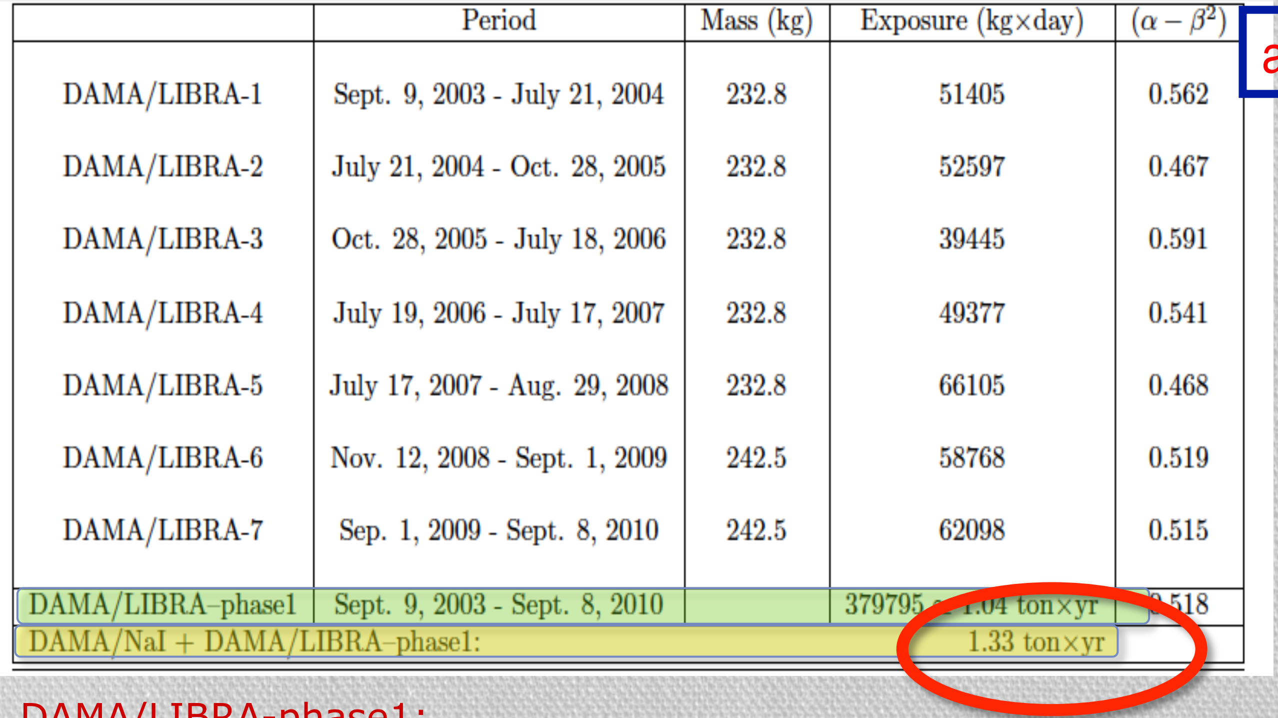
$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23)\cdot 10^{-4}$$

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



Thus, here and hereafter keV means keV electron equivalent

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 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

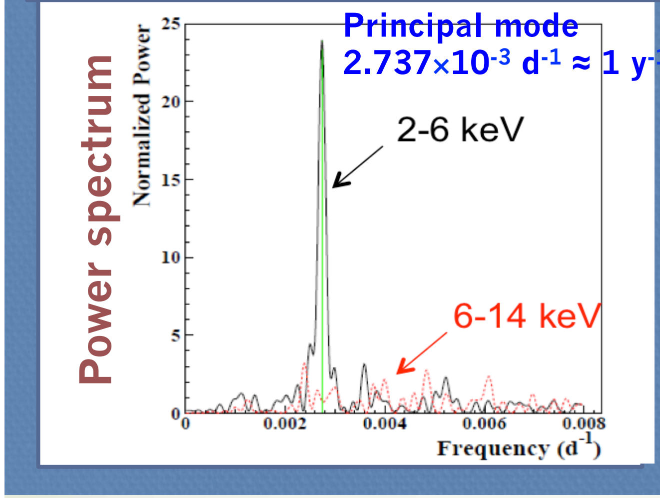
DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

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

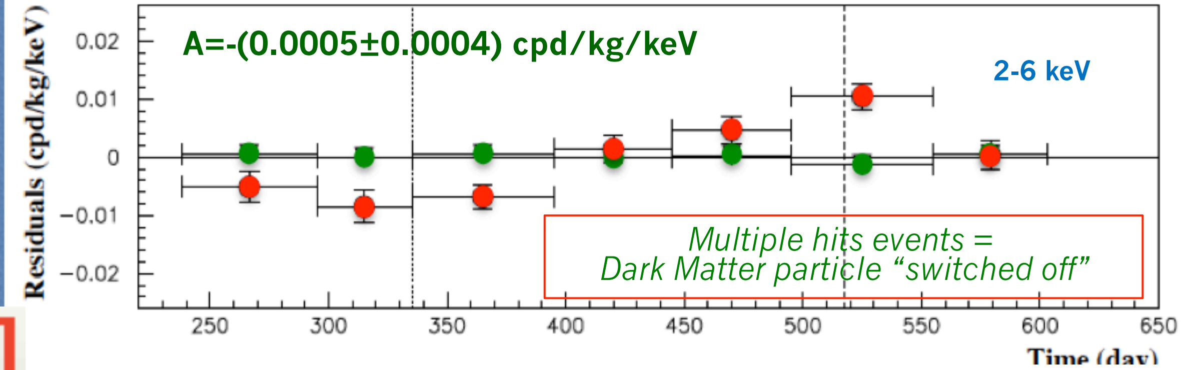
Measured modulation amplitudes (A), period (T) and phase (t_0) from single-hit residual rate vs time

	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	**0.0190 ±0.0020**	**0.996 ±0.0002**	**134 ± 6**	**9.5σ**
(2-5) keV	**0.0140 ±0.0015**	**0.996 ±0.0002**	**140 ± 6**	**9.3σ**
(2-6) keV	**0.0112 ±0.0012**	**0.998 ±0.0002**	**144 ± 7**	**9.3σ**

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



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



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

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

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at more than 9 σ C.L.

Model Independent Annual Modulation Result

Max-lik analysis of single hit events

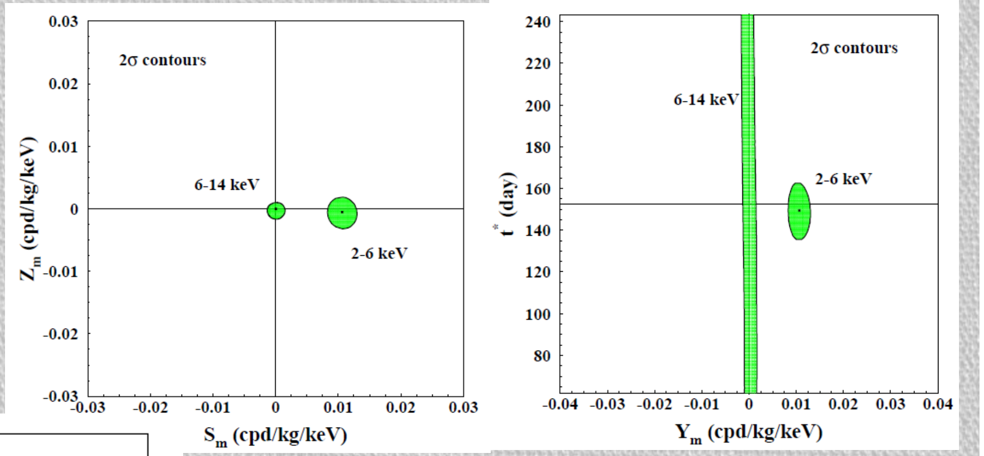
DAMA/NaI + DAMA/LIBRA-phase1

Total exposure: 487526 kg×day = **1.33 ton×yr**

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

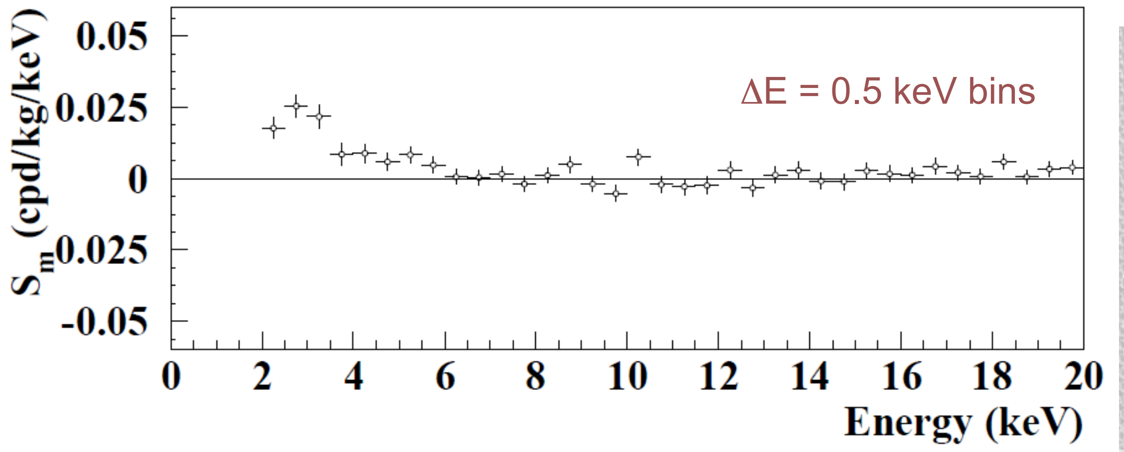
$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right] + Z_m \sin\left[\omega\left(t - t_0\right)\right] = S_0 + Y_m \cos\left[\omega\left(t - t^*\right)\right]$$

- **No 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



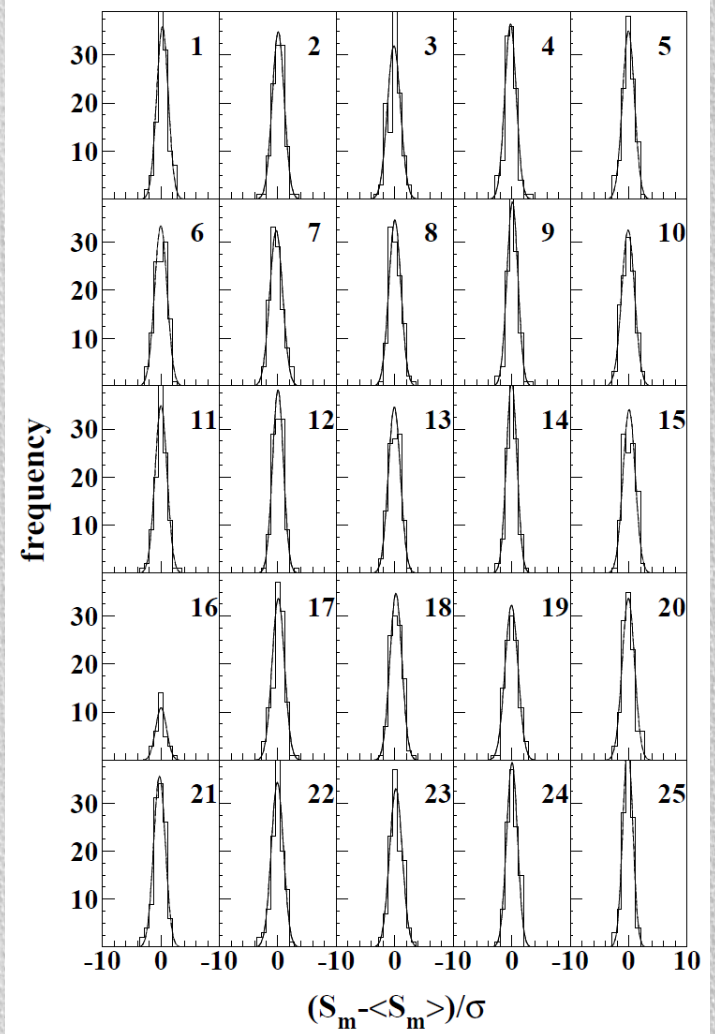
No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy all the many peculiarities of the signature are available.

Statistical distributions of the modulation amplitudes (S_m)

a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)
b) $<S_m>$ = mean values over the detectors and the annual cycles for each energy bin; σ = error on S_m

DAMA/LIBRA-phase1 (7 years)
total exposure: 1.04 ton×yr

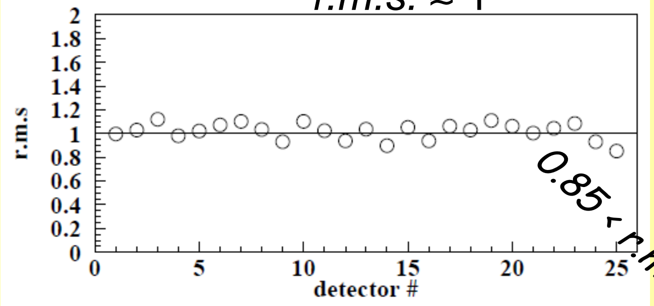
Each panel refers to each detector separately; 112 entries = 16 energy bins in 2-6 keV energy interval × 7 DAMA/LIBRA-phase1 annual cycles (for crys 16, 2 annual cycle, 32 entries)



2-6 keV

Standard deviations of
$\mathbf{(S_m\text{-}\langle S_m\rangle)/\sigma}$
for each detectors

r.m.s. ≈ 1



0.85 < r.m.s. < 1.12

$x=(S_m\text{-}<S_m>)/\sigma,$

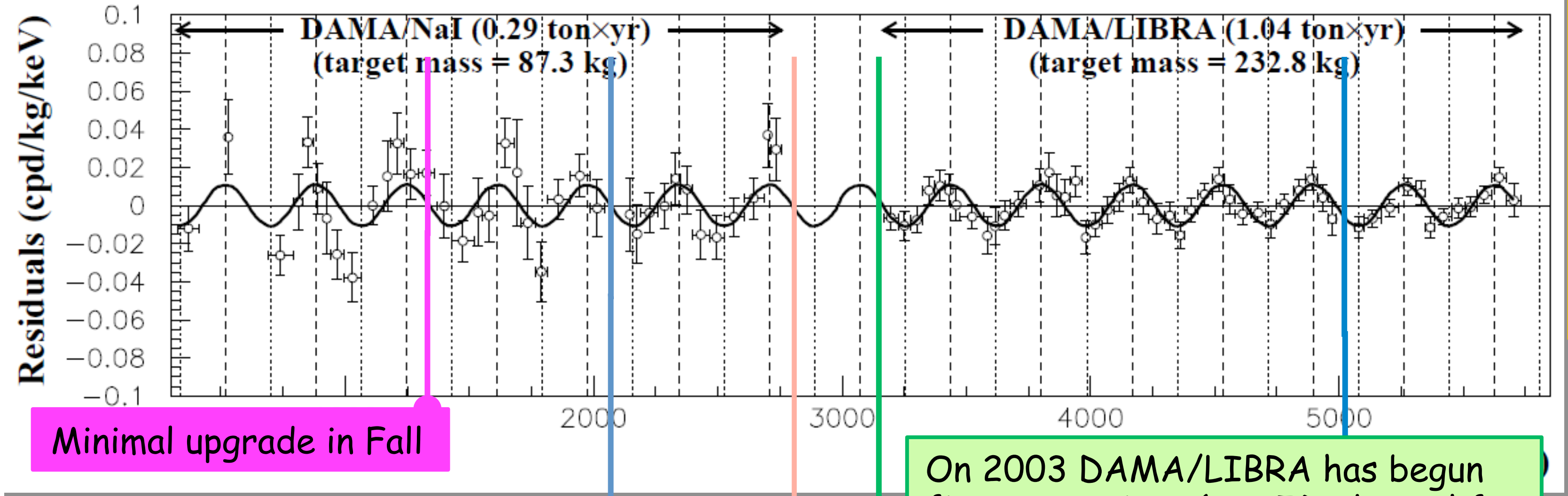
$\chi^2=\Sigma\, x^2$

Individual S_m values follow a normal distribution since $\mathbf{(S_m\text{-}<S_m>)/\sigma}$ is distributed as a Gaussian with a unitary standard deviation (r.m.s.)

→ $\mathbf{S_m}$ statistically well distributed in all the detectors, energy bin and annual cycles

DAMA/NaI & DAMA/LIBRA main upgrades and improvements

single-hit residual rate vs time



Minimal upgrade in Fall

July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector): (i) TD VXI Tektronix; (ii) Digital Unix DAQ system; (iii) GPIB-CAMAC.

July 2002 DAMA/NaI data taking completed

On 2003 DAMA/LIBRA has begun first operations (one TD channel for each PMT; two for each detector)

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:
(i) one detector has been recovered by replacing a broken PMT
(ii) new optimization of some PMTs and HVs performed
(iii) All TD replaced with new ones
(iv) new DAQ with optical read-out installed

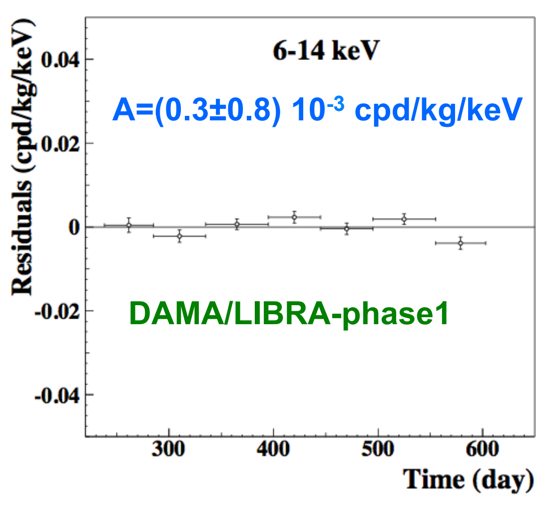
PHASE2

The second DAMA/LIBRA upgrade in Fall 2010: replacement of all the PMTs with higher Q.E. ones
(+ new preamplifiers in fall 2012 & other developments in progress)

DAMA/LIBRA-phase2 in data taking

Rate behaviour above 6 keV

- **No Modulation above 6 keV**

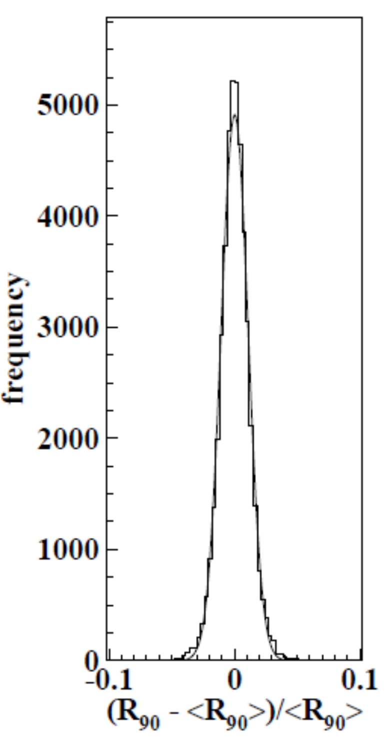


Mod. Ampl. (6-10 keV): cpd/kg/keV

(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
  - 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

σ ≈ 1%, fully accounted by statistical considerations

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

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

No role for μ in DAMA annual modulation result

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

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

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:**

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

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

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

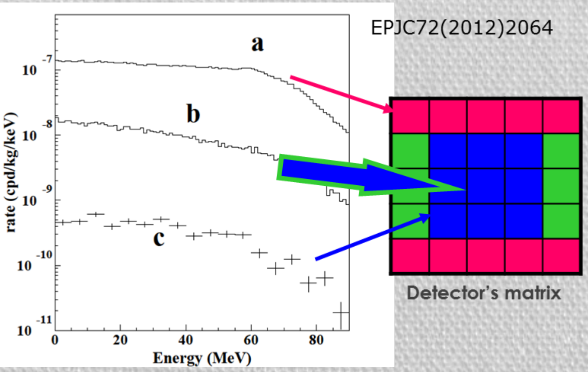
✓ **Inconsistency of the phase between DAMA signal and μ modulation**

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)

The DAMA phase: May 26 ± 7 days (stable over 13 years)

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

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

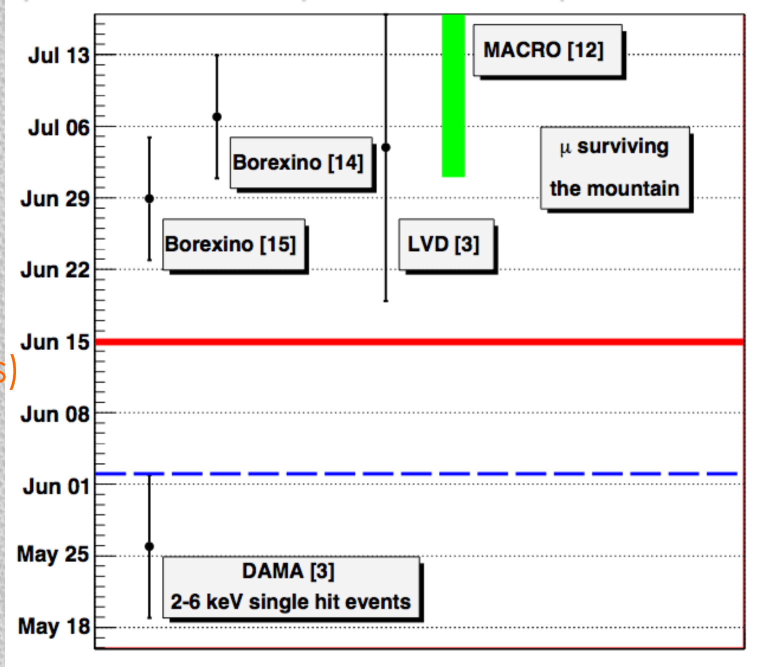


EPJC72(2012)2064

MonteCarlo simulation

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

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



- Contributions to the total neutron flux at LNGS;
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by:
    - neutrons,
    - muons,
    - solar neutrinos.

$$\Phi_k = \Phi_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$$
$$R_k = R_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$$

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

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

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

+ In no case neutrons (of whatever origin), 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).

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

Final model independent result
DAMA/NaI+DAMA/LIBRA-phase1

Presence of modulation over 14 annual cycles at 9.3σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 14 independent experiments of 1 year each one

The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.33 ton × yr (14 annual cycles)

In fact, as required by the DM annual modulation signature:

1) The *single-hit* events show a clear cosine-like modulation, as expected for the DM signal

2) Measured period is equal to (0.998±0.002) yr, well compatible with the 1 yr period, as expected for the DM signal

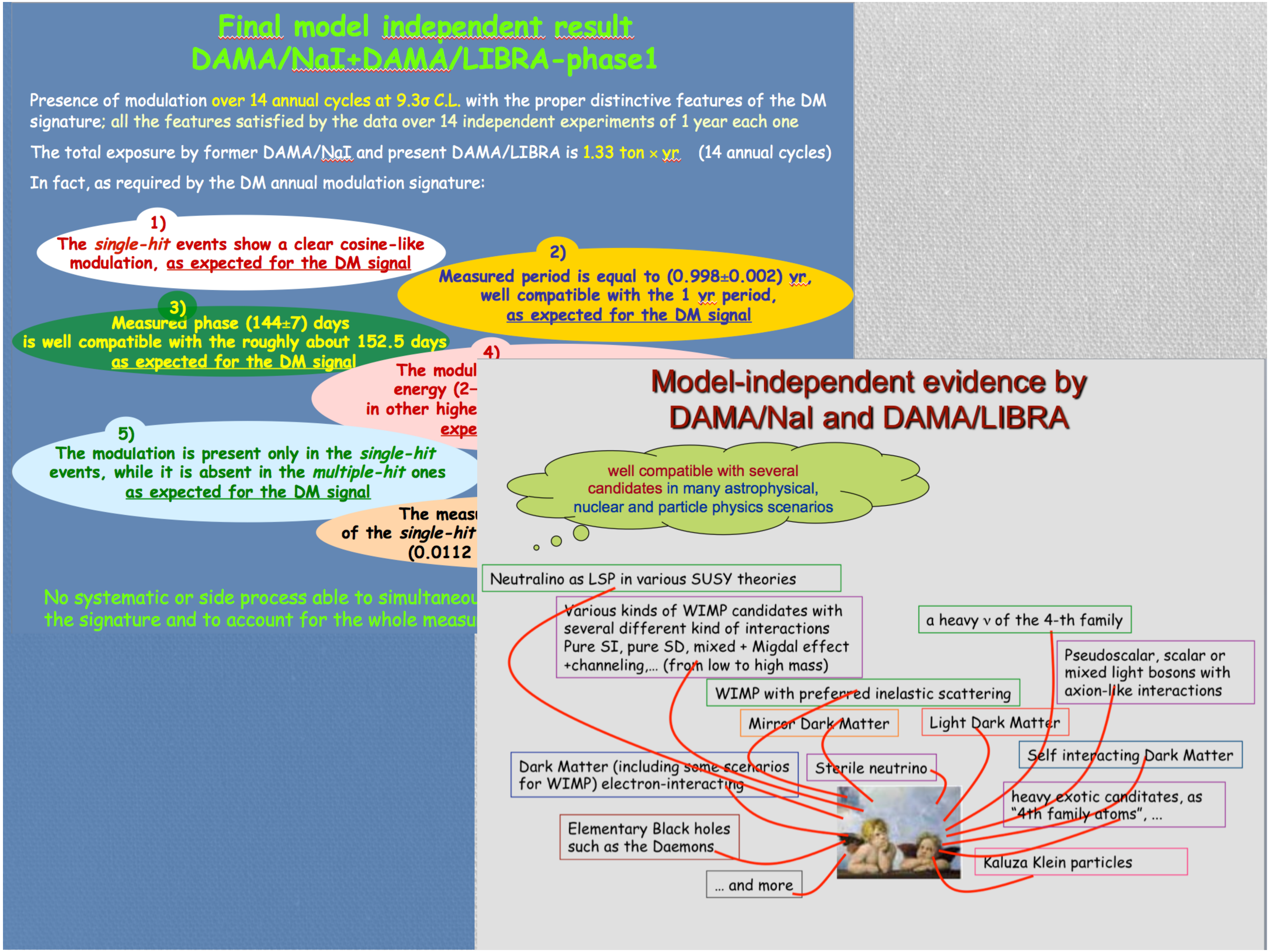
3) Measured phase (144±7) days is well compatible with the roughly about 152.5 days as expected for the DM signal

4) The modulation is present only in the low energy (2—6) keV energy interval and not in other higher energy regions, consistently with expectation for the DM signal

5) The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal

6) The measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2-6) keV energy interval is: (0.0112 ± 0.0012) cpd/kg/keV (9.3σ C.L.).

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



Final model independent result DAMA/NaI+DAMA/LIBRA-phase1

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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", ...

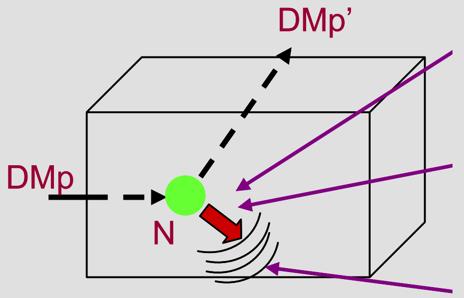
Elementary Black holes such as the Daemons

Kaluza Klein particles

... and more

... an example in literature...

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



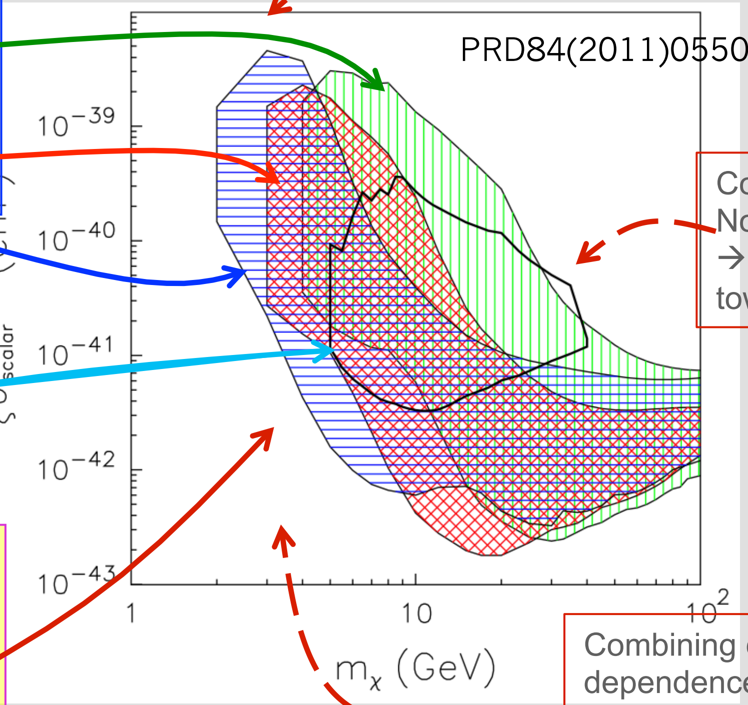
Regions in the nucleon cross section vs DM particle mass plane

- 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

Scratching Below the Surface of the Most General Parameter Space

(S. Scopel talk in DM2 session at MG14)

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

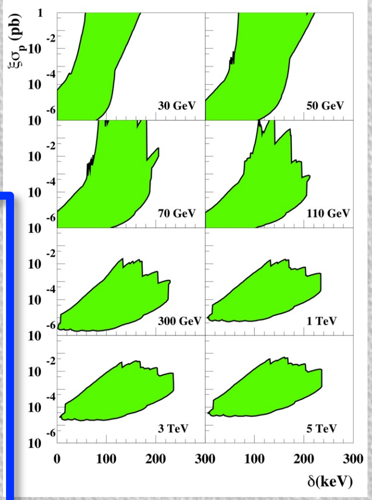
DMp with preferred inelastic interaction:

$\chi^- + N \rightarrow \chi^+ + N$

- 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 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.

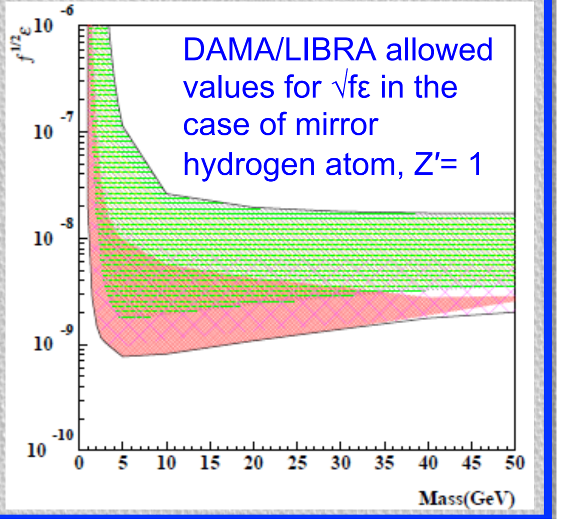
Mirror Dark Matter

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

(See EPJC75(2015)400)

- 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

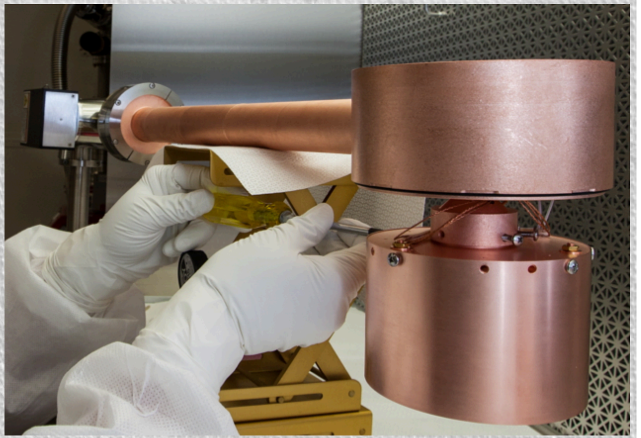


DAMA/LIBRA allowed values for √fε in the case of mirror hydrogen atom, Z′= 1

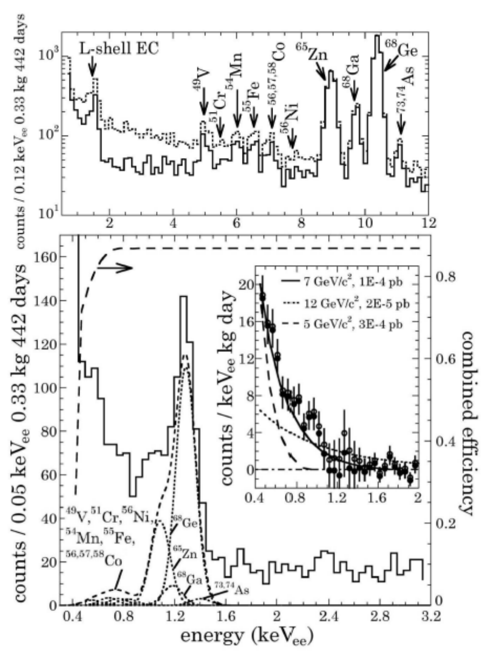
Positive hints from CoGeNT (ionization detector)

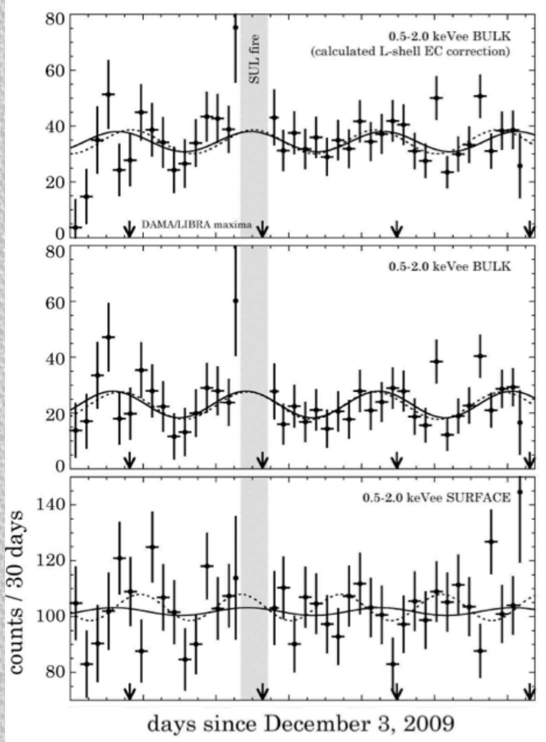
arXiv:1401.3295

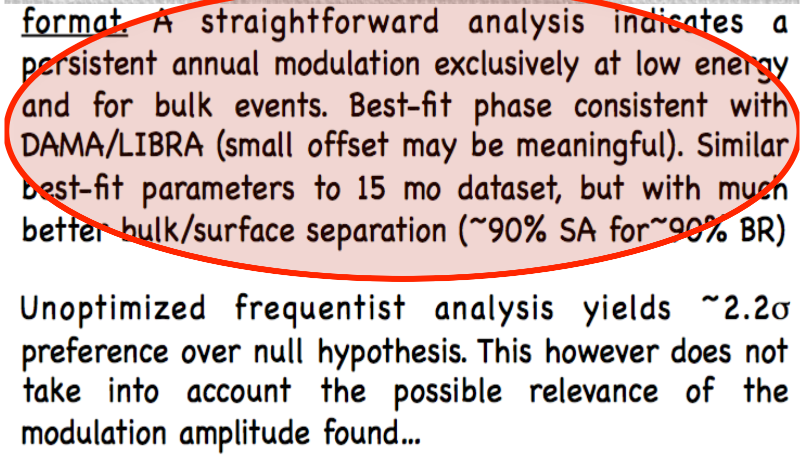
Experimental site: Soudan Underground Lab (2100 mwe)
Detector: 440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure: 146 kg x day (dec '09 - mar '11)



- ✓ Irreducible excess of bulk-like events below 3 keVee observed;
- ✓ annual modulation of the rate in 0.5-4.5 keVee at ~2.2σ C.L.





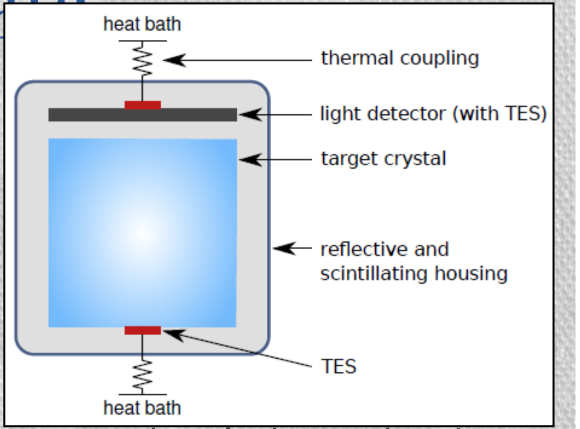


format. A straightforward analysis indicates a persistent annual modulation exclusively at low energy and for bulk events. Best-fit phase consistent with DAMA/LIBRA (small offset may be meaningful). Similar best-fit parameters to 15 mo dataset, but with much better bulk/surface separation (~90% SA for ~90% BR)

Unoptimized frequentist analysis yields ~2.2σ preference over null hypothesis. This however does not take into account the possible relevance of the modulation amplitude found...

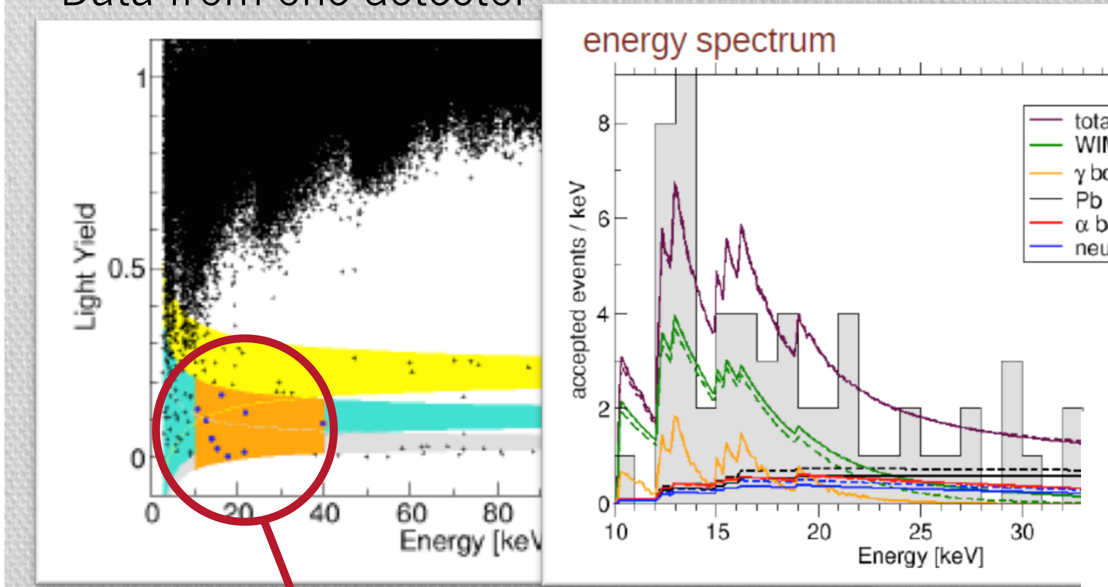
- 6 years of data at hand.
- CoGeNT upgrade: C-4 is coming up very soon
- C-4 aims at x4 total mass increase, bckg decrease, and substantial threshold reduction. Soudan is still the lab

Double read-out bolometric technique (scintillation vs heat)?

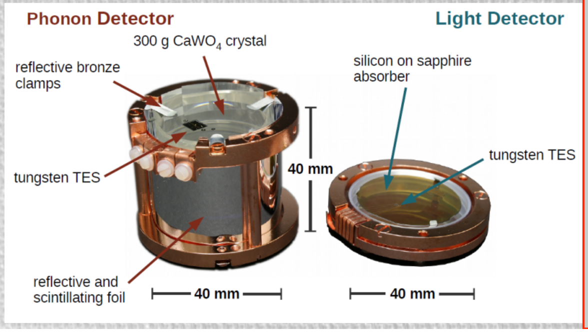


CRESST at LNGS: 33 $CaWO_4$ crystals (10 kg mass)
data from 8 detectors. Exposure: ≈ 730 kg x day

Data from one detector



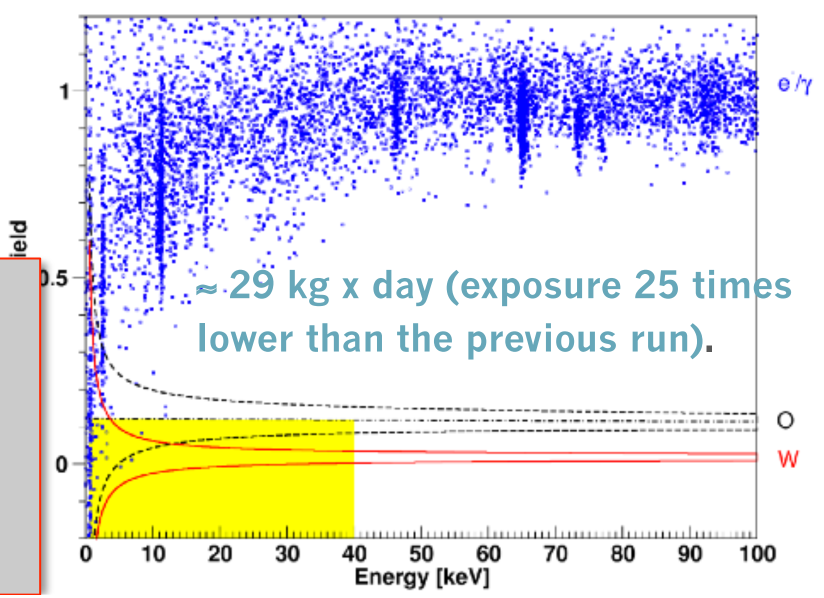
67 total events observed in O-band;



Latest runs with lower energy threshold does not confirm the previous 4 σ excess?! →
Large systematics can be present in this kind of approach

background-only hypothesis rejected with high statistical significance → **additional source of events needed (DM?)**

crucial role: efficiencies + stability + calibrations



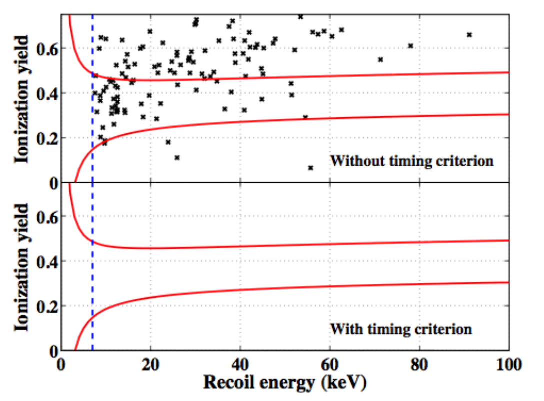
≈ 29 kg x day (exposure 25 times lower than the previous run).

Results from double read-out bolometric technique (ionization vs heat): CDMS–Si

Si excluded in previous analysis.

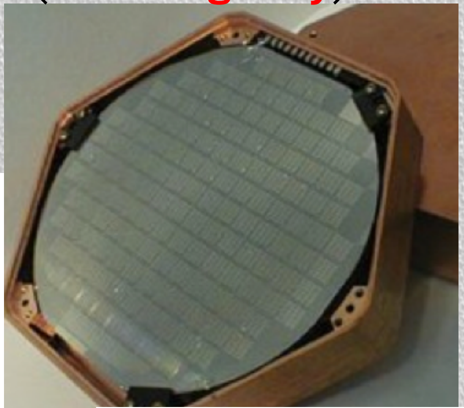
Results of CDMS-II with the Si detectors published in two close-in-time data releases:

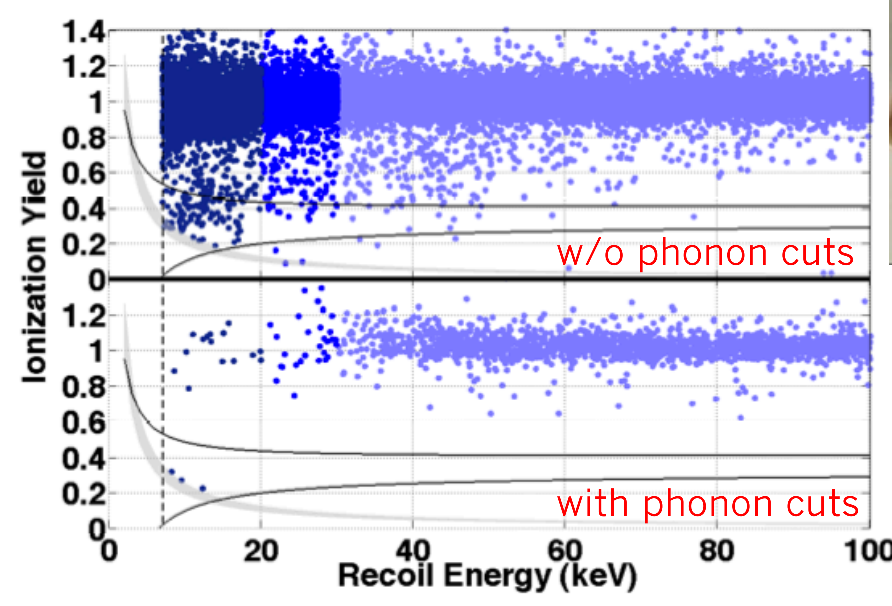
- *no events* in six detectors (**55.9 kg×day**)
- *three events* in eight (over 11) detectors (**140.2 kg×day**)

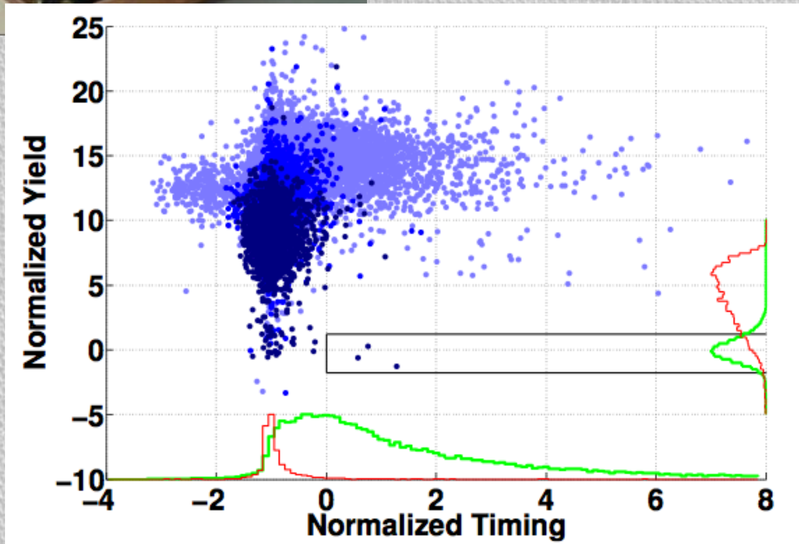


arXiv:1304.3706
arXiv:1304.4279

- 1.2 kg Si (11 x 106g)
- July 2007- September 2008







after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day.
Estimated residual background 0.41

A profile likelihood analysis favors a signal hypothesis at 99.81% CL (~3 σ, p-value: 0.19%).

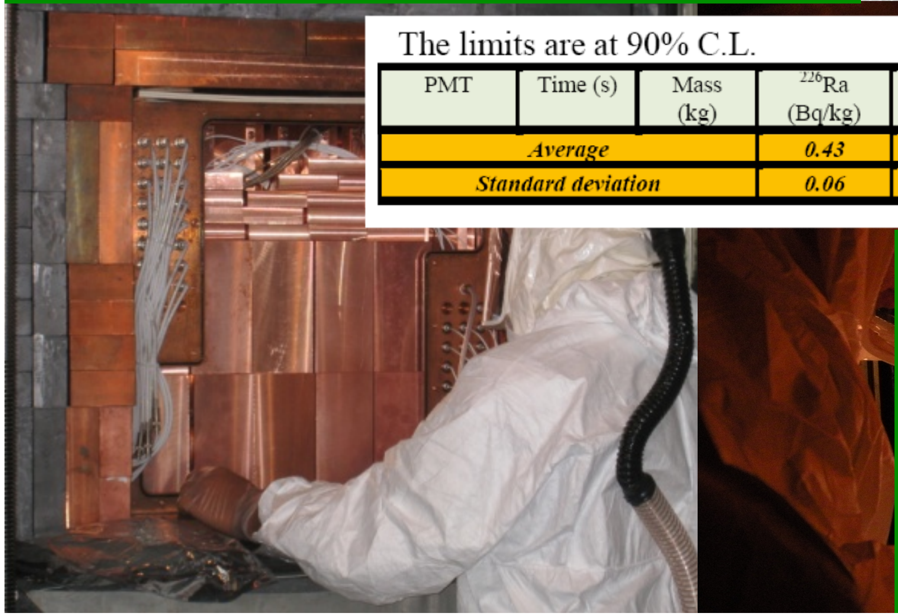
DAMA/LIBRA – phase2 JINST 7(2012)03009

more IJMPA28(2013)1330022

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



The limits are at 90% C.L.

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*	*-*	*-*

- 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 JINST 7(2012)03009

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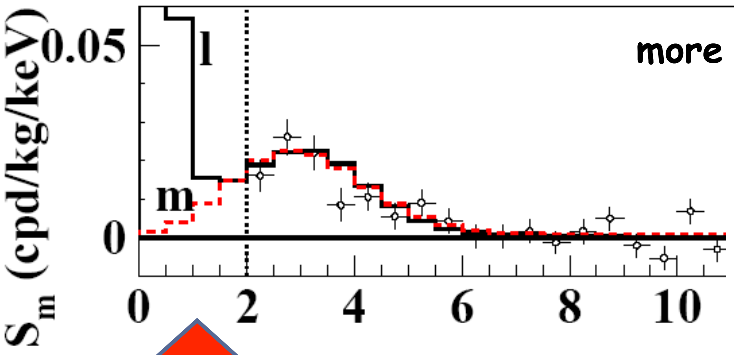
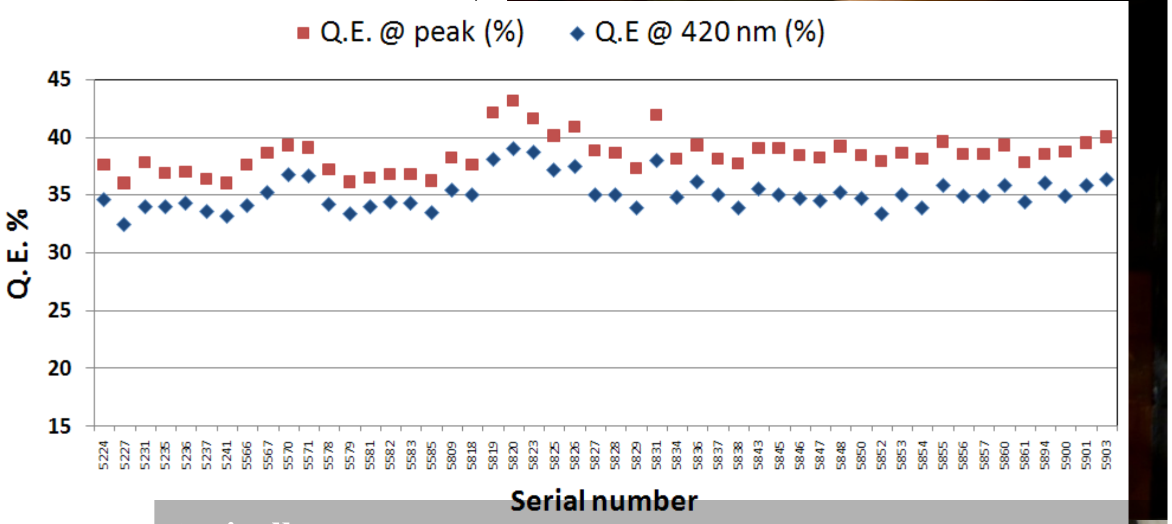
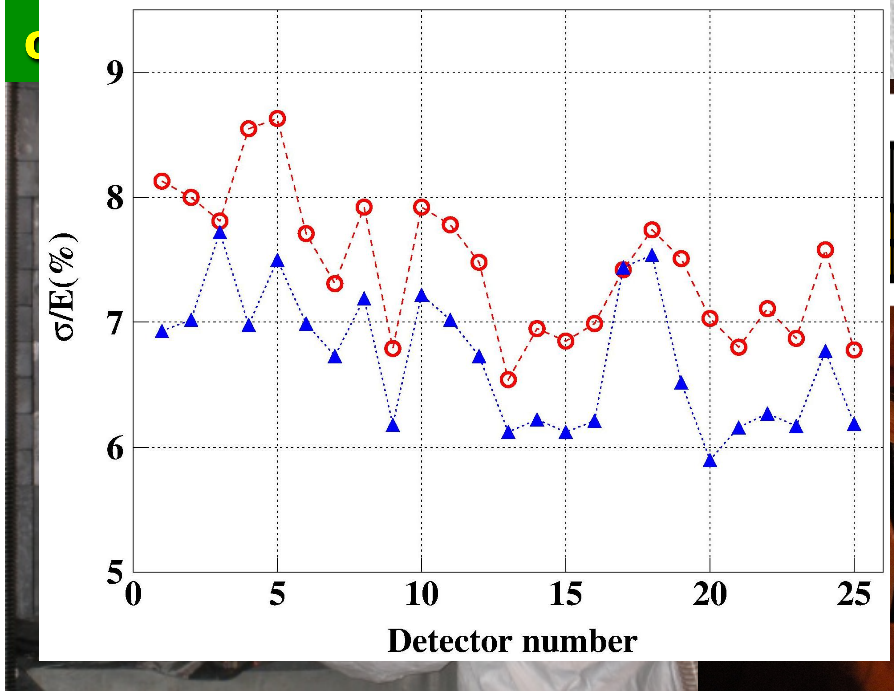


Second upgrade on Nov/Dec 2010: all PMTs replaced with new



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



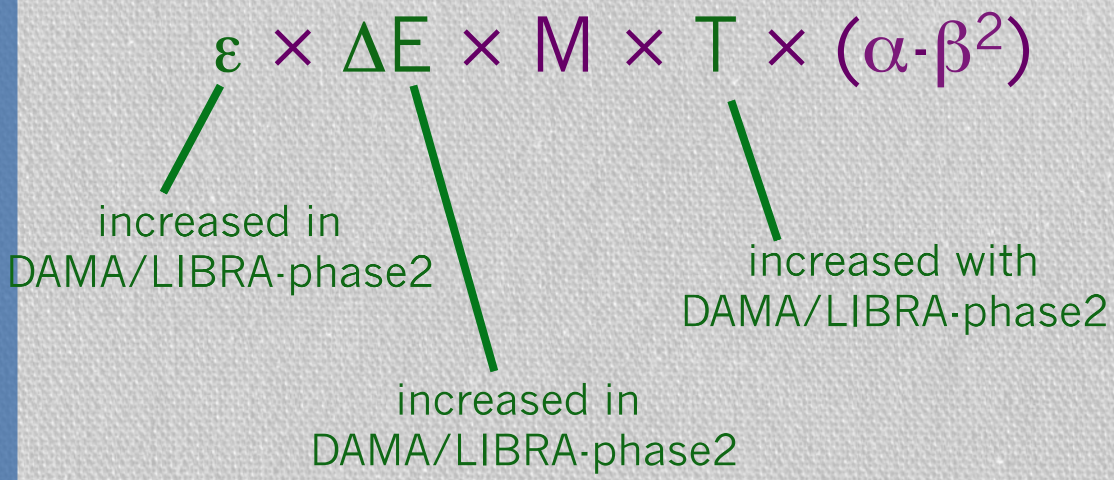
^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
-	*47*	*0.12*	*83*	*0.54*	*-*	*-*
-	*10*	*0,02*	*17*	*0.16*	*-*	*-*

- 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

DM annual modulation signature

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



$$\varepsilon \times \Delta E \times M \times T \times (\alpha\text{-}\beta^2)$$

increased in DAMA/LIBRA-phase2

increased in DAMA/LIBRA-phase2

increased with DAMA/LIBRA-phase2

→ 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:

- the nature of the DMp
  - ✓ to disentangle among the 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?

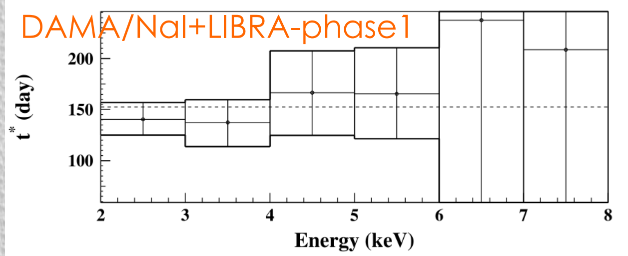
possible diurnal effects in sidereal time

- ✓ 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.

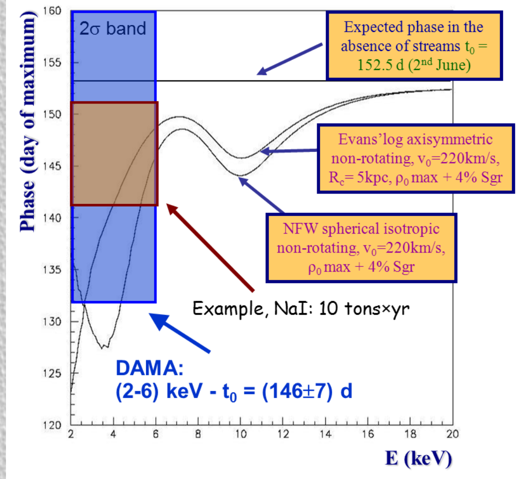
- astrophysical models
  - ✓ velocity and position distribution of DMp in the galactic halo, possibly due to:
    - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal “streams”;
    - caustics in the halo;
    - gravitational focusing effect of the Sun enhancing the DM flow (“spike“ and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

A step towards such investigations:

➔**DAMA/LIBRA-phase2 running with lower energy threshold**



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



The annual modulation phase depends on :

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

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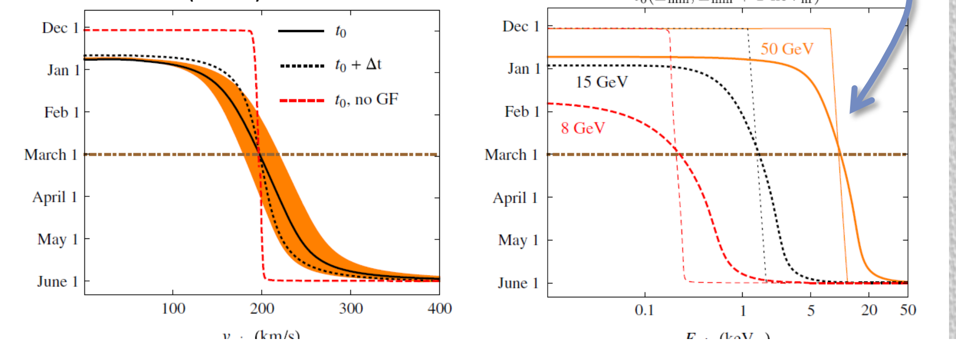


Other signatures?

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

Diurnal effects

EPJC 74 (2014) 2827

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

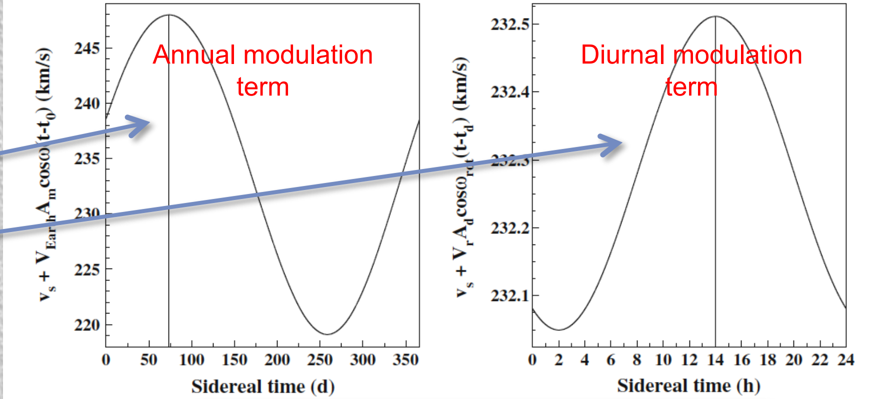
Velocity of the detector in the terrestrial laboratory:

$$\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t),$$

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:

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

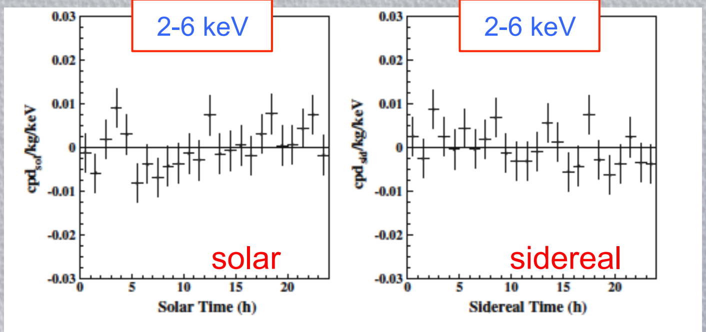
The ratio R_{dy} is a model independent constant:

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

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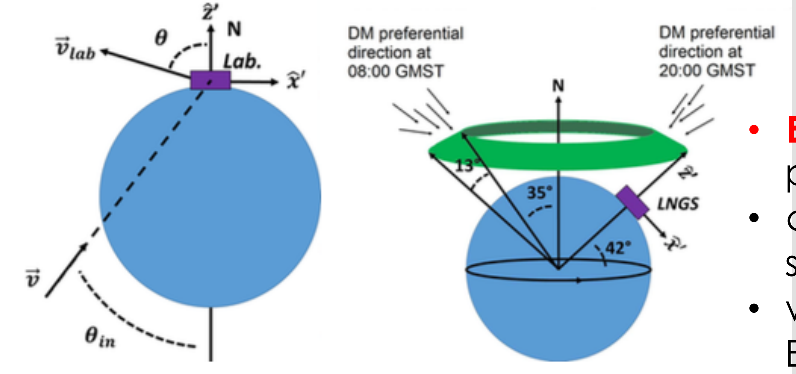
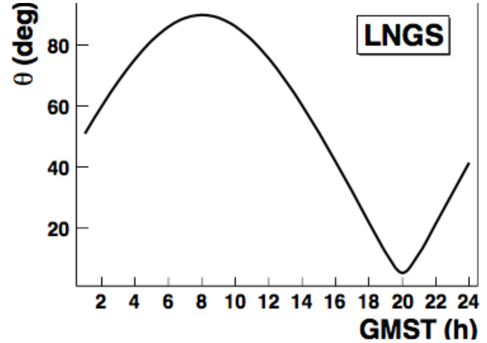
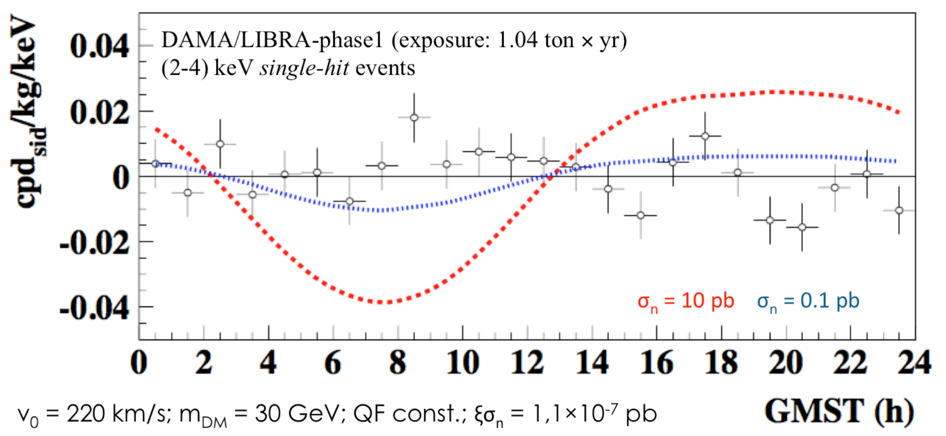


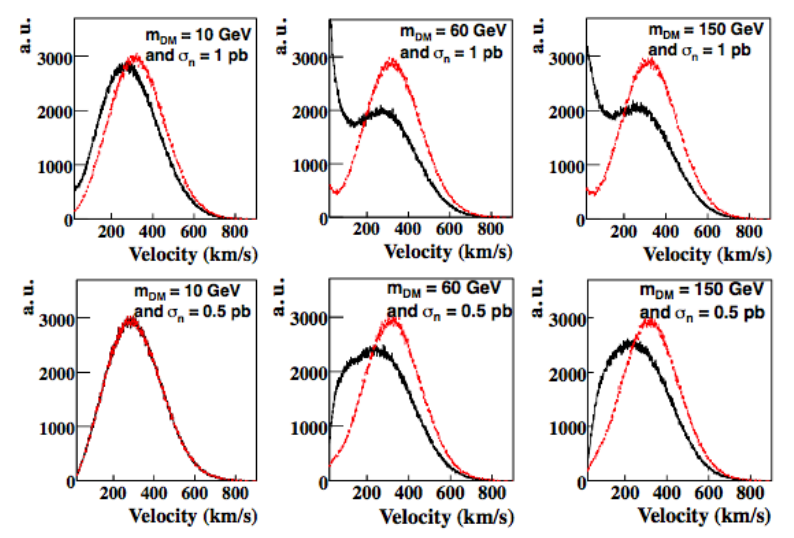
- **Earth Shadow Effect** could be expected for DM candidate particles inducing just nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM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



v_0 = 220 km/s; m_{DM} = 30 GeV; QF const.; $\xi\sigma_n = 1{,}1\times10^{-7}$ pb



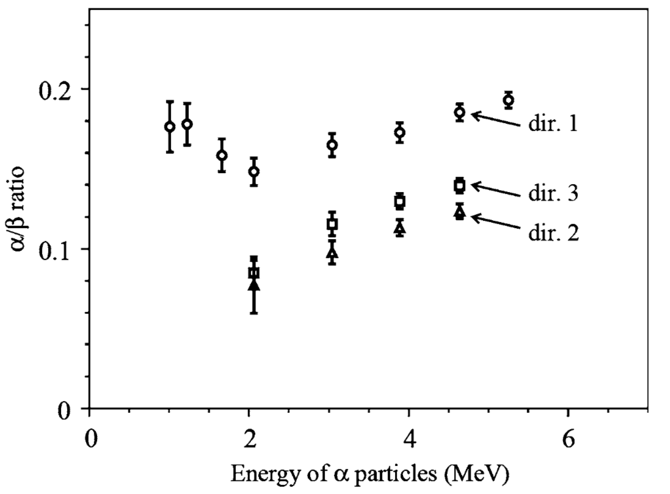
Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the ξ vs σ_n plane for each m_{DM}.

Directionality technique

- Identification of the presence of DM candidates inducing just nuclear recoils by exploiting the non-isotropic nuclear recoil distribution correlated to the Earth velocity

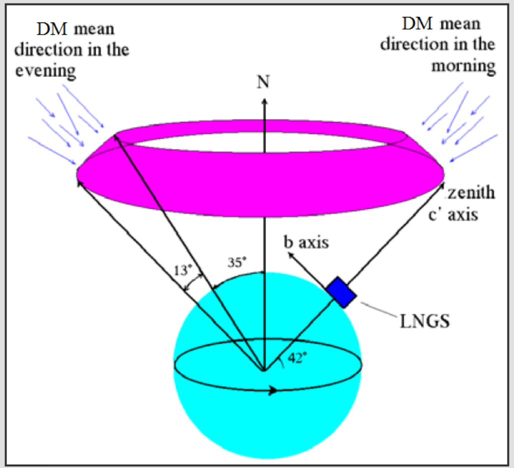
EPJ C73 (2013) 2276

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



Nuclear recoils are expected to be strongly correlated with impinging direction of those DM candidates

This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day

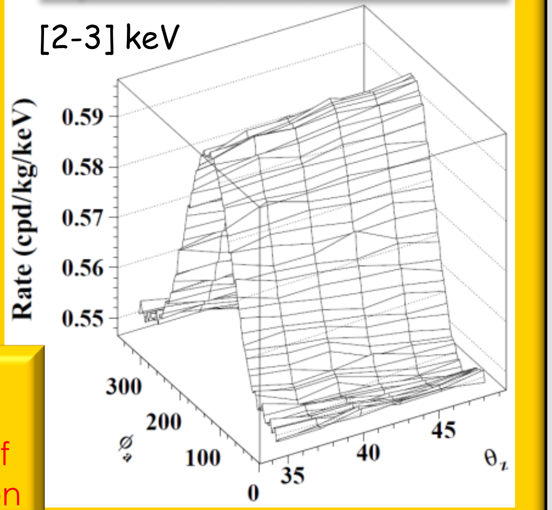


The light output and the pulse shape of $ZnWO_4$ detectors depend on the direction of those impinging candidates with respect to the crystal axes

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

No anisotropy for e.m. signals

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



These and others competitive features of $ZnWO_4$ detectors could permit a first realistic attempt towards directionality

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

Conclusions

- Different solid techniques can give complementary results
- Further efforts to demonstrate the solidity of some techniques and developments are needed
- Higher exposed mass not a synonymous of higher sensitivity
- DAMA model-independent positive evidence at 9.3 σ C.L. & full sensitivity to many kind of DM candidates, inducing both nuclear recoils and/or e.m. radiation, of astrophysical, nuclear and particle Physics scenarios as well as to low and large DM masses
- DAMA/LIBRA-phase2 running with the aim to disantangle at least among some of the many possible scenarios, to reach higher precision in modulation parameters (in particular on the phase), to investigate second order effects
- R&D towards possible future DAMA/LIBRA-phase3 in progress, and more

The model independent signature is the definite strategy to investigate the presence of Dark Matter particle component(s) in the Galactic halo, but with reliable set-ups, stability, routine calibrations, procedures, … as DAMA reached