New results from DAMA/LIBRA: final model independent results of DAMA/LIBRA-phase1

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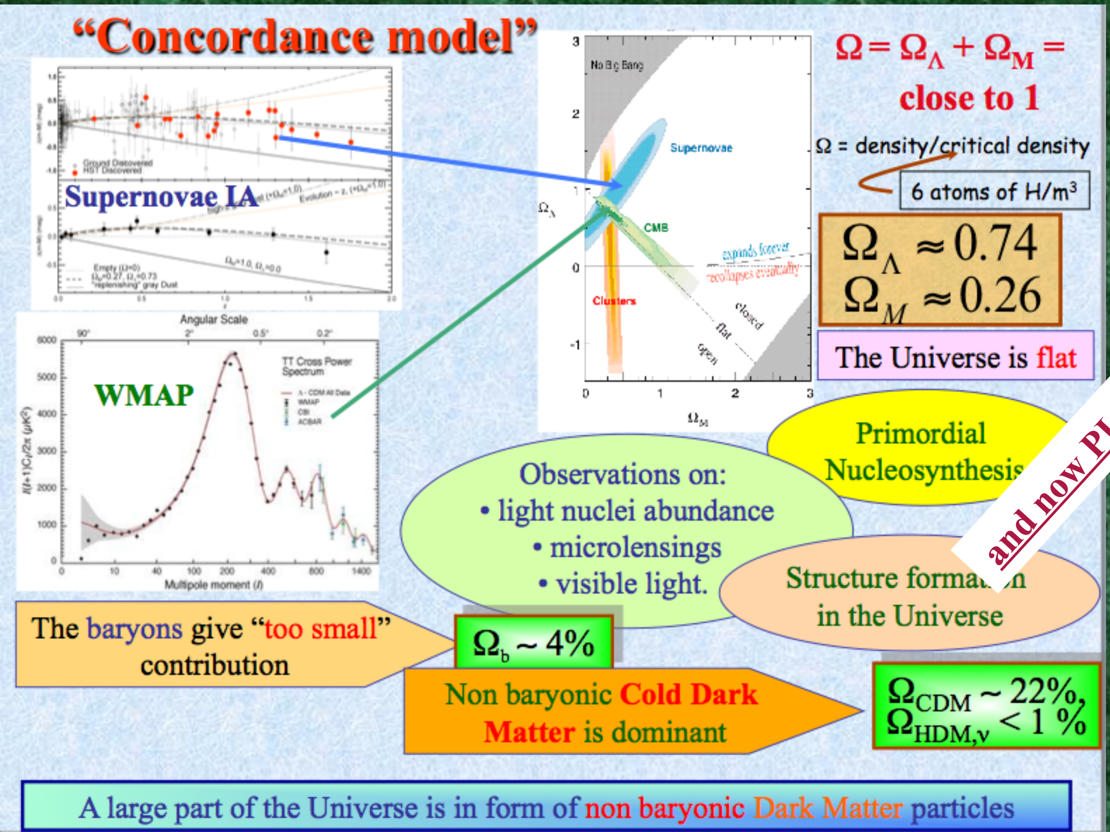
The Dark Side of the Universe: about a century of experimental evidences ...

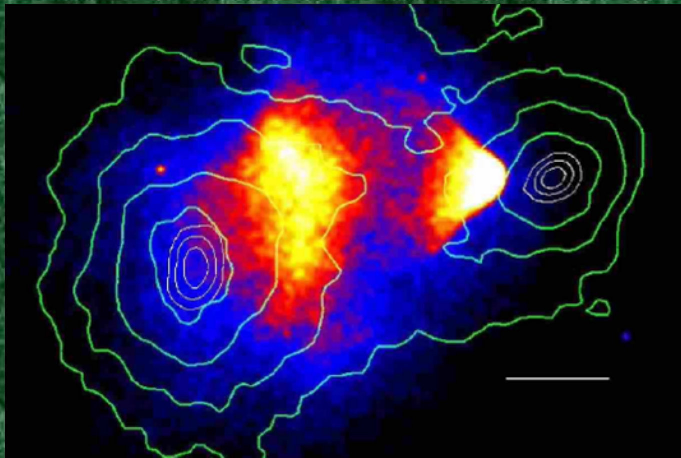
First evidence and confirmations:

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

Other experimental evidences

- ✓ from LMC motion around Galaxy
- ✓ from X-ray emitting gases surrounding elliptical galaxies
- ✓ from hot intergalactic plasma velocity distribution in clusters
- ✓ ...
- ✓ bullet cluster 1E0657-558





Efforts to find alternative explanations to DM were proposed e.g.:

- ✓ Modified Gravity Theory (MOG) in the 1980s
- ✓ Modified Newtonian Dynamics (MOND) theory in 1981

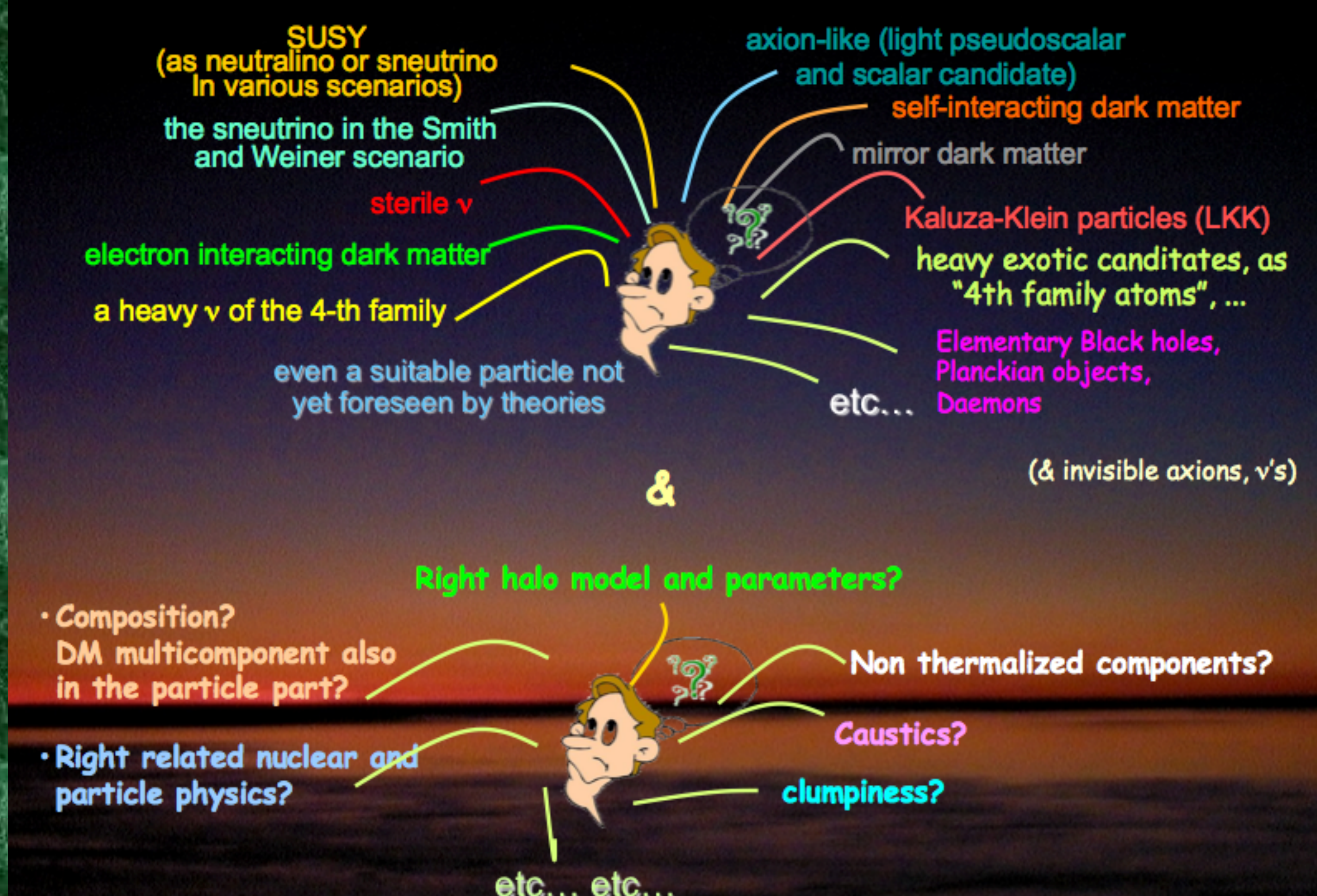
They hypothesize that the theory of gravity is incomplete and that a new gravitational theory might explain the experimental observations:

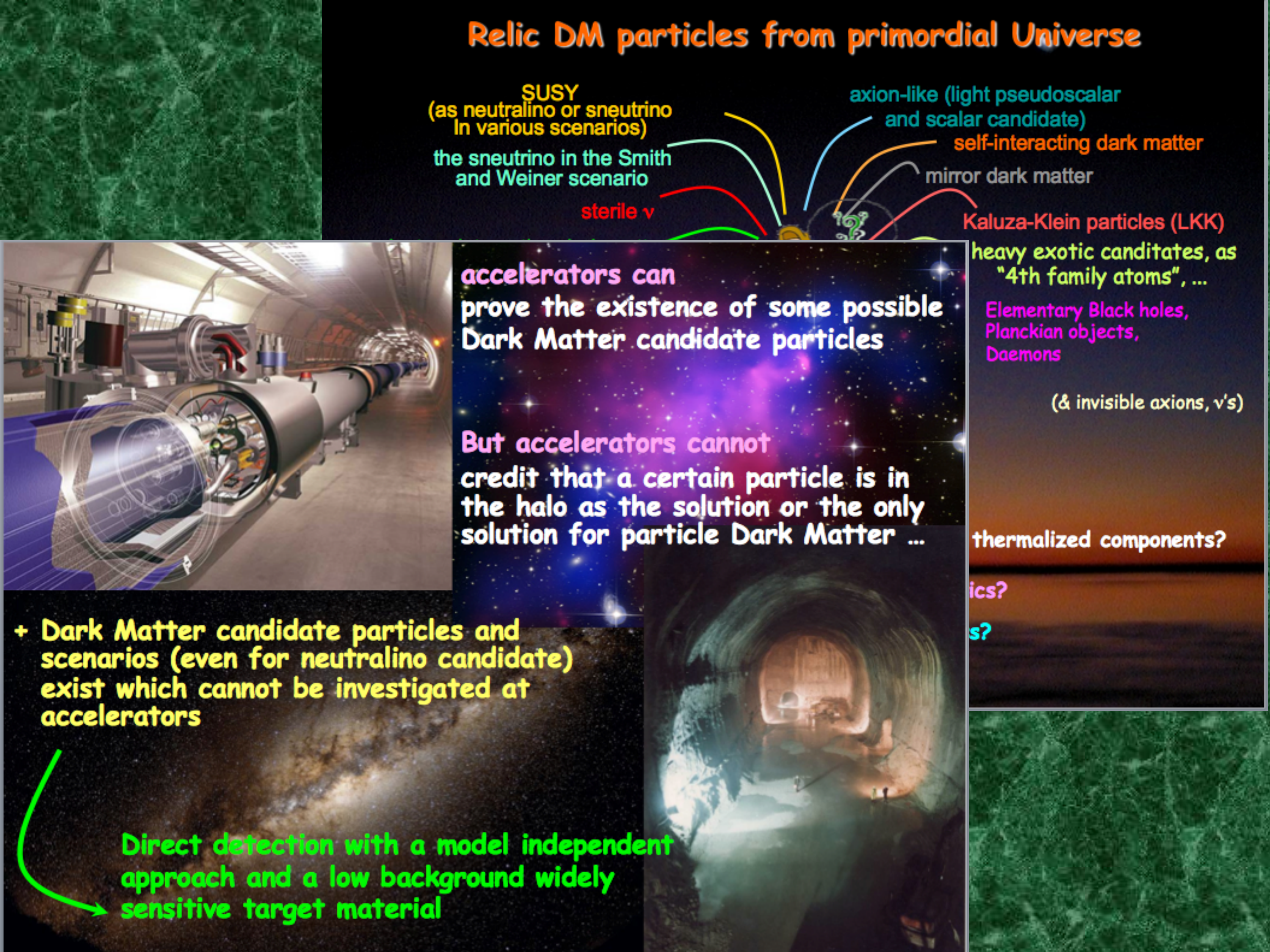
- ✓ MOND modifies the law of motion for very small accelerations
- ✓ MOG modifies the Einstein's theory of gravitation to account for an hypothetical fifth fundamental force in addition to the gravitational, electromagnetic, strong and weak ones.

BUT

- ✓ no general underlying principle;
- ✓ generally unable to account for all small and large scale observations;
- ✓ they fail to reproduce accurately the Bullet Cluster;
- ✓ generally require some amount of DM particles as seeds for the structure formation.

Relic DM particles from primordial Universe

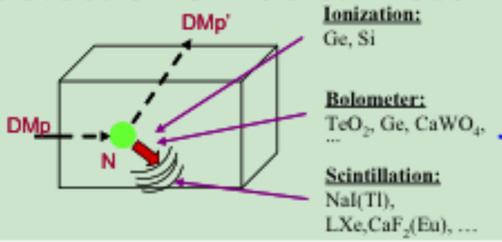



Relic DM particles from primordial Universe
SUSY
(as neutralino or sneutrino
In various scenarios)
the sneutrino in the Smith
and Weiner scenario
sterile ν
axion-like (light pseudoscalar
and scalar candidate)
self-interacting dark matter
mirror dark matter
Kaluza-Klein particles (LKK)
heavy exotic canditates, as
"4th family atoms", ...
Elementary Black holes,
Planckian objects,
Daemons
(& invisible axions, ν's)
thermalized components?
ics?
s?
accelerators can
prove the existence of some possible
Dark Matter candidate particles
But accelerators cannot
credit that a certain particle is in
the halo as the solution or the only
solution for particle Dark Matter ...
+ Dark Matter candidate particles and
scenarios (even for neutralino candidate)
exist which cannot be investigated at
accelerators
Direct detection with a model independent
approach and a low background widely
sensitive target material

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



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

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

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

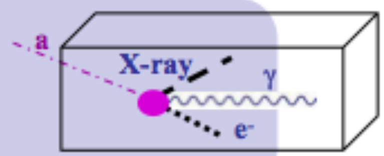
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

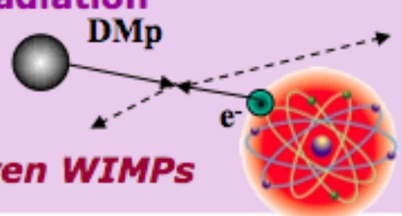
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

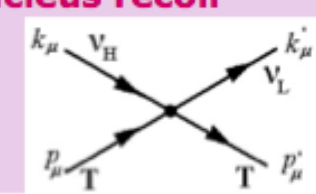
  → detection of e.m. radiation



... even WIMPs

- Interaction of light DMp (LDM) on e^- or nucleus with production of a lighter particle → detection of electron/nucleus recoil energy

e.g. sterile ν



... also other possibilities ...

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

- ... 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 a-priori assumption on the nature and interaction type of the DM particles + use of large data selection/subtraction by uncertain techniques (existing systematics and side processes mimicing the nuclear recoil-like events which can neither be distinguished nor estimated and subtracted at needed level of precision on the contrary of usual claims)

2 different questions:

- **Are there Dark Matter particles in the galactic halo?**

The exploitation of the annual modulation DM signature with highly radiopure NaI(Tl) as target material can permit to answer to this question by direct detection and in a way largely independent on the nature of the candidate and on the astrophysical, nuclear and particle Physics assumptions

→ DAMA/NaI and DAMA/LIBRA

- **Which are exactly the nature of the Dark Matter particle(s) and the related astrophysical, nuclear and particle Physics scenarios?**

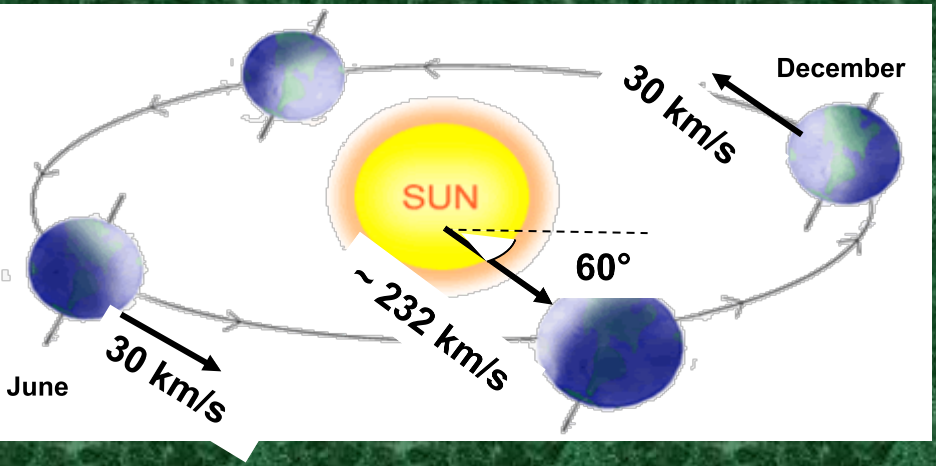
This requires subsequent model-dependent corollary analyses (see e.g. in recent DAMA – and other – literature;… and more)

N.B. It does not exist any approach to investigate the nature of the candidate in the direct and indirect DM searches, which can offer these latter information independently on assumed astrophysical, nuclear and particle Physics scenarios…

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} ~ 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 seasons

The relevance of ULB NaI(Tl) as target-material

- Well known technology
- High duty cycle
- Large mass possible
- "Ecological clean" set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- λ of the NaI(Tl) scintillation light well directly match PMTs sensitivity
- Uniform response in the realized detectors
- High light response (5.5 - 7.5 ph.e./keV in DAMA/LIBRA-phase1)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios on the contrary of other proposed target-materials (and approaches)
- Sensitive to both high (mainly by Iodine target) and low mass (mainly by Na target) candidates
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up
- etc.

ULB NaI(Tl) also allows the study of several rare processes

High benefits/cost

To develop ULB NaI(Tl): many years of work, specific experience in the specific detector, suitable raw materials availability/selections, developments of purification strategies, additives, growing/handling protocols, selective cuts, abrasives, etc. etc. → long dedicated time and efforts.

The developments themselves are difficult and uncertain experiments.

ULB NaI(Tl) – as whatever ULB detector - cannot be simply bought or made by another researcher for you …

Roma2,Roma1,LNGS,IHEP/Beijing

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

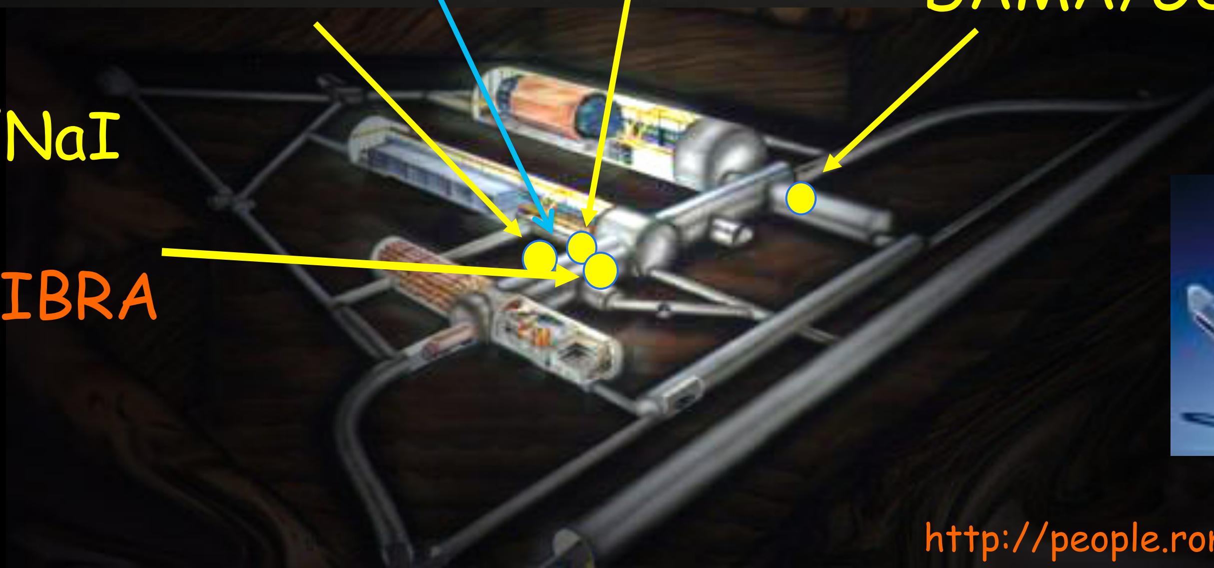
DAMA/R&D

DAMA/LXe

DAMA/Ge

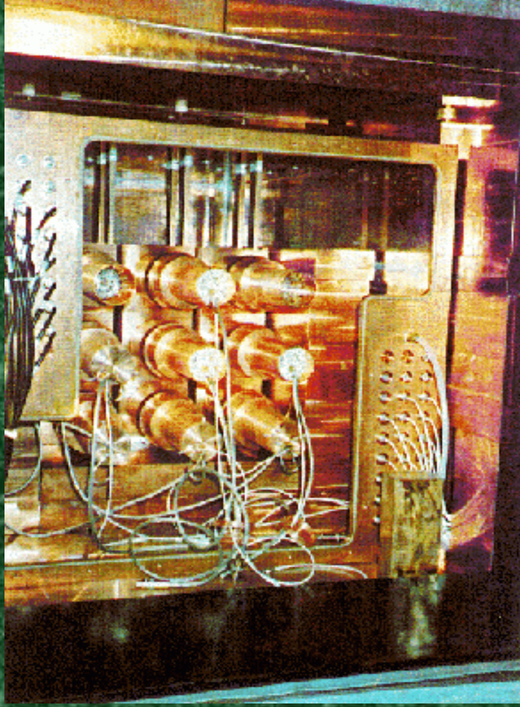
DAMA/NaI

DAMA/LIBRA



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

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



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

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

Results on rare processes:

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

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- Annual Modulation Signature

PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004) 2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008) 023506, MPLA23(2008)2125.

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

total exposure (7 annual cycles) 0.29 ton × yr

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

As a result of a 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)

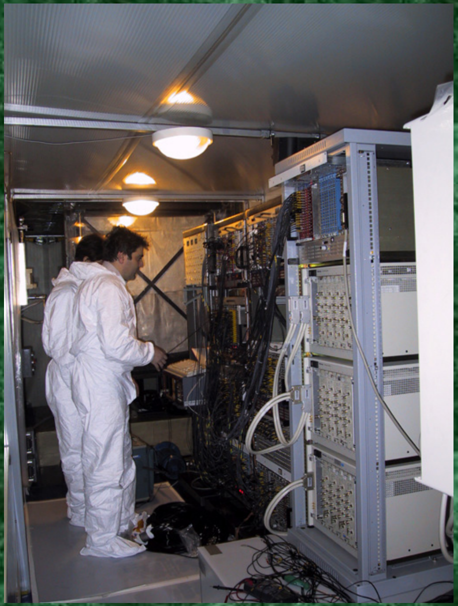
Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

- ***Radiopurity,performances, procedures, etc.:*** NIMA592(2008)297, JINST 7 (2012) 03009
- ***Results on DM particles:*** *Ann. Mod. Signature:* EPJC56(2008)333, EPJC67(2010)39,arXiv:1308.5109
  related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022
- ***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

DAMA @ LNGS





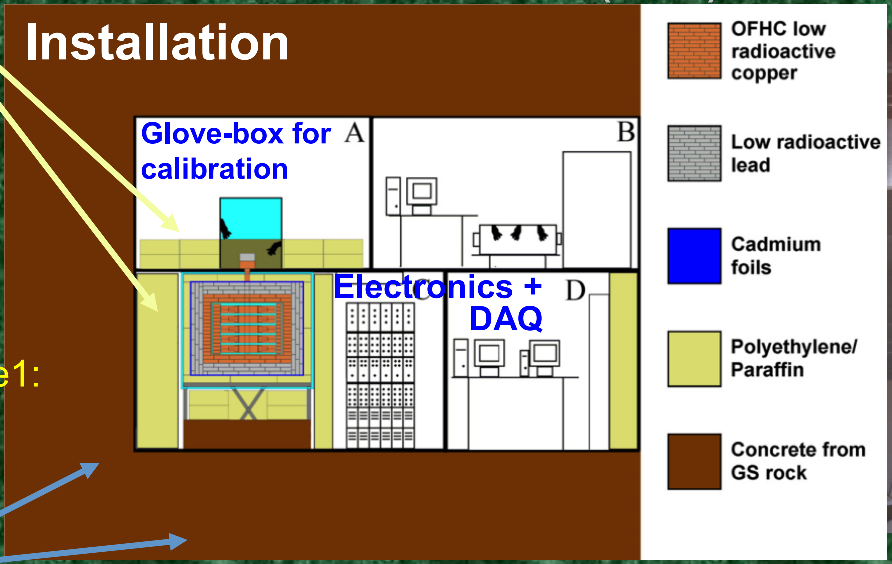



The DAMA/LIBRA set-up

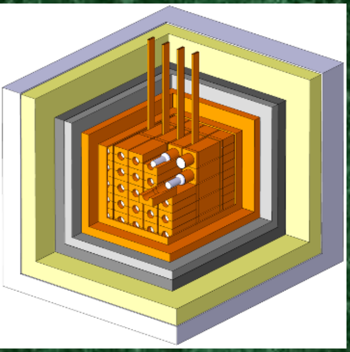
For details, radiopurity, performances, procedures, etc.
NIMA592(2008)297, JINST 7(2012)03009

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



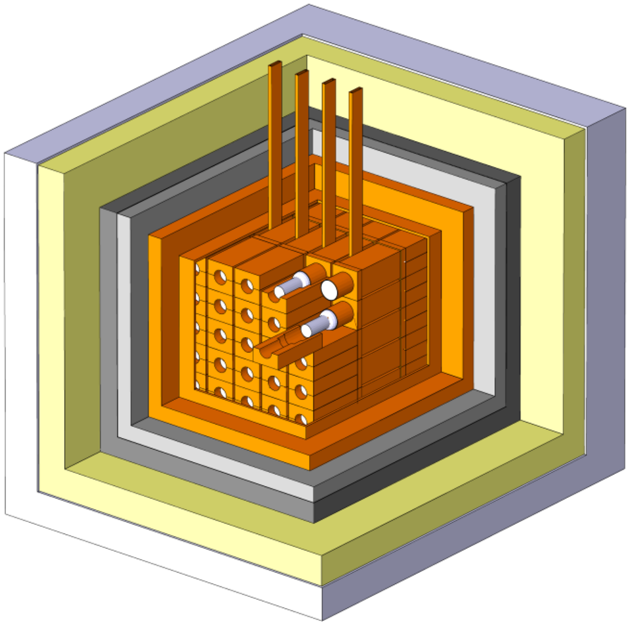
DAMA/LIBRA-phase1:
5.5-7.5 phe/keV



~ 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

Shield from environmental radioactivity

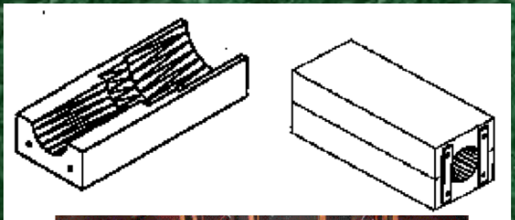


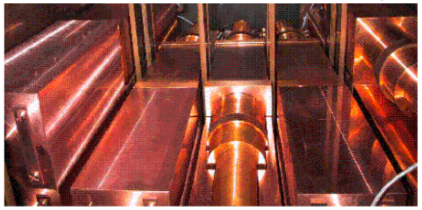
Heavy shield:

>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, ≈ 1 m concrete (mostly outside the installation)

High radiopure materials, most underground since ≥15 years

Pb and Cu etching and handling in clean room.
Storage underground in packed HP N_2 atmosphere





shaped Cu shield surrounding light guides and PMTs

Three-level system to exclude Radon from the detectors:

- Walls and floor of the inner installation sealed in Supronyl (2×10^{-11} cm^2/s permeability).
- Whole shield in plexiglas box maintained in HP Nitrogen atmosphere in slight overpressure with respect to environment
- Detectors in the inner Cu box in HP Nitrogen atmosphere in slight overpressure with respect to environment

Residual radioactivity in some components of the Cu box (95% C.L.)

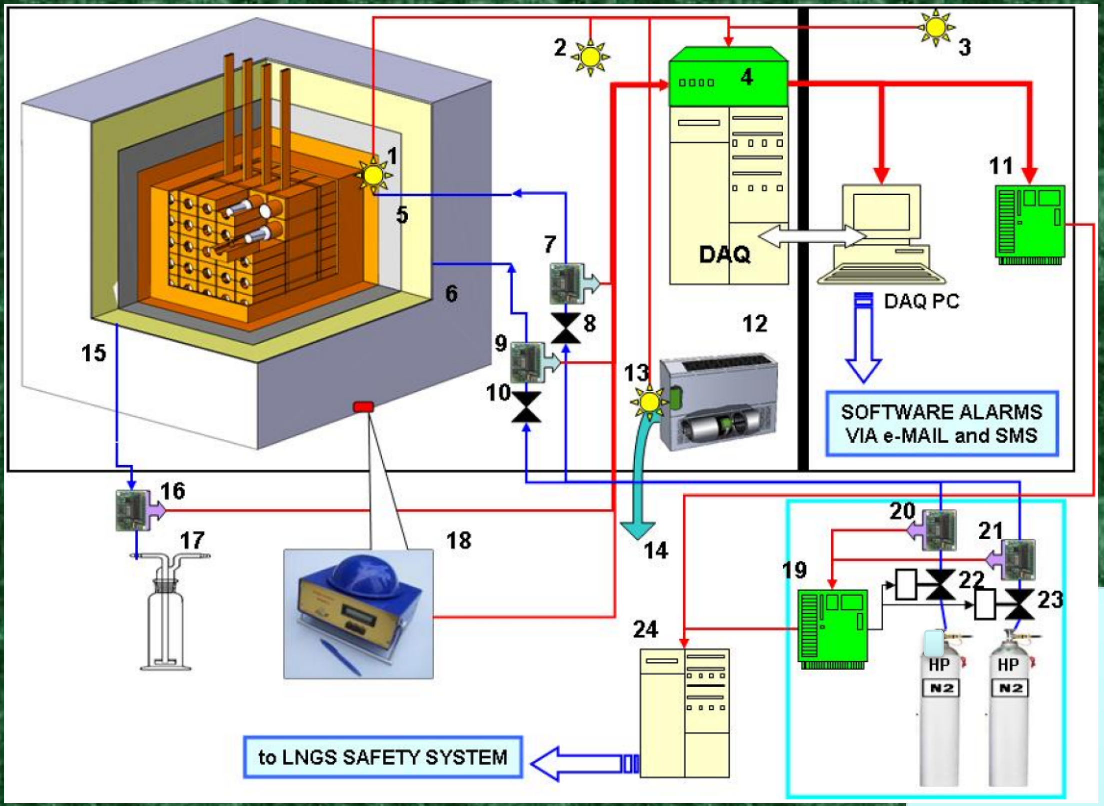
Materials	^{238}U (ppb)	^{232}Th (ppb)	^{nat}K (ppm)
Cu	< 0.5	< 1	< 0.6
feedthroughs	—	< 1.6	< 1.8
Neoprene	—	< 54	< 89

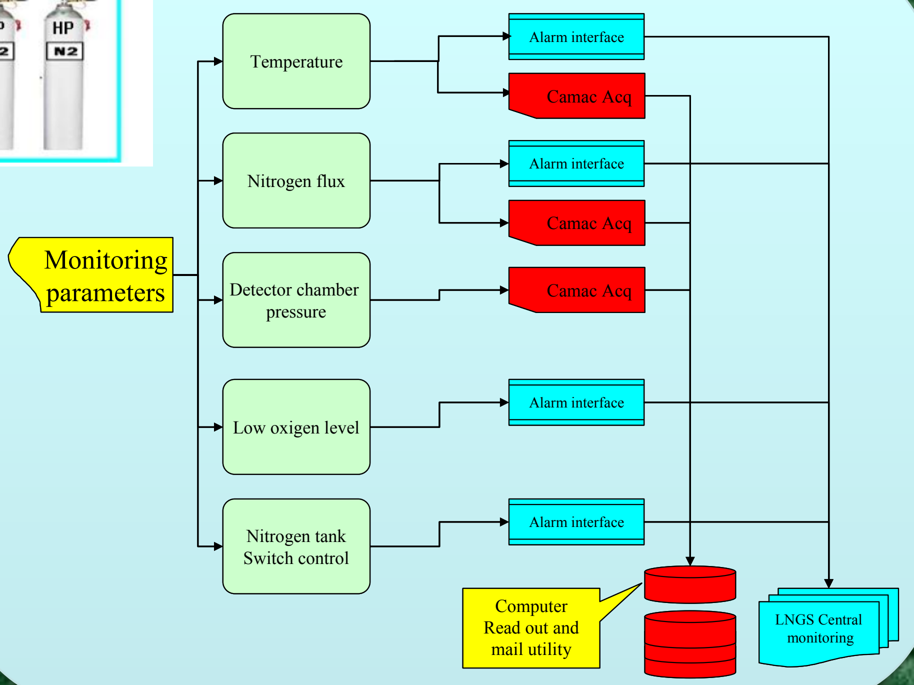
Sensitivity limited by the method

Residual contaminants in some components of the passive shield (95% C.L.)

Materials	^{238}U (ppb)	^{232}Th (ppb)	^{nat}K (ppm)
Cu	< 0.5	< 1	< 0.6
boliden Pb	< 8	< 0.03	< 0.06
boliden2 Pb	< 3.6	< 0.027	< 0.06
polish Pb	< 7.4	< 0.042	< 0.03
polyethylene	< 0.3	< 0.7	< 2
plexiglass	< 0.64	< 27.2	< 3.3

Some aspects of the monitoring/alarm system





+ Rn meter inside the first (of three) insulation level (where the Rn is at level of sensitivity of the Rn meter, that is few Bq/m^3)

+ several other acquired parameters & software alarms

The first DAMA/LIBRA upgrade in fall 2008

- Replacement of some PMTs in HP N_2 atmosphere
- Mounting of the new Acqiris TD (Digitizers + Crate)
- Mounting of the new DAQ system with optical read-out

Since Oct. 2008 again in data taking

The second DAMA/LIBRA upgrade in fall 2010 => DAMA/LIBRA-phase2

- Short interruption to allow the second upgrade
- Replacement of all the PMTs with higher Q.E. ones from dedicated developments
- Goal: lowering the software energy threshold of the experiment

New PMTs with higher Q.E.

DAMA/LIBRA-phase2 *in data taking*

&

New preamplifiers installed fall 2012 + special trigger modules

Other new components in the electronic chain in development

Which NaI(Tl) ?

N.B.: to get ^{40}K multiply by 10^{-4}

Qualification of NaI(Tl)	K (ppb)	U (ppt)	Th (ppt)	Method of production
Standard	2000	< 500	< 500	Bridgman standard growth
Low Background	< 500	< 500	< 500	K Selected batches Bridgman growth
Very Low Background	< 100	< 50	< 50	K, U+Th Selected batches (CL, BL) + Kyropoulos growth
Ultra Low Background (project Gran Sasso)	<< 40	< 5	< 5	Purified raw materials NaI and TlI + Crafted Kyropoulos growth + Handling protocol

SAINT-GOBAIN CRYSTALS

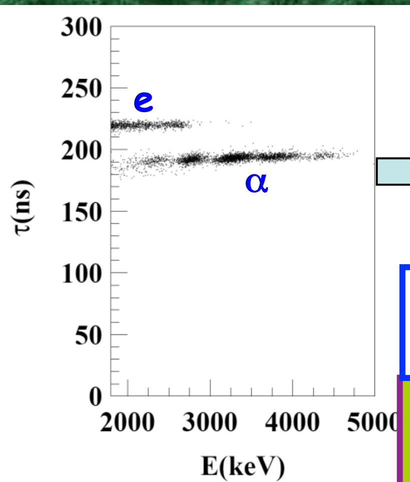
+ as known, determination with the highest sensitivity by measurements with the detectors deep underground:
DAMA/LIBRA see NIMA592(2008)297;
former DAMA/NaI see NCIMA112(1999)545, EPJC18(2000)283 …

1) Not all the cookings have the same taste

2) As whatever VLB or ULB detector used in whatever search for rare processes, VLB or ULB NaI(Tl) cannot be simply "bought"

(for each new realization new materials selections, protocols, purification procedures, etc. developed by/with involved scientists, periodical changes of people in a company, of safety rules, of material sources and sampling, intellectual properties, agreements, etc.)

Some on residual contaminants in new ULB NaI(Tl) detectors



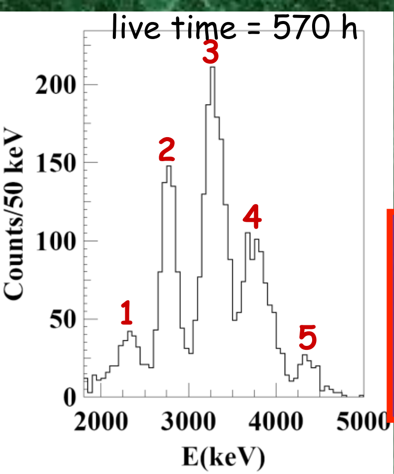
α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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 ⇒ ^{238}U contents in new detectors typically range from 0.7 to 10 ppt

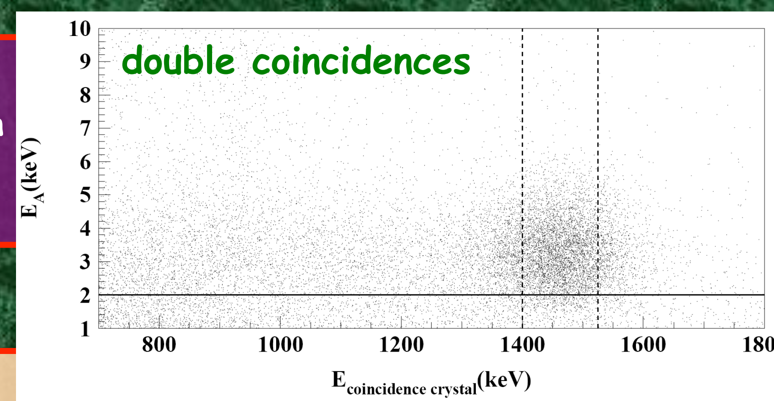


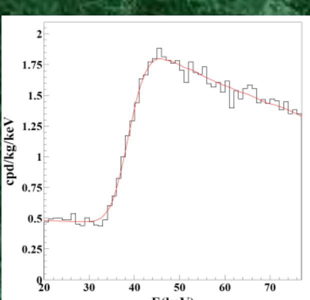
^{238}U chain splitted into 5 subchains: ^{238}U → ^{234}U → ^{230}Th → ^{226}Ra → ^{210}Pb → ^{206}Pb

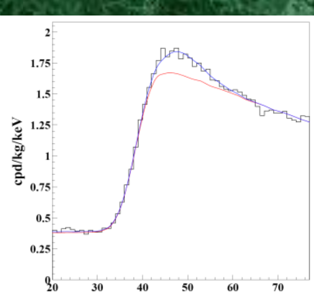
Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U
and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{nat}K residual contamination

The analysis has given for the ^{nat}K content in the crystals values not exceeding about 20 ppb (mean value 13 ppb)







^{129}I and ^{210}Pb

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

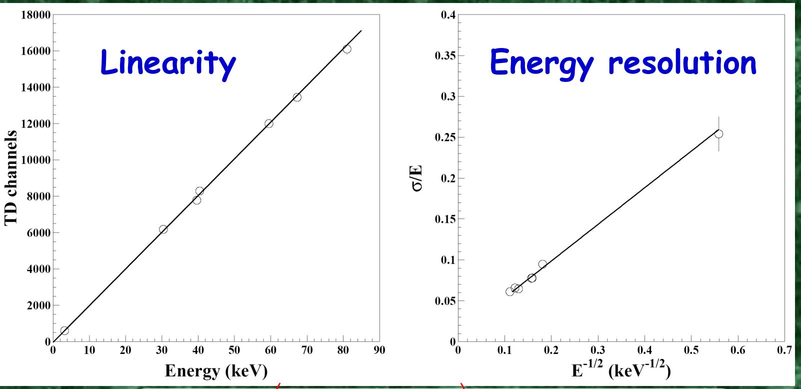
^{210}Pb in the new detectors: (5 – 30) μBq/kg.

No sizable surface pollution by Radon daugthers, thanks to the new handling protocols

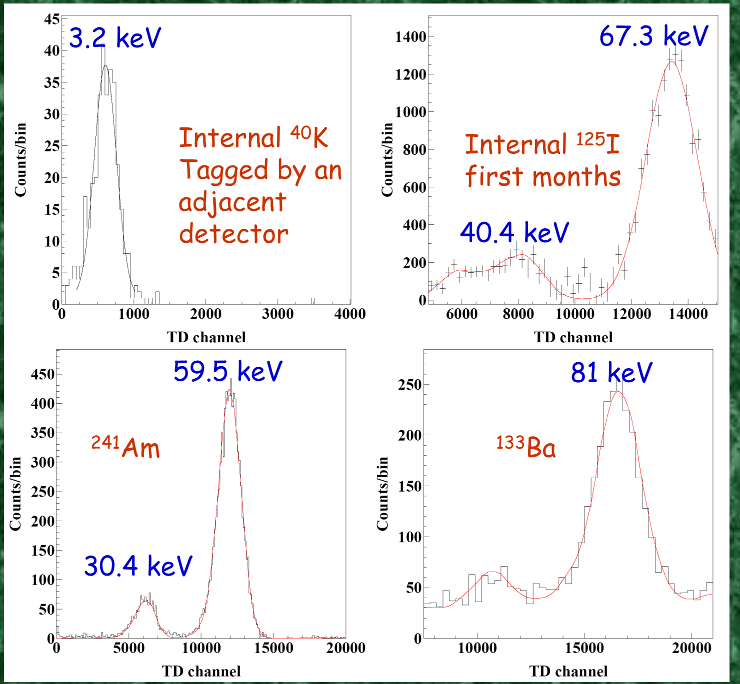
... more on NIMA592(2008)297

DAMA/LIBRA calibrations

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

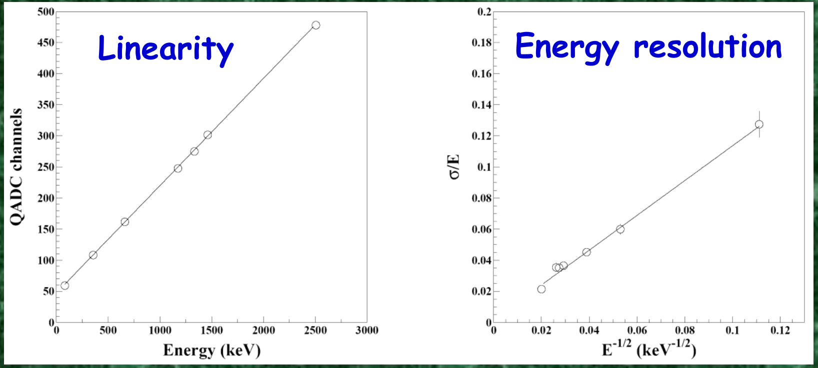


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$



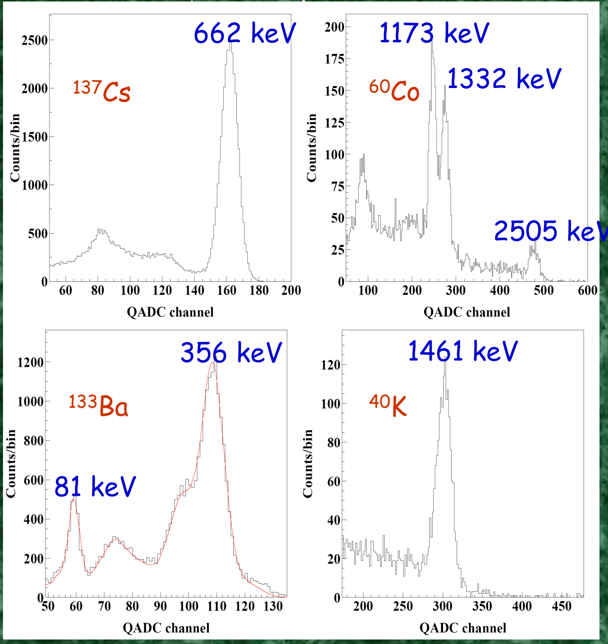
The curves superimposed to the experimental data have been obtained

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



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

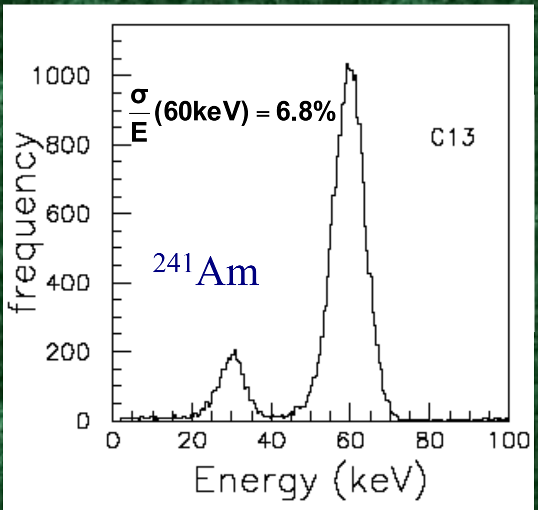
$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23) \cdot 10^{-4}$$



Thus, here and hereafter keV means keV electron equivalent

Examples of energy resolutions

DAMA/LIBRA ULB NaI(Tl)



σ/E @ 122 keV = 13%
at zero field

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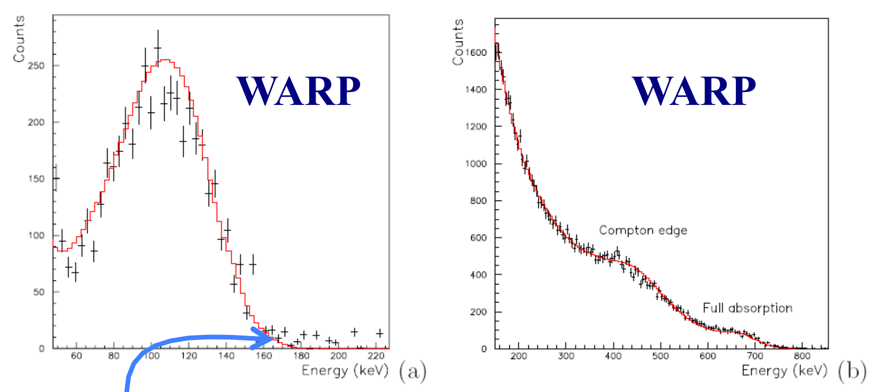

Fig. 2. Energy spectra taken with external γ-ray sources, superimposed with the corresponding Monte Carlo simulations. (a) ^{57}Co source (E = 122 keV, B.R. 85.6%, and 136 keV, B.R. 10.7%), (b) ^{137}Cs source (E = 662 keV).

subtraction of the spectrum ?

ZEPLIN-II

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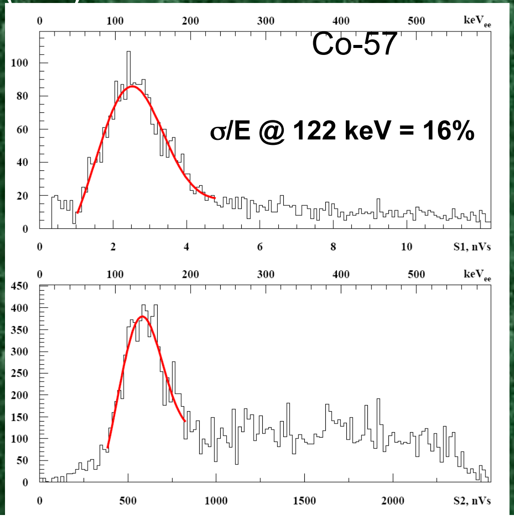


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of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

XENON10

σ/E @ 122 keV = 17%

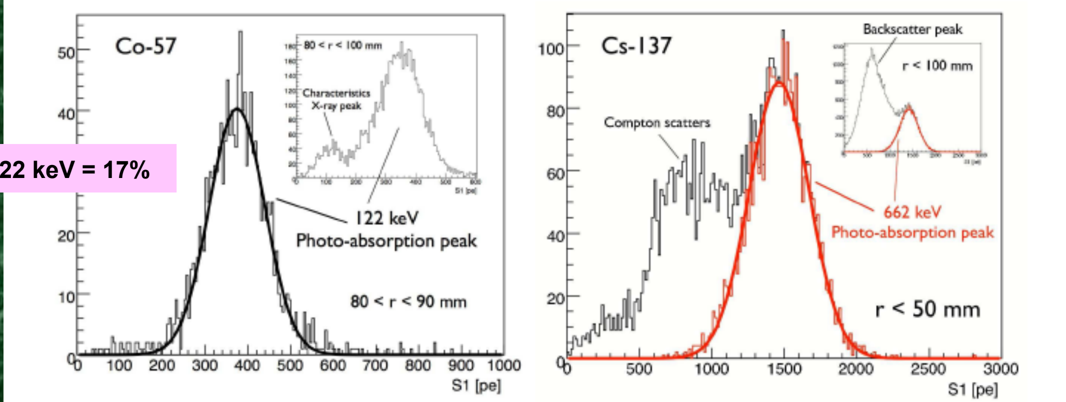
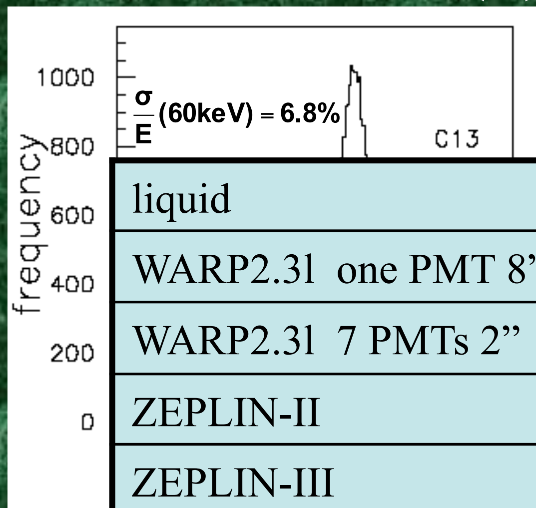


Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

JoP: Conf. Ser. 65 (2007) 012015

Examples of energy resolutions

DAMA/LIBRA ULB NaI(Tl)



σ/E @ 122 keV = 13%
at zero field

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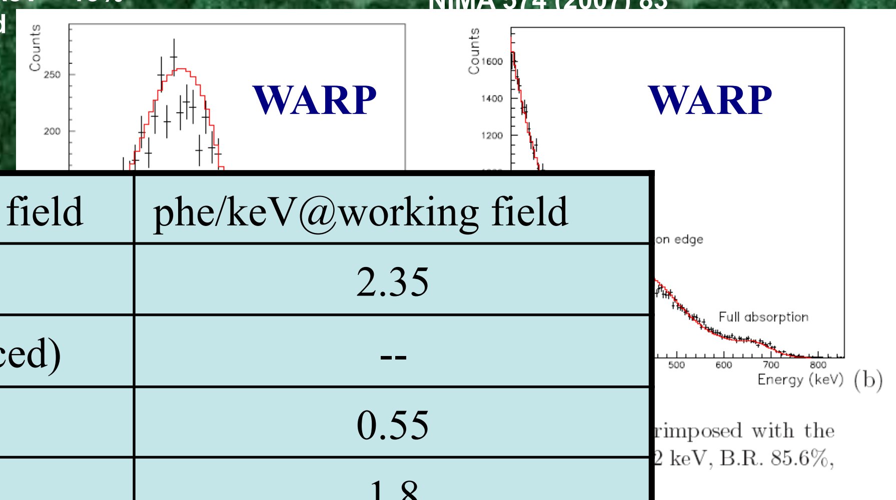

...rimposed with the
...2 keV, B.R. 85.6%,

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

...um ?

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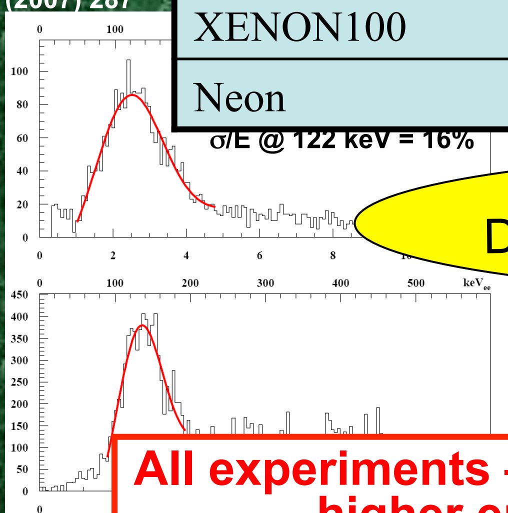
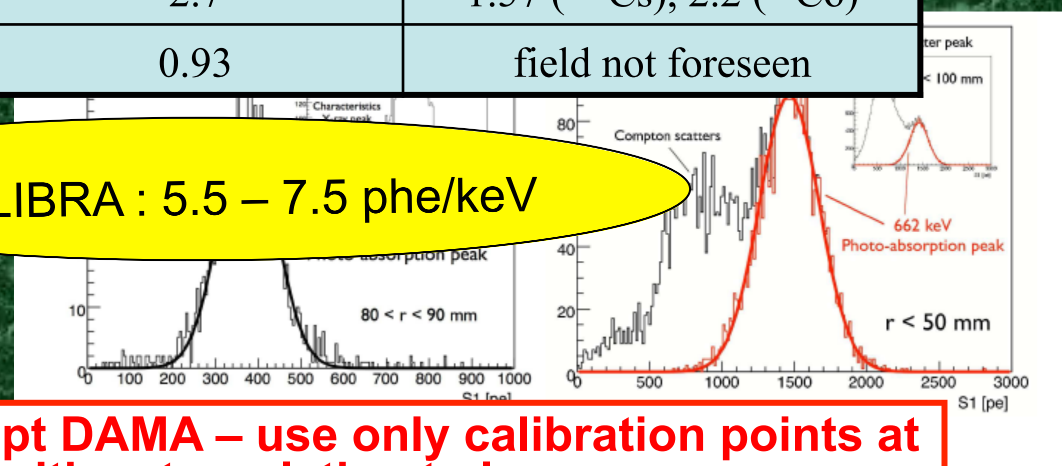


Fig. 5. Typical energy ... (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other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



...he 122 keV ... ation. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

JoP: Conf. Ser. 65 (2007) 012015

DAMA/LIBRA : 5.5 – 7.5 phe/keV

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

Complete DAMA/LIBRA-phase1: a ton x yr experiment? done

EPJC56(2008)333, EPJC67(2010)39, **arXiv:1308.5109**

	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	

- **calibrations: ≈ 9.6 x 10^7 events from sources**
- **acceptance window eff**:

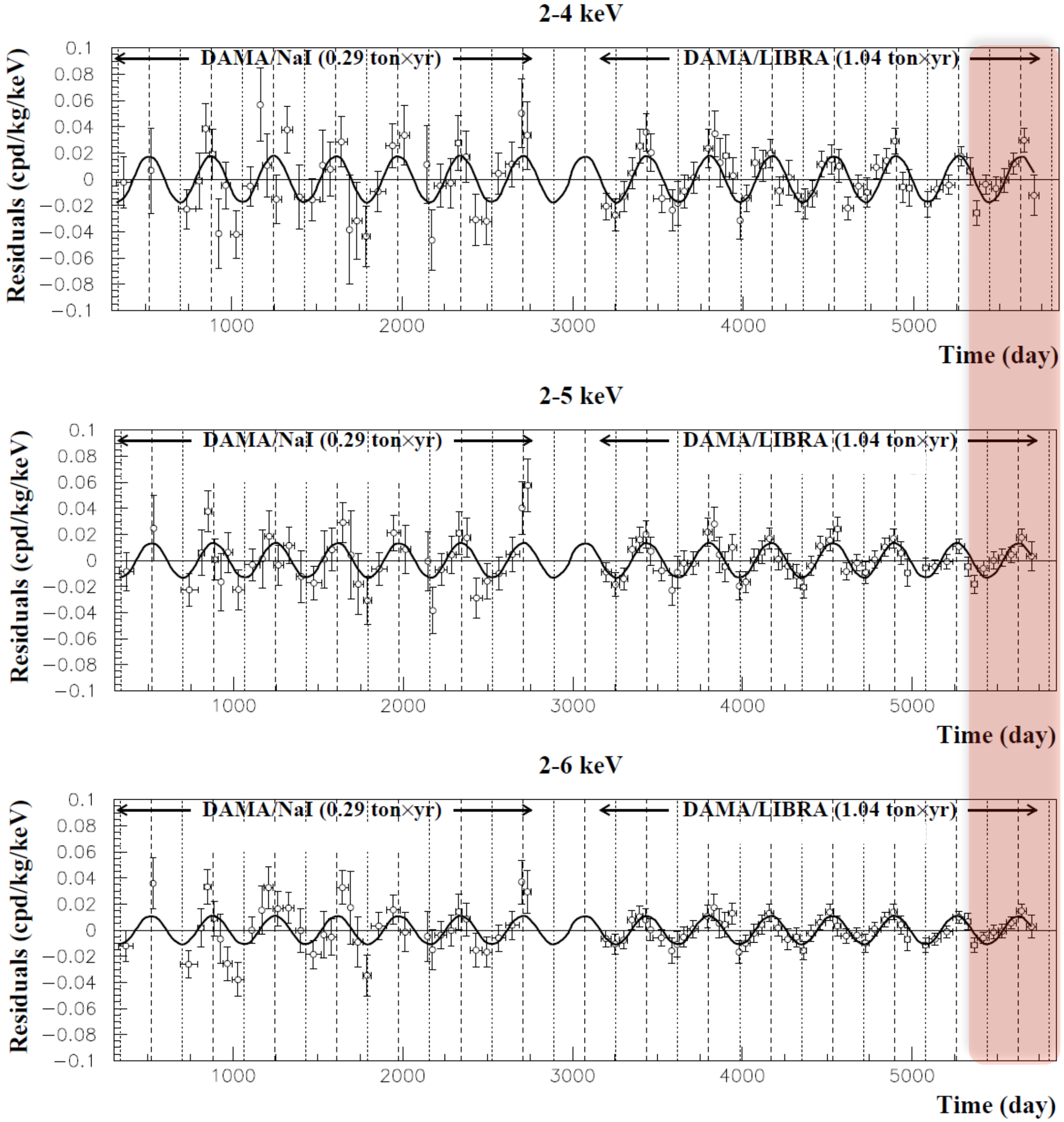
  95 M events (≈3.5M events/keV)

Model Independent DM Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1

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

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



$A\cos[\omega(t-t_0)]$;
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 ⇒ 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 ⇒ 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

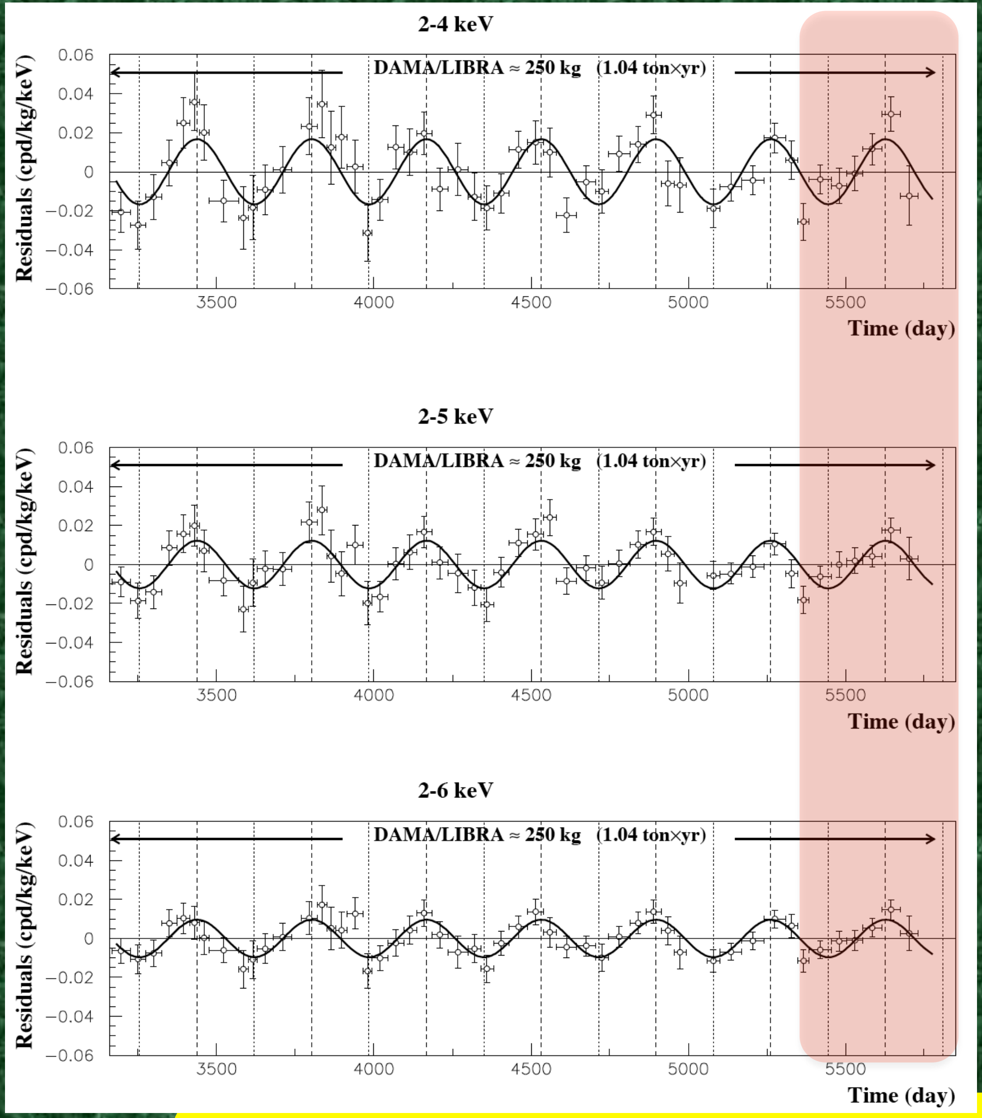
χ^2/dof=154/87 ⇒ P(A=0) = 1.3×10^{-5}

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 (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 ⇒ 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⇒ P(A=0) = 5.2×10^{-5}

2-6 keV

A=(0.0096±0.0013) cpd/kg/keV

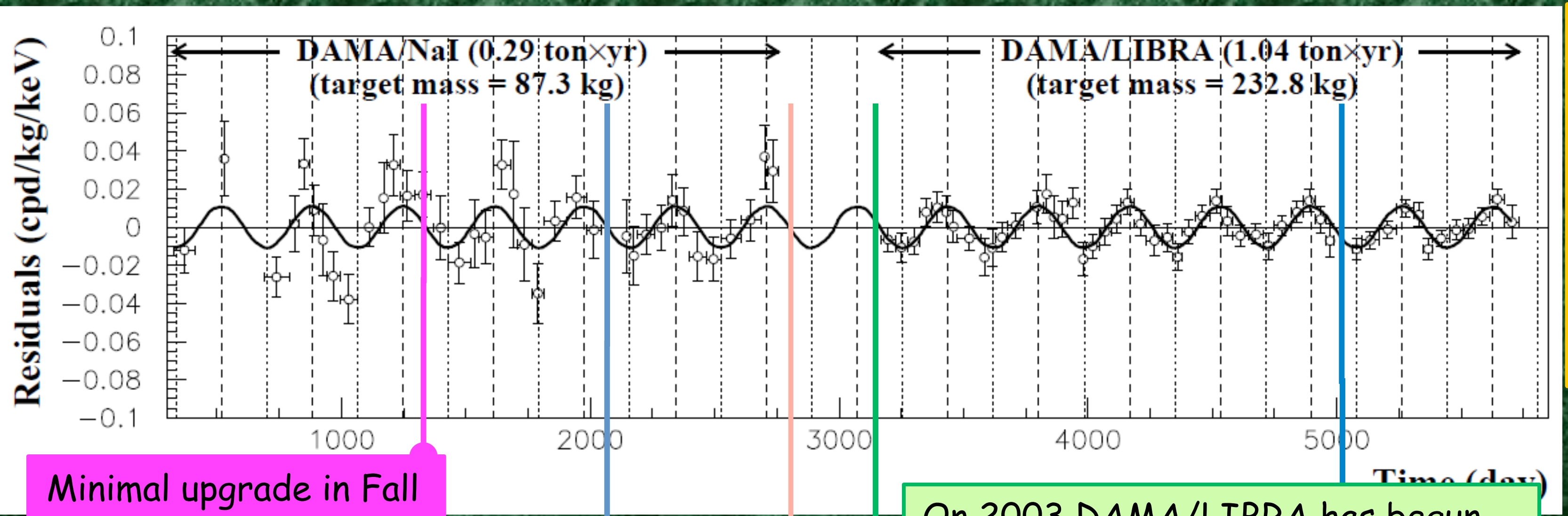
χ^2/dof = 29.3/49 **7.4 σ C.L.**

Absence of modulation? No

χ^2/dof=83.1/50 ⇒ 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 main upgrades and improvements



Minimal upgrade in Fall

PHASE2

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

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.

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

July 2002 DAMA/NaI taking completed

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

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

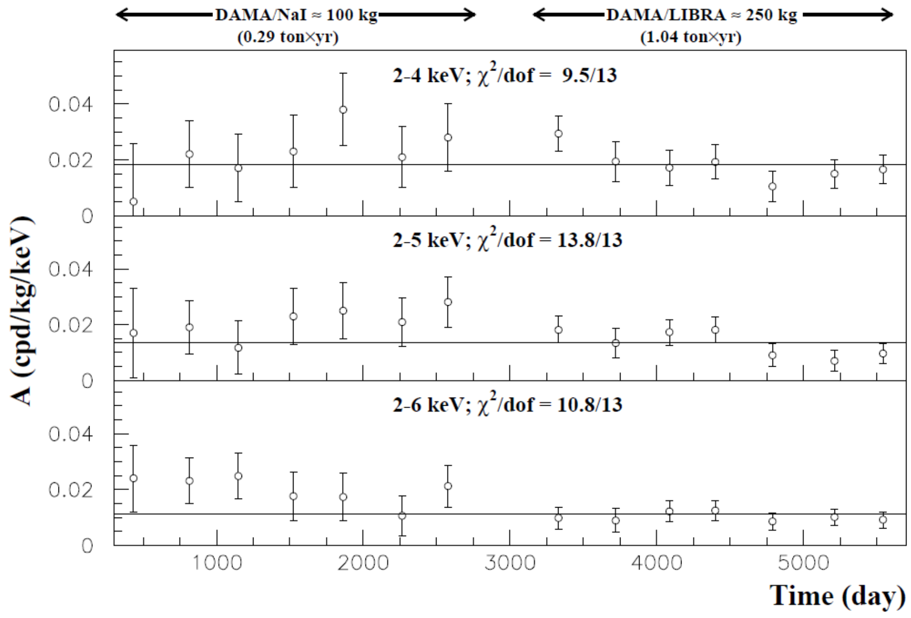
	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI				
(2-4) keV	0.0252 ±0.0050	1.01 ±0.02	125 ±30	5.0σ
(2-5) keV	0.0215 ±0.0039	1.01 ±0.02	140 ±30	5.5σ
(2-6) keV	0.0200 ±0.0032	1.00 ±0.01	140 ±22	6.3σ
DAMA/LIBRA-phase1				
(2-4) keV	0.0178 ±0.0022	0.996 ±0.02	134 ± 7	8.1σ
(2-5) keV	0.0127 ±0.0016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

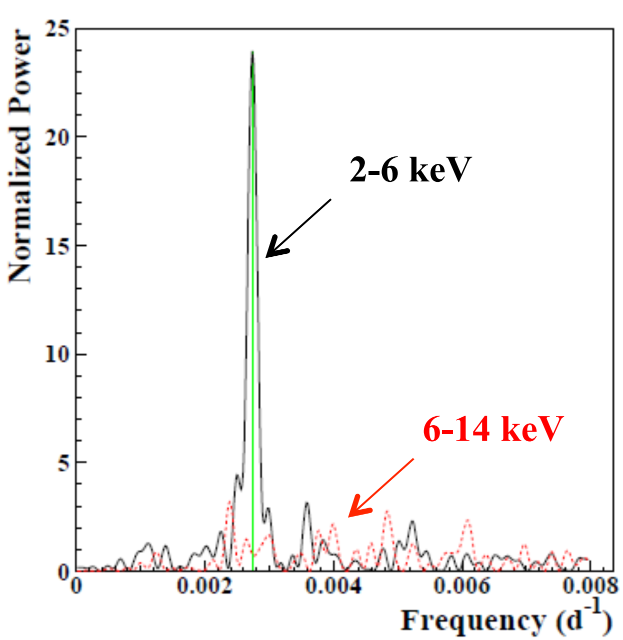
total exposure:
487526 kg×day = 1.33 ton×yr

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:
$2.737 \times 10^{-3}\ d^{-1} \approx 1\ yr^{-1}$

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

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:

$$\sum_i \rightarrow \sum_i \frac{\frac{N}{\Delta r_i^2}}{\sum_j \frac{1}{\Delta r_j^2}} = \frac{N}{\sum_j \frac{1}{\Delta r_j^2}} \cdot \sum_i \frac{1}{\Delta r_i^2}$$

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

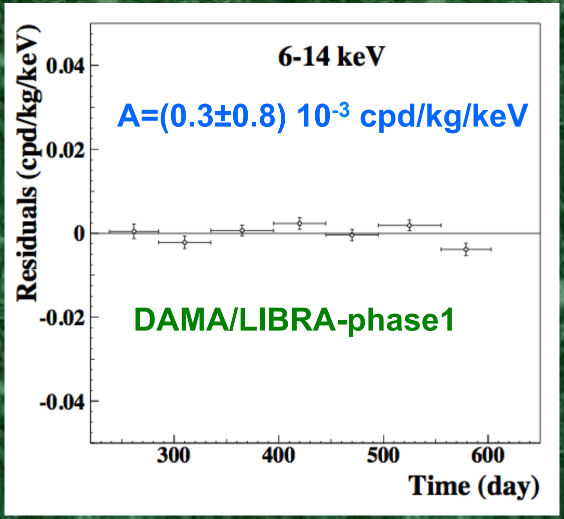
$$\cos\omega t_i \rightarrow \frac{1}{2\Delta t_i}\int_{t_i-\Delta t_i}^{t_i+\Delta t_i} \cos\omega t\, dt$$

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

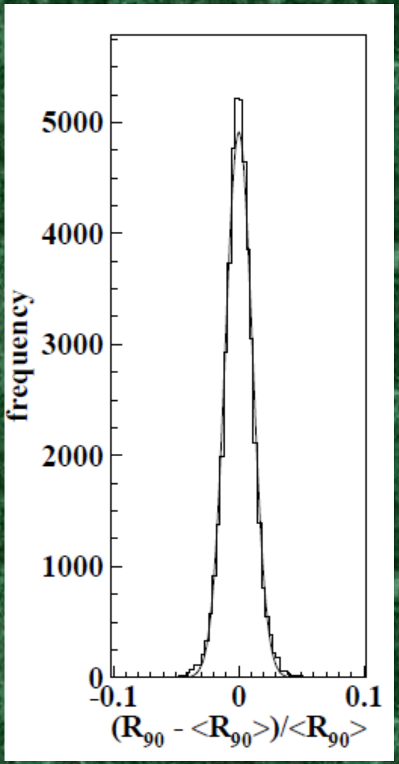
Rate behaviour above 6 keV

- **No Modulation above 6 keV**



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



$\sigma \approx 1\%$, fully accounted by statistical considerations

- **No modulation in the whole energy spectrum:**
  studying integral rate at higher energy, R_{90}

- R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods

  - Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:

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

consistent with zero

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

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

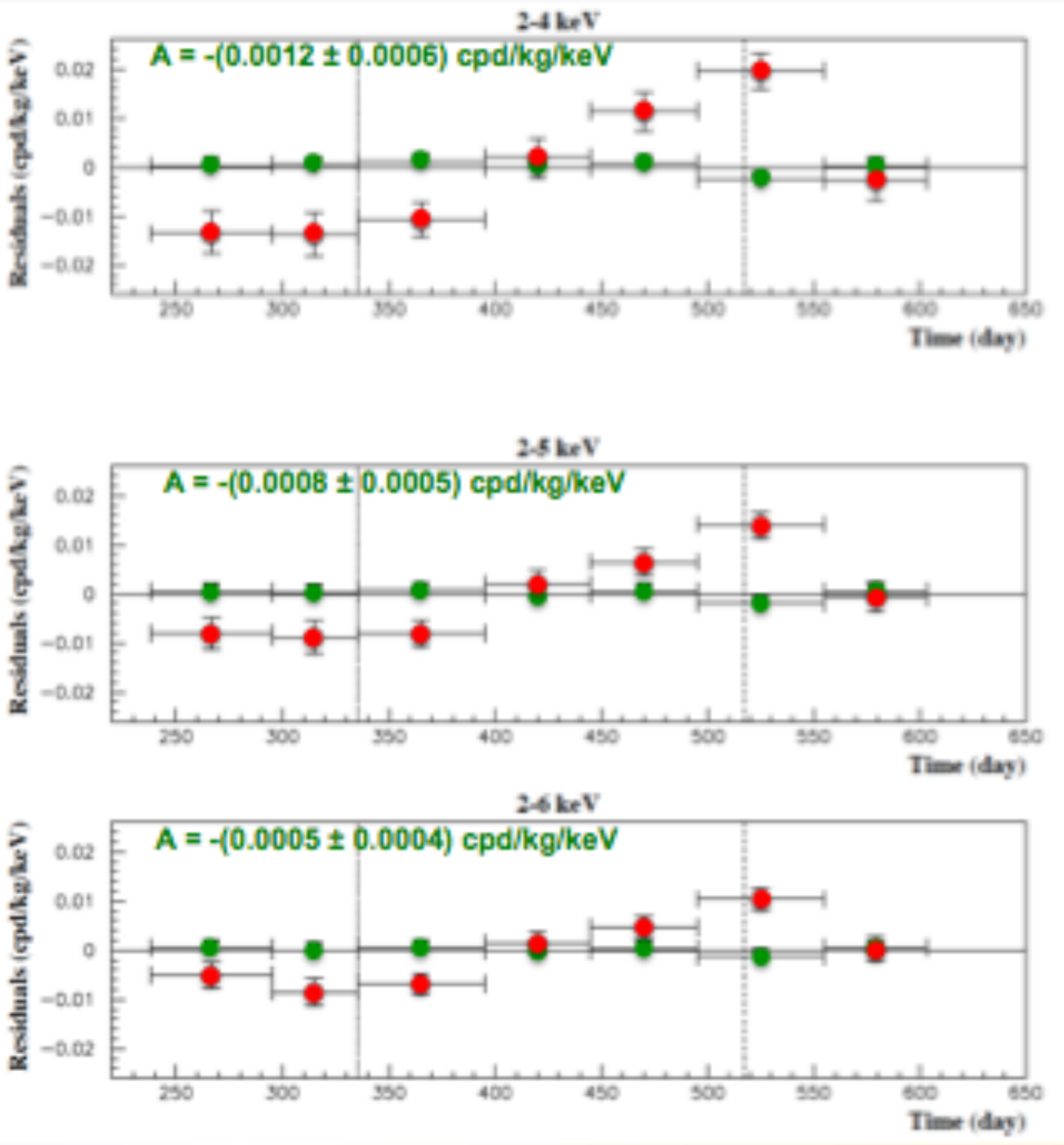
Multiple-hits events in the region of the signal

DAMA/LIBRA-phase1 (7 annual cycles)

- 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

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

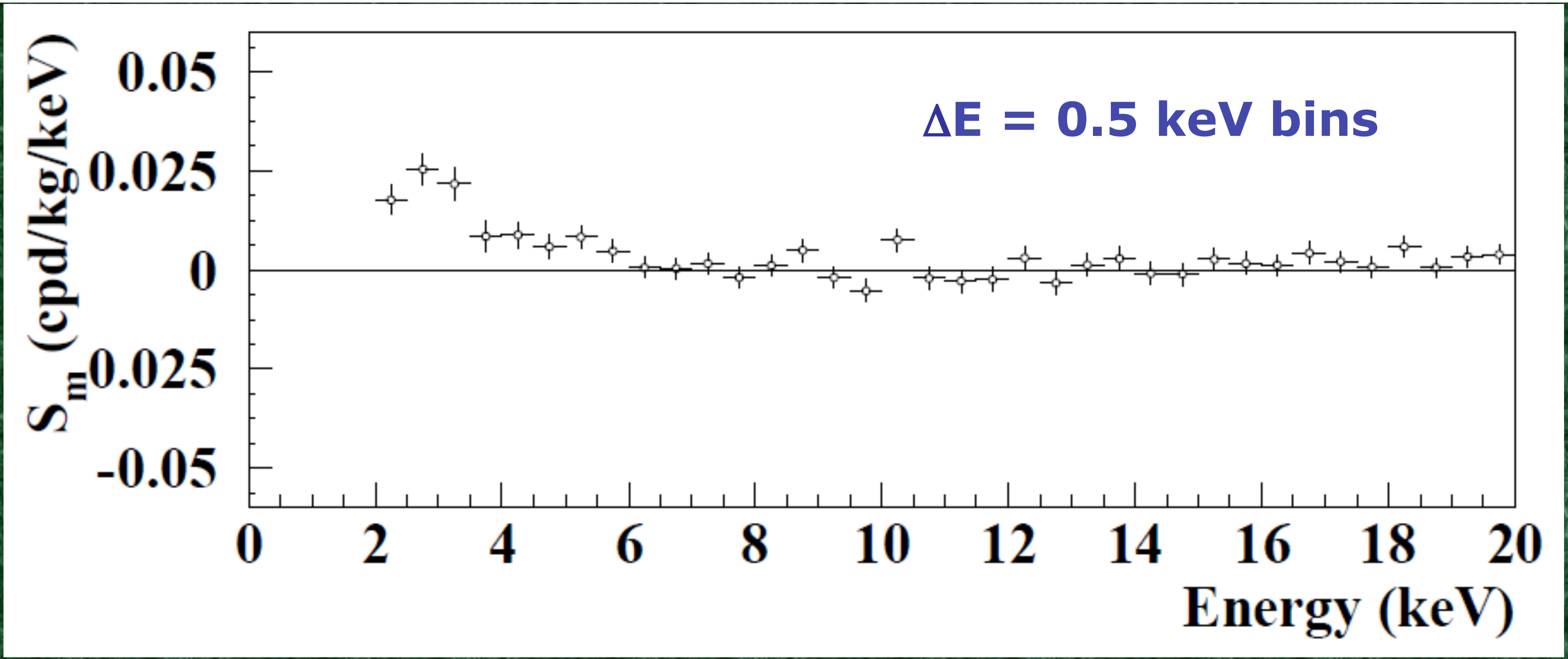
Max-likelihood analysis of the single-hit scintillation events

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

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

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

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



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%)

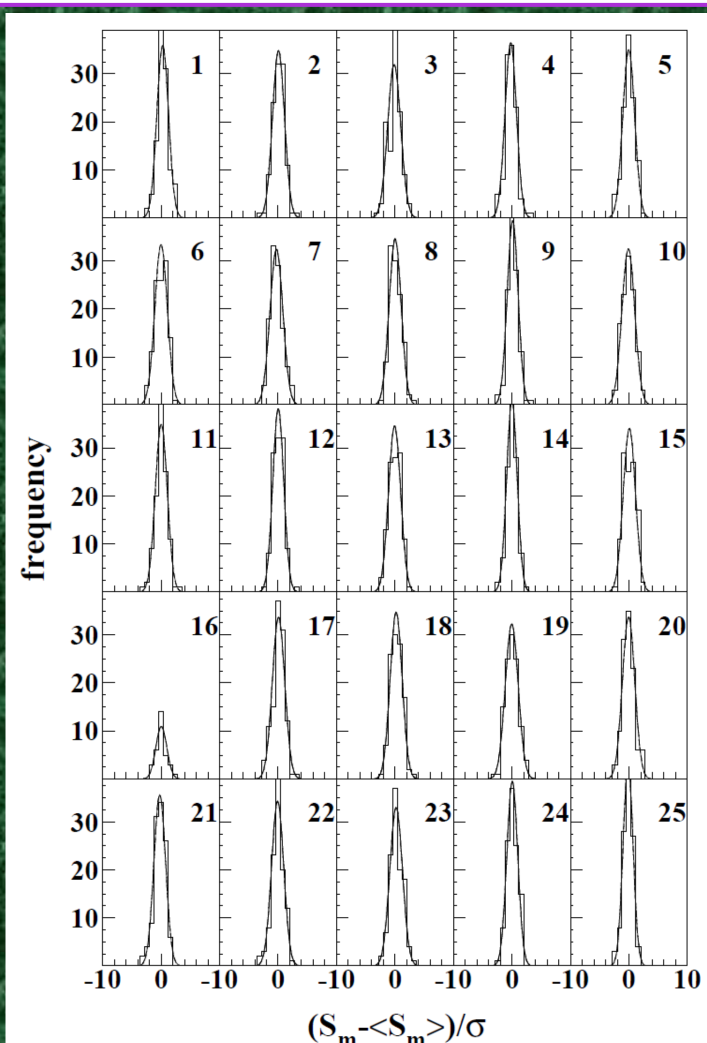
Statistical distributions of the modulation amplitudes (S_m)

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

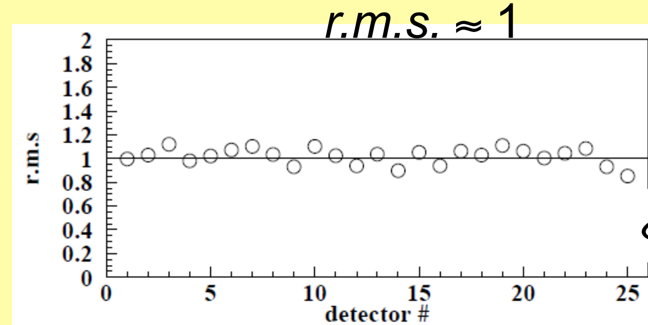


Each panel refers to each detector separately; 112 entries = 16 energy bins in 2-6 keV energy interval × 7 DAMA/LIBRA-phase1 annual cycles (for crys 16, 2 annual cycle, 32 entries)

Standard deviations of **$(S_m - \langle S_m \rangle)/\sigma$** for each detectors

r.m.s. ≈ 1

2-6 keV



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.)

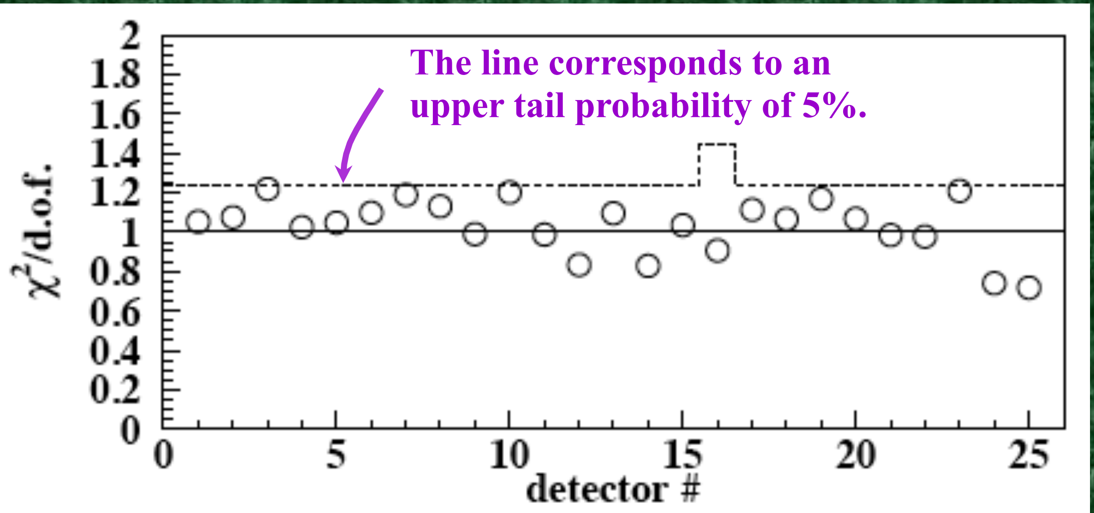
S_m statistically well distributed in all the detectors, energy bin and annual cycles

Statistical analyses about modulation amplitudes (S_m)

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

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

$\chi^2/d.o.f.$ values of S_m distributions for each DAMA/LIBRA-phase1 detector in the (2–6) keV energy interval for the seven annual cycles.



DAMA/LIBRA-phase1 (7 years)

total exposure: 1.04 ton × yr

The $\chi^2/d.o.f.$ values range from 0.72 to 1.22 for all 25 detectors ⇒ at 95% C.L. the observed annual modulation effect is well distributed in all the detectors.

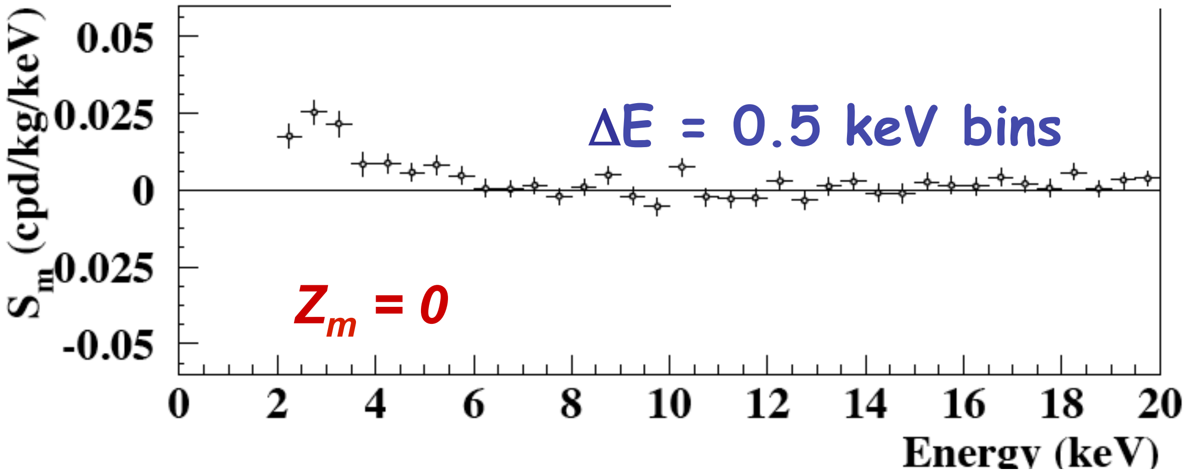
- The mean value of the twenty-five points is 1.030, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to a possible systematics.
- In this case, one would have an additional error of $\leq 3 \times 10^{-4}$ cpd/kg/keV, if quadratically combined, or $\leq 2\times10^{-5}$ cpd/kg/keV, if linearly combined, to the modulation amplitude measured in the (2 – 6) keV energy interval.
- This possible additional error (**≤ 3 %** or **≤ 0.2%**, respectively, of the DAMA/LIBRA modulation amplitude) can be considered as an upper limit of possible systematic effects

Energy distributions of cosine (S_m) and sine (Z_m) modulation amplitudes

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

DAMA/NaI (7 years) & DAMA/LIBRA-phase1 (7 years)

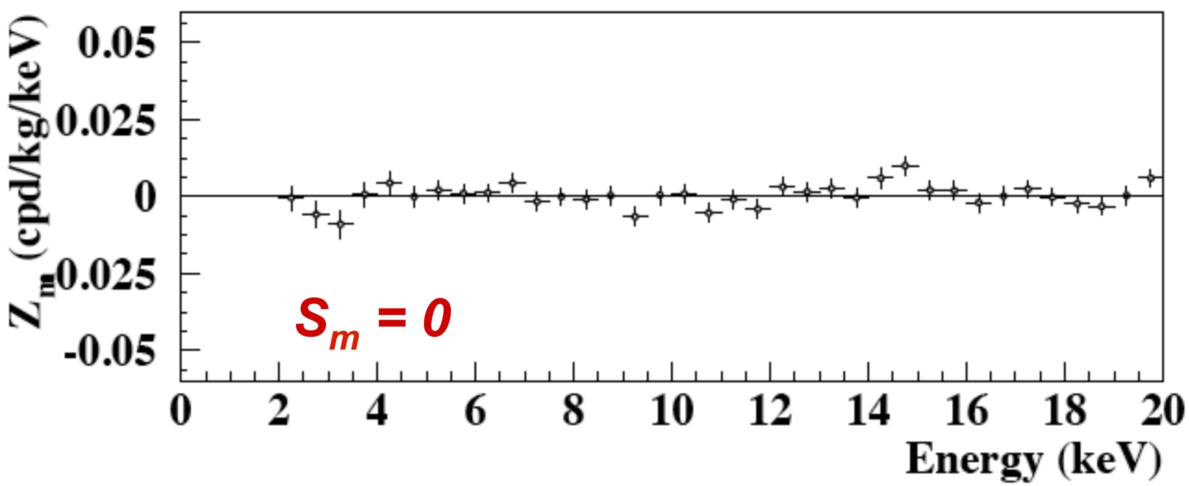
total exposure: 487526 kg×day **= 1.33 ton × yr**



t_0 = 152.5 day (2° June)

maximum at 2° June

as for DM particles



maximum at 1° September

***T/4* days after 2° June**

The χ^2 test in the (2-14) keV and (2-20) keV energy regions (χ^2/dof = 23.0/24 and 46.5/36, probabilities of 52% and 12%, respectively) supports the hypothesis that the $Z_{m,k}$ values are simply fluctuating around zero.

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

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

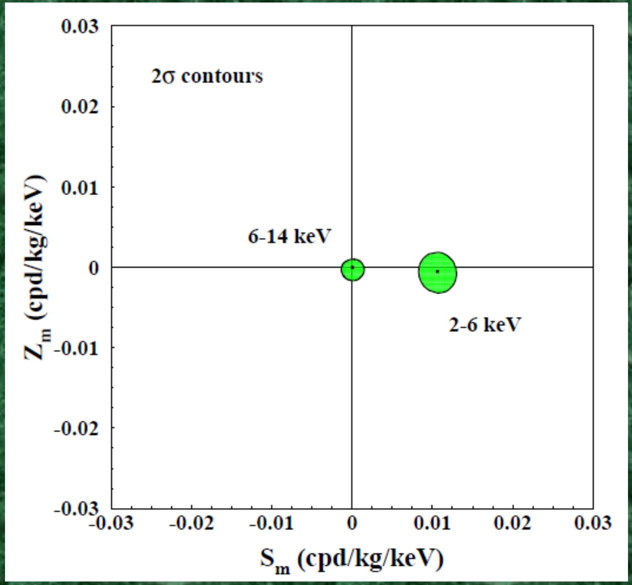
total exposure: 487526 kg×day **= 1.33 ton × yr**

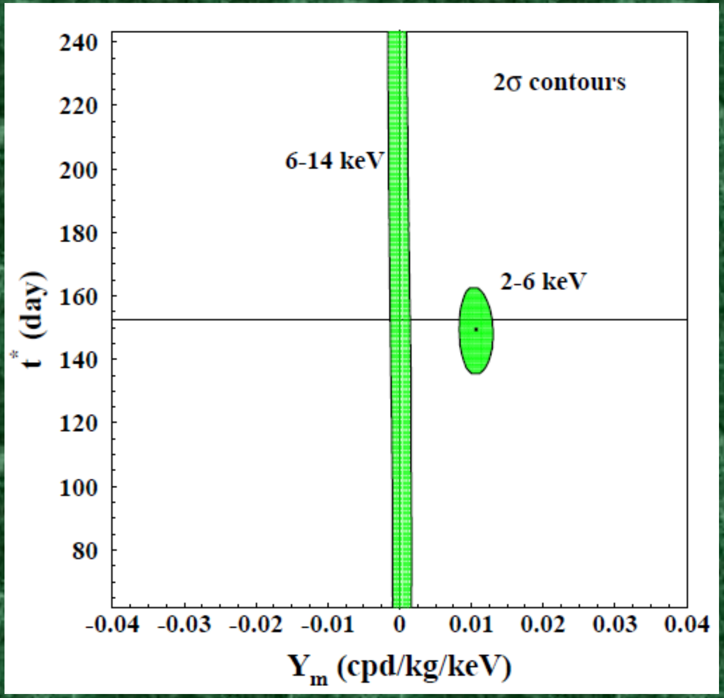
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

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	--

Phase vs energy

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

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

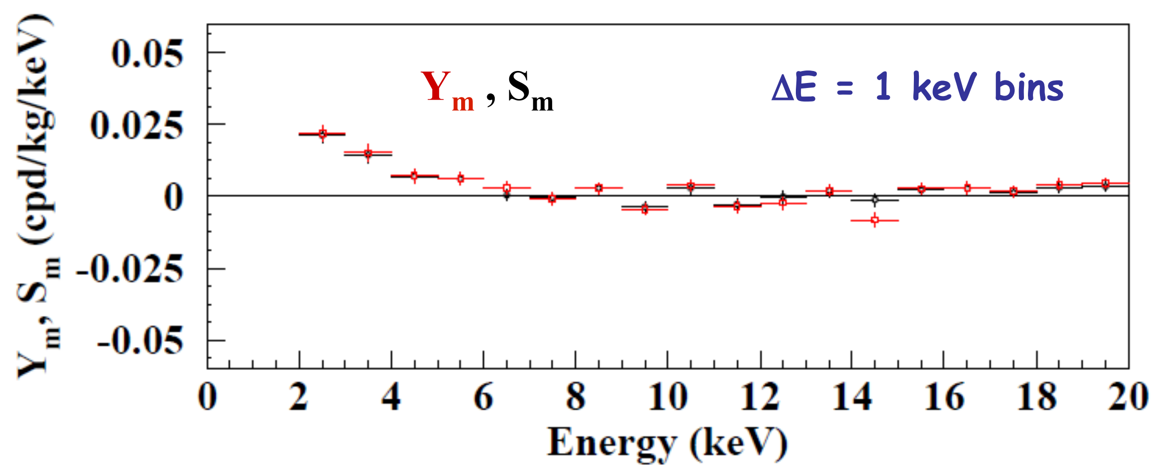
total exposure: 487526 kg×day = 1.33 ton×yr

For DM signals:

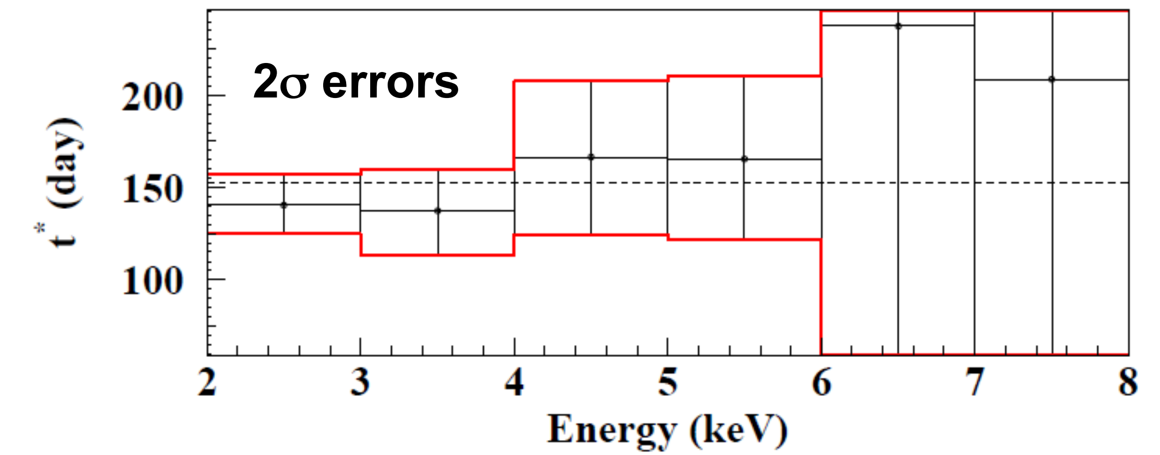
$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

$\omega = 2\pi/T; \quad T = 1\ year$



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



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

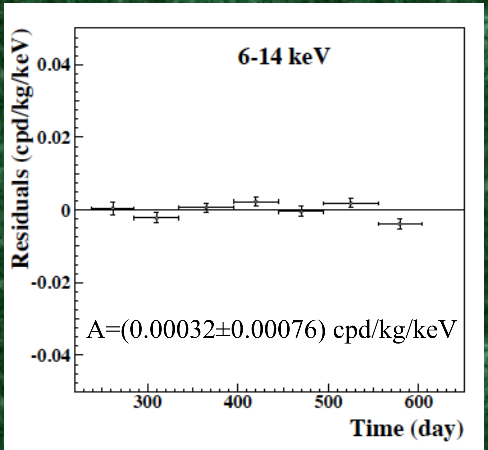
Running conditions stable at a level better than 1% also in the last running period

	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) $\times 10^{-2}$	(0.07 ± 0.13) $\times 10^{-2}$	-(0.26 ± 0.55) $\times 10^{-2}$
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) $\times 10^{-2}$	(0.09 ± 0.17) $\times 10^{-2}$	-(0.03 ± 0.20) $\times 10^{-2}$	(0.15 ± 0.15) $\times 10^{-2}$	(0.03 ± 0.14) $\times 10^{-2}$	(0.08 ± 0.11) $\times 10^{-2}$	(0.06 ± 0.10) $\times 10^{-2}$

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 in DAMA/LIBRA-phase1

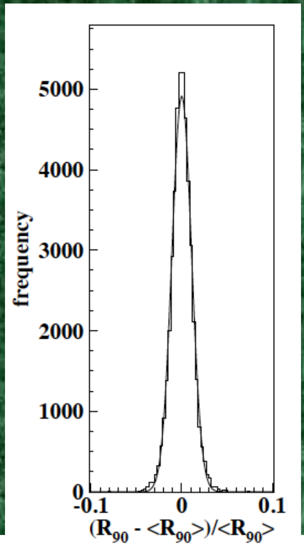
- **No Modulation above 6 keV**



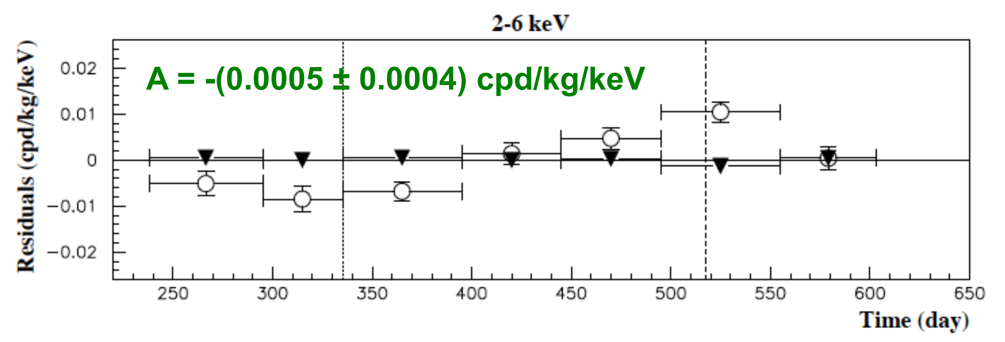
- **No modulation in the whole energy spectrum**

σ ≈ 1%

+ 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 (filled triangles) vs *single-hit* residual rate (open circles)

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**

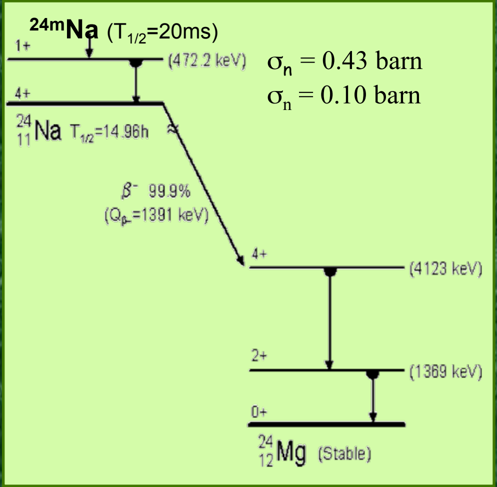
e.g.

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.

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:

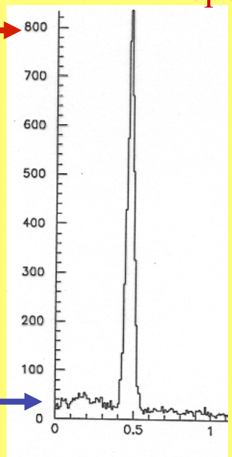
→ $S_m^{(\text{thermal n})} < 0.8 \times 10^{-6}$ cpd/kg/keV (< 0.01% S_m^{observed})

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



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

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:
$\Phi_n = 0.9\ 10^{-7}$ n cm^{-2} s^{-1} (Astropart.Phys.4 (1995)23)

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

HYPOTHESIS: assuming - very cautiously - a 10% neutron modulation: → $S_m^{(fast\ n)} < 10^{-4}$ cpd/kg/keV (< 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 accompained 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

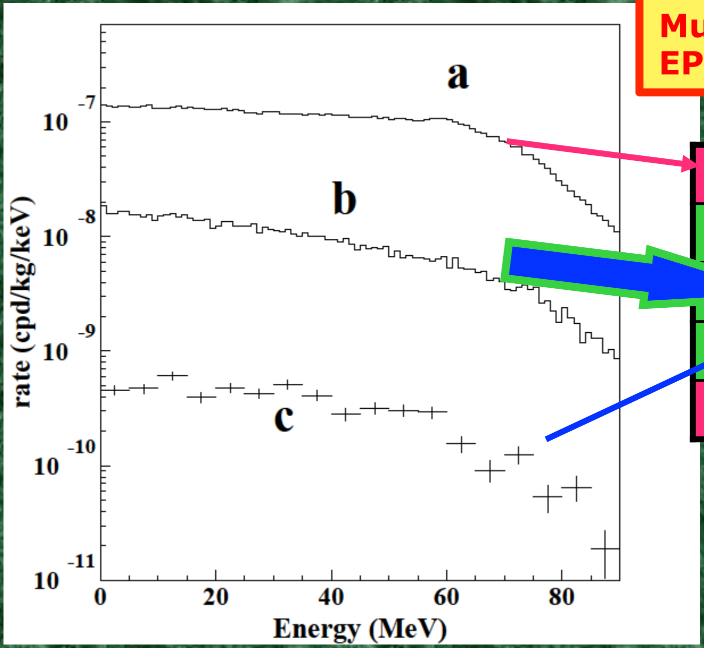
Much more in EPJC72(2012)2064

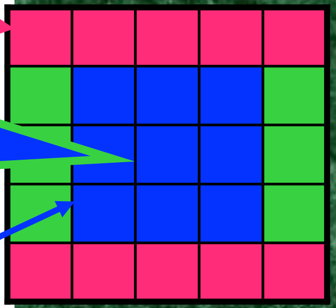
- ✓ **Direct μ interaction in DAMA/LIBRA set-up:**

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

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

& 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/cm²)

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

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

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

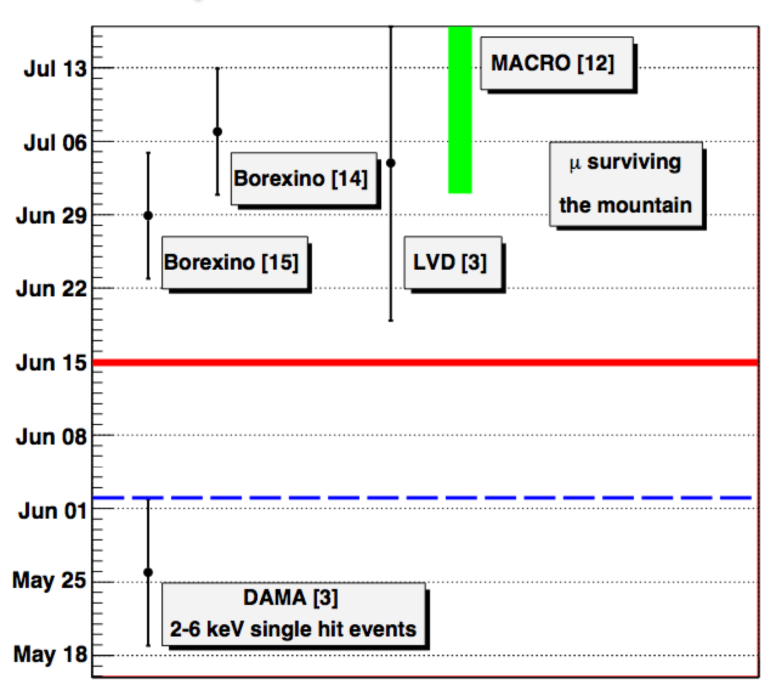
Hyp.: M_{eff} = 15 tons; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)
Knowing that: M_{setup} ≈ 250 kg and ΔE=4keV

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

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

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

Inconsistency of the phase between DAMA signal and μ modulation



μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈$3\cdot10^{-4}$ $m^{-2}s^{-1}$; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)

but

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

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

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

Similar for the whole DAMA/LIBRA-phase1

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

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

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

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

Also this cannot mimic the signature: different phase

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

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, 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)

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 + 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

DAMA/LIBRA-phase1

+ 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

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

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

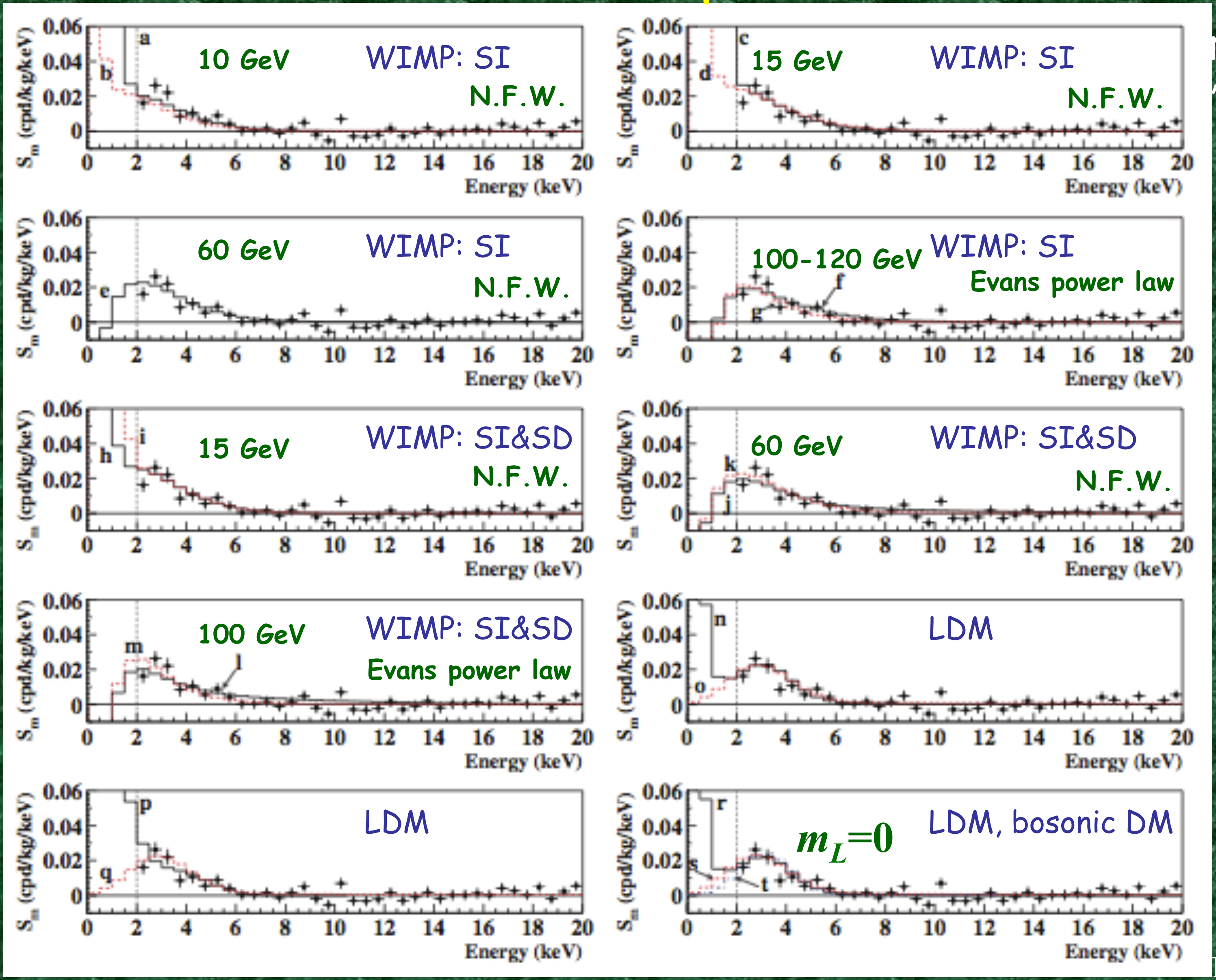
Kaluza Klein particles

… and more

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.) **as well null results 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 possible positive hints In various scenarios

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



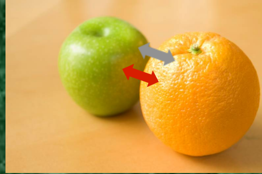
Not best fit
About the same C.L.

$\theta = 2.435$

EPJC56(2008)333,
IJMPA28(2013)1330022

Compatibility with several candidates; other ones are open

About model dependent exclusion plots



Selecting just one simplified model framework, making lots of assumptions, fixing large numbers of parameters … but…

- *which particle?*
- *which couplings? which model for the coupling?*
- *which form factors for each target material and related parameters?*
- *which nuclear model framework for each target material?*
- *Which spin factor for each case?*
- *which scaling laws?*
- *which halo profile?*
- *which halo parameters?*
- *which velocity distribution?*
- *which parameters for velocity distribution?*
- *which v_0?*
- *which v_{esc}?*
- *…etc. etc.*

and experimental aspects ,,,

• marginal and "selected" exposures

•Threshold, energy scale and energy resolution when calibration in other energy region (& few phe/keV)? Stability? Too few calibration procedures and often not in the same running conditions

•Selections of detectors and of data

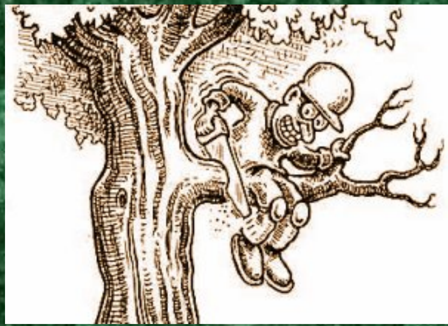
• handling of (many) "subtraction" procedures and stability in time of all the cuts windows and related quantities, etc.? Efficiencies?

• fiducial volume vs disuniformity of detector response in liquids?

•Used values in the calculation

•Used approximations

etc., etc.



+ no uncertainties accounted for

No sensitivity to DM annual modulation signature,

Different target materials

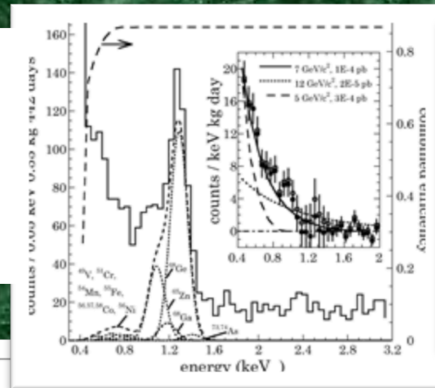
+ generally implications of DAMA model-independent results presented in incorrect/incomplete/non-updated way

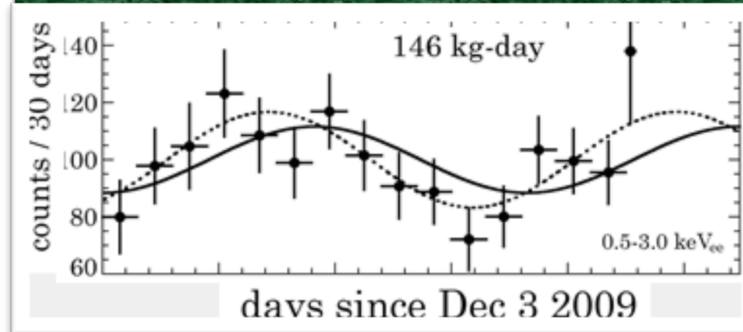
Exclusion plots have no "universal validity" and cannot disproof a model independent result in any given general model framework (they depend not only on the general assumptions largely unknown at present stage of knowledge, but on the details of their cooking) + **generally overestimated** + methodological robustness (see R. Hudson, Found. Phys. 39 (2009) 174) + etc.

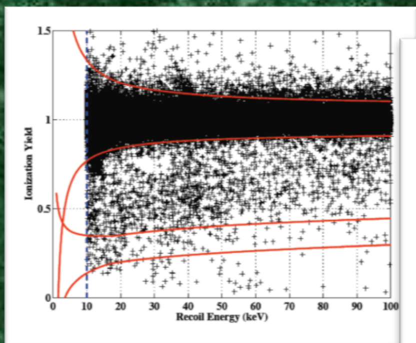
On the other hand, possible positive hints should be interpreted. Large space for compatibility.

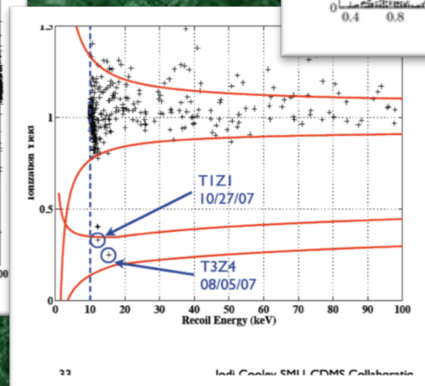
DAMA vs possible positive hints 2010 - 2013

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



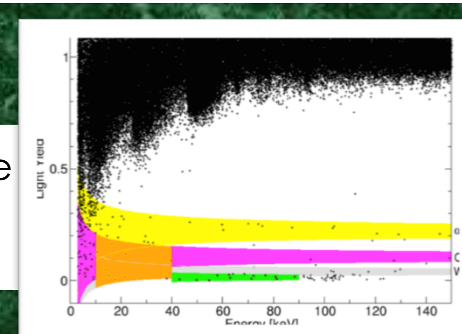


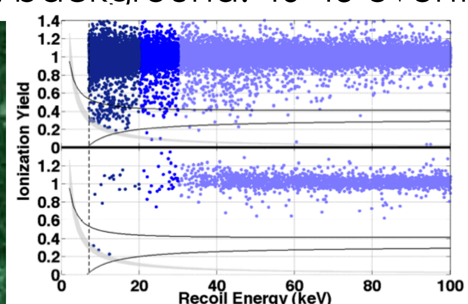




CDMS-Ge:
after many data selections and cuts, 2 Ge candidate recoil-like survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)

CRESST: after many data selections and cuts, 67 candidate recoil-like in the O/Ca bands survive in an exposure of 730 kg x day (estimated as expected residual background: 40-45 events, depending on minimization)





CDMS-Si:
after many data selections and cuts, 3 Si candidate recoil-like survive in an exposure of 140.2 kg x day. estimated as expected residual background 0.41

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

New data from COGENT

from talk by Collar at TAUP2013

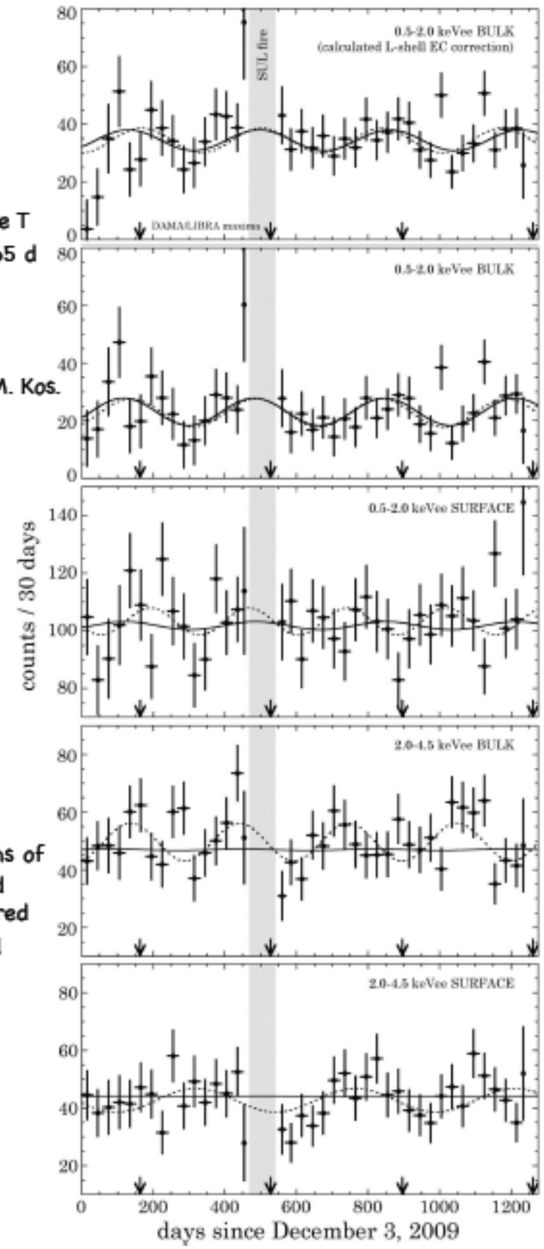
What is new?

- Detector recovered from 3 mo post-fire outage w/o significant changes in performance. It has been continuously 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. Data to be released in energy, time-stamp, and rise-time 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...

Dotted: free T
Solid: T= 365 d

See also poster by M. Kos.

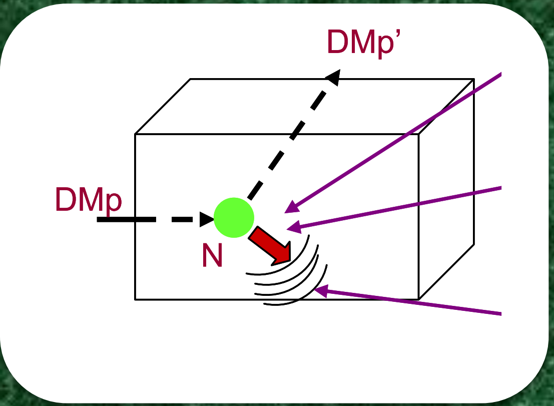
Additional four months of unanalyzed data acquired (run is still ongoing)



& 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)

... an example ...

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



Regions in the nucleon cross section vs DM particle mass plane

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

Including the Migdal effect
→Towards lower mass/higher σ

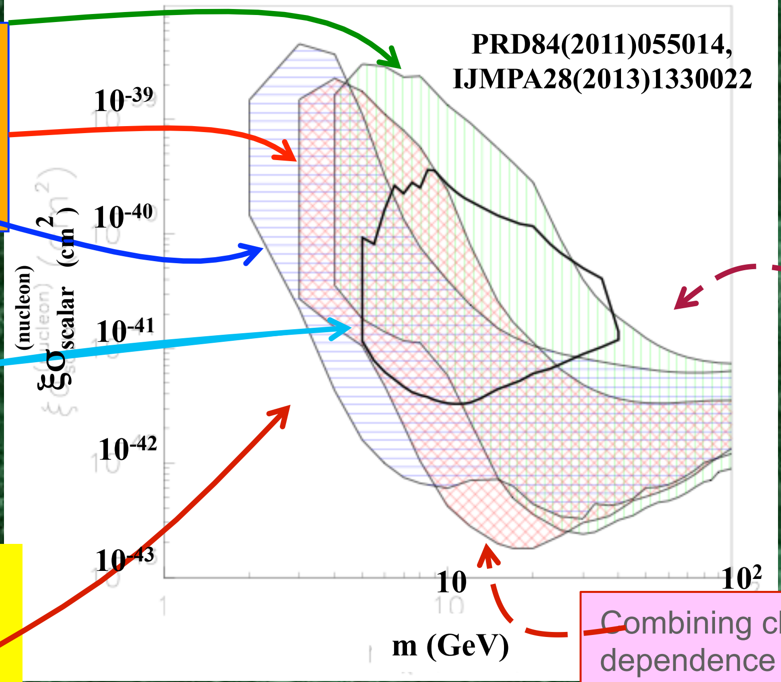
DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent quenching Factors (red)

7.5σ C.L.

CoGeNT

1.64σ C.L.

q.f. at a fixed assumed value



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

Compatibility also with CRESST and CDMS, if the two CDMS-Ge recoil-like events, the three CDMS-Si and the CRESST ones surviving the many applied cuts in marginal exposures are assumed as nuclear recoils induced by DM interactions

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

... examples in some given frameworks

DM particle with preferred inelastic interaction

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

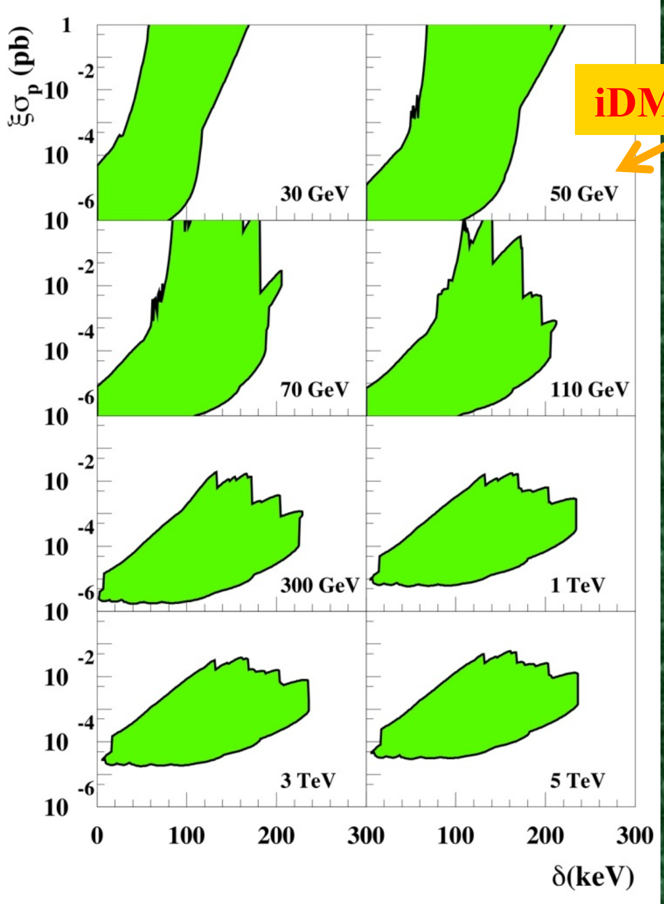
$$\chi^- + N \rightarrow \chi^+ + N$$

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

→ Kinematical constraint for iDM

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

DAMA/NaI+DAMA/LIBRA
Slices from the 3-dimensional allowed volume



iDM interaction on Iodine nuclei

Fund. Phys. 40(2010)900

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

- 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.

arXiv:1007.2688

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

… and much more considering experimental and theoretical uncertainties

Possible constraints from indirect searches? Few examples

Some DM candidate particles in some scenarios might annihilate in celestial bodies if certain conditions are assumed as fulfilled

Possible positive hint in Pamela

- **Pamela positron fraction deviates from predictions of an assumed secondary production model; but, some analogous models also exist with different secondary production giving no/less**

- Other known sources can account for a similar positron fraction (see literature): pulsars, supernova explosions near the Earth, SNR

- Interpretation in terms of DM particle annihilation requires a very large boost factor (≈ 400): i) boost the cross section, ii) play with the propagation parameters, iii) consider extra-source (subhalos, IMBHs)

+ no excess is observed in the anti-proton spectrum

→ no direct constraint

if Dark Matter in PAMELA, the particle seems to be "leptofillic" to reconcile the antiproton and the positron data; this would be lost by experiments investigating just presence of nuclear-recoil-like events while detected in DAMA

Negative results e.g from measurements of "upgoing" muons produced by ν_μ

model dependent result + the real DM particle(s) may not annihilate at all or may annihilate but a "steady state" may not be reached, etc. + subtraction of the existing competing processes, offered by the atmospheric neutrinos + model uncertainties.

↓

it does not exist a biunivocal correspondence between the observables in the two kinds of experiments: direct and indirect. In principle, the different cross-sections can be correlated, but only when a specific model is adopted and by non-directly proportional relations

↓

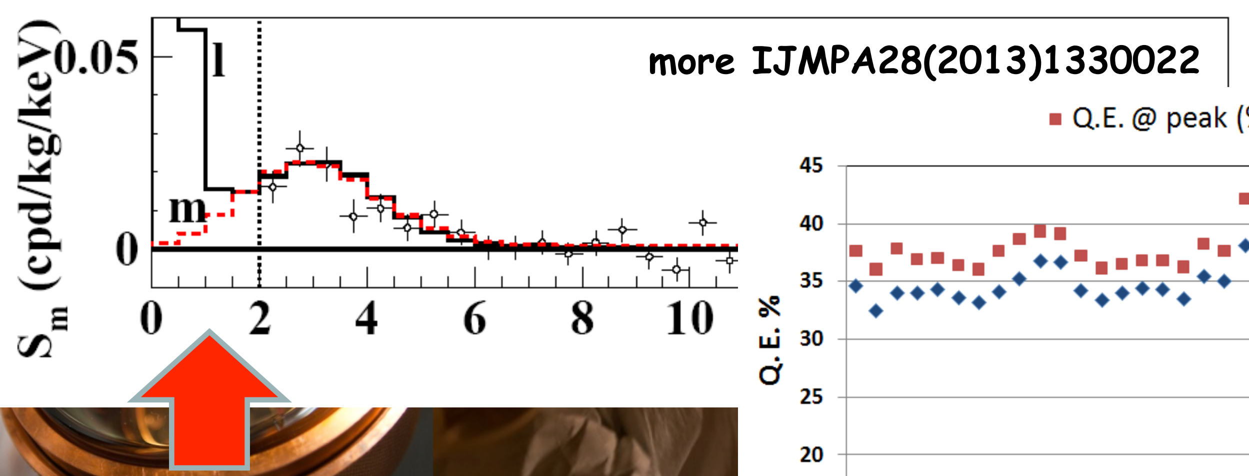
no direct constraint

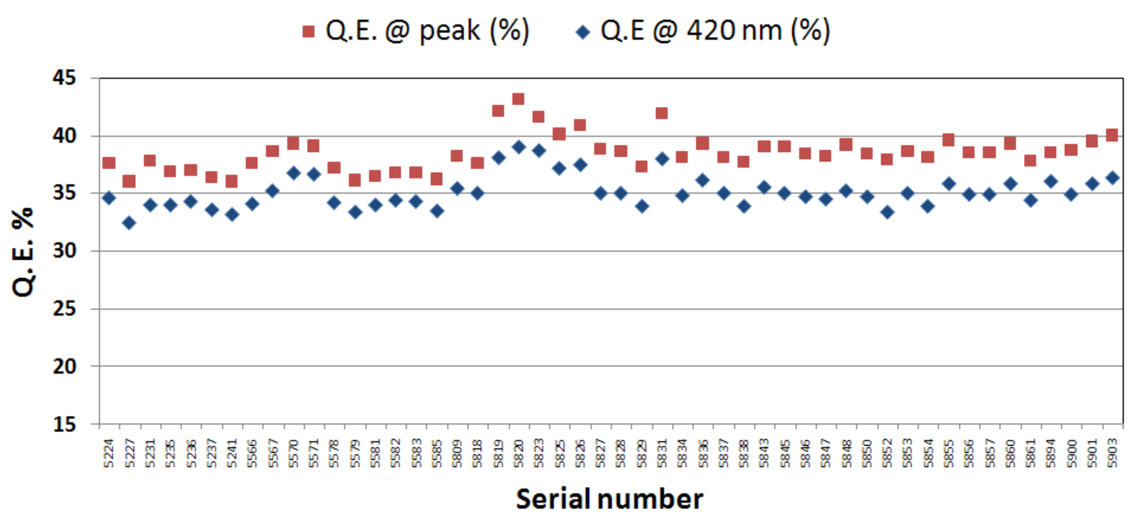
Conclusion # 1

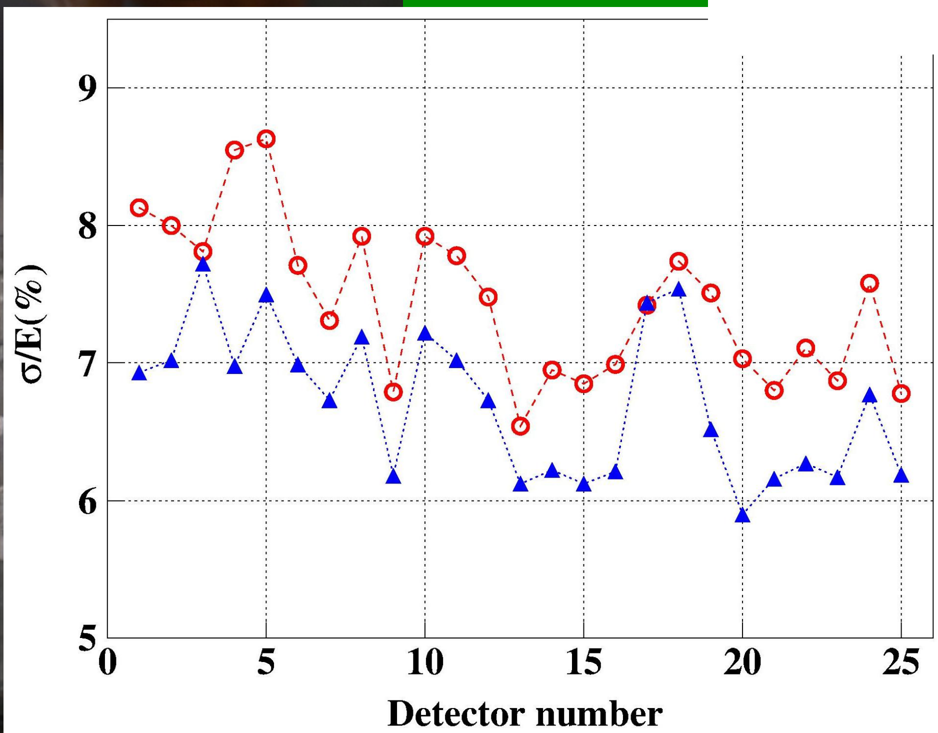
- Positive evidence for the presence of DM particles in the galactic halo now supported at 9.3σ C.L. (cumulative exposure 1.33 ton × yr – 14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1)
- The modulation parameters determined with increased precision
- Full sensitivity to many kinds of DM candidates and interactions types (both inducing recoils and/or e.m. radiation), full sensitivity to low and high mass candidates.
- No experiment exists whose result can be directly compared in a model independent way with those by DAMA/NaI and DAMA/LIBRA (in general: no direct model independent comparison is possible in the field among activities using different target-materials and/or approaches)

- Possible positive hints in direct searches compatible with DAMA in various scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties.
- Indirect model dependent searches not in conflict.
- New/updated corollary analyses in progress; other effects under investigation
- Investigations of rare processes other than DM

DAMA/LIBRA – phase2 JINST 7(2012)03009







ed with new

	^{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	-	-

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

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

DM annual modulation signature

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

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

ε: increased in DAMA/LIBRA-phase2

ΔE: increased in DAMA/LIBRA-phase2

T: increased with DAMA/LIBRA-phase2

→ Upgrade at fall 2010 & running time
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

DAMA/LIBRA-phase 2

- ✓ Replacement of all the PMTs with new higher Q.E. ones at fall 2010
- ✓ 1 keV software energy threshold at hand (JINST 7(2012)03009)
- ✓ *In data taking* in the new configuration with lower software energy threshold
- ✓ New preamplifiers and trigger modules 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
- ✓ New investigation on dark matter peculiarities and second order effects
- ✓ Special data takings for other rare processes

… and more

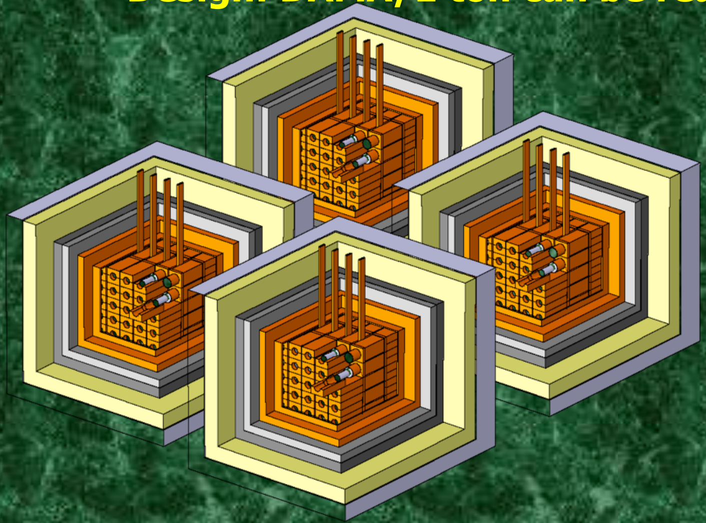
Starting studies towards an interesting phase-3 …

The strong interest in the low energy range suggest the possibility of a new development of high Q.E. PMTs with increased radiopurity to directly couple them to the DAMA/LIBRA crystals, removing the special quartz light guides which act also as otical window obtaining an ultimate number of ph.e./keV.

… and multi-purpose DAMA/1ton

1) Proposed since 1996 (DAMA/NaI and DAMA/LIBRA intermediate steps)
2) Technology largely at hand and still room for further improvements in the low-background characteristics of the set-up (NaI(Tl) crystals, PMTs, shields, etc.)
3) 1 ton detector: the cheapest, the highest duty cycle, the clear signature, fast realization in few years

Design: DAMA/1 ton can be realized by adding 3 replicas of DAMA/LIBRA:



- the detectors of similar size than those already used
- the features of low-radioactivity of the set-up and of all the used materials would be assured by many years of experience in the field
- electronic chain and controls would profit by the previous experience and by the use of compact devices already developped, tested and used.
- new digitizers will offer high expandibility and high performances
- the daq can be a replica of that of DAMA/LIBRA

- **Some R&Ds carried out**

Development of detectors with anisotropic response (ADAMO project)

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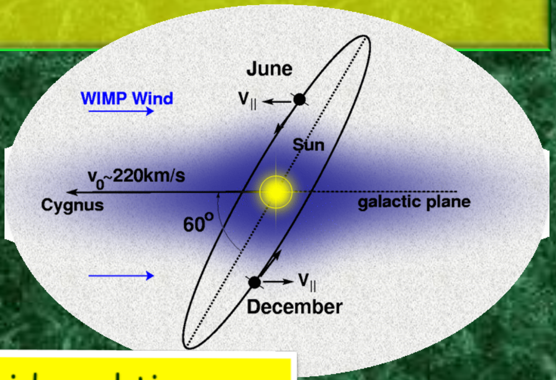
Anisotropic detectors are of great interest for many applicative fields, e.g.:
⇒ they can offer a unique way to study directionality for Dark Matter candidates that induce nuclear recoils

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



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

Two strategies

Development of $ZnWO_4$ scintillators

- ✓ Both light output and pulse shape have anisotropic behavior and can provide two independent ways to study directionality
- ✓ Very high reachable radio-purity;
- ✓ Threshold at keV feasible;

Development of Carbon Nano Tubes (CNT) detectors

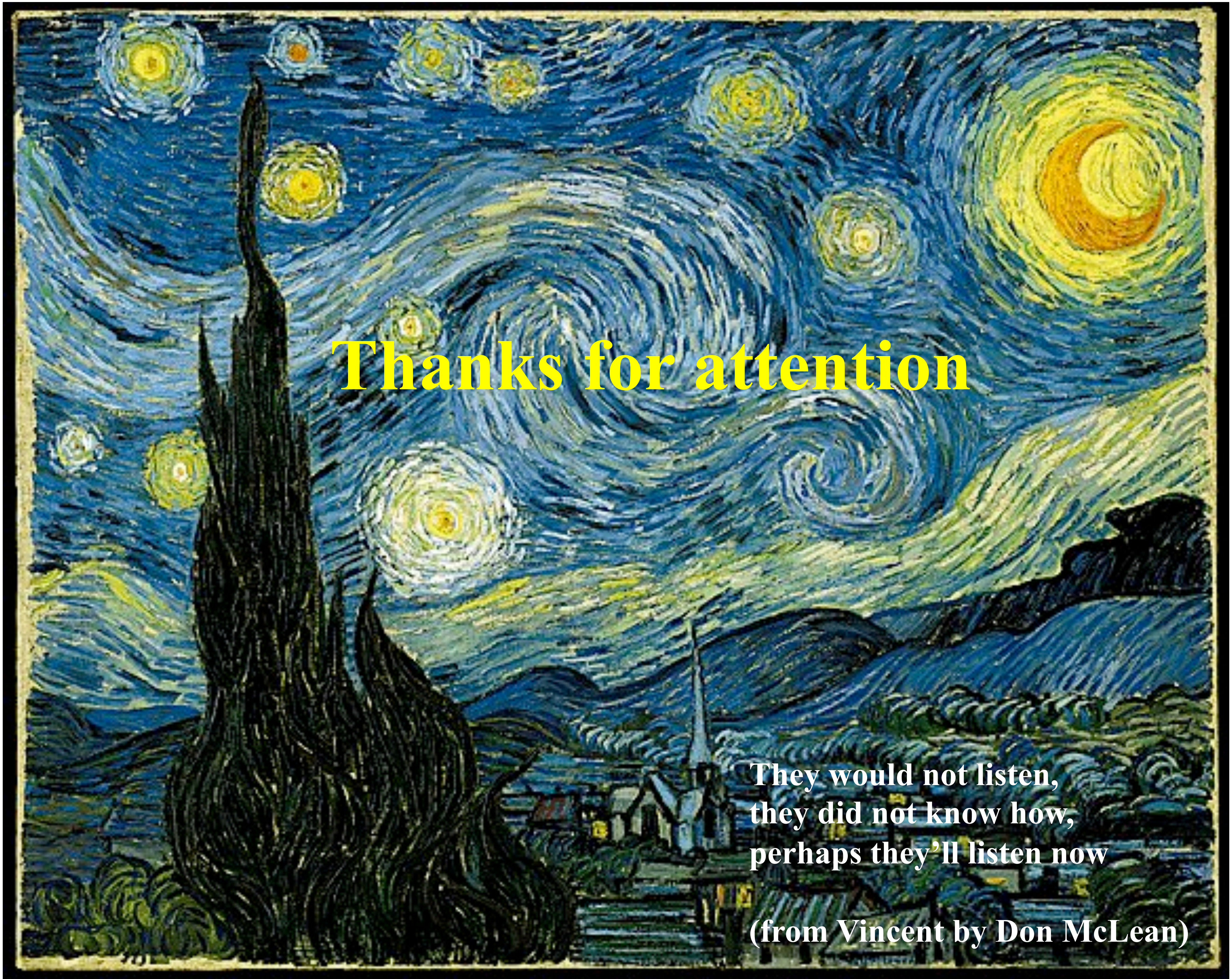
The detection principle is based on variation of the transport properties due to the particle irradiation

The intrinsic 1-D nature of CNTs makes them very promising for the study of directionality

- Spin-off and patents
- 3D detectors multi-wire chamber-like with nanotechnology
- Possible other applications:
  - Particle Physics;
  - Health Physics;
  - etc..

DAMA/LIBRA still the highest radiopure set-up in the field with the largest full sensitive mass, full control of running conditions, the largest duty-cycle, exposure orders of magnitude larger than any other activity in the field, etc.

… and many new perspectives


Thanks for attention
They would not listen,
they did not know how,
perhaps they'll listen now
(from Vincent by Don McLean)