Il lato oscuro dell'Universo: risultati da DAMA/LIBRA-fase1

OAR, INAF – Monte Porzio

8 Ottobre 2013

P. Belli

INFN-Roma Tor Vergata

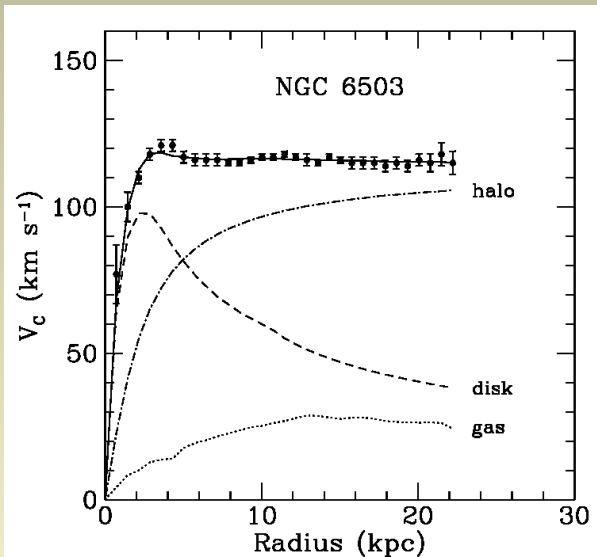# The Dark Side of the Universe: experimental evidences ...

First evidence and confirmations:

1933 **F. Zwicky:** studying dispersion velocity of Coma galaxies

1936 **S. Smith:** studying the Virgo cluster

**1974** **two groups:** systematical analysis of *mass density* vs *distance from center* in many galaxies

COMA Cluster

Other experimental evidences

✓ from LMC motion around Galaxy

✓ from X-ray emitting gases surrounding elliptical galaxies

✓ from hot intergalactic plasma velocity distribution in clusters

✓ ...

NGC 6503

halo

disk

gas

Rotational curve of a spiral galaxy

✓ bullet cluster 1E0657-558
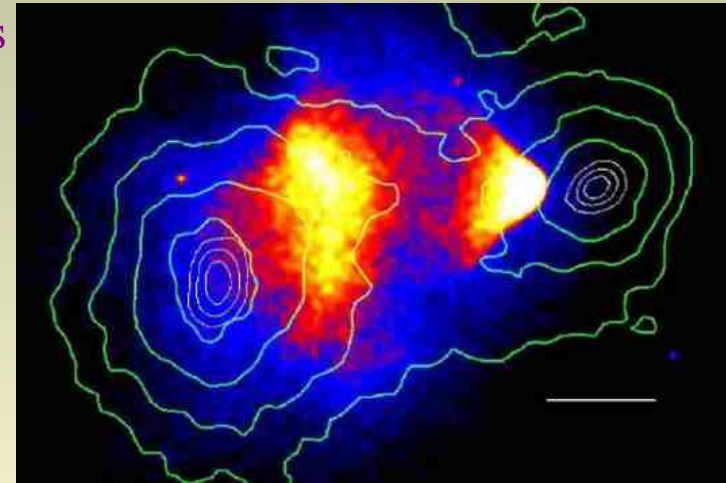
$M_{\text{visible Universe}} \ll M_{\text{gravitational effect}} \Rightarrow$ about 90% of the mass is DARK

"Concordance ΛCDM model"

Supernovae IA

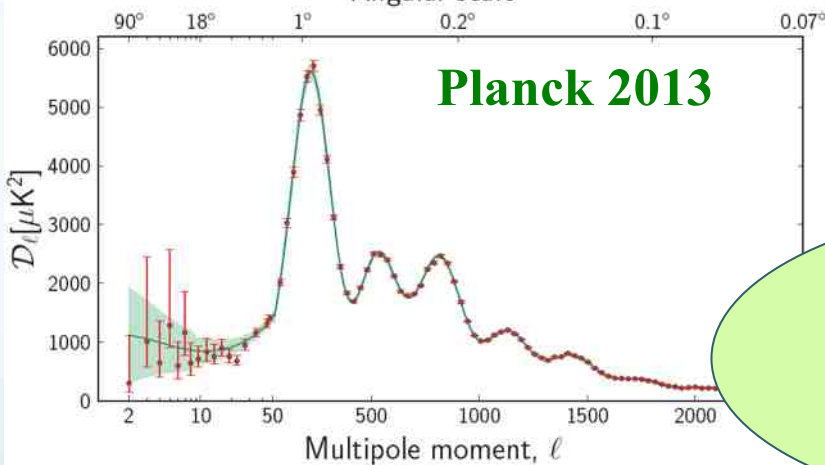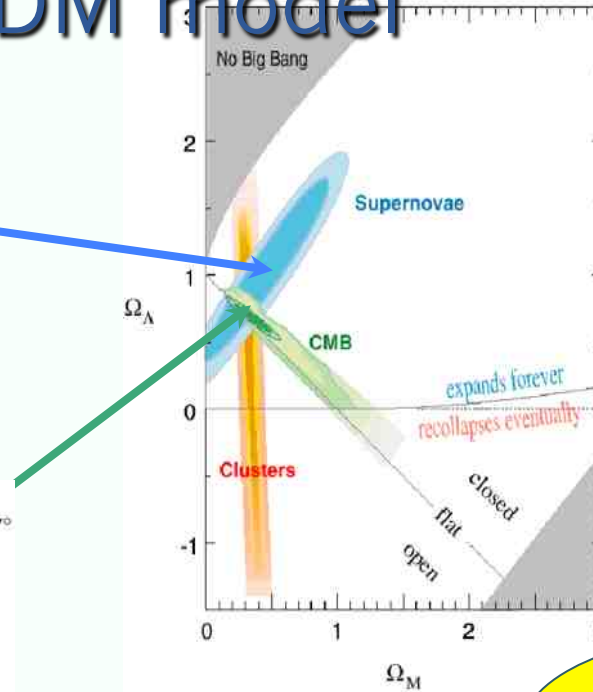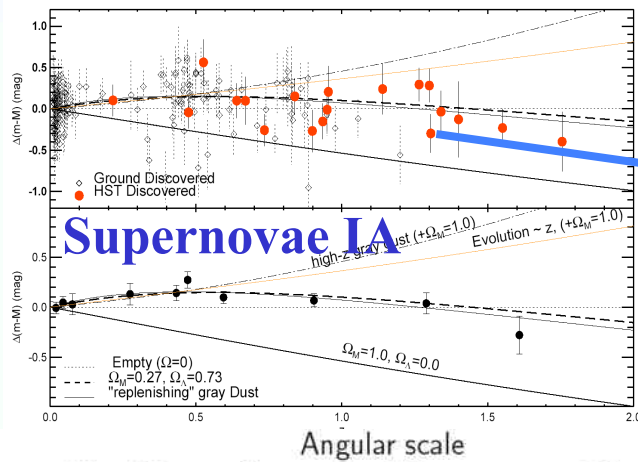**Planck 2013**

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

Ω = density/critical density

6 atoms of H/m^3

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

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

$\Omega_b \sim 5\%$

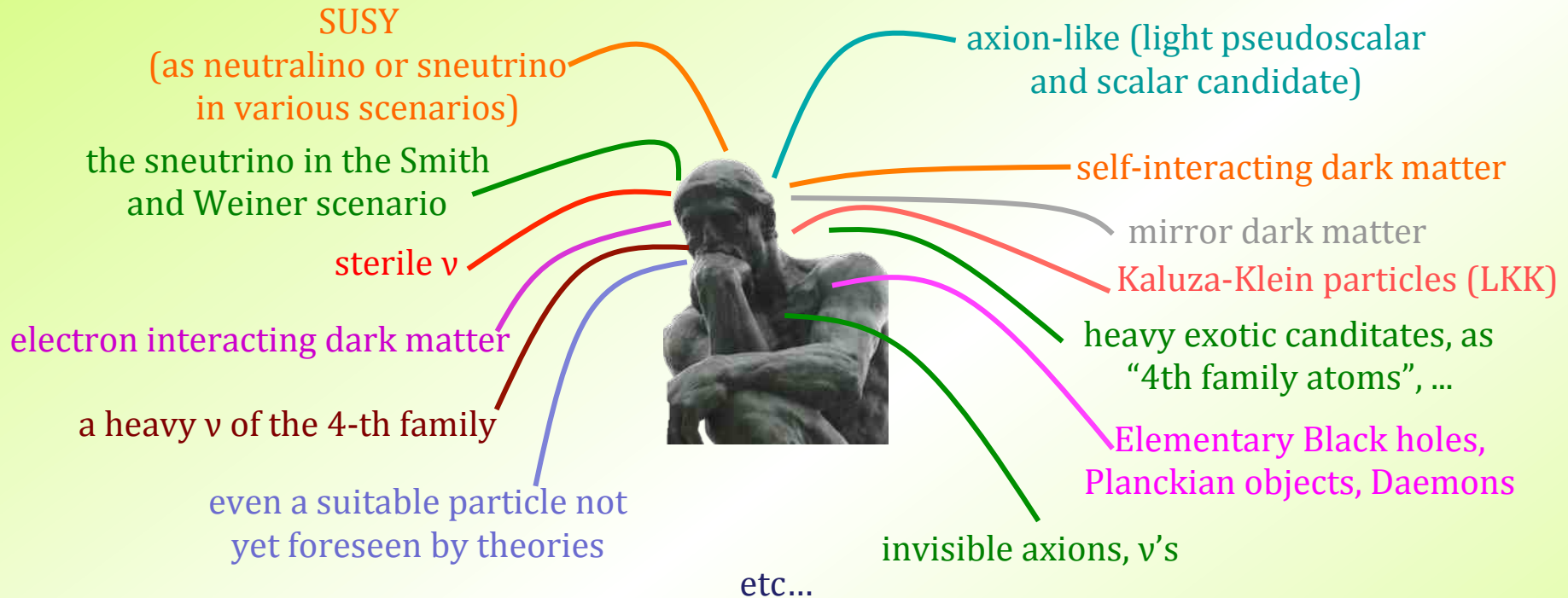Non baryonic Cold Dark Matter is dominant

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

~ 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

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

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

etc…

Moreover, several questions arise about:

- interaction type with ordinary matter and its description
- related nuclear and particle physics
- halo model and parameters
- halo composition. DM multicomponent also in the particle sector?
- non thermalized components?
- caustics?
- clumpiness?
- etc.

Hunting the Dark Matter particles

Direct

Indirect

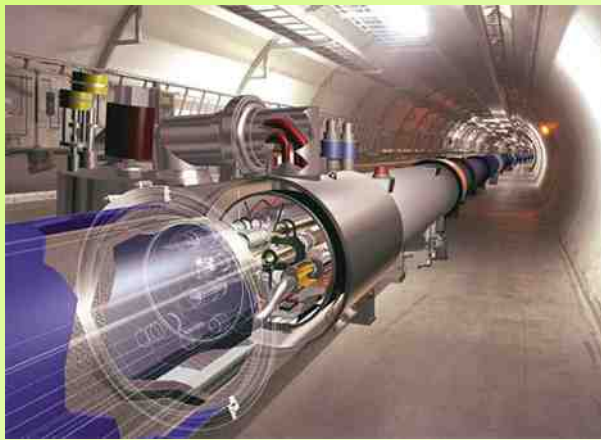Accelerators

Hunting the Dark Matter particles

Direct

Indirect

Accelerators

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
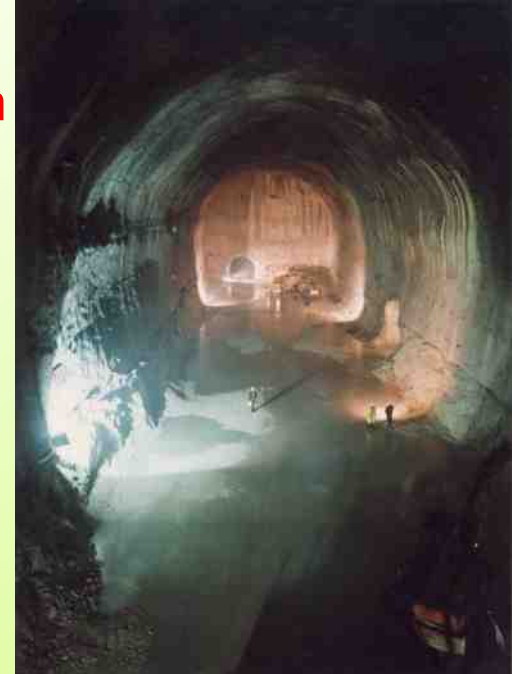
Hunting the Dark Matter particles

Direct

Indirect

Accelerators

Hunting the Dark Matter particles

Indirect

- **High-energy neutrinos**
- **Gamma-rays**
- **Antimatter in the space (anti-protons)**
- **Antimatter in the space (positrons)**
- **Effects of DM on astrophysical objects**

But:
- **model dependent results**
- **strong modeling of the background is needed**
- **other sources of positrons/gamma-rays/anti-matter/… are present**

Hunting the Dark Matter particles
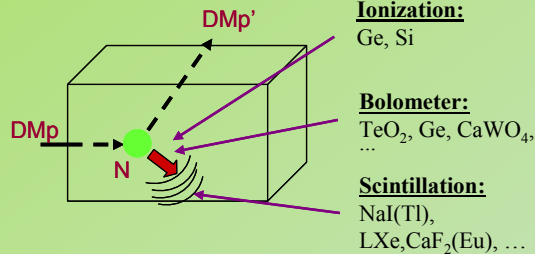

Direct

Indirect

Accelerators

Some direct detection processes:

- Scatterings on nuclei
  → detection of nuclear recoil energy

Ionization:
Ge, Si

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

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

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

  → W has Two mass states $\chi+$, $\chi-$ with δ mass splitting

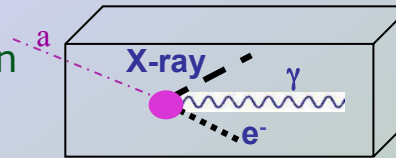 → Kinematical constraint for the inelastic scattering of $\chi-$ on a nucleus

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

- Excitation of bound electrons in scatterings on nuclei
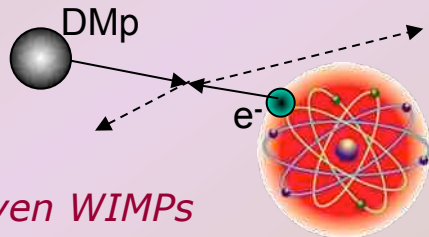 → detection of recoil nuclei + e.m. radiation

- Conversion of particle into e.m. radiation
  → detection of γ, X-rays, e⁻

  X-ray γ
  a
  e⁻

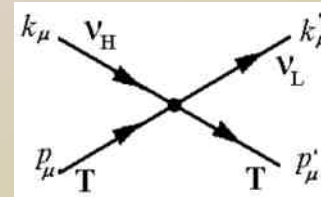- Interaction only on atomic electrons
  → detection of e.m. radiation

  DMp

  e⁻

  ... even WIMPs

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

  → detection of electron/nucleus recoil energy

  k_μ ν_H k'_μ
  ν_L
  p_μ T   T p'_μ

  e.g. sterile ν

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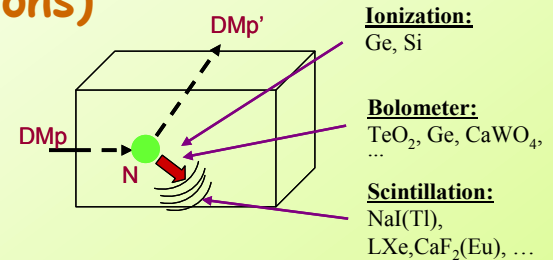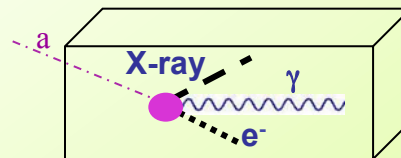
... also other ideas ...

- **... and more**

The 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 rejection of electromagnetic background (adding systematical effects and lost of candidates with pure electromagnetic productions)

DMp'

Ionization:
Ge, Si

DMp

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

N

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

a

X-ray

γ

e^-

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

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Drukier, Freese, Spergel PRD86
Freese et al. PRD88
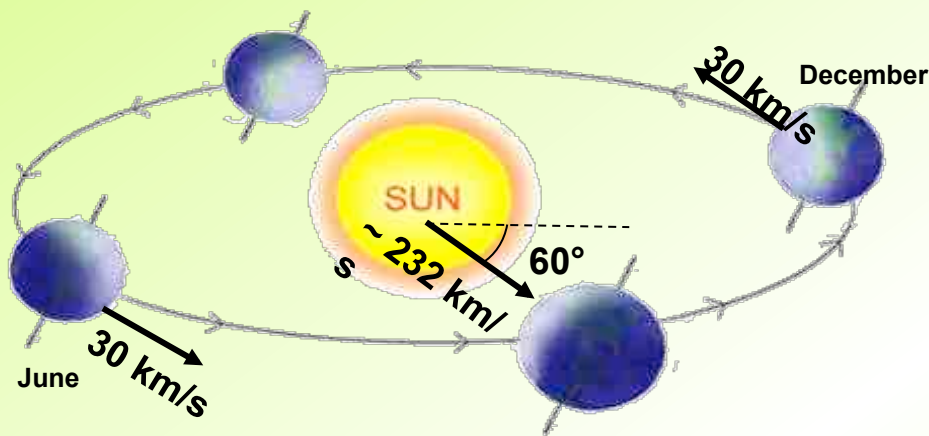
- $v_{sun} \sim 232$ km/s (Sun velocity in the halo)
- $v_{orb} = 30$ km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, $T = 1$ year
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

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

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

Expected rate in given energy bin changes because the revolution motion of the Earth around the Sun, which is moving in the Galaxy

Requirements of the 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

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

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

+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati
+ in some studies on ββ 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
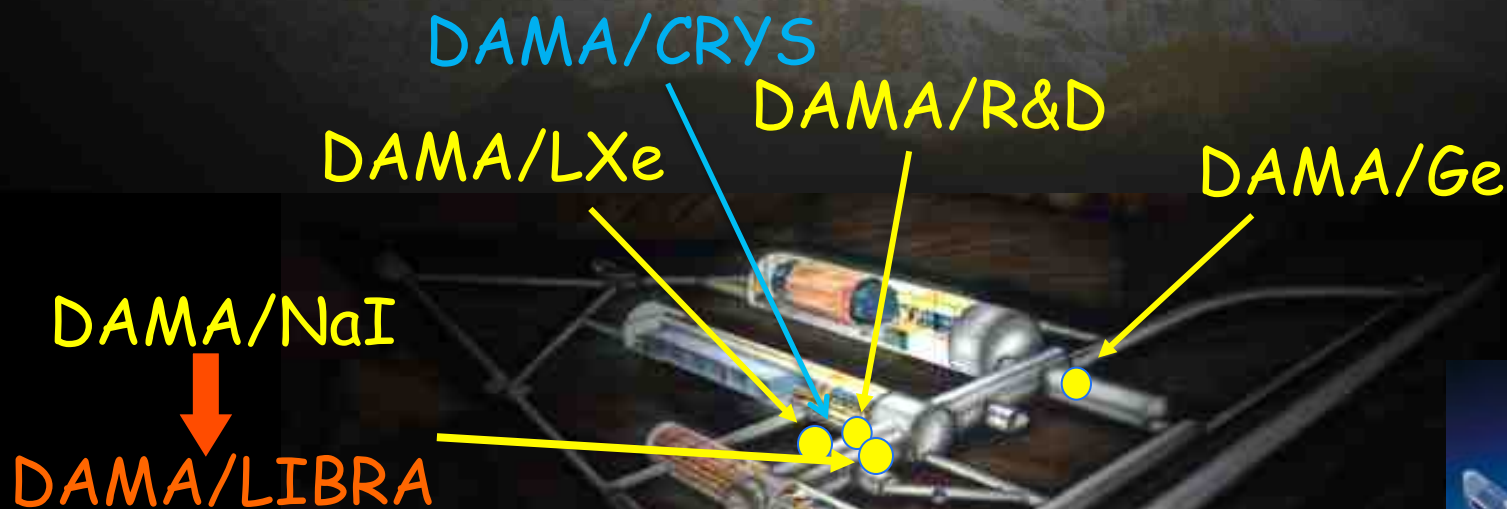
The pioneer DAMA/NaI:
≈100 kg highly radiopure NaI(Tl)

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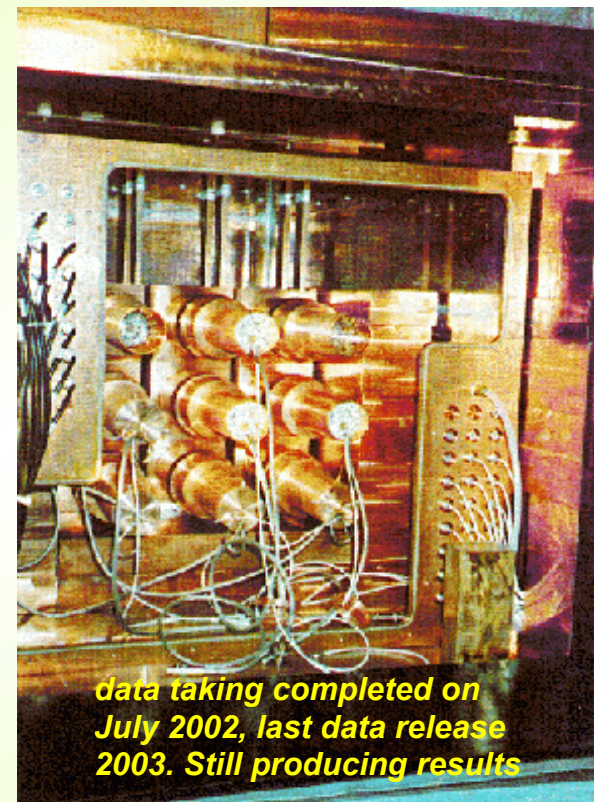
model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

total exposure (7 annual cycles)   0.29 ton×yr

The DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium **I**odide **B**ulk for **RA**re 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, arXiv:1308.5109. Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022
- ➢ Results on rare processes: PEP violation EPJC62(2009)327; CNC in I EPJC72(2012)1920; IPP in ^{241}Am decay EPJA49(2013)64

DAMA @ LNGS

...calibration procedures

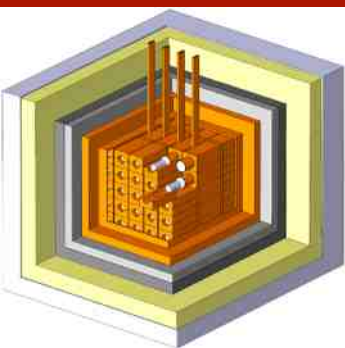# *The* DAMA/LIBRA set-up

Polyethylene/paraffin

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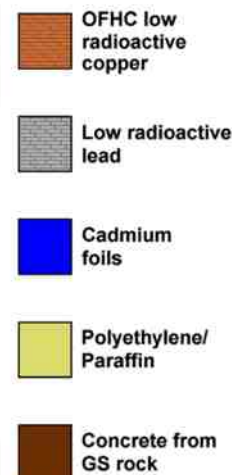- two PMTs working in coincidence at the single ph. el. threshold

5.5-7.5 phe/keV

Installation

Glove-box for calibration A

B

Electronics + DAQ D

| OFHC low radioactive copper |
| Low radioactive lead |
| Cadmium foils |
| Polyethylene/ Paraffin |
| Concrete from GS rock |

~ 1m concrete from GS rock

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of 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
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy
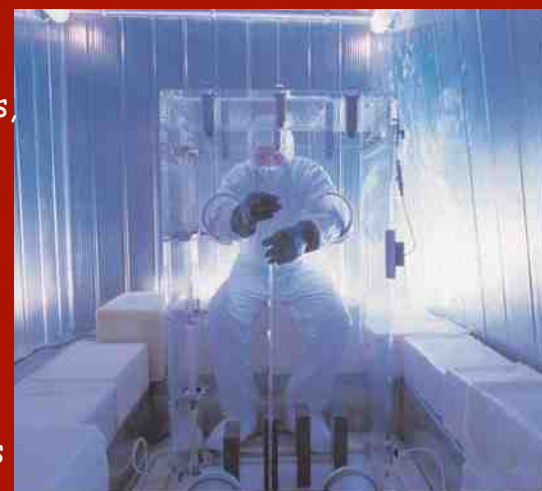
Some on residual contaminants in new ULB NaI(Tl) detectors
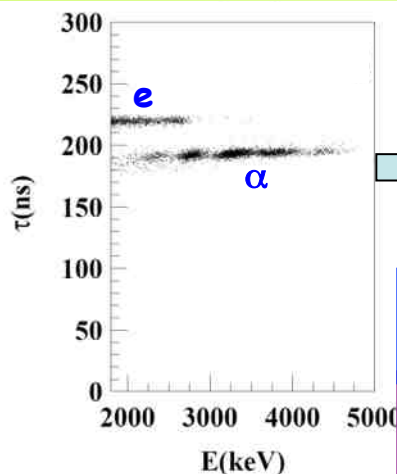
α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/day

Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/ chemical radiopurification, new selection of overall materials, new protocol for growing and handling

^{232}Th residual contamination
From time-amplitude method. If ^{232}Th chain at equilibrium: it ranges from 0.5 ppt to 7.5 ppt

^{238}U residual contamination
First estimate: considering the measured α and ^{232}Th activity, if ^{238}U chain at equilibrium $\Rightarrow$ ^{238}U contents in new detectors typically range from 0.7 to 10 ppt

live time = 570 h

^{238}U chain splitted into 5 subchains: ^{238}U $\rightarrow$ ^{234}U $\rightarrow$ ^{230}Th $\rightarrow$ ^{226}Ra $\rightarrow$ ^{210}Pb $\rightarrow$ ^{206}Pb

Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U
and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{nat}K residual contamination
The analysis has given for the ^{nat}K content in the crystals values not exceeding about 20 ppb

double coincidences
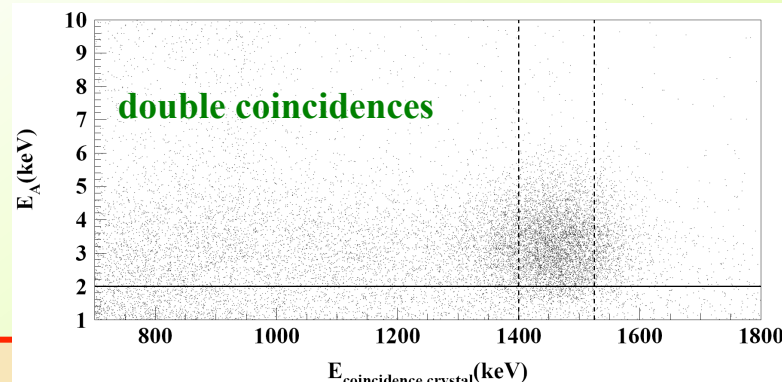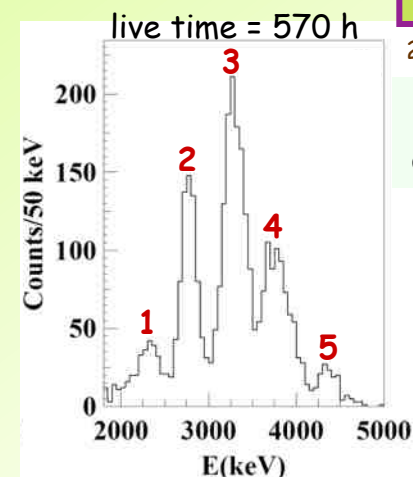
^{129}I and ^{210}Pb

^{129}I/^{nat}I ≈1.7×10^{-13} for all the new detectors

^{210}Pb in the new detectors: (5 – 30) μBq/kg.
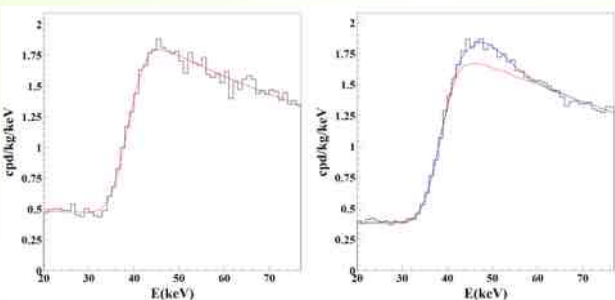
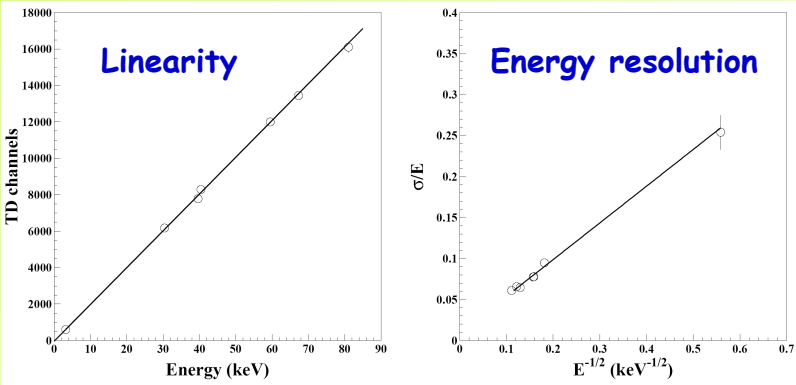No sizable surface pollution by Radon daugthers, thanks to the new handling protocols

... more on

NIMA592(2008)297

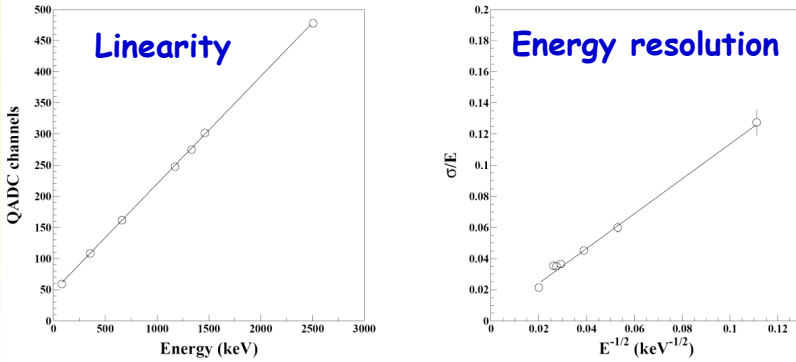# DAMA/LIBRA calibrations

<u>Low energy</u>: 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
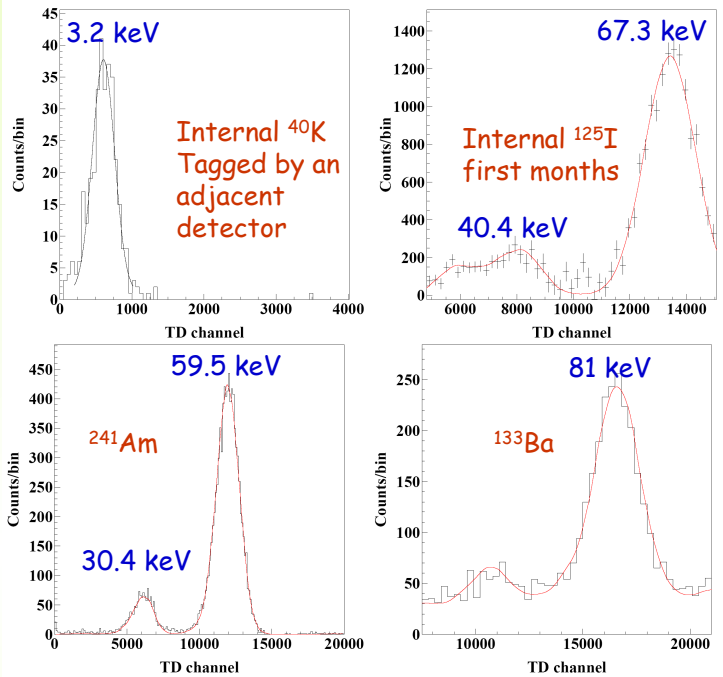

Linearity

Energy resolution

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

<u>High energy</u>: 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

Linearity

Energy resolution

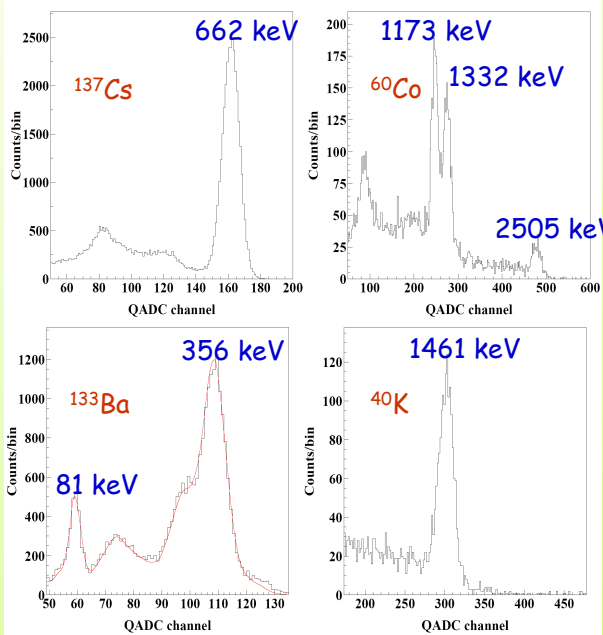The signals (unlike low energy events) for high energy events are taken only from one PMT

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

Thus, here and hereafter keV means keV electron equivalent

3.2 keV — Internal ^{40}K Tagged by an adjacent detector

67.3 keV — Internal ^{125}I first months — 40.4 keV

59.5 keV — ^{241}Am — 30.4 keV

81 keV — ^{133}Ba

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

662 keV — ^{137}Cs

1173 keV 1332 keV — ^{60}Co — 2505 keV

356 keV — ^{133}Ba — 81 keV

1461 keV — ^{40}K

Examples of energy resolutions

DAMA/ LIBRAULB NaI(Tl)

$\frac{\sigma}{E}$ (60keV) = 6.8%

C13

^{241}Am

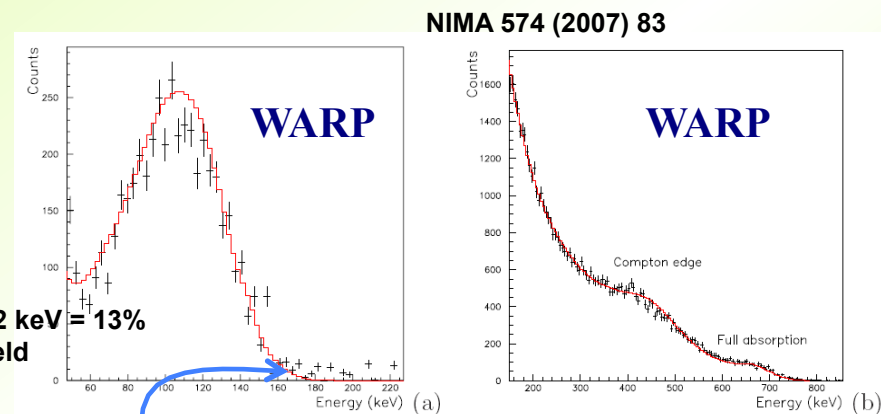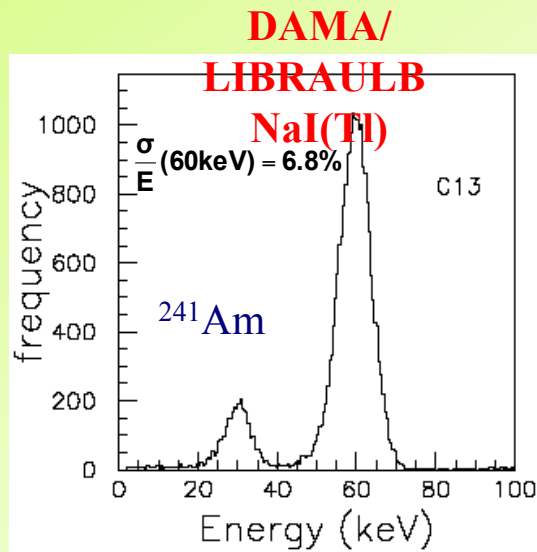**NIMA 574 (2007) 83**

WARP

WARP

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 ?
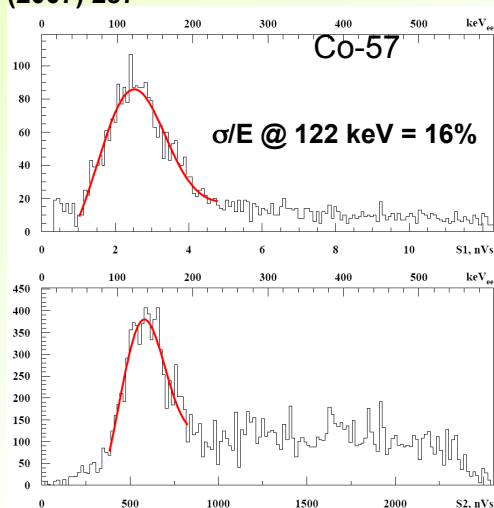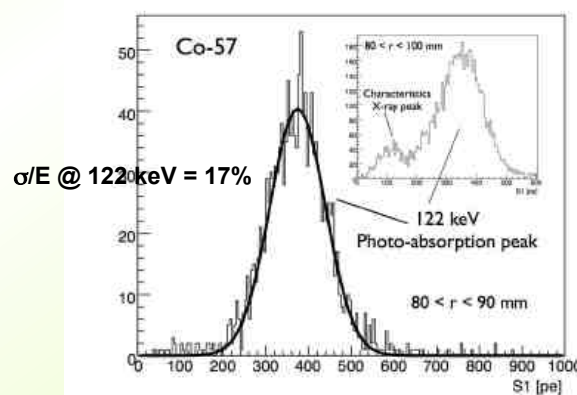
ZEPLIN-II

AP 28 (2007) 287

Co-57

σ/E @ 122 keV = 16%

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

Co-57

σ/E @ 122 keV = 17%

122 keV Photo-absorption peak

80 < r < 90 mm

Cs-137

Backscatter peak

r < 100 mm
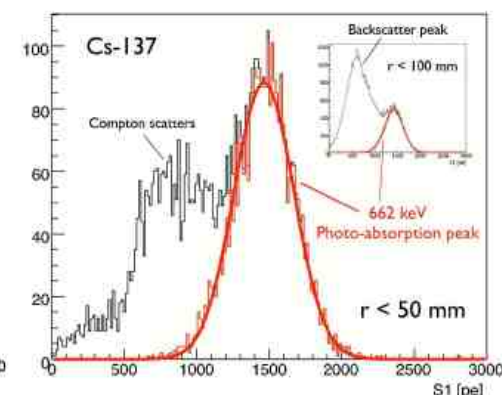
Compton scatters

662 keV Photo-absorption peak

r < 50 mm

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)

$\frac{\sigma}{E}$ (60keV) = 6.8%
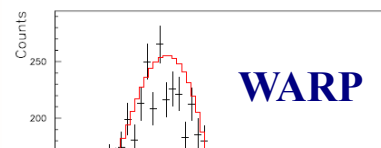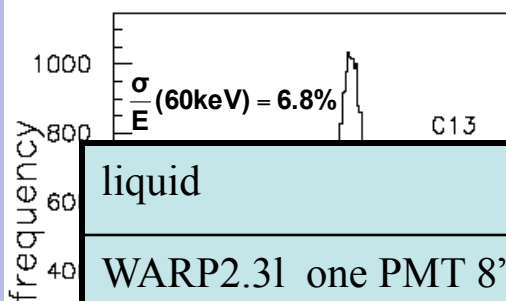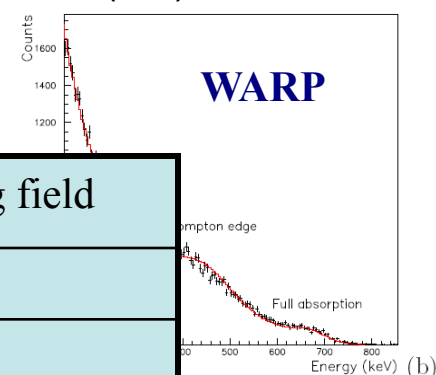
WARP

WARP

liquid	phe/keV@zero field	phe/keV@working field
WARP2.3l one PMT 8"	--	2.35
WARP2.3l 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

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

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.

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
- arXiv:1308.5109 (ROM2F/2013/13)
- calibrations: ≈96 M events from sources
- acceptance window eff: 95 M events (≈3.5 M events/keV)

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

START of DAMA/LIBRA – phase 2
- **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
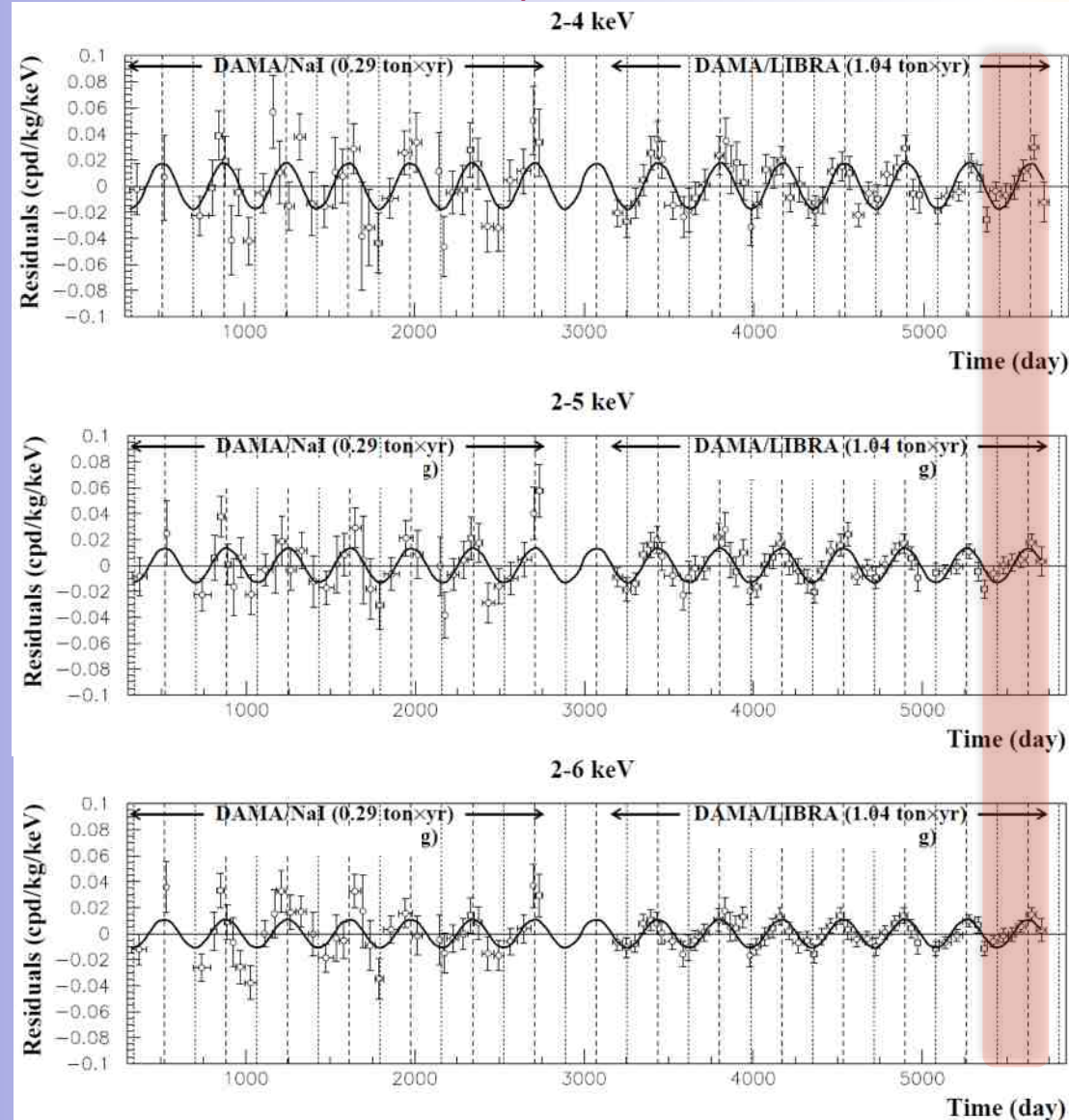
... continuously running

Model Independent DM Annual Modulation Result

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

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

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

2-4 keV

A=(0.0179±0.0020) cpd/kg/keV

χ^2/dof = 87.1/86   **9.0 σ C.L.**

Absence of modulation? No
χ^2/dof=169/87 $\Rightarrow$ P(A=0) = 3.7×10^{-7}

2-5 keV

A=(0.0135±0.0015) cpd/kg/keV

χ^2/dof = 68.2/86   **9.0 σ C.L.**

Absence of modulation? No
χ^2/dof=152/87 $\Rightarrow$ P(A=0) = 2.2×10^{-5}

2-6 keV

A=(0.0110±0.0012) cpd/kg/keV

χ^2/dof = 70.4/86   **9.2 σ C.L.**

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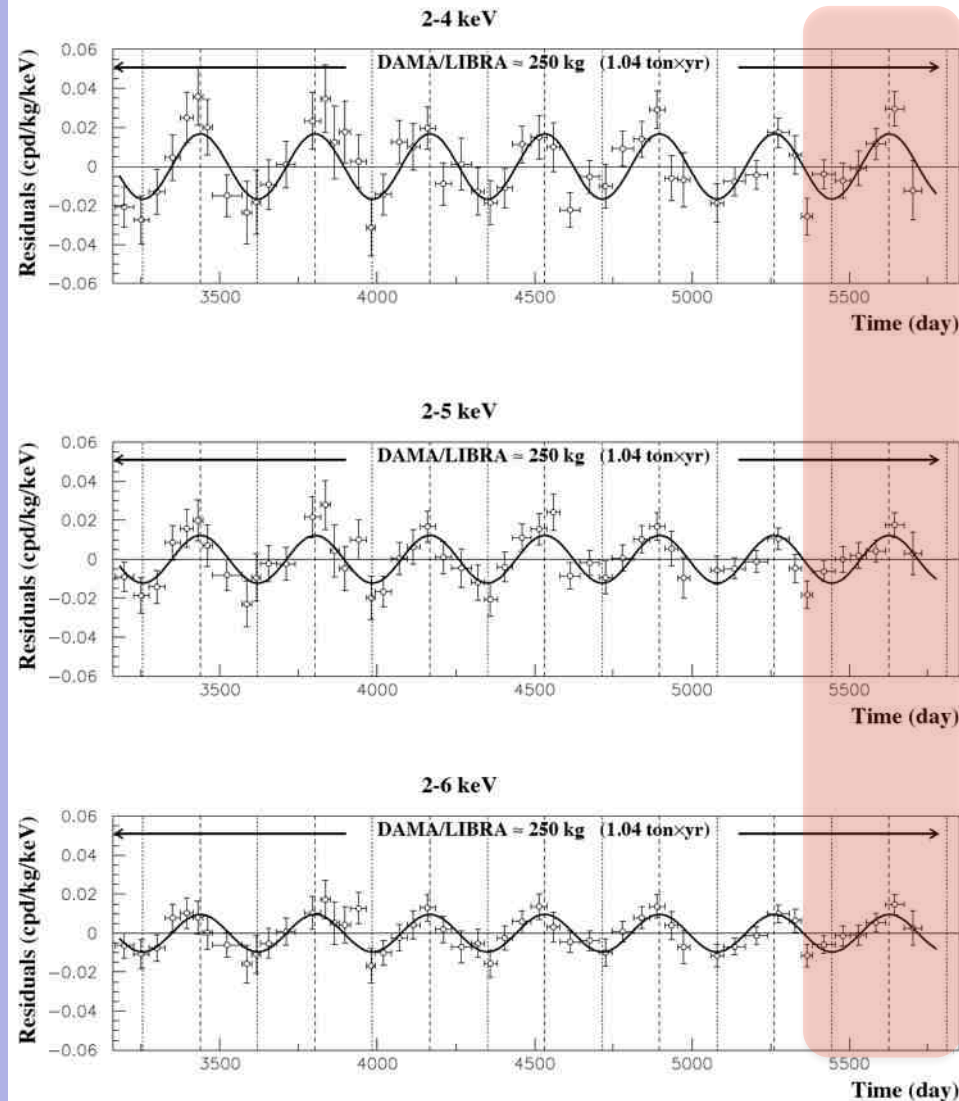χ^2/dof=154/87 $\Rightarrow$ P(A=0) = 1.3×10^{-5}

The data favor the presence of a modulated behavior with proper features at 9.2σ C.L.

Model Independent DM Annual Modulation Result

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

DAMA/LIBRA-phase1

Fit on DAMA/LIBRA-phase1(1.04 ton × yr)

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

2-4 keV

A=(0.0167±0.0022) cpd/kg/keV

χ^2/dof = 52.3/49   **7.6 σ C.L.**

Absence of modulation? No

χ^2/dof=111.2/50 $\Rightarrow$ P(A=0) =1.5×10^{-6}

2-5 keV

A=(0.0122±0.0016) cpd/kg/keV

χ^2/dof = 41.4/49   **7.6 σ C.L.**

Absence of modulation? No

χ^2/dof=98.5/50 $\Rightarrow$ P(A=0) = 5.2×10^{-5}

2-6 keV

A=(0.0096±0.0013) cpd/kg/keV

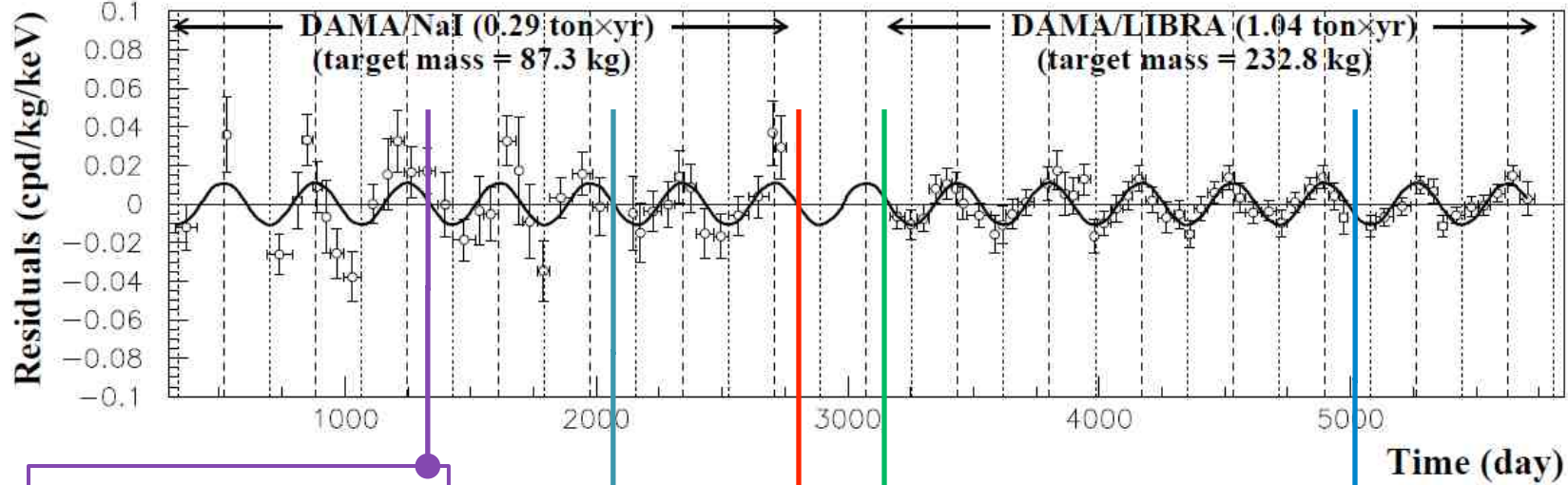χ^2/dof = 29.3/49   **7.4 σ C.L.**

Absence of modulation? No

χ^2/dof=83.1/50 $\Rightarrow$ P(A=0) = 2.2×10^{-3}

The data of DAMA/NaI + DAMA/LIBRA-phase1 favor the presence of a modulated behavior with proper features at 9.2σ C.L.

DAMA/NaI & DAMA/LIBRA experiments main upgrades and improvements

PHASE2

Minimal upgrade in Fall

On 2003 DAMA/LIBRA has begun first operations

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

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:
① one detector recovered by replacing a broken PMT
② a new optimization of some PMTs and HVs performed
③ all the TD replaced with new ones (U1063A Acqiris 8-bit 1GS/s DC270 High-Speed cPCI Digitizers)
④ a new DAQ with optical read-out installed.

The second DAMA/LIBRA upgrade in Fall 2010:
Replacement of all the PMTs with higher Q.E. ones from dedicated developments
(+new preamp in Fall 2012 and other developments in progress)
DAMA/LIBRA-phase2 *in data taking*

Modulation amplitudes (A), period (T) and phase (t_0) measured in DAMA/NaI and DAMA/LIBRA-phase1

|	A(cpd/kg/keV)	T=$2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI				
(2-4) keV	0.0252 ±0.0050	1.01 ±0.02	125 ±30	5.0σ
(2-5) keV	0.0215 ±0.0039	1.01 ±0.02	140 ±30	5.5σ
(2-6) keV	0.0200 ±0.0032	1.00 ±0.01	140 ±22	6.3σ
DAMA/LIBRA-phase1				
(2-4) keV	0.0178 ±0.0022	0.996 ±0.02	134 ± 7	8.1σ
(2-5) keV	0.0127 ±0.0016	0.996 ±0.02	137 ± 8	7.9σ
(2-6) keV	0.0097 ±0.0013	0.998 ±0.02	144 ± 8	7.5σ
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

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

DAMA/NaI (0.29 ton x yr) +
DAMA/LIBRA-phase1 (1.04 ton x yr)

total exposure:
487526 kg×day = 1.33 ton×yr

χ^2 **test** (χ^2 **= 9.5, 13.8 and 10.8 over 13** *d.o.f.* **for the three energy intervals, respectively; upper tail probability 73%, 39%, 63%) and** *run test* **(lower tail probabilities of 41%, 29% and 23% for the three energy intervals, respectively) accept at 90% C.L. the hypothesis that the modulation amplitudes are normally fluctuating around their best fit values.**
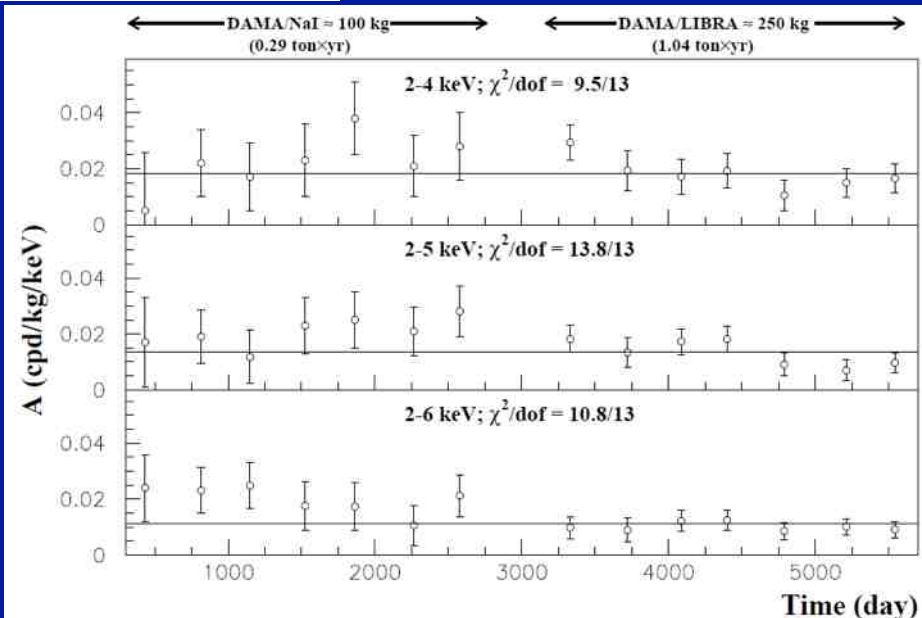
Compatibility among the annual cycles

Power spectrum of single-hit residuals
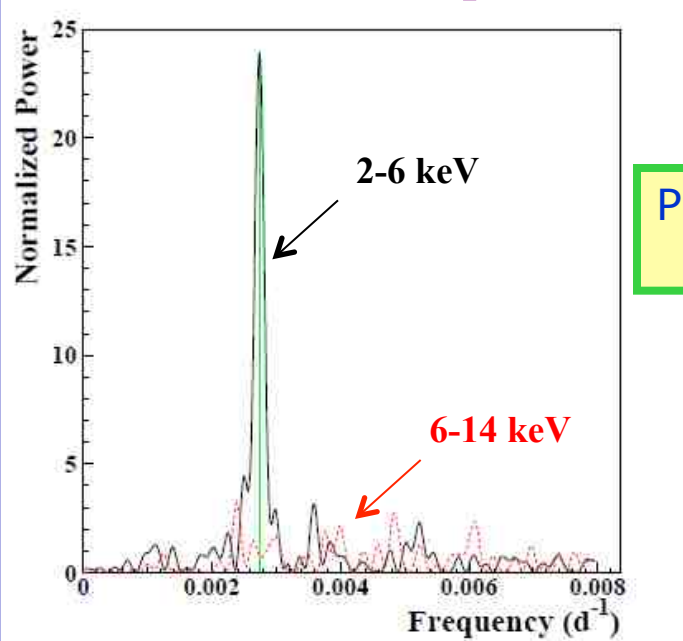
DAMA/NaI (7 years) + DAMA/LIBRA-phase1 (7 years)
total exposure: 1.33 ton×yr

Principal mode in the 2-6 keV region:
2.737×10^{-3} d^{-1} $\approx$ 1 yr^{-1}

Not present in the 6-14 keV
region (only aliasing peaks)

The Lomb-Scargle periodogram, as reported in DAMA papers,
always according to Ap.J. 263 (1982) 835, Ap.J. 338 (1989) 277
with the treatment of the experimental errors and of the time
binning:

Given a set of data values r_i, $i = 1, \ldots N$ at respective observation
times t_i, the Lomb-Scargle periodogram is:

$$P_N(\omega) = \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_i(r_i - \bar{r})\cos\omega(t_i - \tau)\right]^2}{\sum_i \cos^2\omega(t_i - \tau)} + \frac{\left[\sum_i(r_i - \bar{r})\sin\omega(t_i - \tau)\right]^2}{\sum_i \sin^2\omega(t_i - \tau)}\right\}$$

where: $\quad \bar{r} = \frac{1}{N}\sum_1^N r_i \qquad \sigma^2 = \frac{1}{N-1}\sum_1^N(r_i - \bar{r})^2$

and, for each angular frequency $\omega = 2\pi f > 0$ of interest, the time-offset τ is:

$$\tan(2\omega\tau) = \frac{\sum_i \sin(2\omega t_i)}{\sum_i \cos(2\omega t_i)}$$

In order to take into account the different time binning
and the residuals' errors we have to rewrite the
previous formulae replacing:

$$\sum_i \quad \rightarrow \quad \sum_i \frac{\frac{N}{\Delta r_i^2}}{\sum_j \frac{1}{\Delta r_j^2}} = \frac{N}{\sum_j \frac{1}{\Delta r_j^2}} \cdot \sum_i \frac{1}{\Delta r_i^2}$$
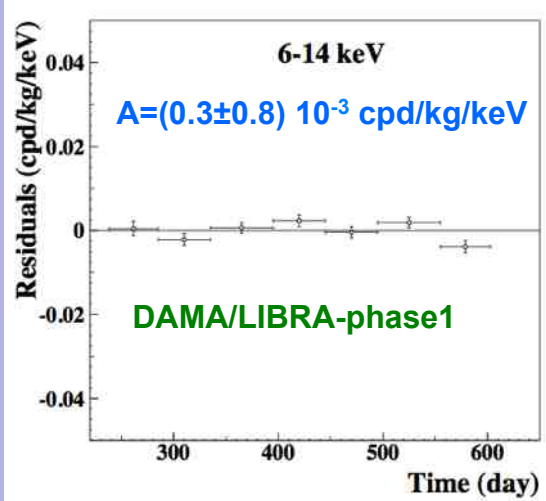
$$\sin\omega t_i \quad \rightarrow \quad \frac{1}{2\Delta t_i}\int_{t_i - \Delta t_i}^{t_i + \Delta t_i}\sin\omega t\, dt$$

$$\cos\omega t_i \quad \rightarrow \quad \frac{1}{2\Delta t_i}\int_{t_i - \Delta t_i}^{t_i + \Delta t_i}\cos\omega t\, dt$$

The Nyquist frequency is ≈3 y^{-1} (≈0.008 d^{-1}); meaningless higher
frequencies, washed off by the integration over the time binning.

Clear annual modulation is evident in (2-6) keV, while it is absent just above 6 keV

Rate behaviour above 6 keV

- **No Modulation above 6 keV**

6-14 keV

A=(0.3±0.8) 10⁻³ cpd/kg/keV

$A = (0.3 \pm 0.8)\, 10^{-3}$ cpd/kg/keV

DAMA/LIBRA-phase1

Mod. Ampl. (6-10 keV): cpd/kg/keV
(0.0016 ± 0.0031) DAMA/LIBRA-1
$-(0.0010 \pm 0.0034)$ DAMA/LIBRA-2
$-(0.0001 \pm 0.0031)$ DAMA/LIBRA-3
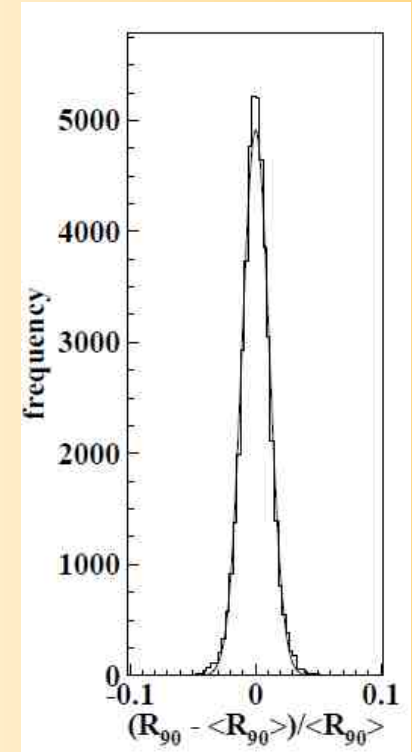$-(0.0006 \pm 0.0029)$ DAMA/LIBRA-4
$-(0.0021 \pm 0.0026)$ DAMA/LIBRA-5
(0.0029 ± 0.0025) DAMA/LIBRA-6
$-(0.0023 \pm 0.0024)$ DAMA/LIBRA-7
→ statistically consistent with zero

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	$-(0.05 \pm 0.19)$ cpd/kg
DAMA/LIBRA-2	$-(0.12 \pm 0.19)$ cpd/kg
DAMA/LIBRA-3	$-(0.13 \pm 0.18)$ cpd/kg
DAMA/LIBRA-4	(0.15 ± 0.17) cpd/kg
DAMA/LIBRA-5	(0.20 ± 0.18) cpd/kg
DAMA/LIBRA-6	$-(0.20 \pm 0.16)$ cpd/kg
DAMA/LIBRA-7	$-(0.28 \pm 0.18)$ 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

Multiple-hits events in the region of the signa

- Each detector has its own TDs read-out → pulse profiles of *multiple-hits* events (multiplicity > 1) acquired (exposure: 1.04 ton×yr).

- The same hardware and software procedures as those followed for *single-hit* events

signals by Dark Matter particles do not belong to *multiple-hits* events, that is:

> **multiple-hits events** = **Dark Matter particles events "switched off"**

Evidence of annual modulation with proper features as required by the DM annual modulation signature:
- present in the ***single-hit*** residuals
- absent in the ***multiple-hits*** residual

A = -(0.0012 ± 0.0006) cpd/kg/keV

A = -(0.0008 ± 0.0005) cpd/kg/keV

A = -(0.0005 ± 0.0004) cpd/kg/keV
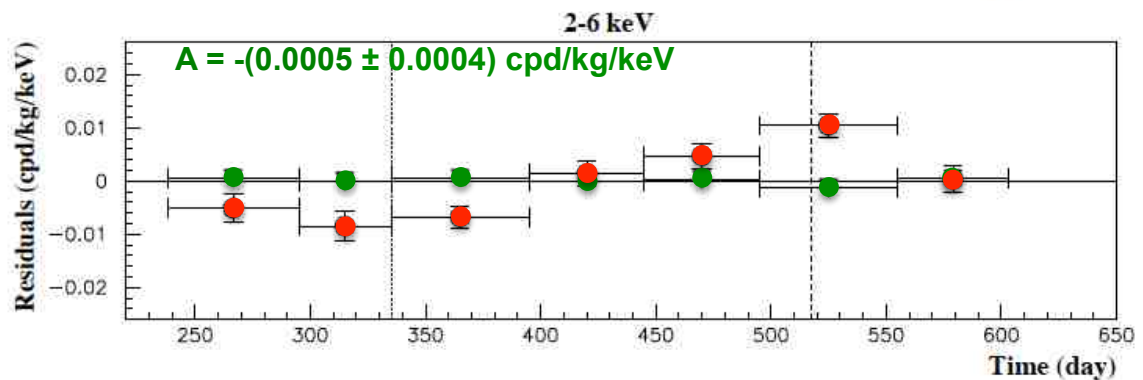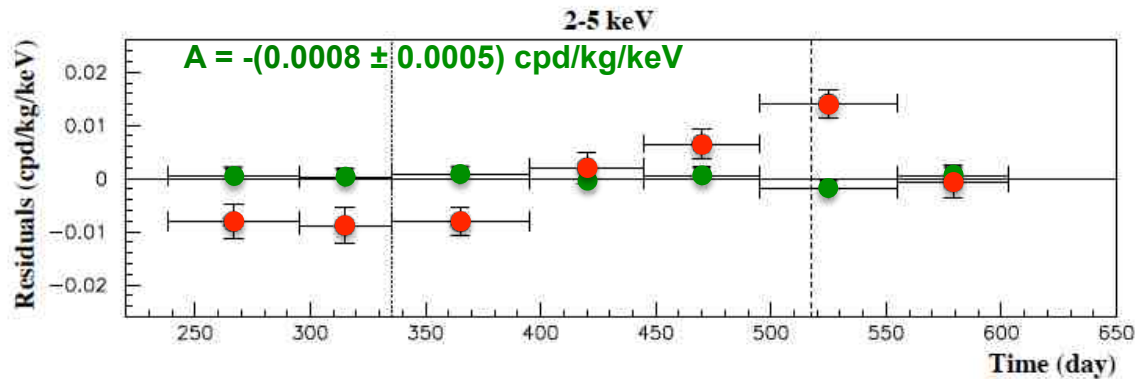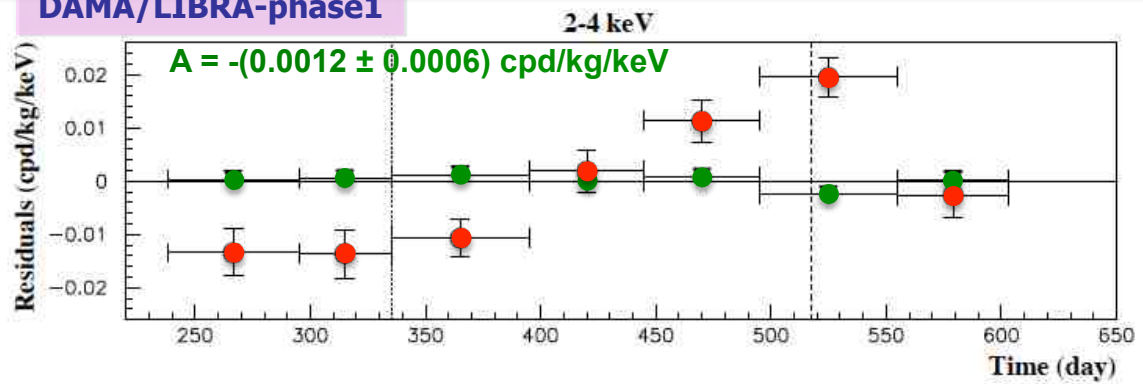
This result offers an additional strong support for the presence of Dark Matter particles in the galactic halo, further excluding any side effect either from hardware or from software procedures or from background
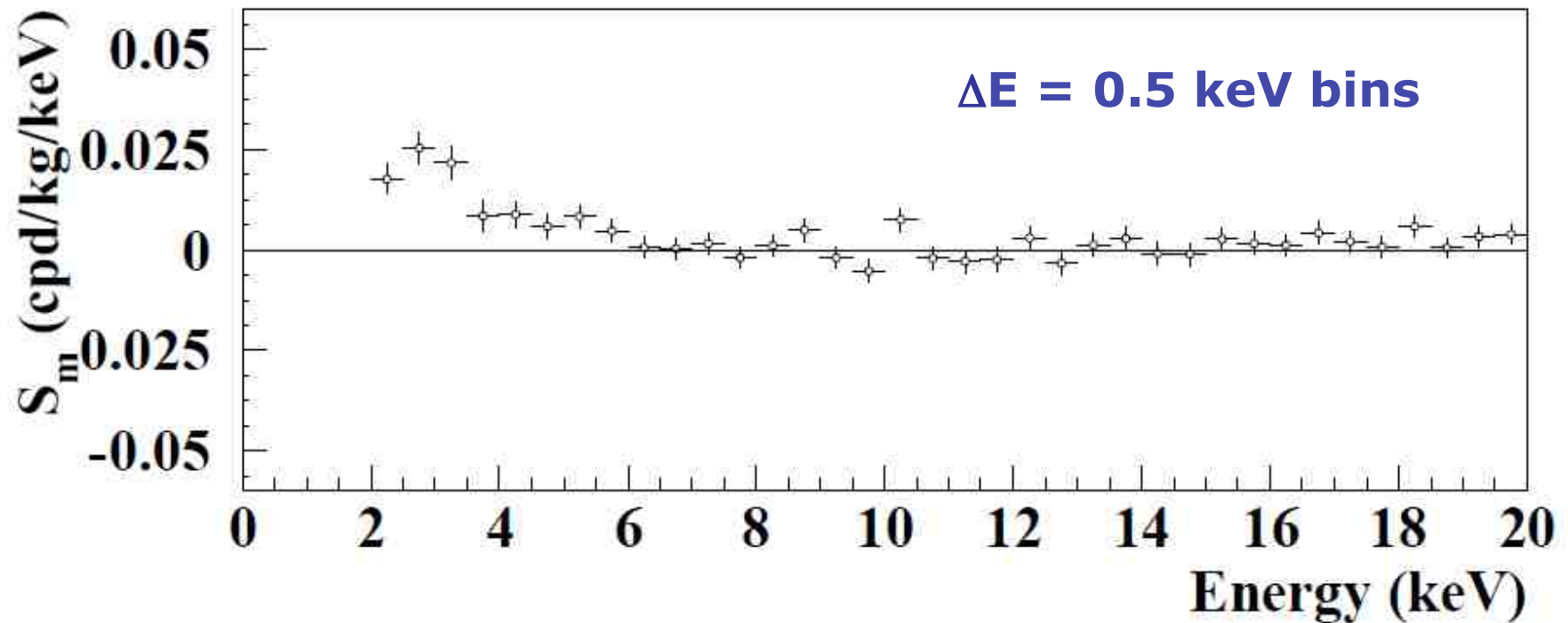
Energy distribution of the modulation amplitudes

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

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

DAMA/NaI **+ DAMA/LIBRA-phase1**

total exposure: 487526 kg×day ≈**1.33 ton×yr**

ΔE = 0.5 keV bins

A clear modulation is present in the (2-6) keV energy interval, while S_m values compatible with zero are present just above

The S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability 15%)

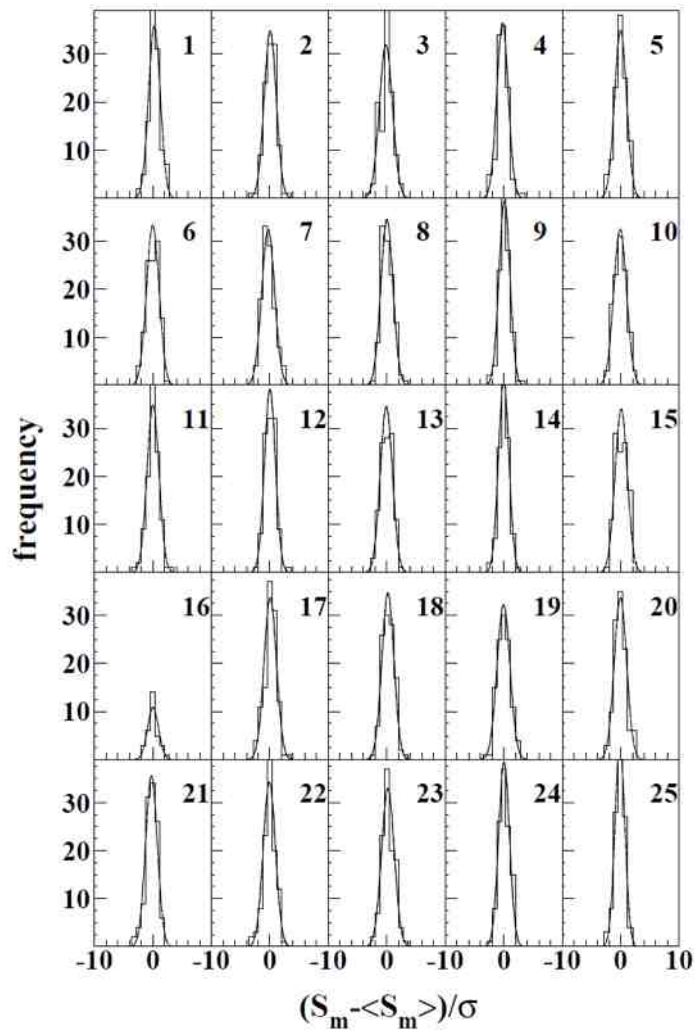# *Statistical distributions of the modulation amplitudes (S_m)*

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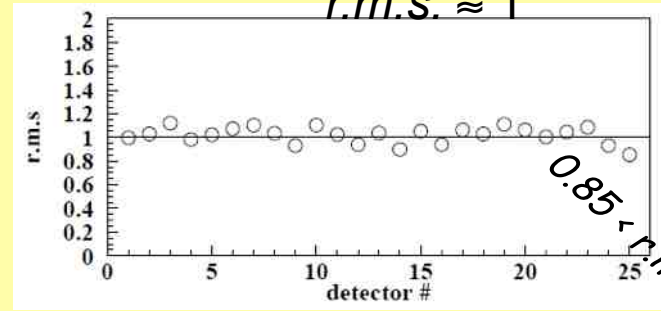
DAMA/LIBRA-phase1 (7 years)
total exposure: 1.04 ton×yr

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
$(S_m-\langle S_m\rangle)/\sigma$
for each detectors
r.m.s. ≈ 1

0.85 < r.m.s. < 1.12

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

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

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

⟹ **S_m** statistically well distributed in all the detectors, energy bin and annual cycles

Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

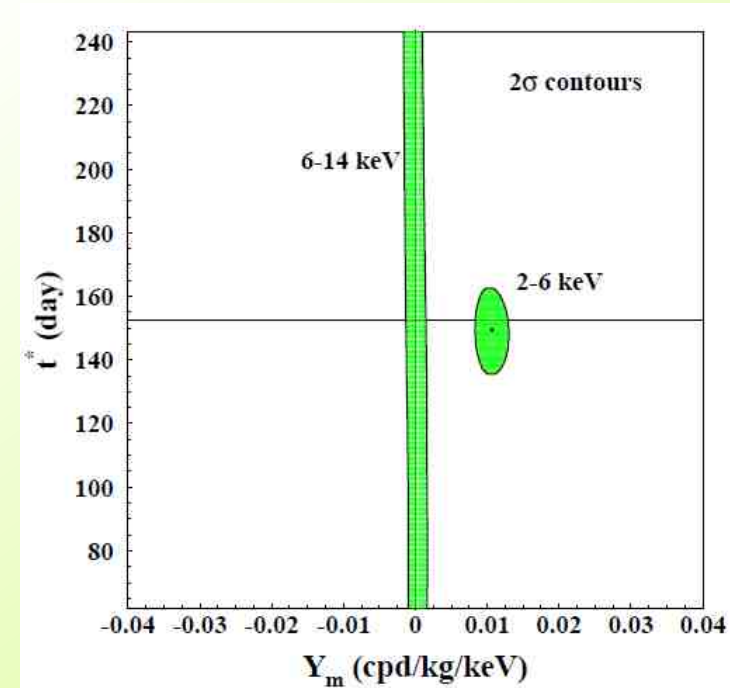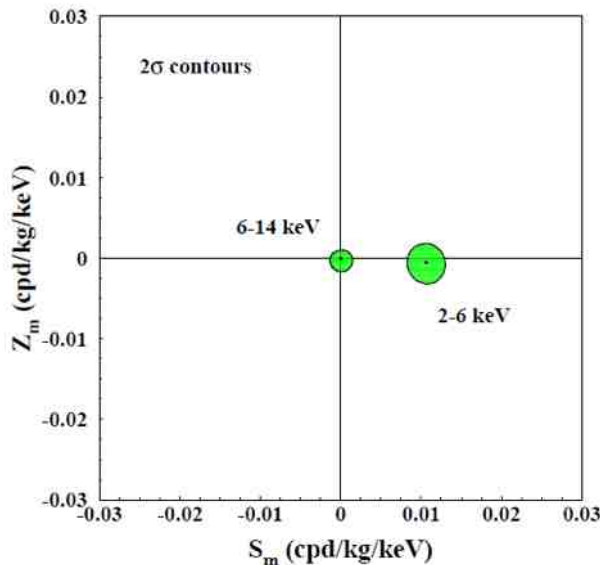DAMA/NaI (7 years) + **DAMA/LIBRA-phase1 (7 years)**

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

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

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $t^* \approx t_0 = 152.5d$
- $\omega = 2\pi/T$
- $T = 1$ year

Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)

E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t^* (day)
2-6	0.0106 ± 0.0012	-0.0006 ± 0.0012	0.0107 ± 0.0012	149.5 ± 7.0
6-14	0.0001 ± 0.0007	0.0000 ± 0.0005	0.0001 ± 0.0008	--

The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about S_m already exclude any sizable presence of systematical effects

Additional investigations on the stability parameters

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation

Running conditions stable at a level better than 1% also in the two new running periods

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4	DAMA/LIBRA-5	DAMA/LIBRA-6	DAMA/LIBRA-7
Temperature (°C)	-(0.0001 ± 0.0061)	(0.0026 ± 0.0086)	(0.001 ± 0.015)	(0.0004 ± 0.0047)	(0.0001 ± 0.0036)	(0.0007 ± 0.0059)	(0.0000 ± 0.0054)
Flux N_2 (l/h)	(0.13 ± 0.22)	(0.10 ± 0.25)	-(0.07 ± 0.18)	-(0.05 ± 0.24)	-(0.01 ± 0.21)	-(0.01 ± 0.15)	-(0.00 ± 0.14)
Pressure (mbar)	(0.015 ± 0.030)	-(0.013 ± 0.025)	(0.022 ± 0.027)	(0.0018 ± 0.0074)	-(0.08 ± 0.12) ×10^{-2}	(0.07 ± 0.13) ×10^{-2}	-(0.26 ± 0.55) ×10^{-2}
Radon (Bq/m^3)	-(0.029 ± 0.029)	-(0.030 ± 0.027)	(0.015 ± 0.029)	-(0.052 ± 0.039)	(0.021 ± 0.037)	-(0.028 ± 0.036)	(0.012 ± 0.047)
Hardware rate above single ph.e. (Hz)	-(0.20 ± 0.18) × 10^{-2}	(0.09 ± 0.17) × 10^{-2}	-(0.03 ± 0.20) × 10^{-2}	(0.15 ± 0.15) × 10^{-2}	(0.03 ± 0.14) × 10^{-2}	(0.08 ± 0.11) × 10^{-2}	(0.06 ± 0.10) × 10^{-2}

All the measured amplitudes well compatible with zero
+ none can account for the observed effect
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)
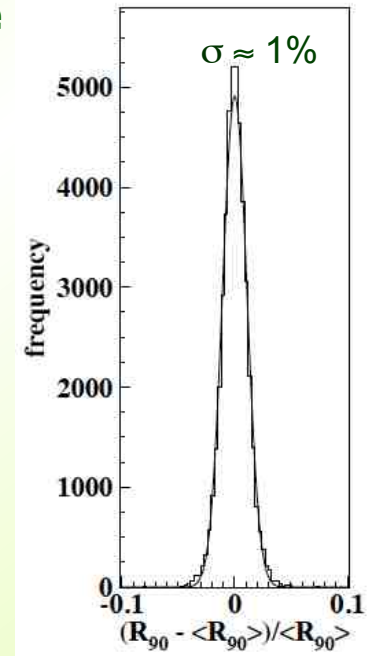
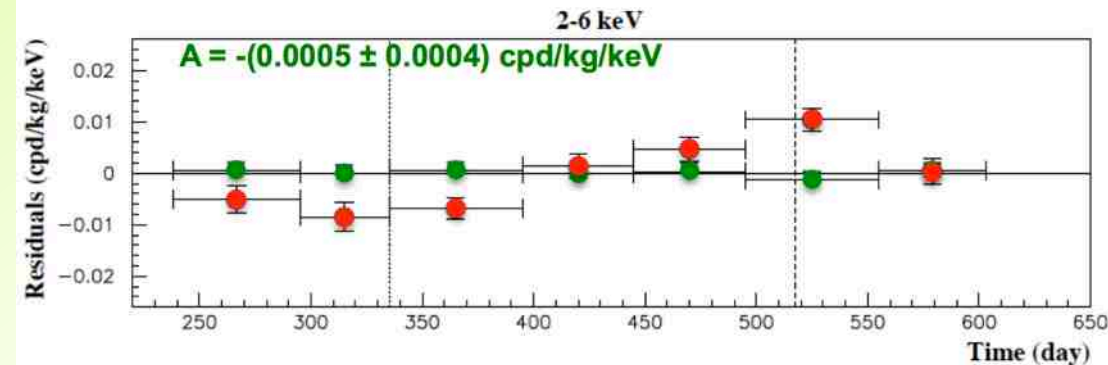# Summarizing on a hypothetical background modulation

• **No Modulation above 6 keV**

• **No modulation in the whole energy spectrum**

+ **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 in the 2-6 keV *multiple-hits* residual rate**

multiple-hits residual rate (green points) vs single-hit residual rate (red points)

**No background modulation (and cannot mimic the signature):
all this accounts for the all possible sources of bckg**

Nevertheless, additional investigations performed ...   **See DAMA literature**

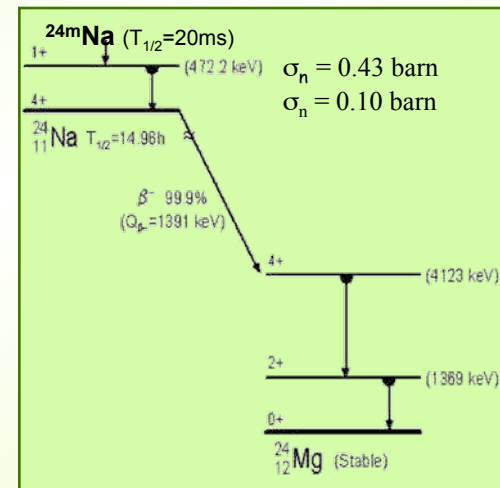# Can a possible thermal neutron modulation account for the observed effect?

NO

- Thermal neutrons flux measured at LNGS :

$$\Phi_n = 1.08 \ 10^{-6} \ n \ cm^{-2} \ s^{-1} \ (N.Cim.A101(1989)959)$$

- Experimental upper limit on the thermal neutrons flux "*surviving*" the neutron shield in DAMA/LIBRA:
  - ➤ studying triple coincidences able to give evidence for the possible presence of ^{24}Na from neutron activation:

$$\Phi_n < 1.2 \times 10^{-7} \ n \ cm^{-2} \ s^{-1} \ (90\%C.L.)$$

- Two consistent upper limits on thermal neutron flux have been obtained with DAMA/NaI considering the same capture reactions and using different approaches.

^{24m}**Na** $(T_{1/2}=20ms)$

1+   (472.2 keV) $\sigma_n = 0.43$ barn

4+ $\sigma_n = 0.10$ barn

$^{24}_{11}Na \ T_{1/2}=14.96h$

β^- 99.9%
$(Q_{\beta^-}=1391 \ keV)$

4+   (4123 keV)

2+   (1369 keV)

0+

$^{24}_{12}Mg$ (Stable)

Evaluation of the expected effect:

▶ Capture rate = $\Phi_n \ \sigma_n \ N_T <$ 0.022 captures/day/kg

HYPOTHESIS: assuming very cautiously a 10% thermal neutron modulation:

➤ $S_m^{(thermal \ n)} < 0.8 \times 10^{-6}$ cpd/kg/keV ($< 0.01\%$ $S_m^{observed}$)

In all the cases of neutron captures (^{24}Na, ^{128}I, ...) a possible thermal n modulation induces a variation in all the energy spectrum

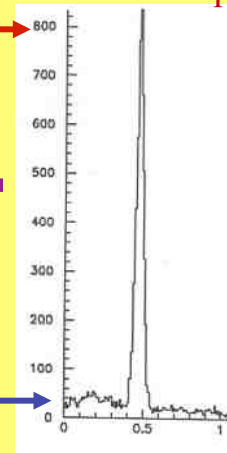**Already excluded also by R_{90} analysis**

MC simulation of the process

When $\Phi_n = 10^{-6}$ n cm^{-2} s^{-1}:

$7 \cdot 10^{-5}$ cpd/kg/keV

$1.4 \cdot 10^{-3}$ cpd/kg/keV

E (MeV)

Can a possible fast neutron modulation account for the observed effect?

NO

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield

Measured fast neutron flux @ LNGS:
$\Phi_n = 0.9 \cdot 10^{-7}$ n cm^{-2} s^{-1} (Astropart.Phys.4 (1995)23)

By MC: differential counting rate above 2 keV $\approx 10^{-3}$ cpd/kg/keV

HYPOTHESIS: assuming - very cautiously - a 10% neutron modulation:

$S_m^{(fast \, n)} < 10^{-4}$ cpd/kg/keV $\quad (< 0.5\% \, S_m^{observed})$

- Experimental upper limit on the fast neutrons flux "*surviving*" the neutron shield in DAMA/LIBRA:
  - through the study of the inelastic reaction ^{23}Na(n,n')^{23}Na*(2076 keV) which produces two γ's in coincidence (1636 keV and 440 keV):

$$\Phi_n < 2.2 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \text{ (90\%C.L.)}$$

  - well compatible with the measured values at LNGS. This further excludes any presence of a fast neutron flux in DAMA/LIBRA significantly larger than the measured ones.

Moreover, a possible fast n modulation would induce:
- ▶ a variation in all the energy spectrum (steady environmental fast neutrons always accompanied by thermalized component)

  already excluded also by R_{90}

- ▶ a modulation amplitude for multiple-hit events different from zero

  already excluded by the multiple-hit events

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

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

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

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

Detector's matrix

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

R_n = (fast n by μ)/(time unit) = Φ_μ 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)

Annual modulation amplitude at low energy due to μ **modulation**:

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

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

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

$S_m^{(m)}$ < (0.3-2.4) × 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

For many others arguments
EPJC72(2012)2064
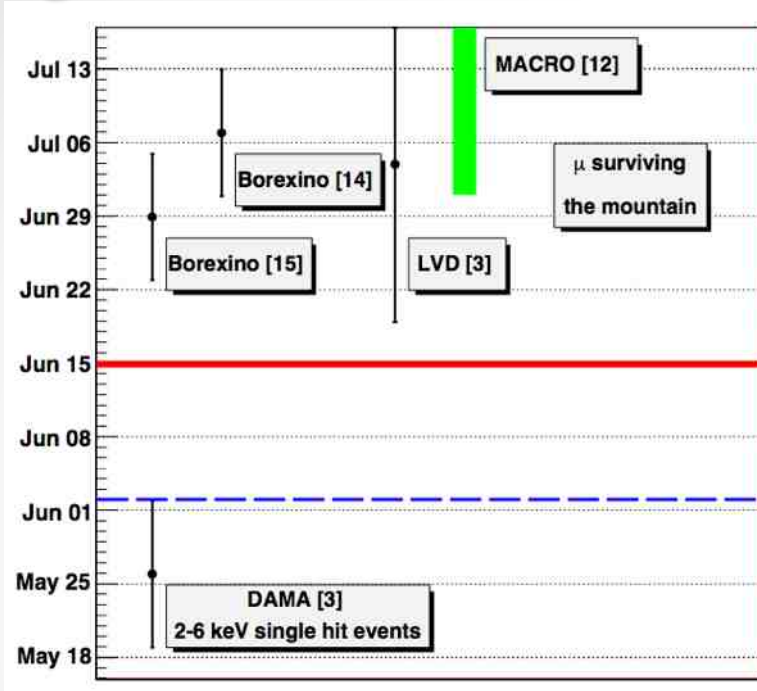
μ flux @ LNGS (MACRO, LVD, BOREXINO) $\approx 3 \cdot 10^{-4}$ m^{-2}s^{-1}; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)

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

It cannot mimic the signature: different phase

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

Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5\times10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield$\rightarrow$ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + instrinsic 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 for 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 152.5 days, as expected for the DM signal

4. The modulation is present only in the low energy (2-6) keV 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-hits,* as expected for the DM signal

6. The measured modulation amplitude in NaI(Tl) of the *single-hit* events in (2-6) keV 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

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

well compatible with several candidates (in many possible 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

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

Sterile neutrino

Self interacting Dark Matter

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

Elementary Black holes such as the Daemons
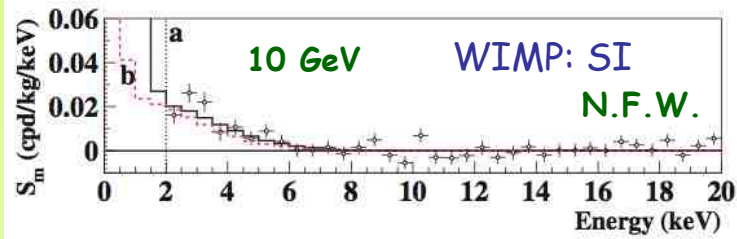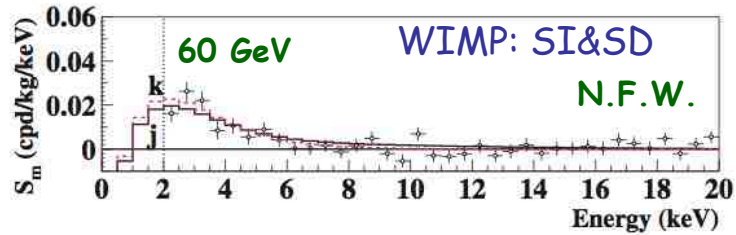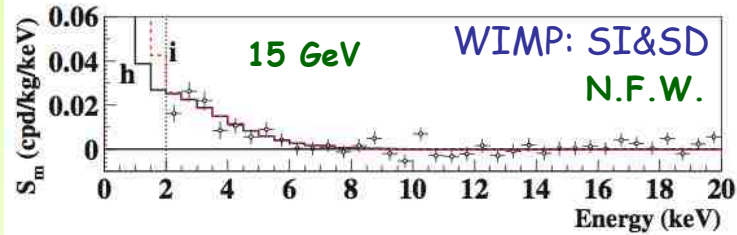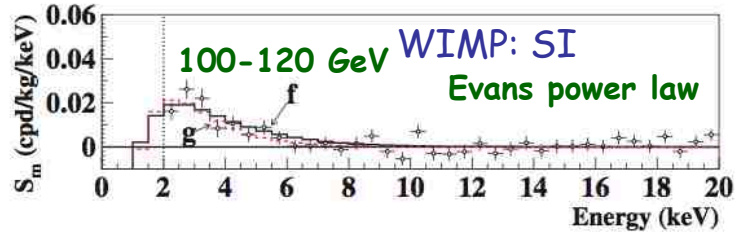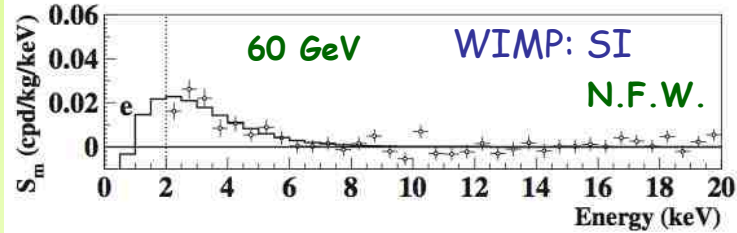
Kaluza Klein particles

... and more

Possible model dependent positive hints from indirect searches (but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.) **not in conflict with DAMA results;**

Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with positive excesses
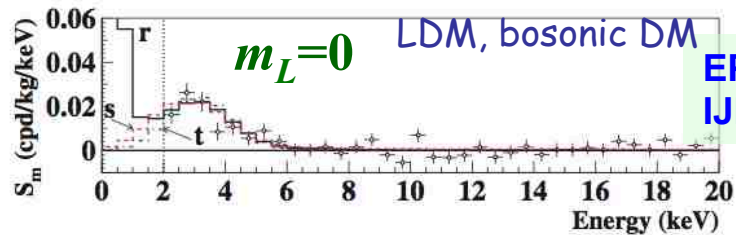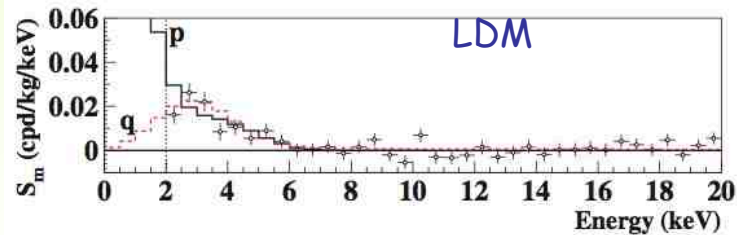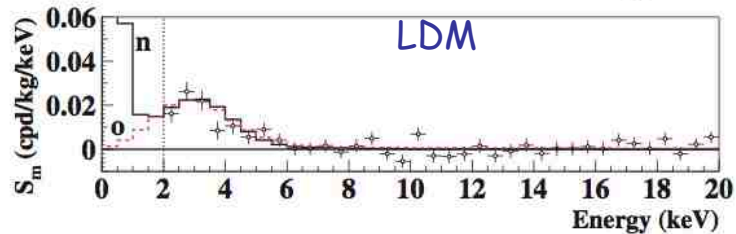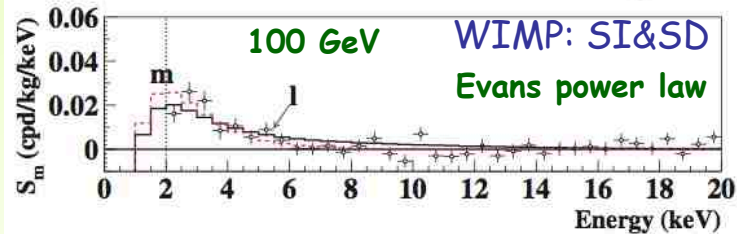
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios
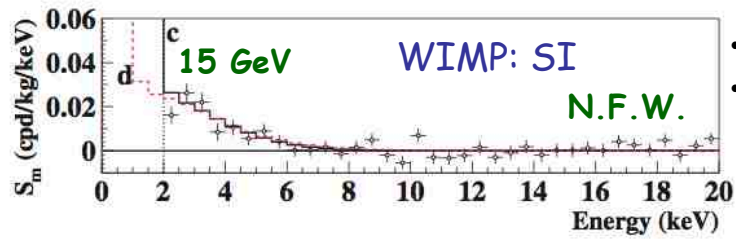
- Not best fit
- About the same C.L.

(a) 10 GeV — WIMP: SI N.F.W.

(c) 15 GeV — WIMP: SI N.F.W.

(e) 60 GeV — WIMP: SI N.F.W.

(f,g) 100-120 GeV — WIMP: SI Evans power law

(h,i) 15 GeV — WIMP: SI&SD N.F.W.

(j,k) 60 GeV — WIMP: SI&SD N.F.W.

$\theta = 2.435$

(l,m) 100 GeV — WIMP: SI&SD Evans power law

(n,o) LDM

(p,q) LDM

(r,s,t) LDM, bosonic DM $m_L = 0$

Compatibility with several candidates; other ones are open

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

Examples of uncertainties in models and scenarios

Nature of the candidate and couplings

- WIMP class particles (neutrino, sneutrino, etc.): SI, SD, mixed SI&SD, preferred inelastic + e.m. contribution in the detection
- Light bosonic particles
- Kaluza-Klein particles
- Mirror dark matter
- Heavy Exotic candidate
- …etc. etc.

Scaling laws of cross sections for the case of recoiling nuclei

- Different scaling laws for different DM particle:

  $\sigma_A \propto \mu^2 A^2 (1+\varepsilon_A)$

  $\varepsilon_A = 0$ generally assumed

  $\varepsilon_A \approx \pm 1$ in some nuclei? even for neutralino candidate in MSSM (see Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301)

Halo models & Astrophysical scenario

- Isothermal sphere ⇒ very simple but unphysical halo model
- Many consistent halo models with different density and velocity distribution profiles can be considered with their own specific parameters (see e.g. PRD61(2000)023512)
- Caustic halo model

- Presence of non-thermalized DM particle components
- Streams due e.g. to satellite galaxies of the Milky Way (such as the Sagittarius Dwarf)
- Multi-component DM halo
- Clumpiness at small or large scale
- Solar Wakes
- …etc. …

Form Factors for the case of recoiling nuclei

- Many different profiles available in literature for each isotope
- Parameters to fix for the considered profiles
- Dependence on particle-nucleus interaction
- In SD form factors: no decoupling between nuclear and Dark Matter particles degrees of freedom + dependence on nuclear potential

Spin Factors for the case of recoiling nuclei

- Calculations in different models give very different values also for the same isotope
- Depend on the nuclear potential models
- Large differences in the measured counting rate can be expected using:

  either SD not-sensitive isotopes

  or SD sensitive isotopes depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the ^{23}Na and ^{127}I cases).

Instrumental quantities

- Energy resolution
- Efficiencies
- Quenching factors
- Channeling effects
- Their dependence on energy
- …

Quenching Factor

- differences are present in different experimental determinations of q for the same nuclei in the same kind of detector depending on its specific features (e.g. q depends on dopant and on the impurities; in liquid noble gas e.g.on trace impurities, on presence of degassing/releasing materials, on thermodynamical conditions, on possibly applied electric field, etc); assumed 1 in bolometers
- channeling effects possible increase at low energy in scintillators (dL/dx)
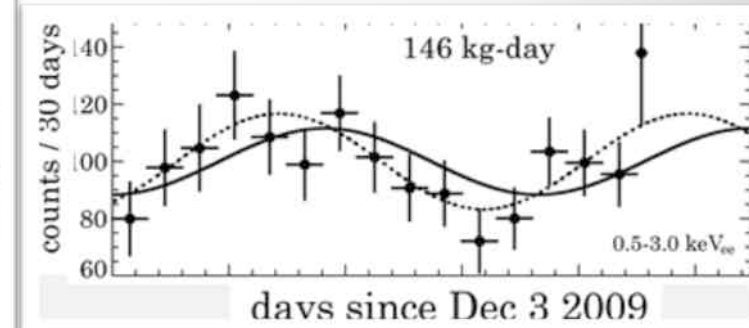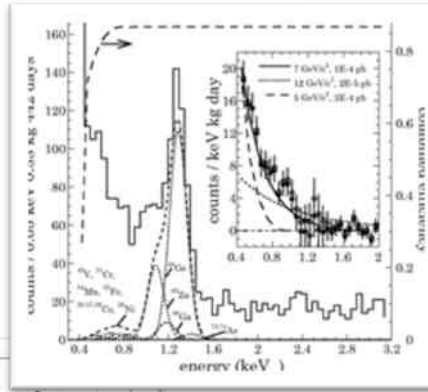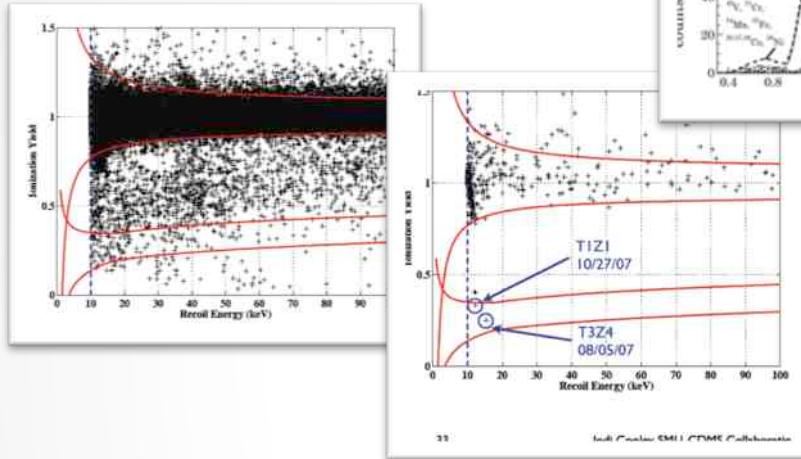- possible larger values of q (AstropPhys33 (2010) 40)

→ energy dependence

… and more …

# DAMA vs possible positive hints 2010 - 2013

CoGeNT:
low-energy rise in the spectrum ("irreducible" by the applied background reduction procedures) + annual modulation

CDMS-Ge:
after many data selections and cuts, 2 Ge recoil-like candidates survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)

CRESST: after many data selections and cuts, 67 recoil-like candidates in the O/Ca bands survive in an exposure of 730 kg x day (expected residual background: 40-45 events, depending on minimization)
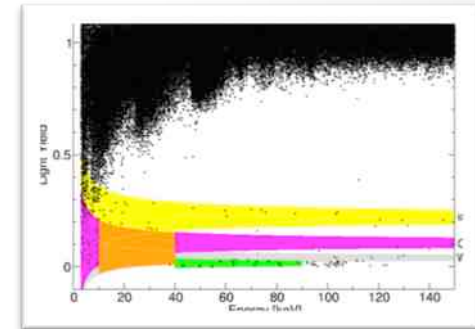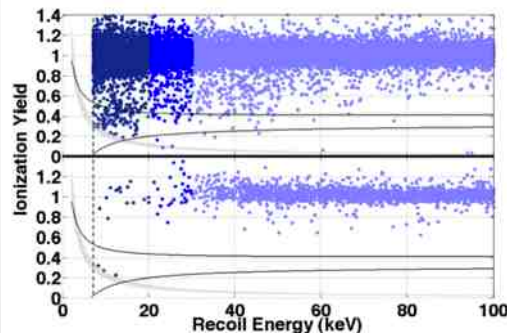
CDMS-Si:
after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

All those recoil-like excesses with respect to an estimated bckg surviving cuts as well as the CoGeNT result are compatible with the DAMA 9.3 σ C.L. annual modulation result in various scenarios

What is new?

- Detector recovered from 3 mo post-fire outage w/o significant changes in performance. It has been <u>continuously</u> taking data ever since. All data are usable (compare to 10%-40% in CDMS low-energy analyses).

- Large exposure allows optimal separation of bulk and surface events down to 0.5 keVee threshold. Rise-time behavior as predicted by simulations and calibrations (PRD 88 (2013) 012002). Smooth variation of fit parameters with energy.

- Paper under review, preprint to appear soon. <u>Data to be released in energy, time-stamp, and rise-time format.</u> 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...

Dotted: free T
Solid: T= 365 d

See also poster by M. Kos.

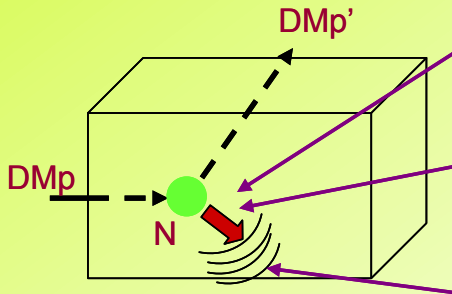Additional four months of unanalyzed data acquired (run is still ongoing)

& also excess of recoil-like events with respect to estimated backgrounds surviving the cuts applied by those expts: CRESST 4 σ C.L. effect, CDMS marginal (exposures orders of magnitude lower than DAMA)
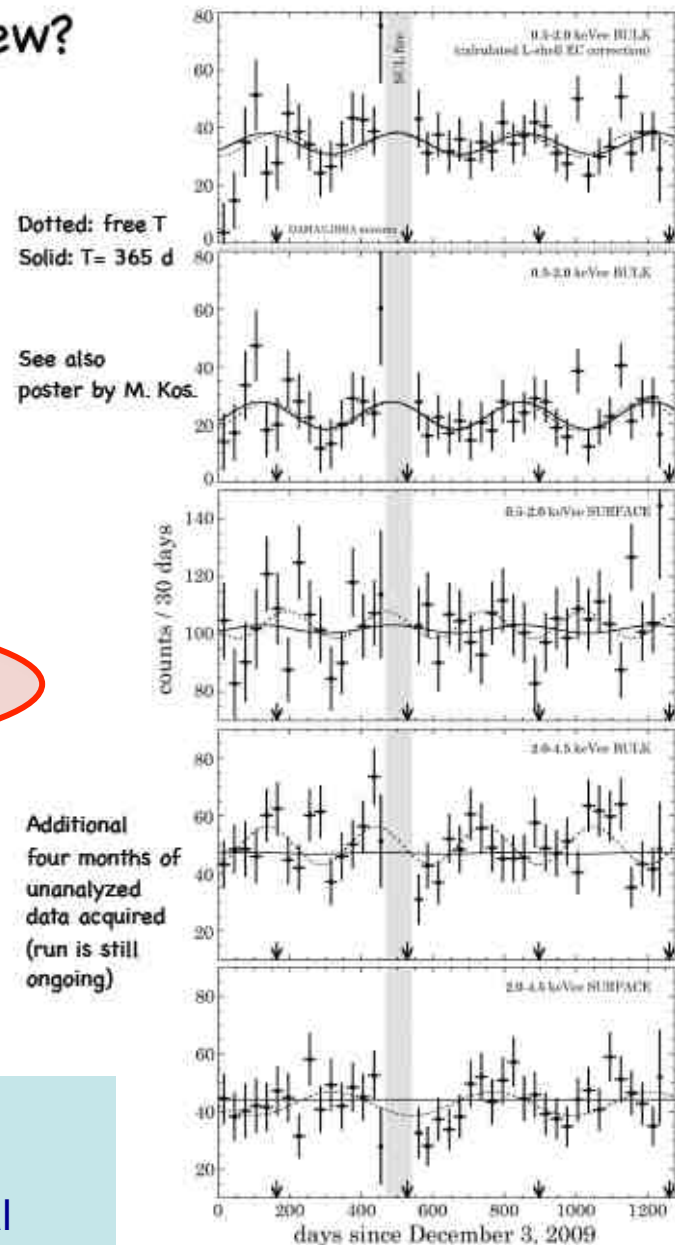
Case of DM particles inducing elastic scatterings on target-nuclei, SI case

DMp'

DMp

N

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
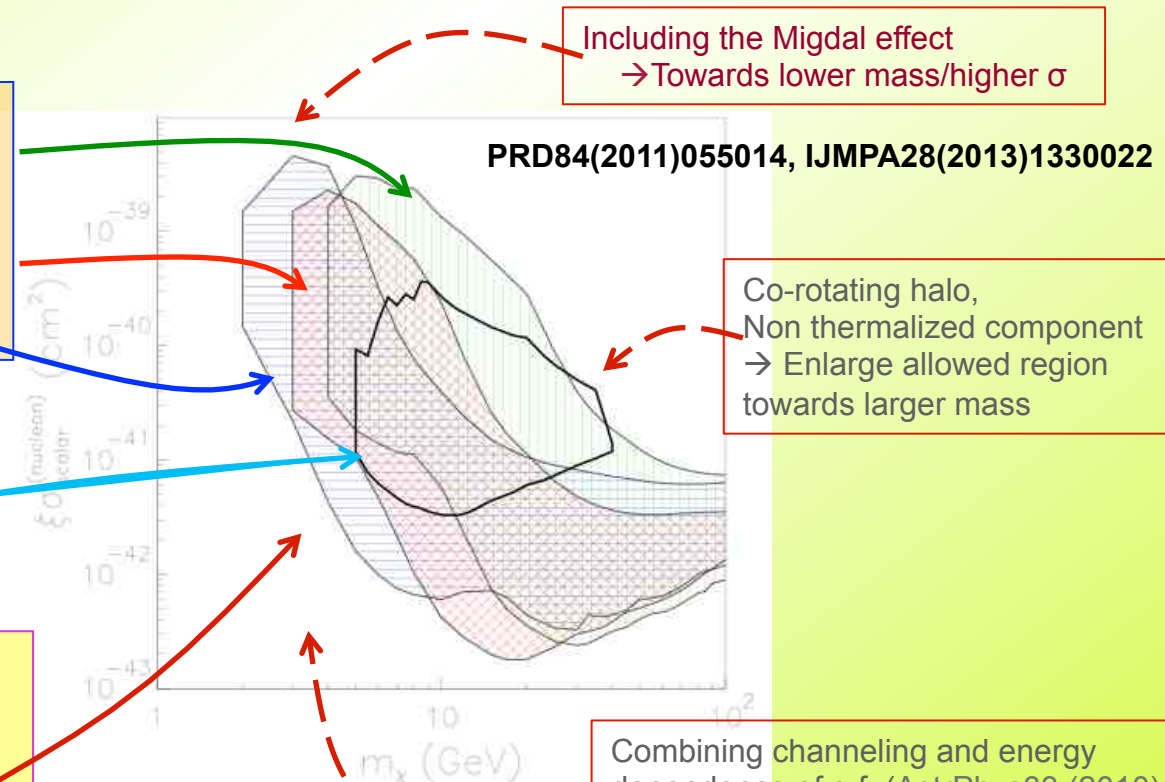→Towards lower mass/higher σ

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.

$\xi \sigma_{SI}^{(nucleon)}$ (cm²)

m_χ (GeV)

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

Another example of compatibility

DM particle with preferred inelastic interaction
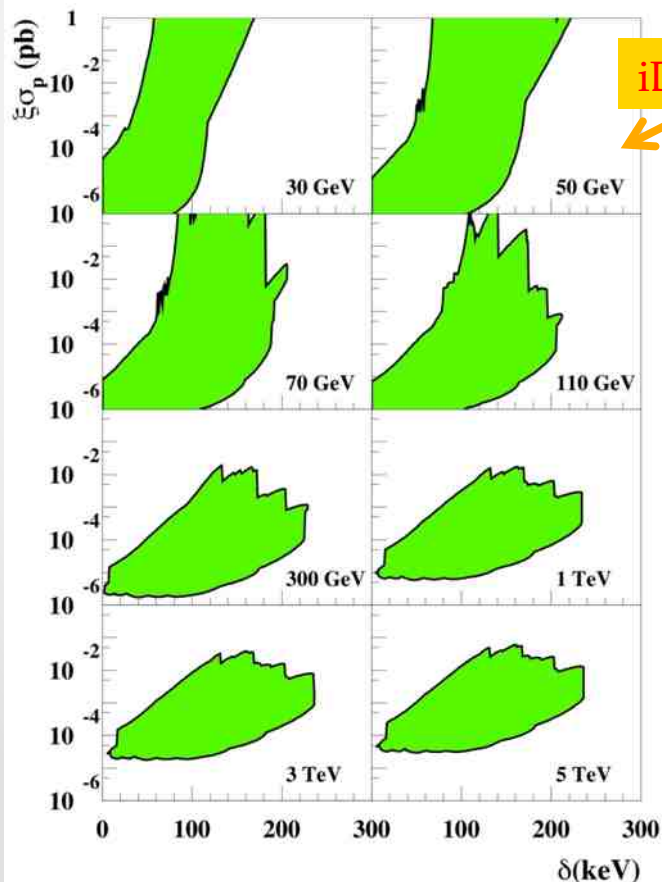
$$\chi^- + N \rightarrow \chi^+ + N$$

In the Inelastic DM (iDM) scenario, WIMPs scatter into an excited state, split from the ground state by an energy comparable to the available kinetic energy of a Galactic WIMP.

- iDM has two mass states χ^+, χ^- with δ mass splitting

- Kinematical constraint for iDM

DAMA/NaI+DAMA/LIBRA Fund. Phys. 40(2010)900
Slices from the 3-dimensional allowed volume

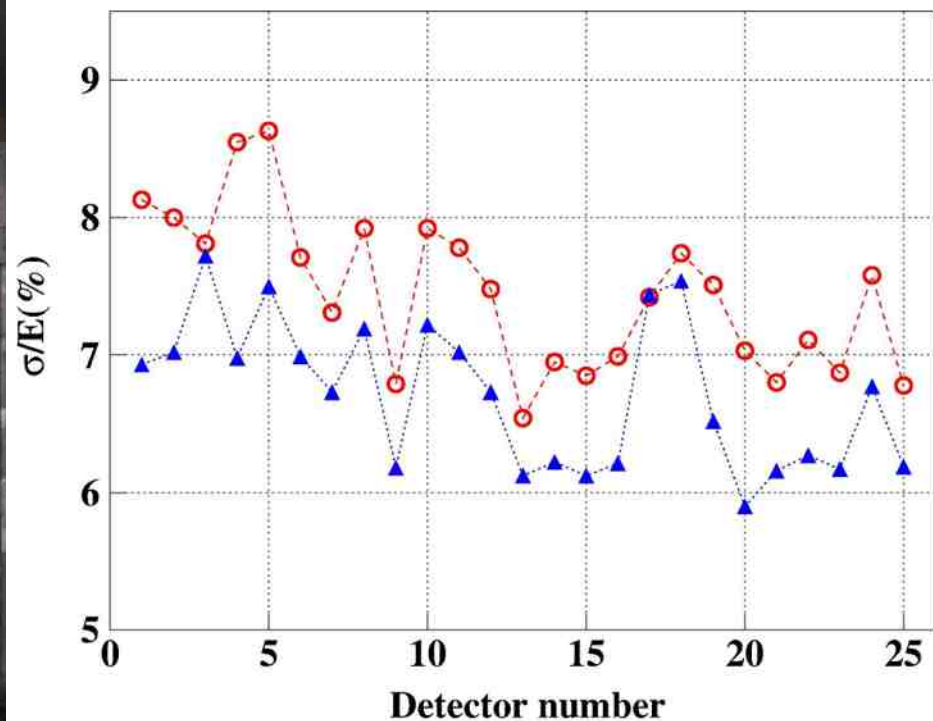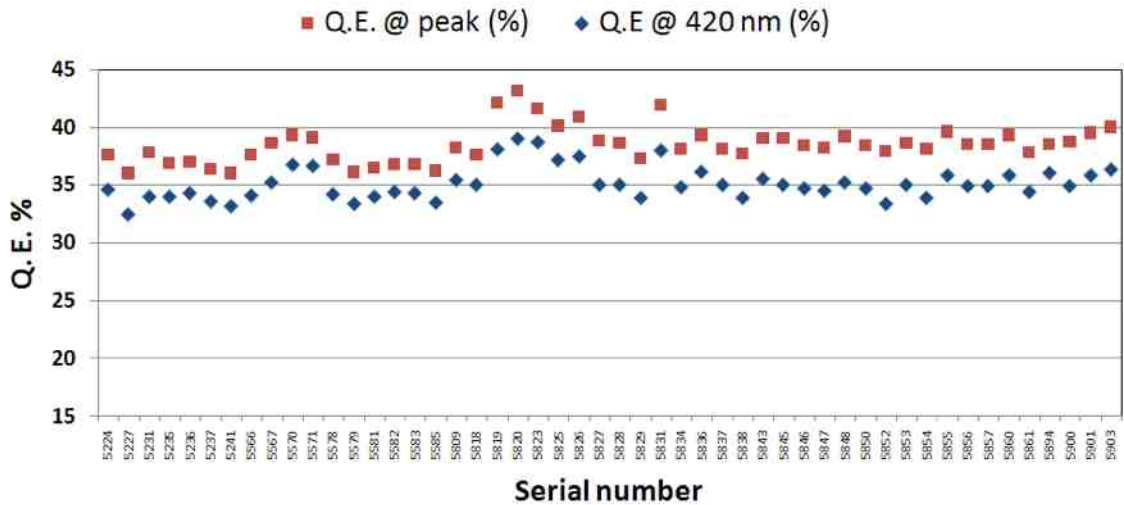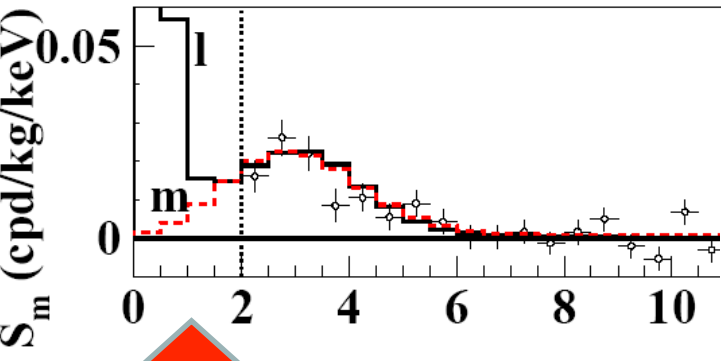$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

iDM interaction on Iodine nuclei

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

arXiv:1007.2688

- 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.

- Inelastic scattering WIMPs with large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

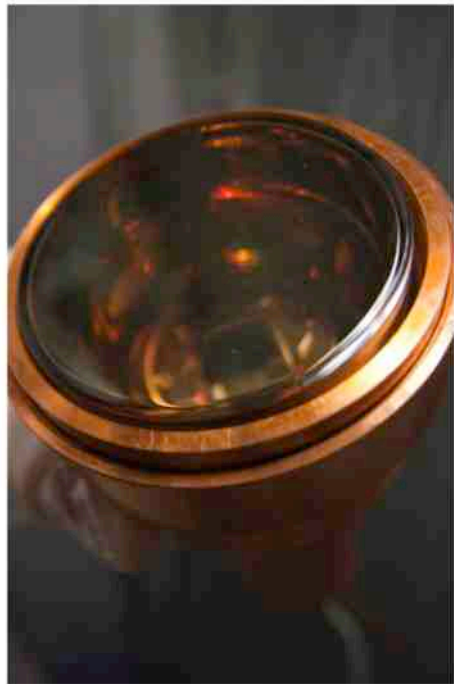**… and more considering experimental and theoretical uncertainties**

ov/Dec
ed with new

Since Dec 2010 data taking and optimizations in this new configuration started

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)

- The modulation parameters determined with better precision

- Full sensitivity to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation.

- Possible positive hints in direct searches are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties. Indirect model dependent searches not in conflict

- New PMTs with higher Q.E.

Moreover, works and efforts for:
- further improvement (phase3);
- DAMA/1ton set up;
- ADAMO project, anisotropic scintillators for directionality

DAMA/LIBRA – phase2 perspectives

- *Continuing data taking* in the new configuration with lower energy threshold (below 2 keV).

- New preamplifiers (installed in Fall 2012), trigger modules and other developments realized to further implement low energy studies.

- Suitable exposure planned in the new configuration to deeper study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects.

- Investigation on dark matter peculiarities and second order effect

- Special data taking for other rare processes.