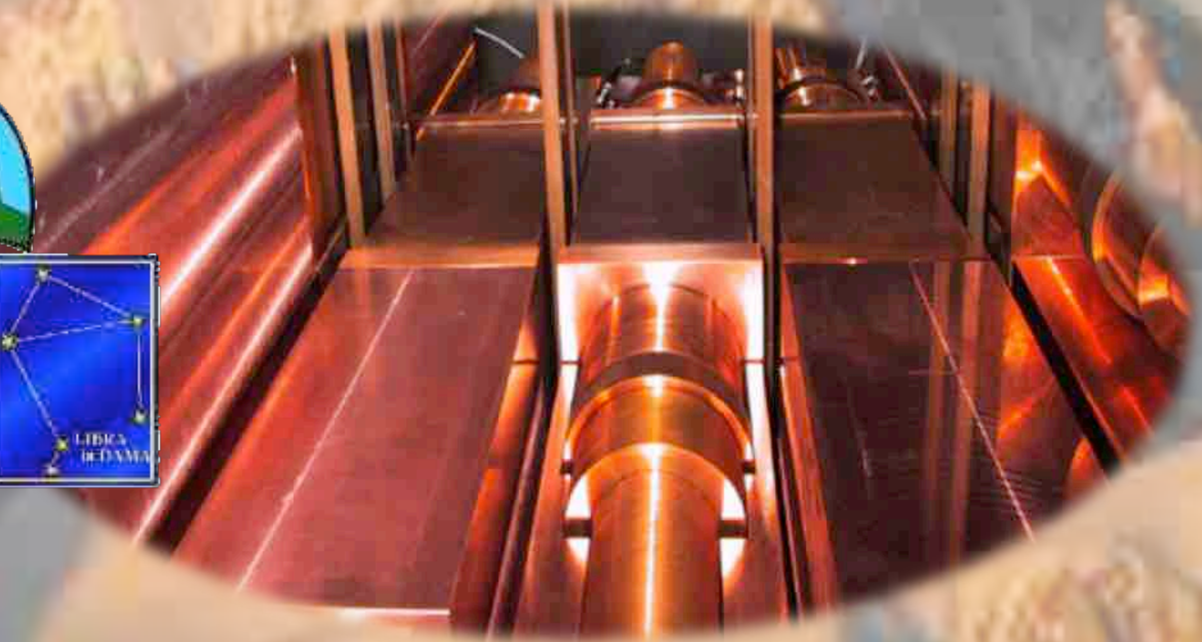
First model-independent results by DAMA/LIBRA–phase2

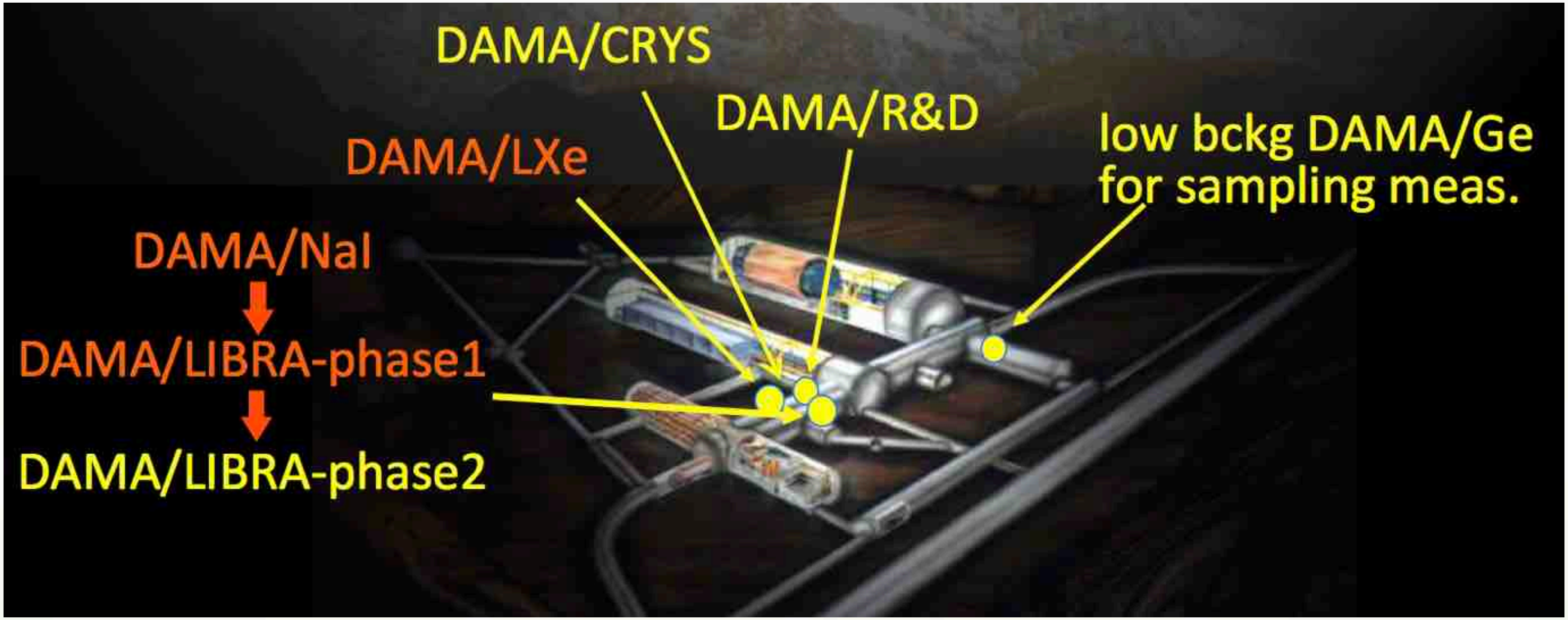


P. Belli
INFN – Roma Tor Vergata

INFN and Univ. Pisa
June 19, 2018

DAMA set-ups

an observatory for rare processes @ LNGS



Collaboration:

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

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

+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

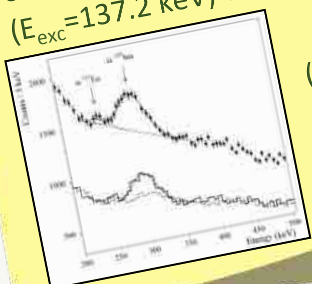
+ in some studies on ββ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

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

Main results obtained by DAMA in the search for rare processes

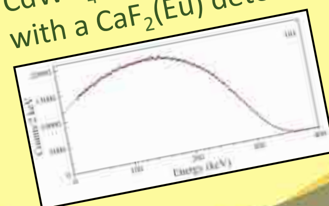
- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{156}Dy, ^{158}Dy, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt (observed $2\nu2\beta$ decay in ^{100}Mo, ^{116}Cd)
- The best experimental sensitivities in the field for 2β decays with positron emission (^{106}Cd)

First observation of α decays of ^{151}Eu with a CaF_2(Eu) scintillator and of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os



($T_{1/2}=5\times10^{18}$yr)

Investigations of rare β decays of ^{113}Cd ($T_{1/2}=8\times10^{15}$yr), ^{113m}Cd with $CdWO_4$ scintillator and ^{48}Ca with a CaF_2(Eu) detector



Observation of correlated e^+e^- pairs emission in α decay of ^{241}Am ($A_{e+e-}/A_\alpha \approx 5\times10^{-9}$)

Search for cluster decays of ^{127}I, ^{138}La and ^{139}La

Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

Search for PEP violating processes in Sodium and in Iodine

Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state

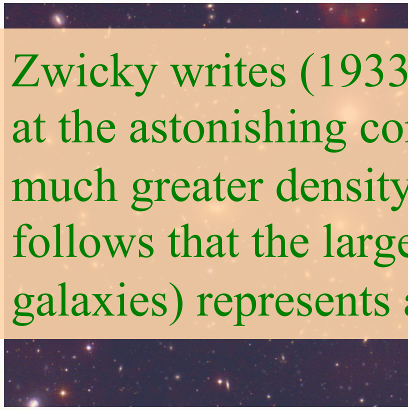
CNC processes, e.g. in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La

Search for ^{7}Li solar axions using resonant absorption in LiF crystal

Dark Matter investigation

… many others are in progress

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



COMA Cluster

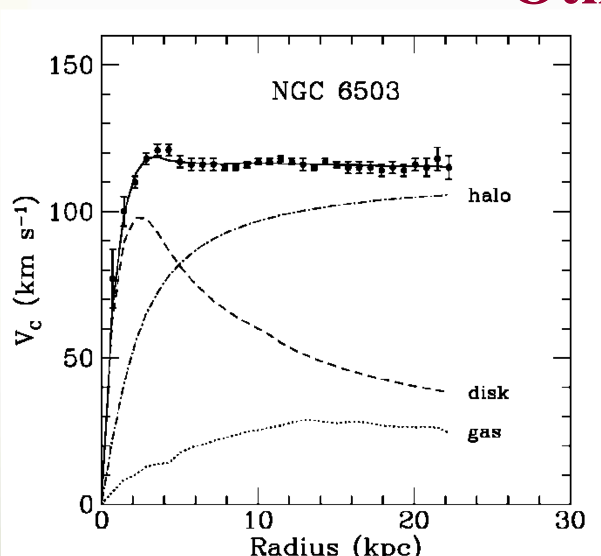
First evidence and confirmations:

Zwicky writes (1933): "If this [overdensity] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter. From these considerations it follows that the large velocity dispersion in Coma (and in other clusters of galaxies) represents an unsolved problem."

1933 F. Zwicky: studying dispersion velocity of Coma galaxies

1936 S. Smith: studying the Virgo cluster

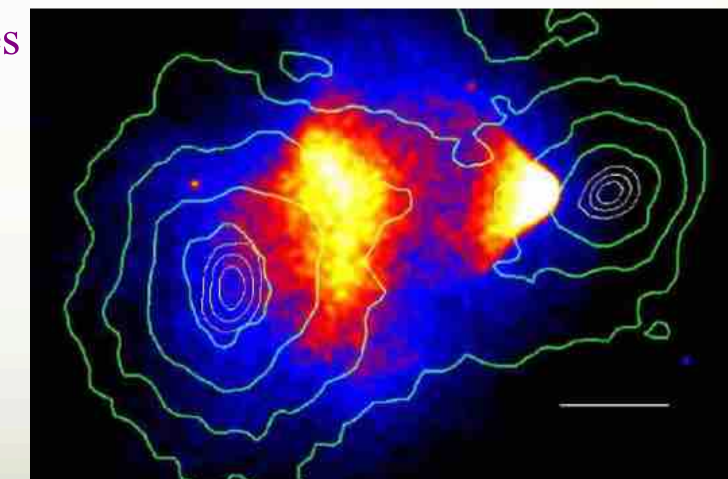
1974 two groups: systematical analysis of *mass density* vs *distance from center* in many galaxies



Rotational curve of a spiral galaxy

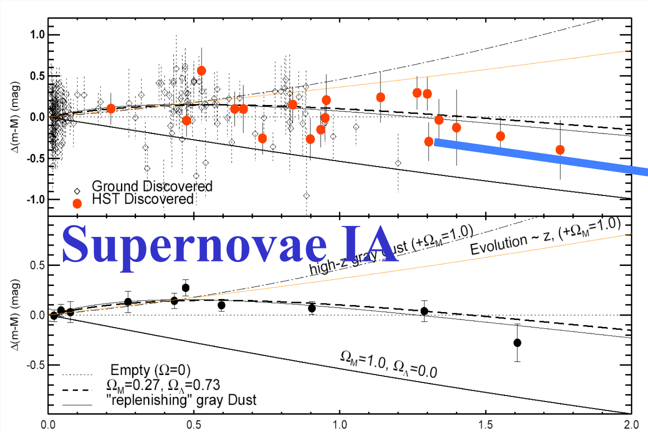
Other experimental evidences

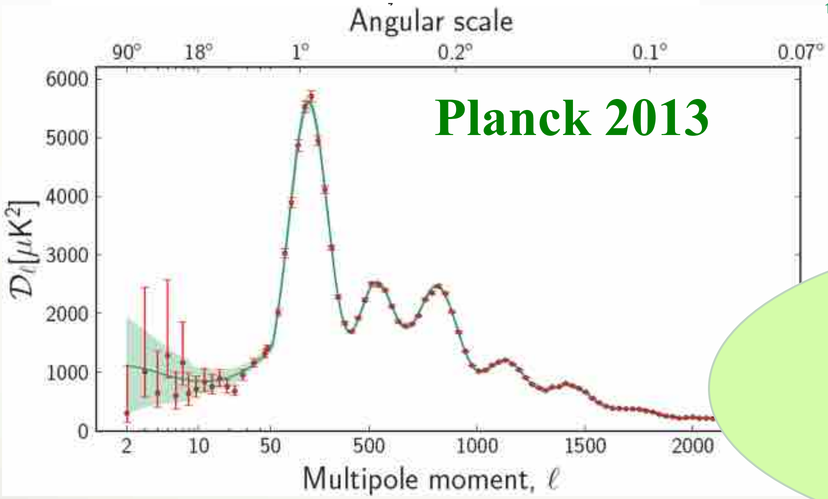
- ✓ from LMC motion around Galaxy
- ✓ from X-ray emitting gases surrounding elliptical galaxies
- ✓ from hot intergalactic plasma velocity distribution in clusters
- ✓ ...
- ✓ bullet cluster 1E0657-558

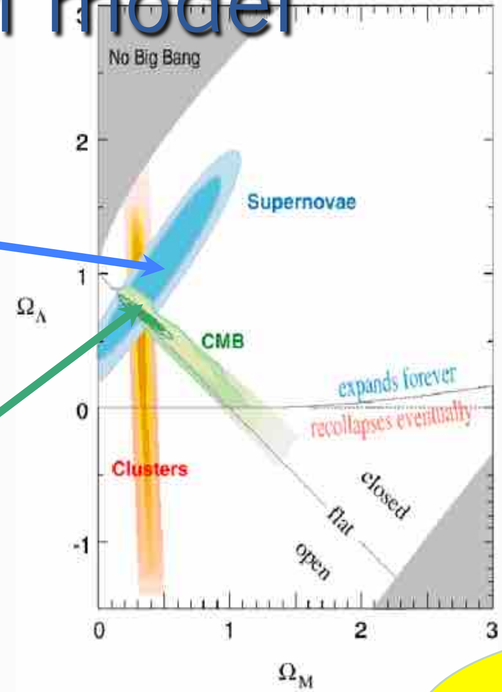


$M_{\text{visible Universe}} << M_{\text{gravitational effect}}$ ⇒ about 90% of the mass is DARK

"Concordance ΛCDM model"







$$\Omega = \Omega_\Lambda + \Omega_M =$$
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

Ω_b ~ 4%

Non baryonic Cold Dark Matter is dominant

Ω_{CDM} ~ 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

etc...

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν's

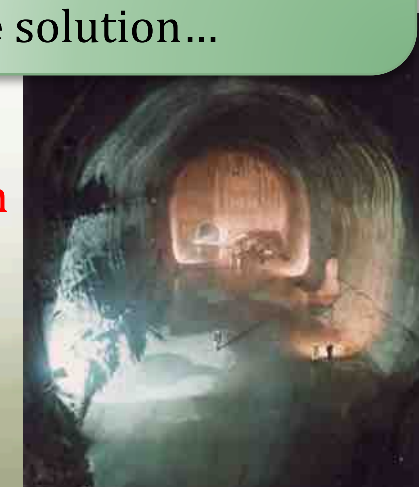
multi-component non-baryonic DM?

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

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

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

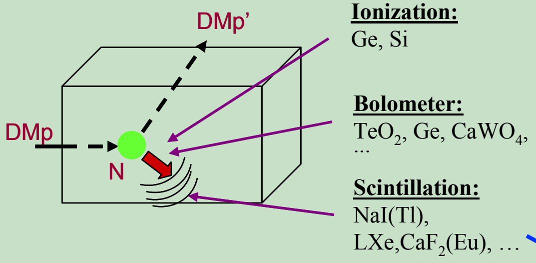
DM direct detection method using a model independent approach and a low-background widely-sensitive target material



Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



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

  → W has 2 mass states $\chi+$, $\chi-$ with δ mass splitting

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

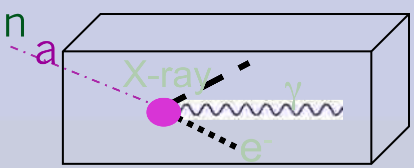
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

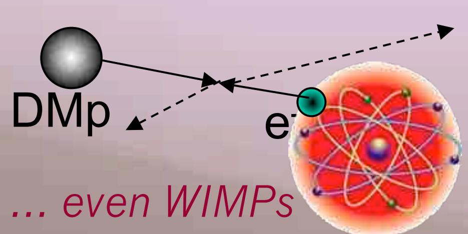
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

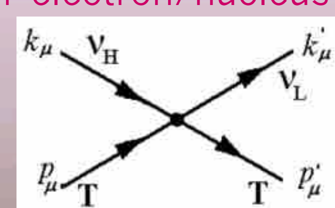


... even WIMPs

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

  → detection of electron/nucleus recoil energy

  e.g. sterile ν



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

... also other ideas ...

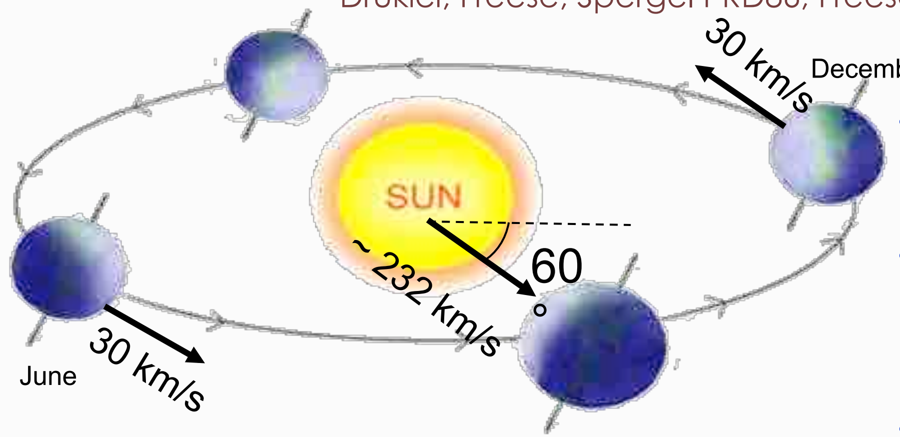
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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

Drukier, Freese, Spergel PRD86; Freese et al. PRD88

Requirements:

1) Modulated rate according cosine
2) In low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios



- v_{sun} ~ 232 km/s (Sun vel in the halo)
- v_{orb} = 30 km/s (Earth vel around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

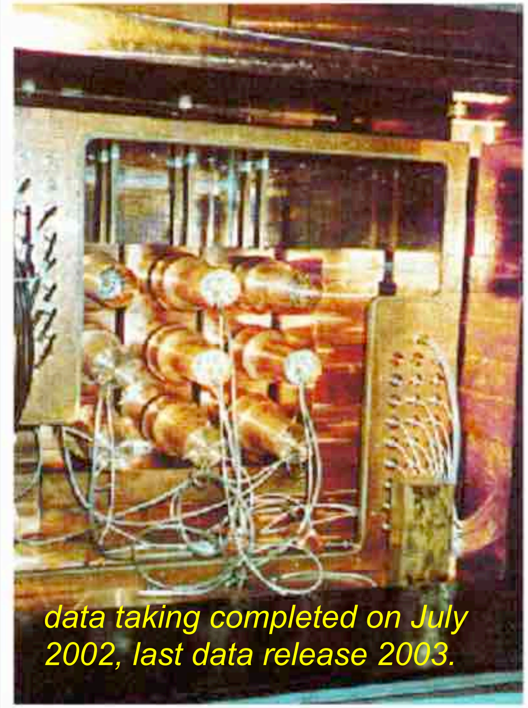
$$v_\oplus(t) = v_{sun} + v_{orb}\cos\gamma\cos[\omega(t-t_0)]$$

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

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

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

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



Performances:

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

Results on rare processes:

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

Results on DM particles:

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

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

total exposure (7 annual cycles) 0.29 ton×yr

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

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

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles,
  - Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  - Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, EPJC75(2015)400, IJMPA31(2016) dedicated issue, EPJC77(2017)83
- Results on rare processes:
  - PEPv: EPJC62(2009)327, arXiv1712.08082;
  - CNC: EPJC72(2012)1920;
  - IPP in ^{241}Am: EPJA49(2013)64

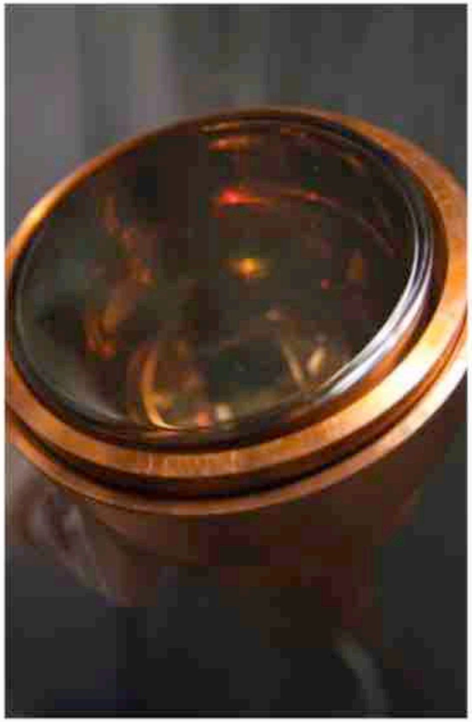
Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

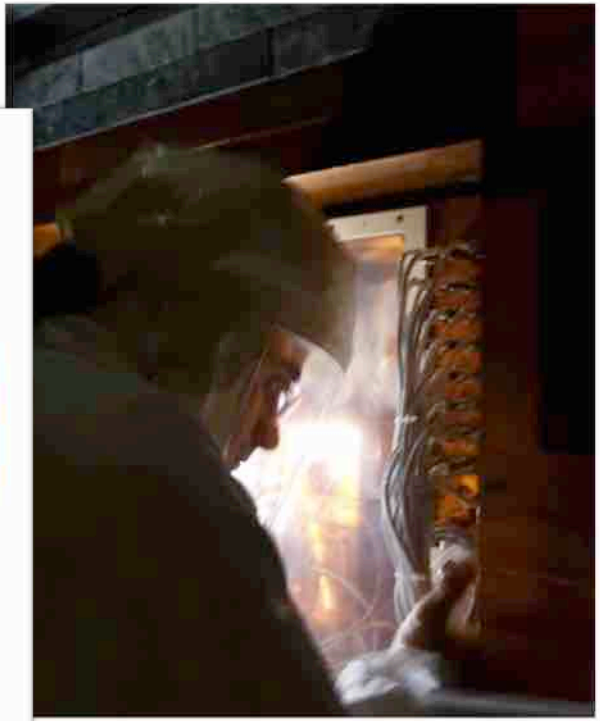
DAMA/LIBRA–phase1 (7 annual cycles, 1.04 ton×yr) confirmed the model-independent evidence of DM: reaching 9.3σ C.L.

DAMA/LIBRA–phase2

JINST 7(2012)03009

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





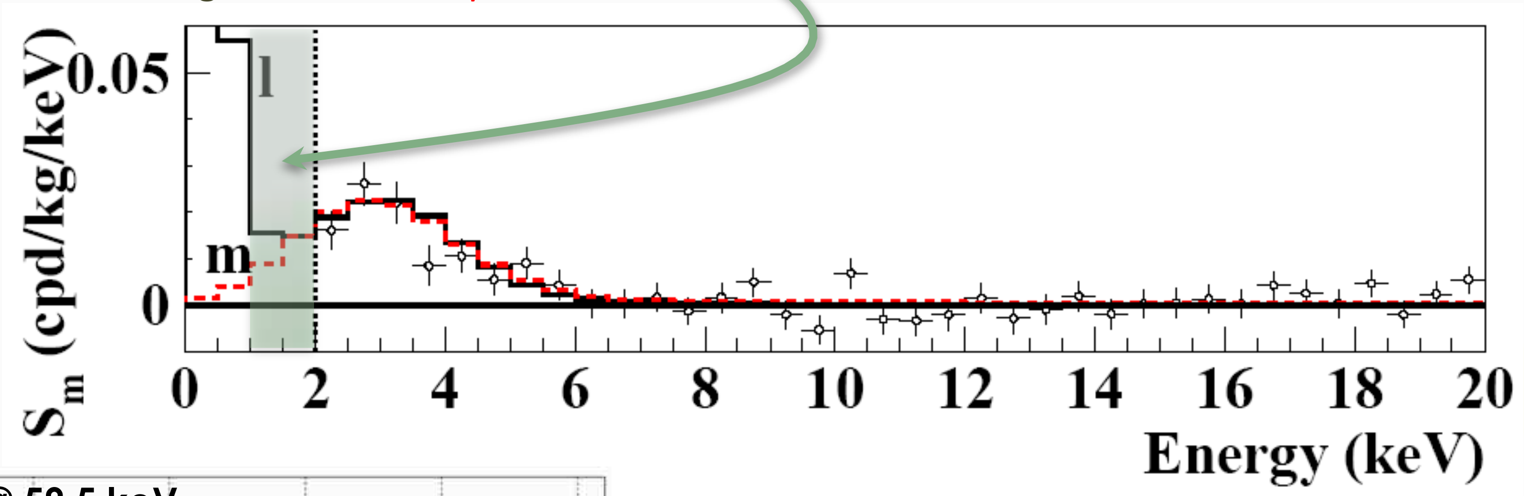
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak

DAMA/LIBRA–phase2

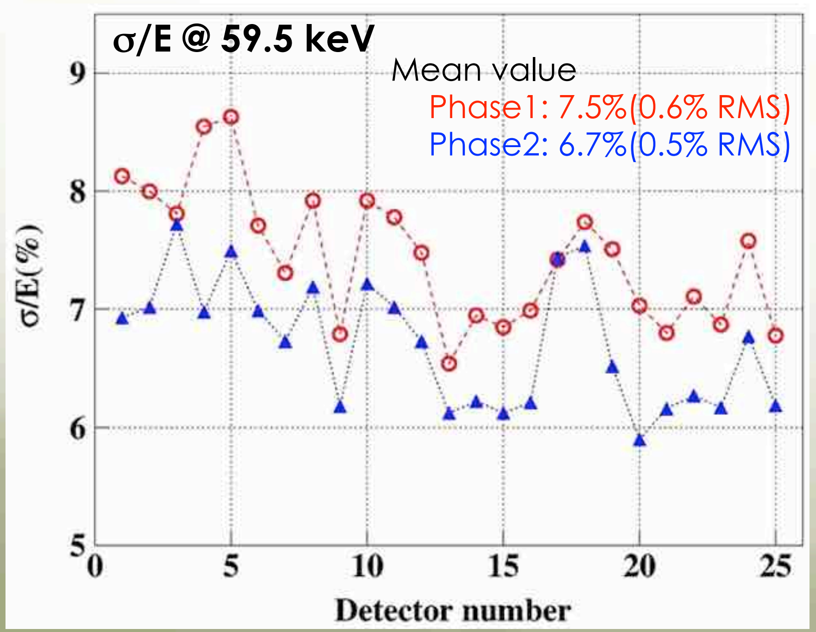
JINST 7(2012)03009

Lowering software energy threshold below 2 keV:

- to study the nature of the particles and features of astrophysical, nuclear and particle physics aspects, and to investigate 2nd order effects
- special data taking for *other rare processes*



The resolution:



The contaminations:

	^{226}Ra (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)
Mean Contamination	0.43	47	0.12	83	0.54
Standard Deviation	0.06	10	0.02	17	0.16

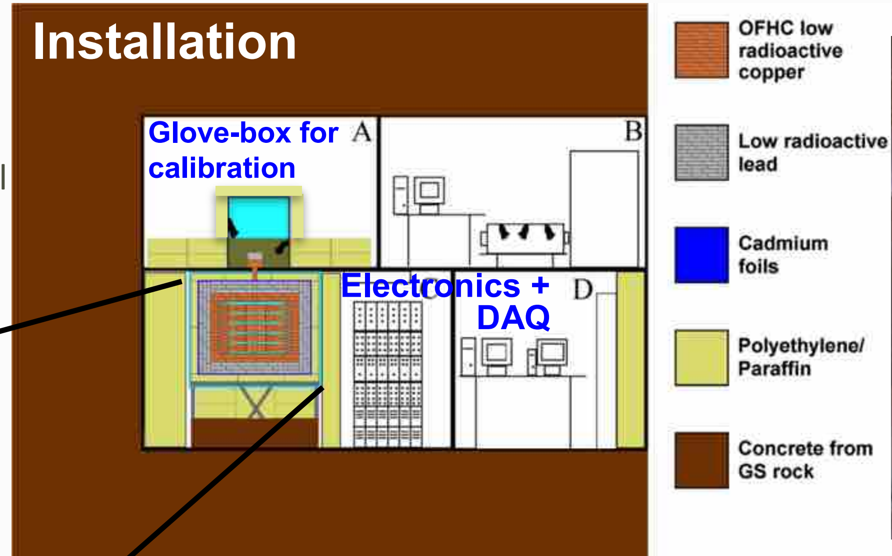
The light responses:

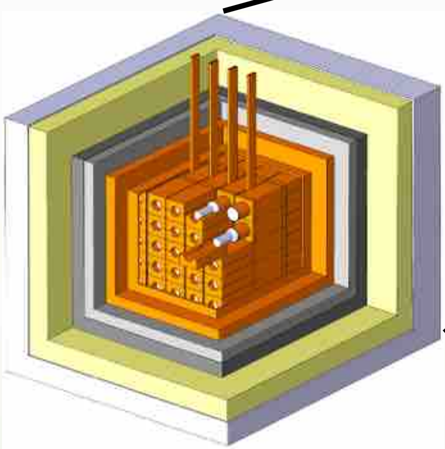
DAMA/LIBRA-phase1: 5.5 – 7.5 ph.e./keV
DAMA/LIBRA-phase2: 6-10 ph.e./keV

The DAMA/LIBRA–phase2 set-up

NIMA592(2008)297, JINST 7(2012)03009, IJMPA31(2017)issue31

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two new high Q.E. PMTs for each crystal working in coincidence at the single ph. el. threshold
- **6-10 phe/keV; 1 keV software energy threshold**





- Whole setup decoupled from ground
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- Dismounting/Installing protocol in HPN_2
- All the materials selected for low radioactivity

- Multiton-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 prod runs
- Never neutron source in DAMA installations
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data

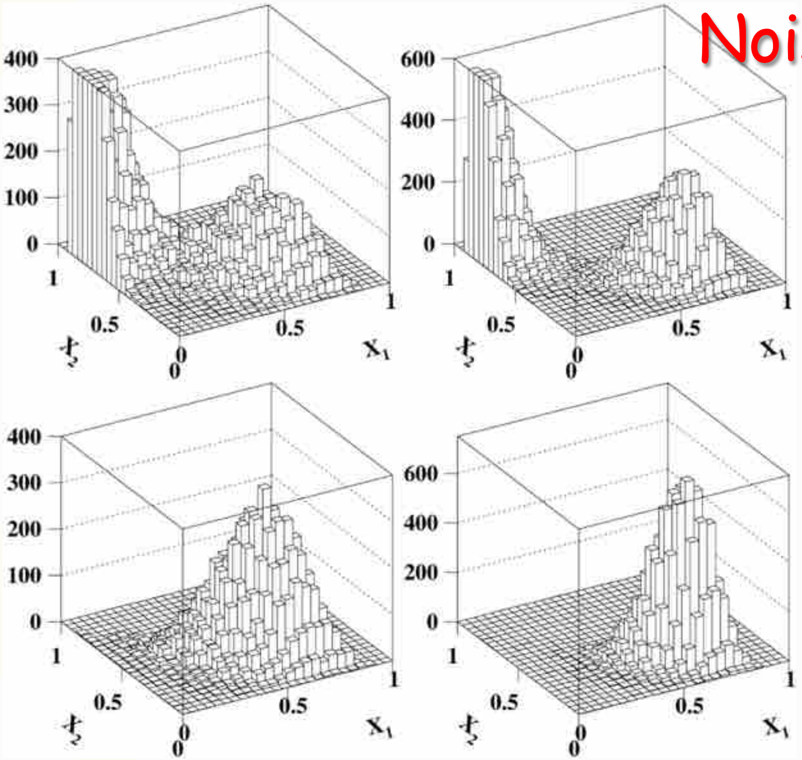
- Pulse shape recorded by Waweform Analyzer Acqiris DC270 (2chs per detector), 1 *Gs/s,* 8 bit, bandwidth 250 MHz both for single-hit and multiple-hit events
- Data collected from low energy up to MeV region, despite the hardware optimization for low energy
- DAQ with optical readout
- New electronic modules

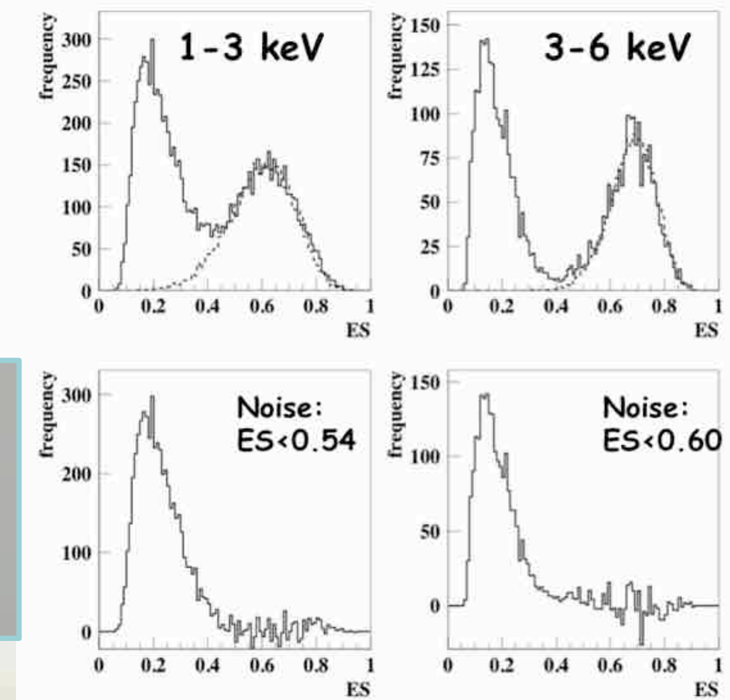
Noise rejection in phase2

JINST 7(2012)03009

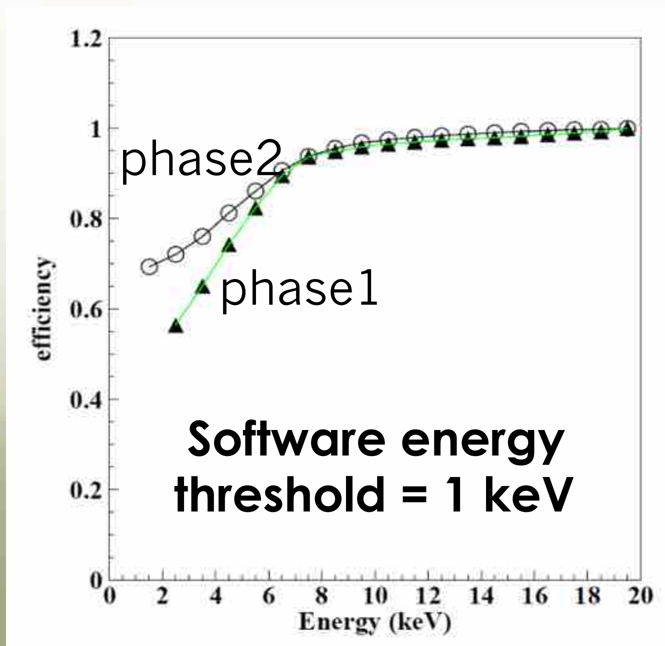
- Comparison of the noise and the scintillation pulses distributions in 1-3 keV and 3-6 keV
- production data vs γ source
- scintillation events well separated from noise

X_1=Area(from 100 to 600 ns)/Area from 0 to 600 ns)
X_2=Area(from 0 to 50 ns)/Area from 0 to 600 ns)





Residual noise events:
(15±62) (<120)
-(18±41) (<51)



→ possible noise contamination, *f*, in the selected events <3% @ software energy threshold

DAMA/LIBRA-phase2 data taking

Second upgrade at end of 2010:

JINST 7(2012)03009

all PMTs replaced with new ones of higher Q.E.

Energy resolution @ 60 keV mean value:

prev. PMTs 7.5% (0.6% RMS)

new HQE PMTs 6.7% (0.5% RMS)

- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 6 a.c.: ≈ 1.3×10^8 events from sources
- ✓ Acceptance window eff. 6 a.c.: ≈ 3.4×10^6 events (≈1.4×10^5 events/keV)

Annual Cycles	Period	Mass (kg)	Exposure	$(\alpha-\beta^2)$
I	Dec 23, 2010 – Sept. 9, 2011	commissioning		
II	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
VI	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527	0.522
VII	Sept. 7, 2016 – Sept. 25, 2017	242.5	75135	0.480

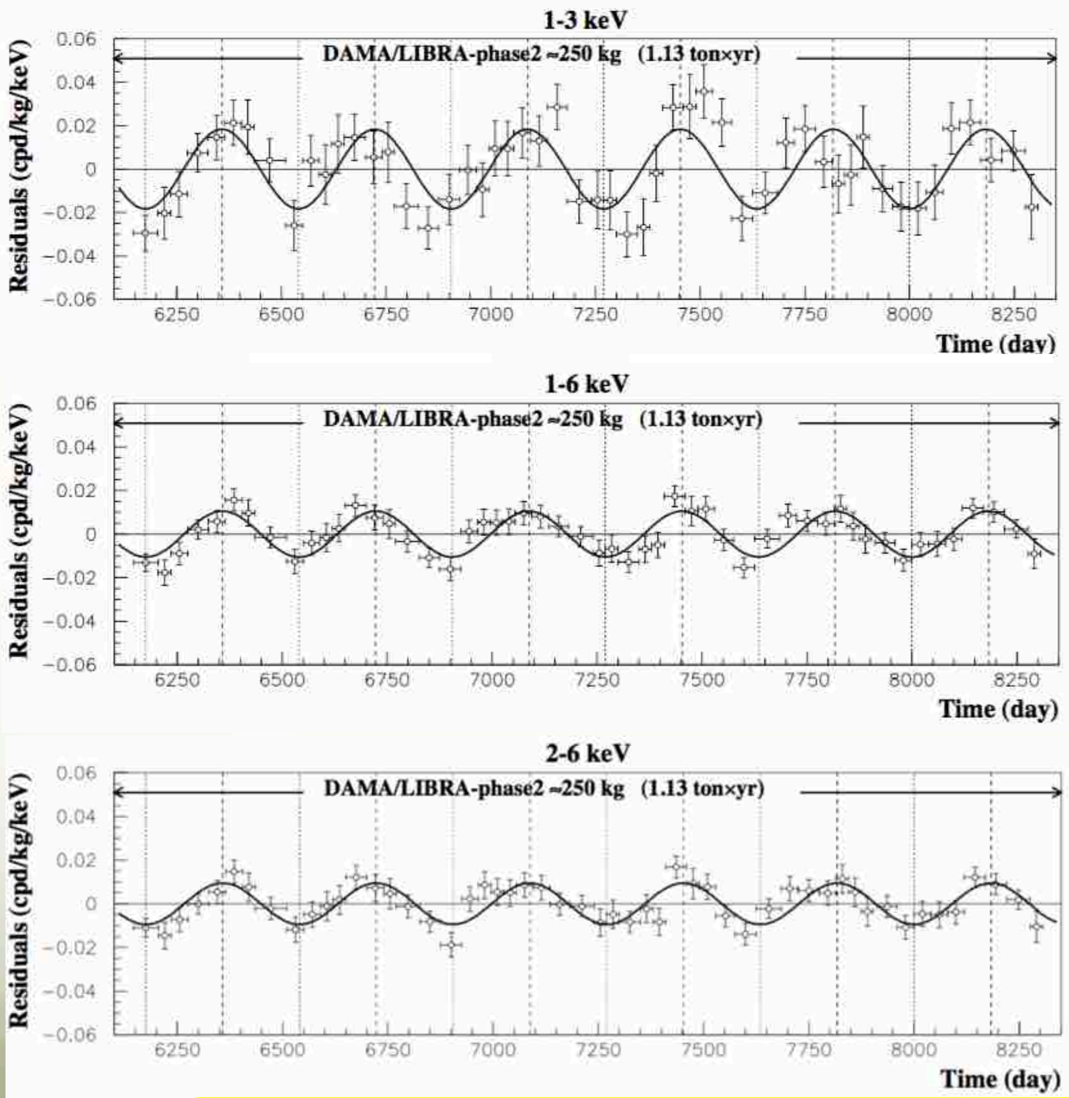
Exposure first data release of DAMA/LIBRA-phase2: **1.13 ton × yr**

Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.46 ton × yr**

DM model-independent Annual Modulation Result

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

DAMA/LIBRA-phase2 (1.13 ton × yr)



Absence of modulation? No

- 1-3 keV: χ^2/dof=127/52 ⇒ P(A=0) = 3×10^{-8}
- 1-6 keV: χ^2/dof=150/52 ⇒ P(A=0) = 2×10^{-11}
- 2-6 keV: χ^2/dof=116/52 ⇒ P(A=0) = 8×10^{-7}

Fit on DAMA/LIBRA-phase2

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

1-3 keV

A=(0.0184±0.0023) cpd/kg/keV

χ^2/dof = 61.3/51 **8.0 σ C.L.**

1-6 keV

A=(0.0105±0.0011) cpd/kg/keV

χ^2/dof = 50.0/51 **9.5 σ C.L.**

2-6 keV

A=(0.0095±0.0011) cpd/kg/keV

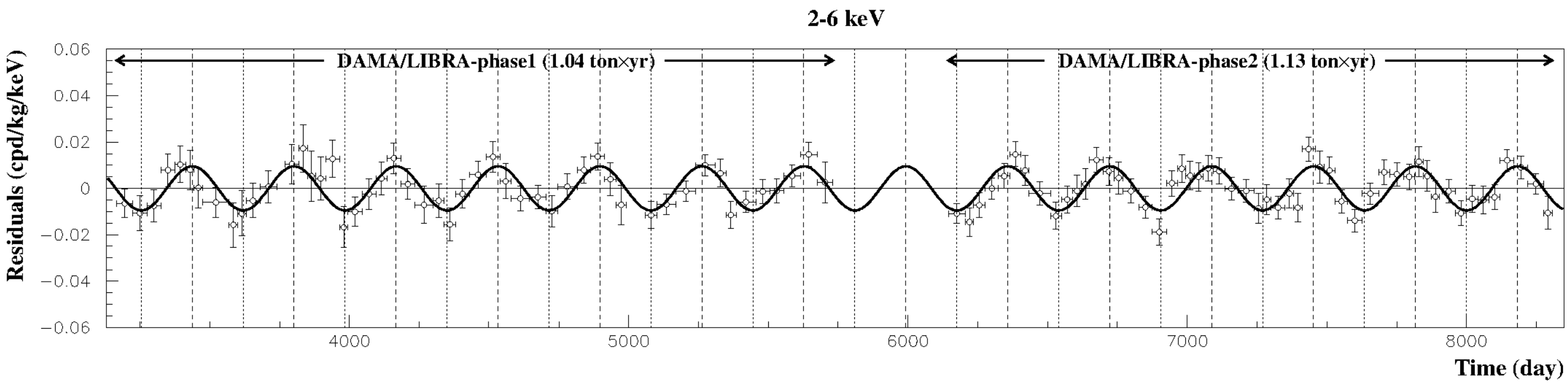
χ^2/dof = 42.5/51 **8.6 σ C.L.**

The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 9.5σ C.L.

DM model-independent Annual Modulation Result

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

DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.17 ton × yr)



Absence of modulation? No

- 2-6 keV: χ^2/dof=199.3/102 ⇒ P(A=0) =2.9×10^{-8}

Fit on DAMA/LIBRA-phase1+ DAMA/LIBRA-phase2

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

2-6 keV

A=(0.0095±0.0008) cpd/kg/keV

χ^2/dof = 71.8/101 **11.9σ C.L.**

The data of DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.9 σ C.L.

Releasing period (T) and phase (t_0) in the fit

	ΔE	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0184±0.0023	1.0000±0.0010	153±7	8.0σ
	(1-6) keV	0.0106±0.0011	0.9993±0.0008	148±6	9.6σ
	(2-6) keV	0.0096±0.0011	0.9989±0.0010	145±7	8.7σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0096±0.0008	0.9987±0.0008	145±5	12.0σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0103±0.0008	0.9987±0.0008	145±5	12.9σ

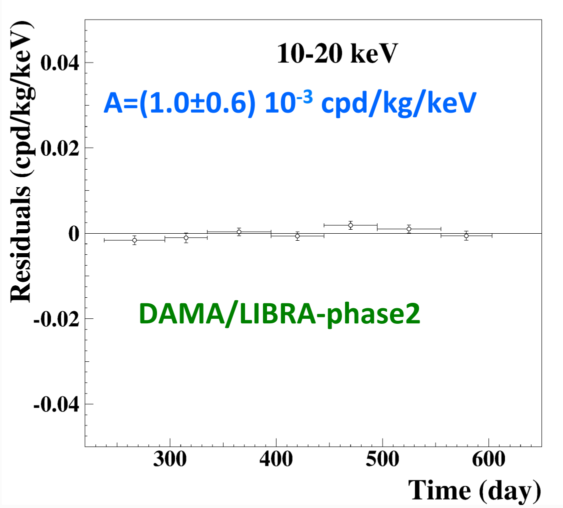
$A\cos[\omega(t-t_0)]$

DAMA/NaI (0.29 ton x yr)
DAMA/LIBRA-ph1 (1.04 ton x yr)
DAMA/LIBRA-ph2 (1.13 ton x yr)

total exposure = 2.46 ton×yr

Rate behaviour above 6 keV

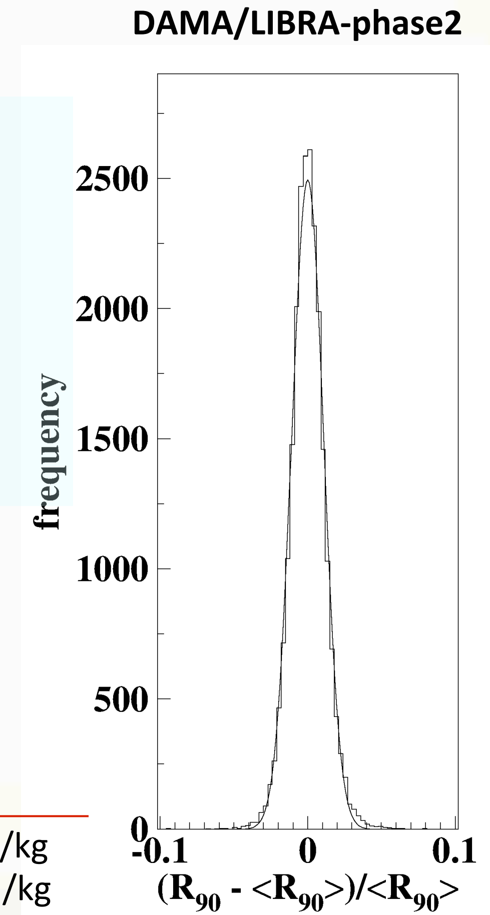
• No Modulation above 6 keV



Mod. Ampl. (6-14 keV): cpd/kg/keV

- (0.0032 ± 0.0017) DAMA/LIBRA-ph2_2
- (0.0016 ± 0.0017) DAMA/LIBRA-ph2_3
- (0.0024 ± 0.0015) DAMA/LIBRA-ph2_4
- -(0.0004 ± 0.0015) DAMA/LIBRA-ph2_5
- (0.0001 ± 0.0015) DAMA/LIBRA-ph2_6
- (0.0015 ± 0.0014) DAMA/LIBRA-ph2_7

→ statistically consistent with zero



σ ≈ 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: **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

Period	Mod. Ampl.
DAMA/LIBRA-ph2_2	(0.12±0.14) cpd/kg
DAMA/LIBRA-ph2_3	-(0.08±0.14) cpd/kg
DAMA/LIBRA-ph2_4	(0.07±0.15) cpd/kg
DAMA/LIBRA-ph2_5	-(0.05±0.14) cpd/kg
DAMA/LIBRA-ph2_6	(0.03±0.13) cpd/kg
DAMA/LIBRA-ph2_7	-(0.09±0.14) cpd/kg

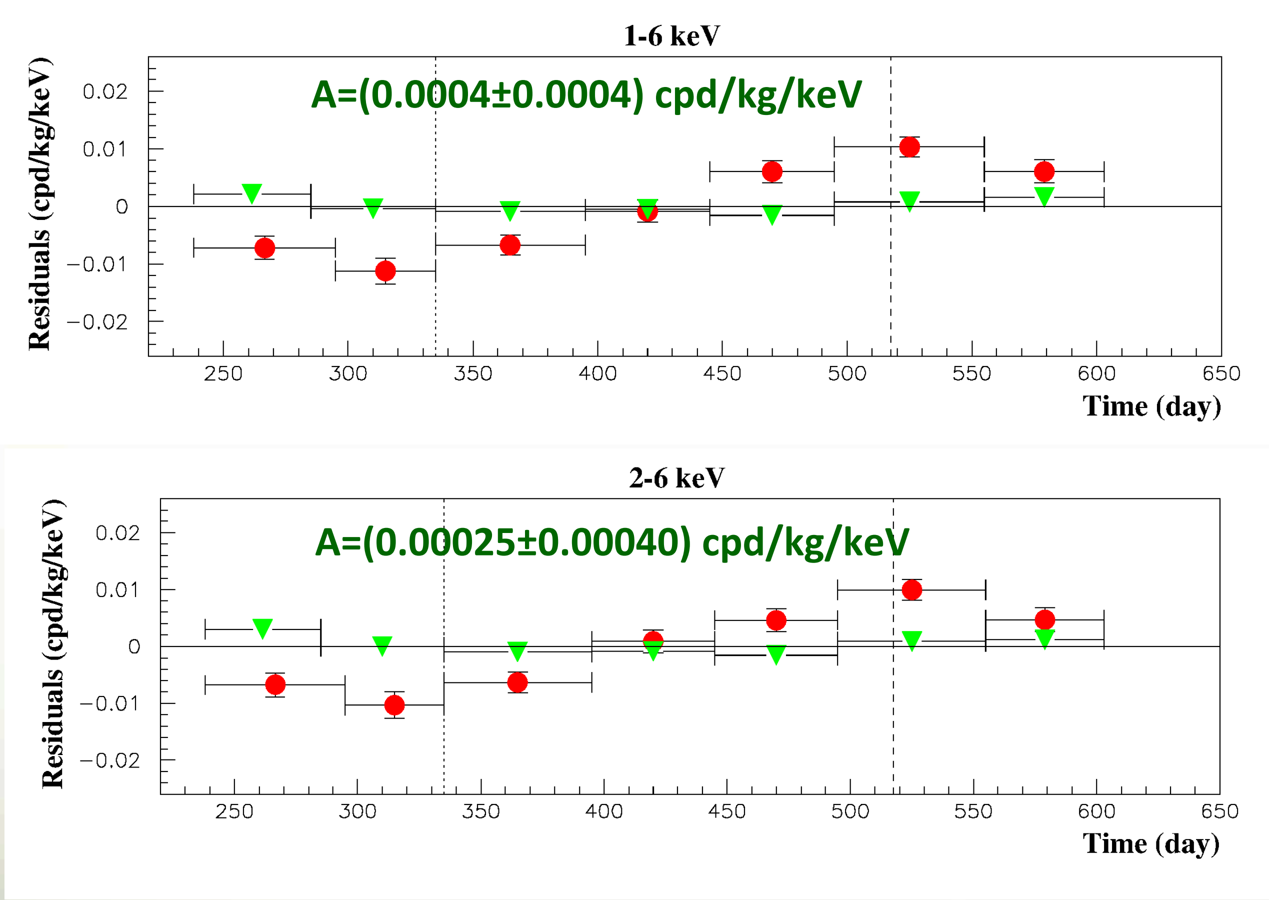
No modulation above 6 keV

This accounts for all sources of bckg and is consistent with the studies on the various components

DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.13 ton × yr)

Multiple hits events = Dark Matter particle “switched off”



Single hit residual rate (red) vs **Multiple hit residual rate (green)**

- Clear modulation in the single hit events;
- No modulation in the residual rate of the multiple hit events

This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

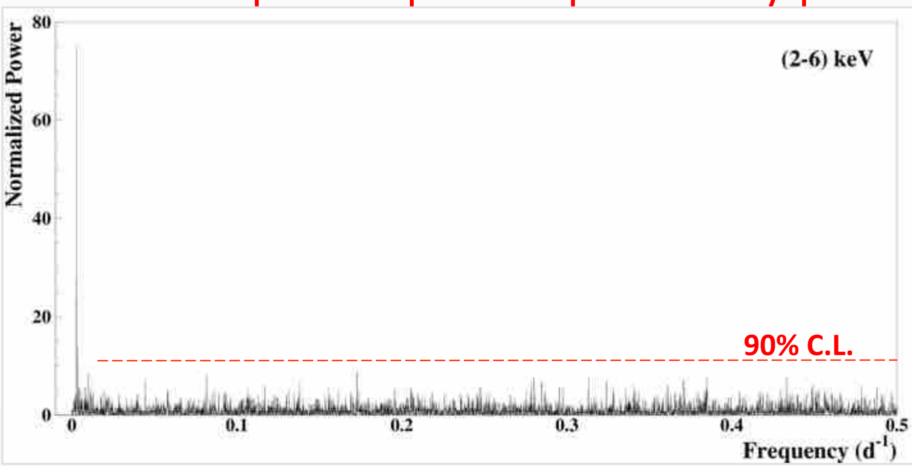
The analysis in frequency

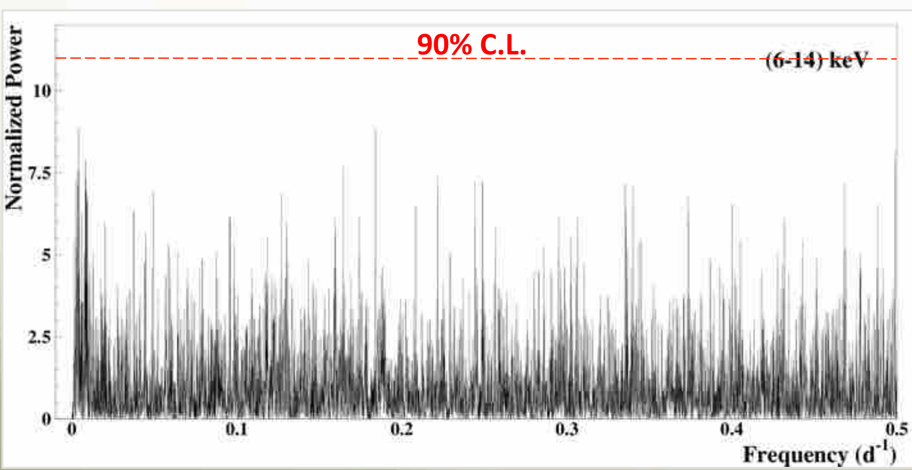
(according to PRD75 (2007) 013010)

To perform the Fourier analysis of the data in a wide region of frequency, the single-hit scintillation events have been grouped in 1 day bins

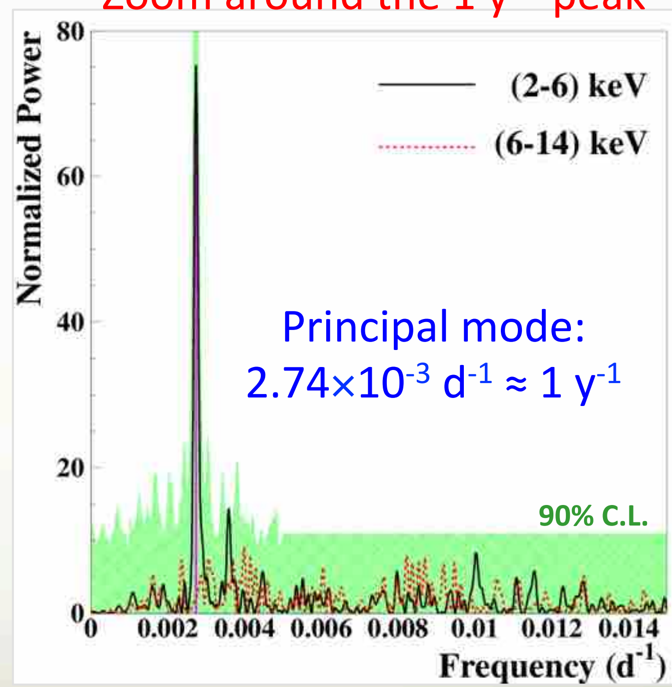
DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (20 yr)
total exposure: 2.46 ton×yr

The whole power spectra up to the Nyquist





Zoom around the 1 y^{-1} peak



Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region

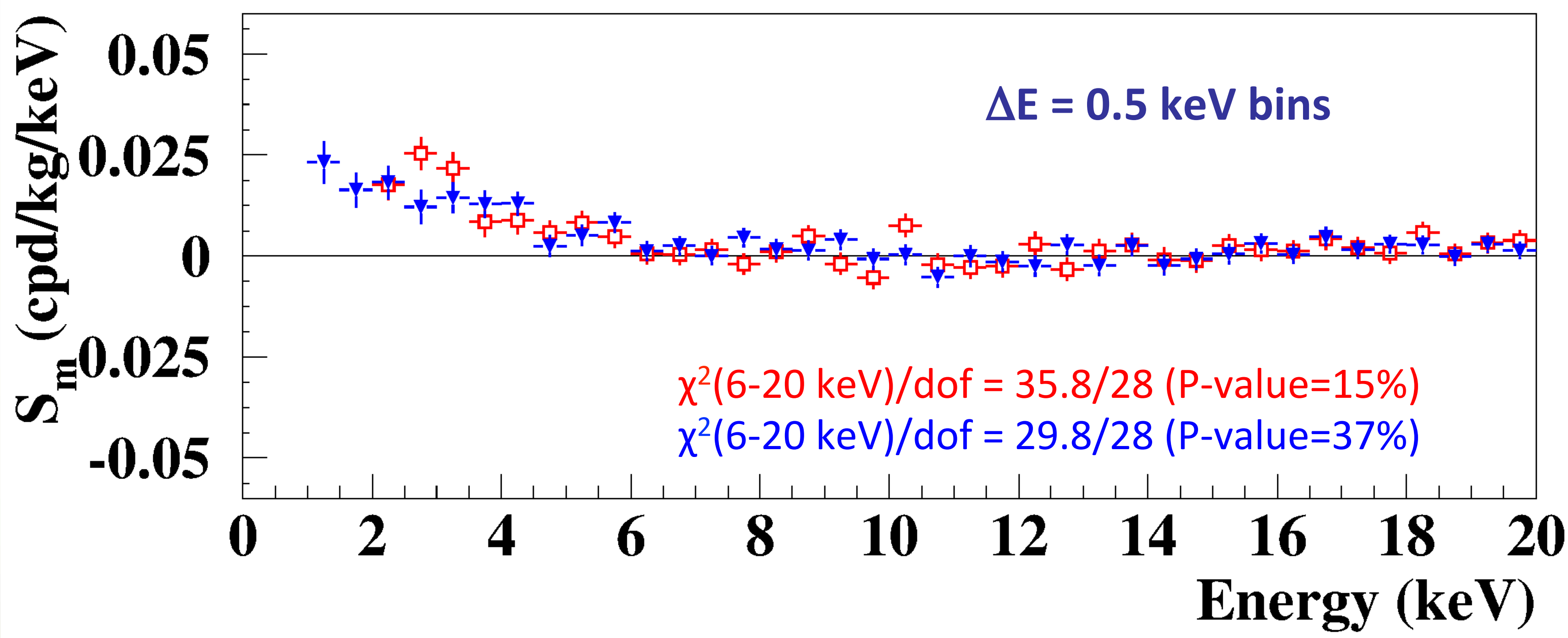
Energy distribution of the modulation amplitudes

Max-likelihood analysis

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

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

DAMA/NaI + DAMA/LIBRA-phase1
vs
DAMA/LIBRA-phase2



The two S_m energy distributions obtained in DAMA/NaI+DAMA/LIBRA-ph1 and in DAMA/LIBRA-ph2 are consistent in the (2–20) keV energy interval:

$\chi^2 = \Sigma (r_1 - r_2)^2/(\sigma_1^2+\sigma_2^2)$	Interval	χ^2/d.o.f.	P
	(2-20) keV	χ^2/d.o.f.=32.7/36	(P=63%)
	(2-6) keV	χ^2/d.o.f.=10.7/8	(P=22%)

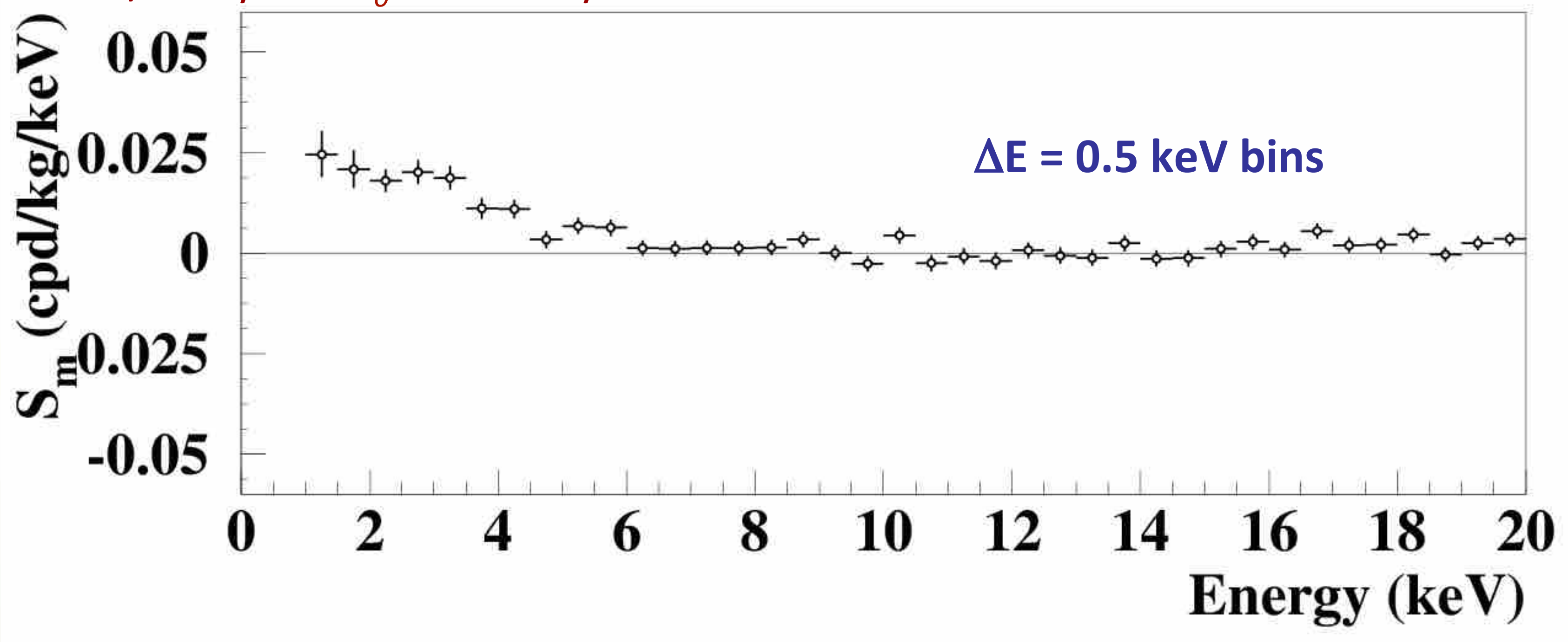
Energy distribution of the modulation amplitudes

Max-likelihood analysis

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

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

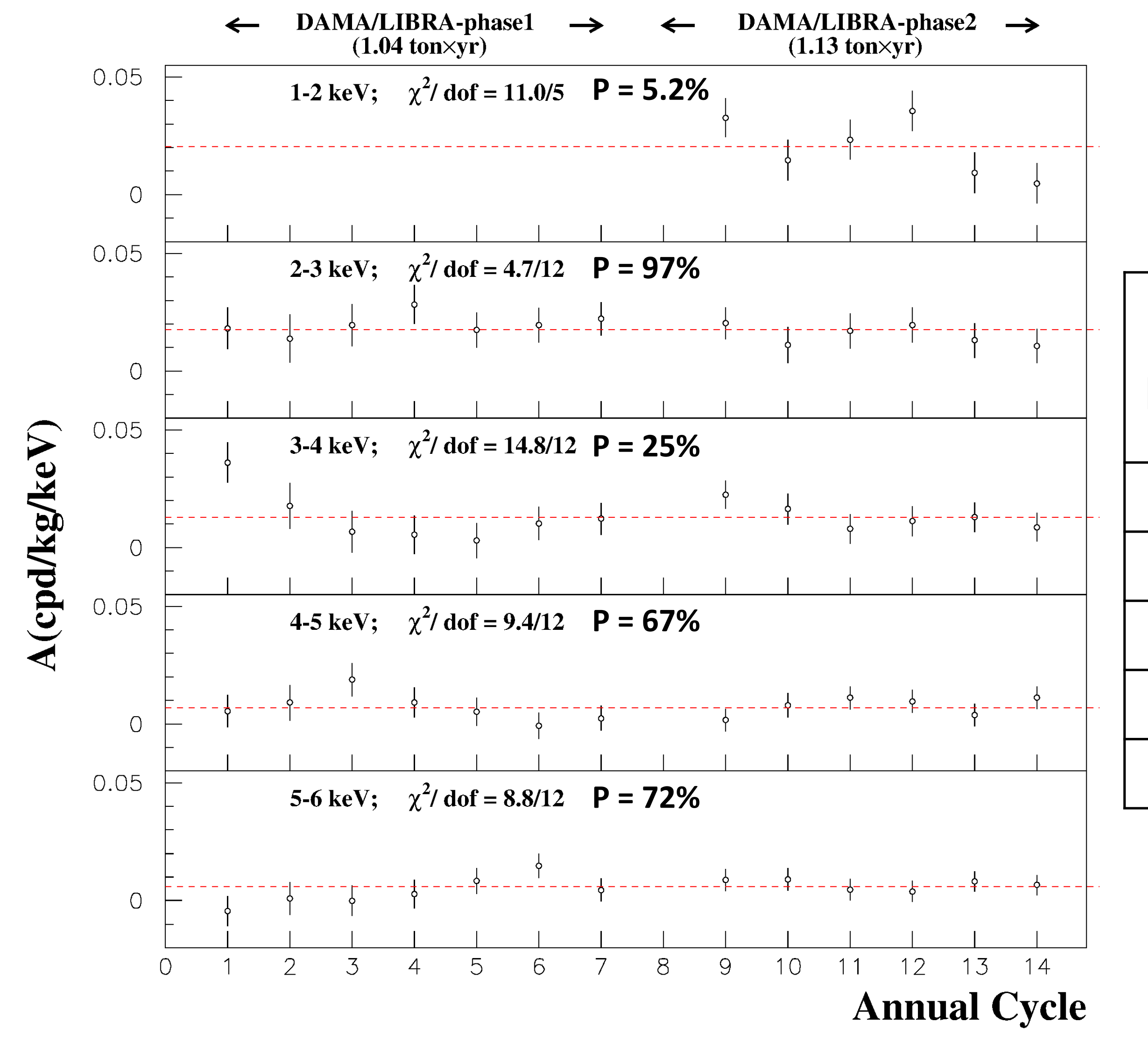
DAMA/NaI + DAMA/LIBRA-phase1
+ DAMA/LIBRA-phase2 (2.46 ton×yr)



A clear modulation is present in the (1-6) keV energy interval, while S_m values compatible with zero are present just above

- The S_m values in the (6–14) keV energy interval have random fluctuations around zero with χ^2 equal to 19.0 for 16 degrees of freedom (upper tail probability 27%).
- In (6–20) keV χ^2/dof = 42.6/28 (upper tail probability 4%). The obtained χ^2 value is rather large due mainly to two data points, whose centroids are at 16.75 and 18.25 keV, far away from the (1–6) keV energy interval. The P-values obtained by excluding only the first and either the points are 11% and 25%.

S_m for each annual cycle

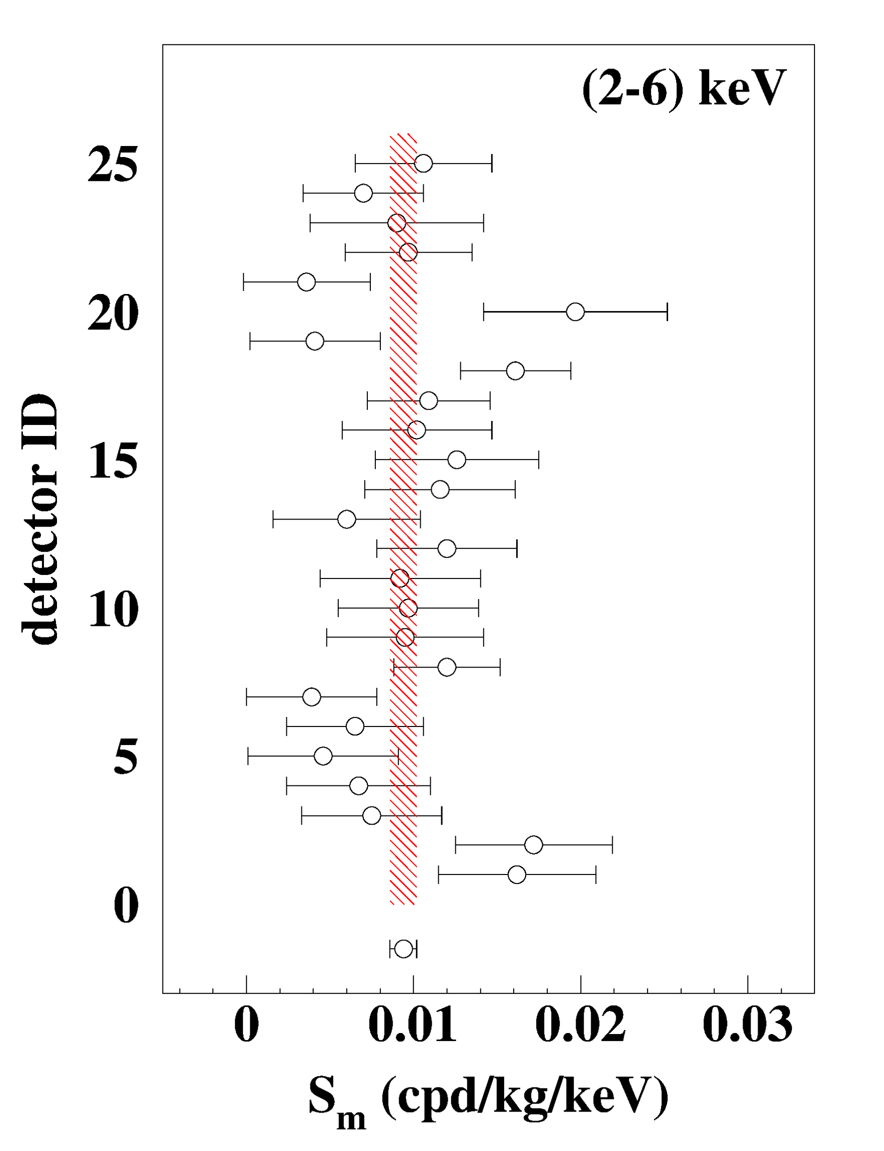


DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: **2.46 ton×yr**

Energy bin (keV)	run test probability	
	Lower	Upper
1-2	70%	70%
2-3	50%	73%
3-4	85%	35%
4-5	88%	30%
5-6	88%	30%

The signal is well distributed over all the annual cycles in each energy bin

S_m for each detector



DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: **2.17 ton×yr**

S_m integrated in the range (2 - 6) keV for each of the 25 detectors (1σ error)

Shaded band = weighted averaged S_m ± 1σ

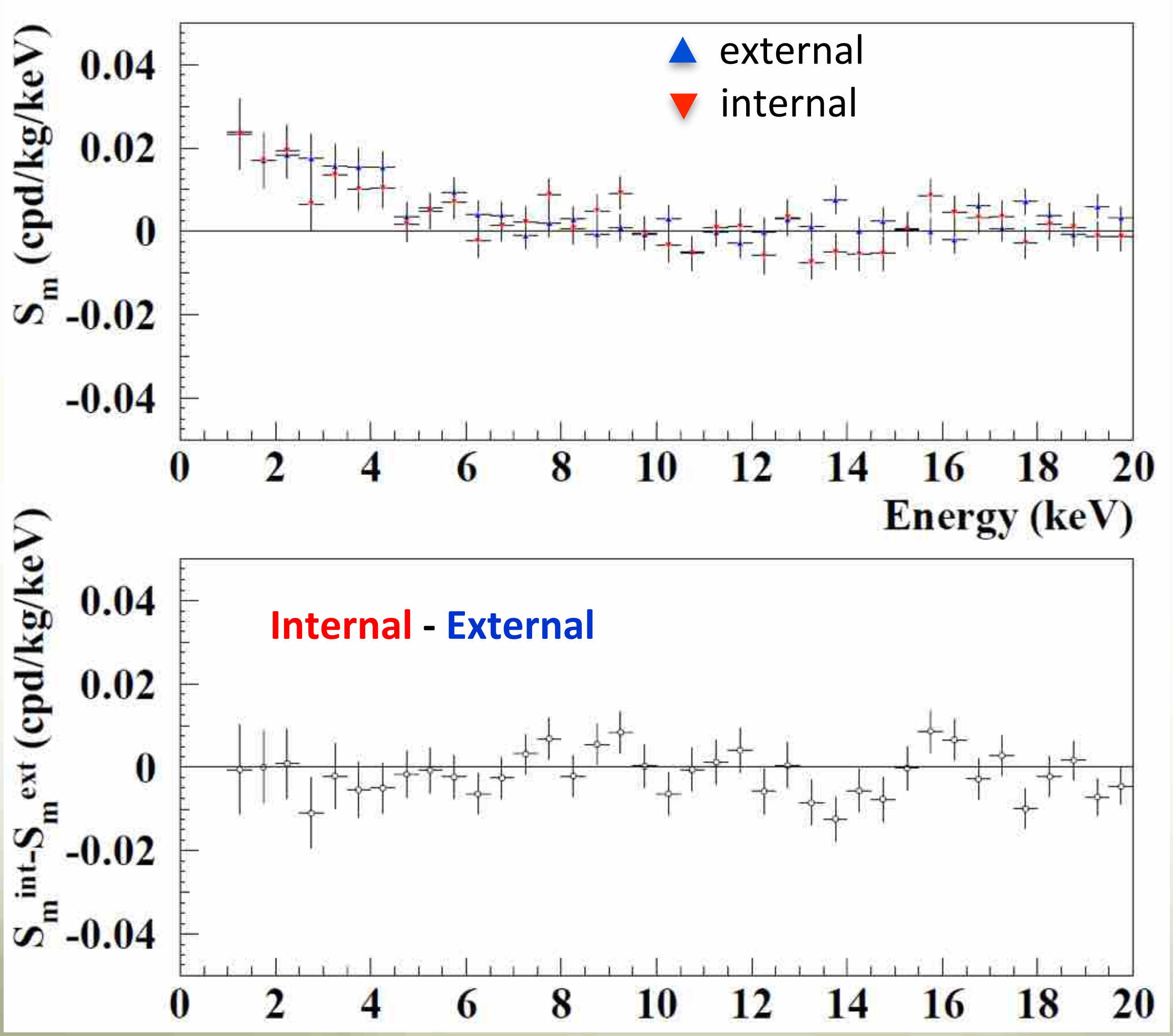
χ^2/dof = 23.9/24 d.o.f.

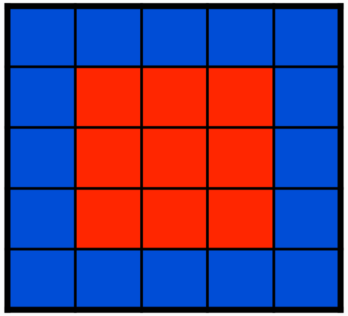
The signal is well distributed over all the 25 detectors.

External vs internal detectors:

DAMA/LIBRA-phase2

ΔE=0.5 keV





1-4 keV χ^2/dof =2.5/6

1-10 keV χ^2/dof =12.1/8

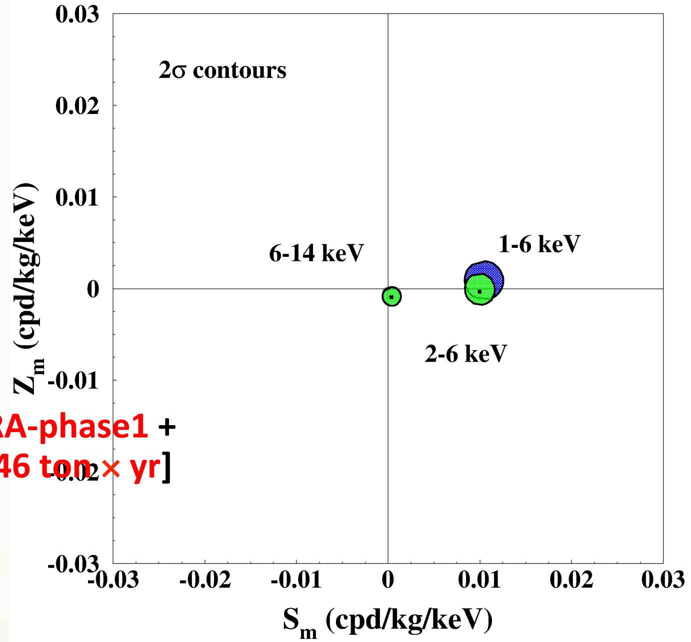
1-20 keV χ^2/dof =40.8/38

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

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

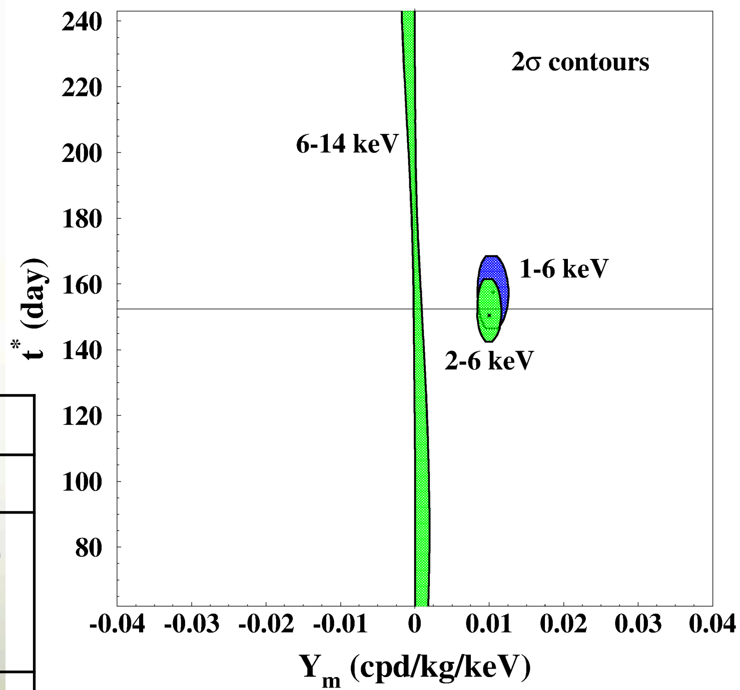
For Dark Matter signals:

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



DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 [2.46 ton × yr]

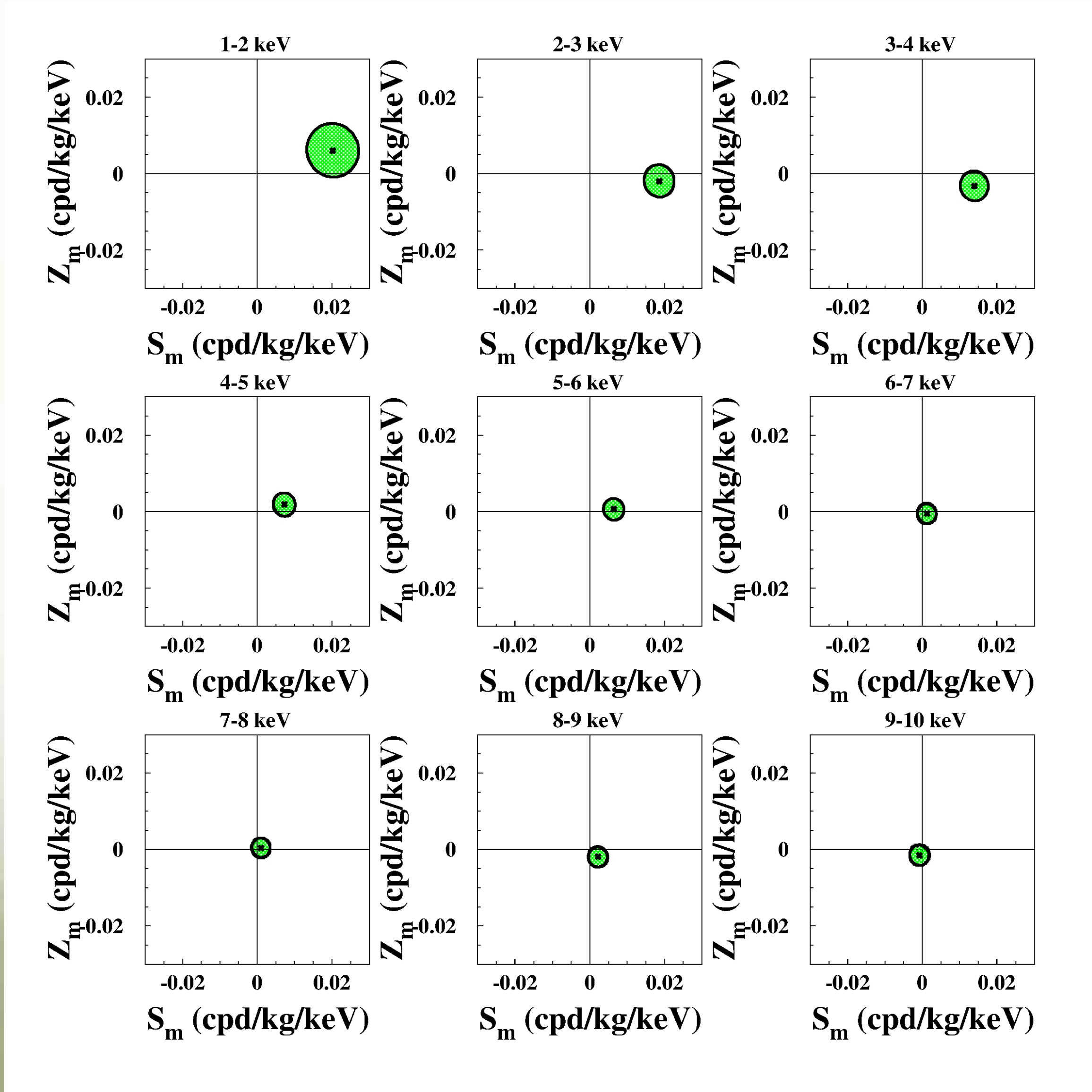
Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)



E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0100 ± 0.0008	- 0.0003 ± 0.0008	0.0100 ± 0.0008	150.5 ± 5.0
6-14	0.0003 ± 0.0005	-0.0009 ± 0.0006	0.0010 ± 0.0013	undefined
DAMA/LIBRA-ph2				
1-6	0.0105 ± 0.0011	0.0009 ± 0.0010	0.0105 ± 0.0011	157.5 ± 5.0

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

2σ contours



DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2

total exposure: 2.46 ton × yr

For Dark Matter induced signals:

$|Z_m| \ll |Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

$\omega = 2\pi/T$

$T = 1$ year

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

Phase vs energy

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

DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (**2.46 ton × yr**)

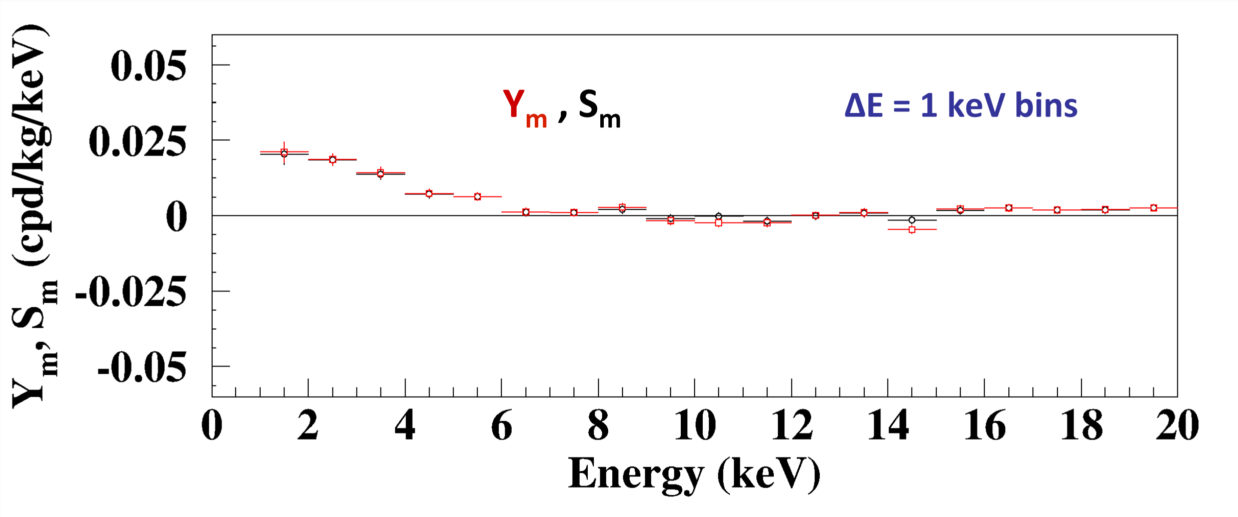
For DM signals:

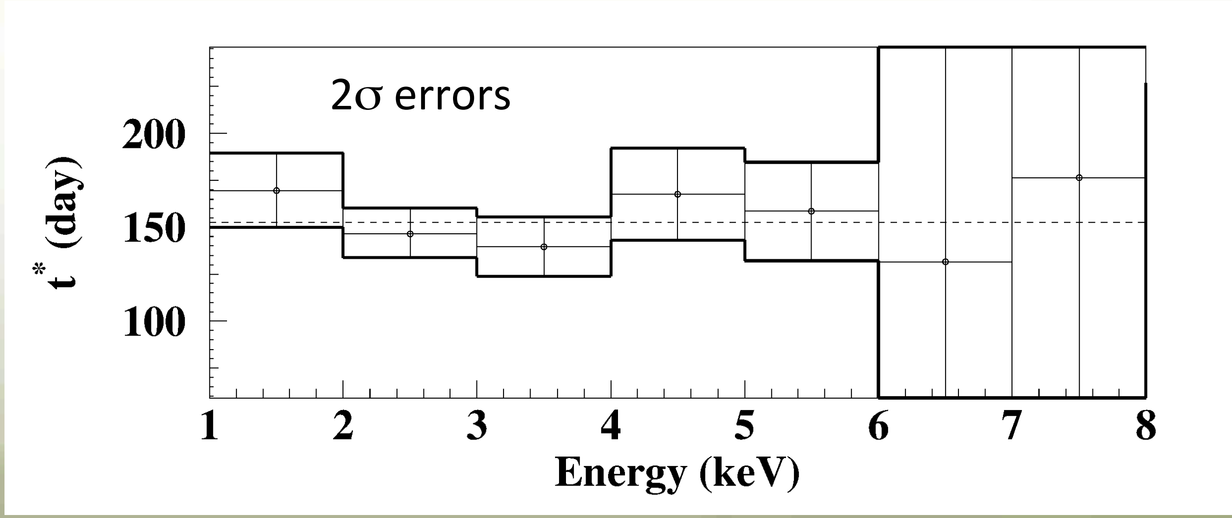
$|Y_m| \approx |S_m|$

$t^* \approx t_0 = 152.5d$

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

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





Stability parameters of DAMA/LIBRA–phase2

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 new running periods

	DAMA/LIBRA-phase2_2	DAMA/LIBRA-phase2_3	DAMA/LIBRA-phase2_4	DAMA/LIBRA-phase2_5	DAMA/LIBRA-phase2_6	DAMA/LIBRA-phase2_7
Temperature (°C)	(0.0012 ± 0.0051)	-(0.0002 ± 0.0049)	-(0.0003 ± 0.0031)	(0.0009 ± 0.0050)	(0.0018 ± 0.0036)	-(0.0006 ± 0.0035)
Flux N_2 (l/h)	-(0.15 ± 0.18)	-(0.02 ± 0.22)	-(0.02 ± 0.12)	-(0.02 ± 0.14)	-(0.01 ± 0.10)	-(0.01 ± 0.16)
Pressure (mbar)	$(1.1 \pm 0.9)\times10^{-3}$	(0.2 ± 1.1))$\times10^{-3}$	$(2.4 \pm 5.4)\times10^{-3}$	$(0.6 \pm 6.2)\times10^{-3}$	$(1.5 \pm 6.3)\times10^{-3}$	$(7.2 \pm 8.6)\times10^{-3}$
Radon (Bq/m^3)	(0.015 ± 0.034)	-(0.002 ± 0.050)	-(0.009 ± 0.028)	-(0.044 ± 0.050)	(0.082 ± 0.086)	(0.06 ± 0.11)
Hardware rate above single ph.e. (Hz)	$-(0.12 \pm 0.16)\times10^{-2}$	$(0.00 \pm 0.12)\times10^{-2}$	$-(0.14 \pm 0.22)\times10^{-2}$	$-(0.05 \pm 0.22)\times10^{-2}$	$-(0.06 \pm 0.16)\times10^{-2}$	$-(0.08 \pm 0.17)\times10^{-2}$

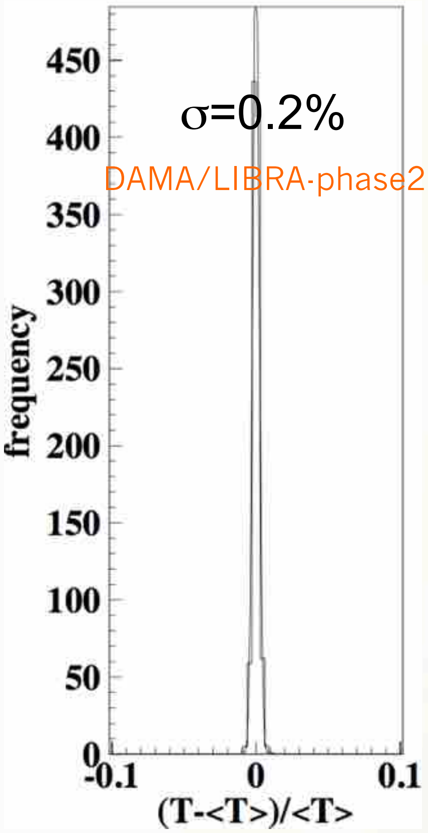
All the measured amplitudes well compatible with zero
+ none can account for the observed effect
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

Temperature

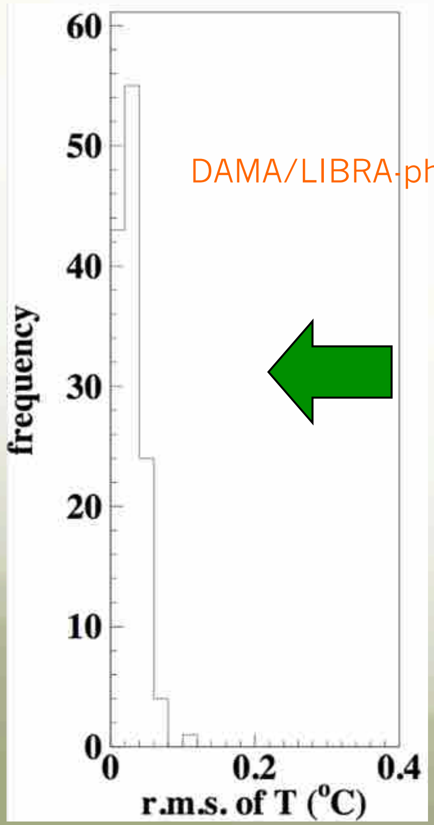
- **Detectors in Cu housings directly in contact with multi-ton shield →huge heat capacity (≈10^6 cal/^{0}C)**
- **Experimental installation continuosly air conditioned (2 independent systems for redundancy)**
- **Operating T of the detectors continuously controlled**

Amplitudes for annual modulation in the operating T of the detectors **well compatible with zero**

	T (°C)
DAMA/LIBRA-ph2_2	(0.0012 ± 0.0051)
DAMA/LIBRA-ph2_3	-(0.0002 ± 0.0049)
DAMA/LIBRA-ph2_4	-(0.0003 ± 0.0031)
DAMA/LIBRA-ph2_5	(0.0009 ± 0.0050)
DAMA/LIBRA-ph2_6	(0.0018 ± 0.0036)
DAMA/LIBRA-ph2_7	-(0.0006 ± 0.0035)



Distribution of the relative variations of the operating T of the detectors



Distribution of the root mean square values of the operating T within periods with the same calibration factors (typically ≈7days):

mean value ≈ 0.03°C

Considering the slope of the light output ≈ -0.2%/ °C: relative light output variation < 10^{-4} :

< 10^{-4} cpd/kg/keV (< 0.5% $S_m^{observed}$)

An effect from temperature can be excluded

+ Any possible modulation due to temperature would always fail some of the peculiarities of the signature

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

- neutrons,
- muons,
- solar neutrinos.

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

EPJC 74 (2014) 3196 (also EPJC 56 (2008) 333, EPJC 72 (2012) 2064,IJMPA 28 (2013) 1330022)

Modulation amplitudes

Source		$\Phi^{(n)}_{0,k}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)		$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2} - 10^{-1}$ eV)	1.08×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8 \times 10^{-6}$	[2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3 \times 10^{-3}$	[2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to$ n from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi^{(\mu)}_0 \simeq 20\ \mu$ m^{-2}d^{-1} [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}\ \nu$ cm^{-2}s^{-1} [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

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

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

+ In no case neutrons (of whatever origin) can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail, such as the neutrons would induce e.g. variations in all the energy spectrum, variation in the multiple hit events,... which were not observed.

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

NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196, IJMPA31(2017)issue31

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

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

Neutralino as LSP in various SUSY theories

Various kinds of WIMP candidates with several different kind of interactions Pure SI, pure SD, mixed + Migdal effect +channeling,... (from low to high mass)

a heavy ν of the 4-th family

Pseudoscalar, scalar or mixed light bosons with axion-like interactions

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

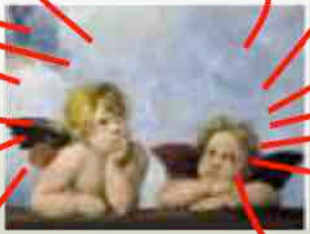
Self interacting Dark Matter

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

Sterile neutrino

heavy exotic canditates, as “4th family atoms”, ...

Elementary Black holes such as the Daemons



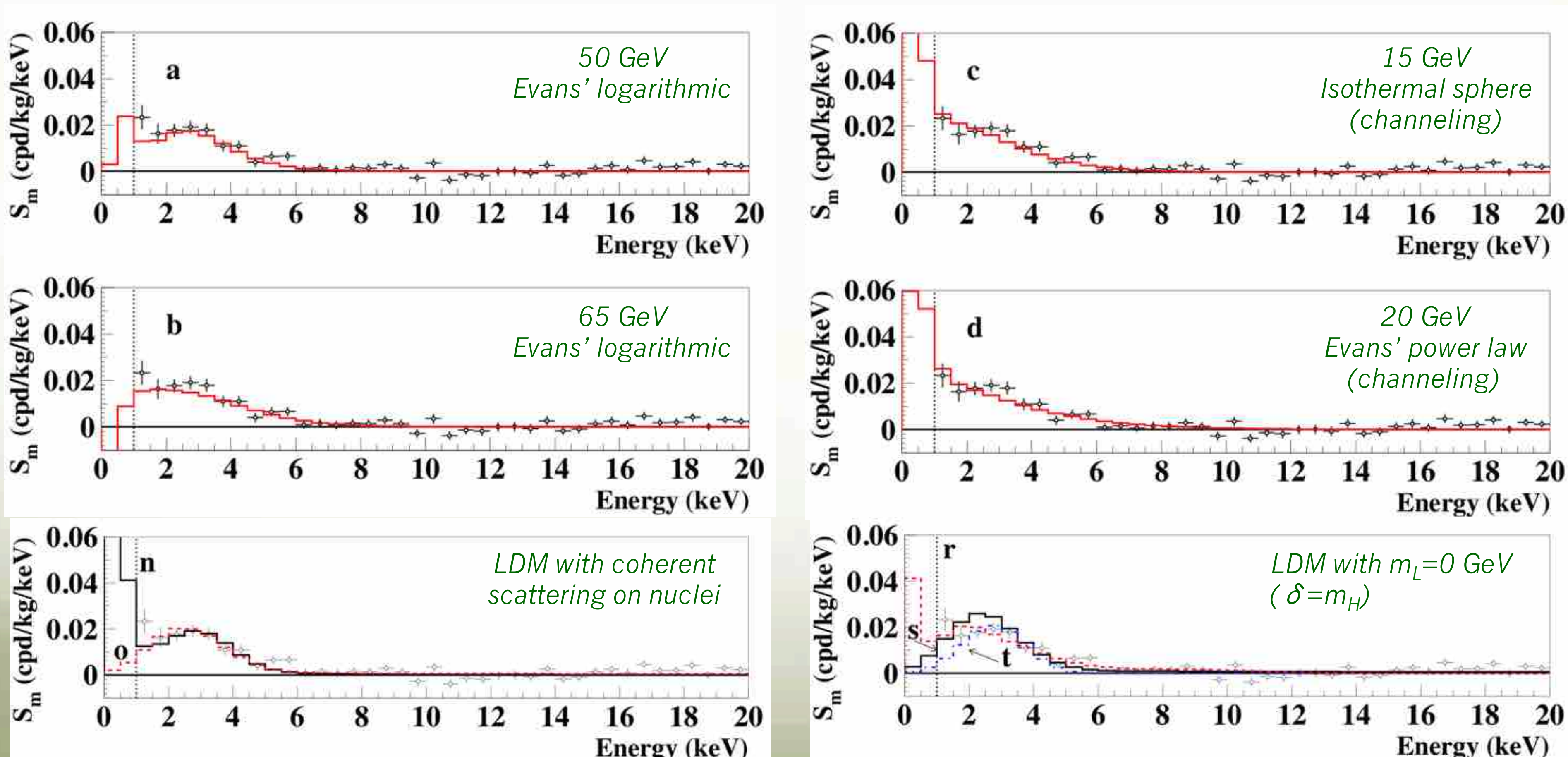
Kaluza Klein particles

... and more

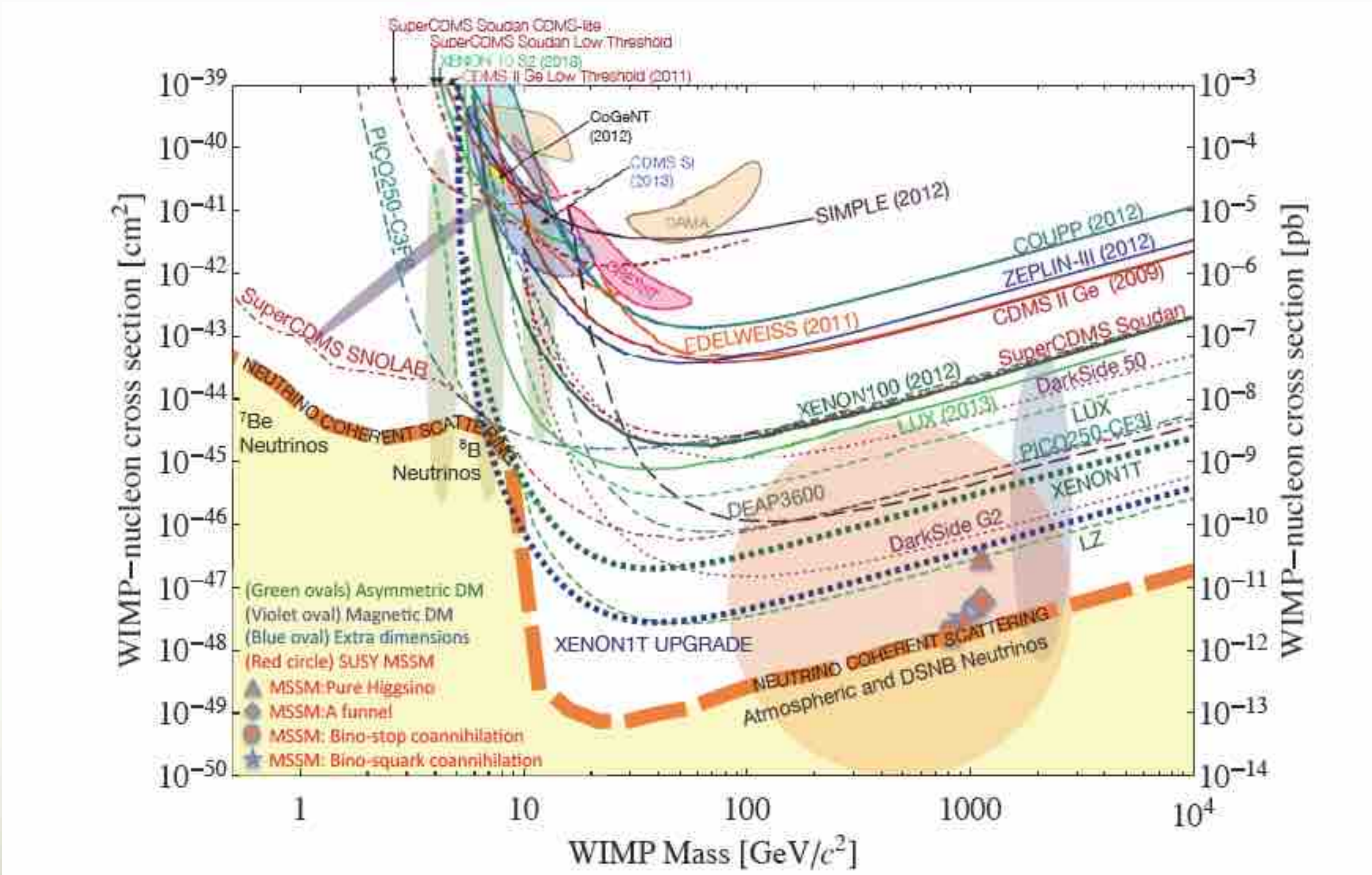
Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

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

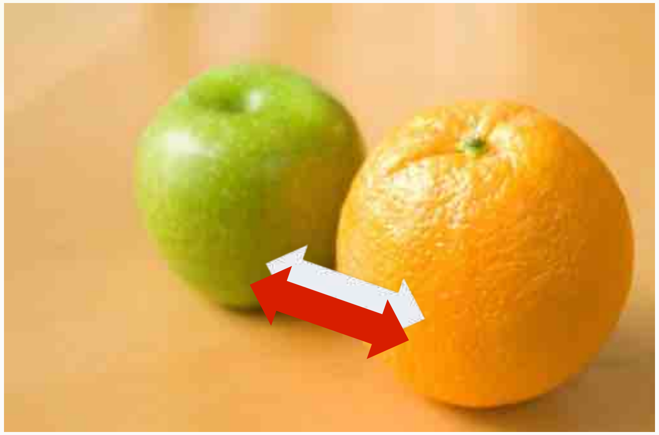
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios



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



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



About interpretations and comparisons

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…

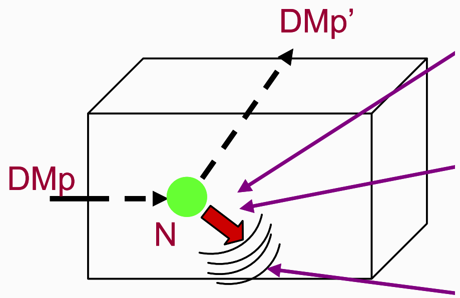
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities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

example…

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



Regions in the nucleon cross section vs DM particle mass plane

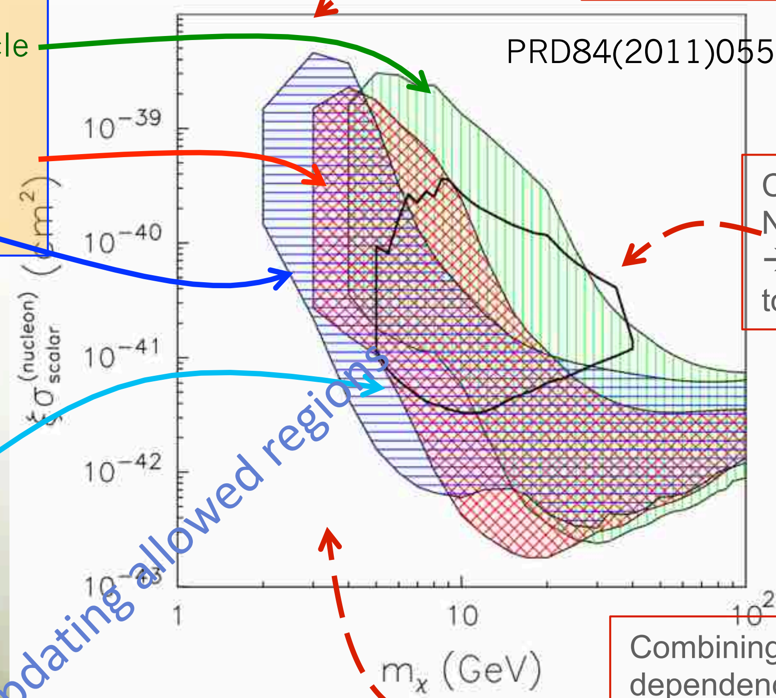
- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters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

Including the Migdal effect
→Towards lower mass/higher σ

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

7.5 σ C.L.

PRD84(2011)055014, IJMPA28(2013)1330022



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

CoGeNT; qf at fixed assumed value

1.64 σ C.L.

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

Other examples

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

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

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

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

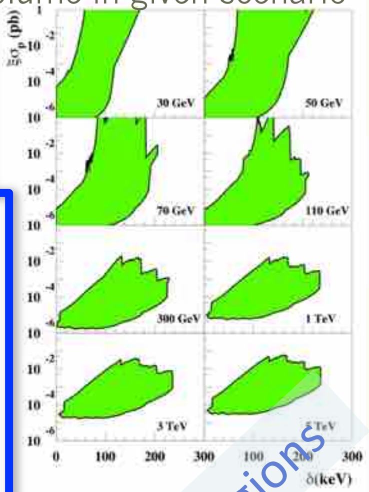
… and much more considering experimental and theoretical uncertainties

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

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

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

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



Fund. Phys. 40(2010)900

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

PRL106(2011)011301

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

Updating allowed regions

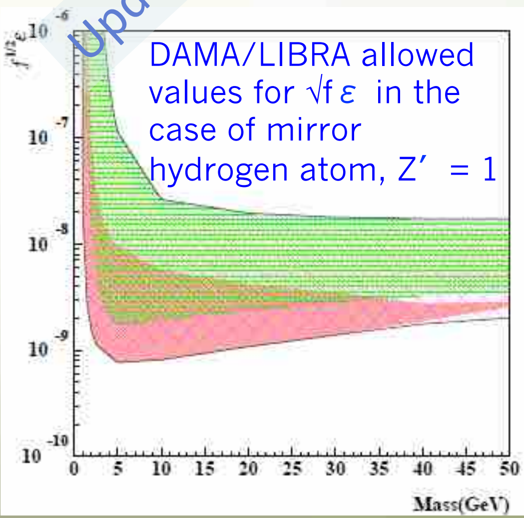
Mirror Dark Matter

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

(See EPJC75(2015)400)

- Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$
- mirror atom scattering of the ordinary target nuclei in the NaI(Tl) detectors of DAMA/LIBRA set-up with the Rutherford-like cross sections.

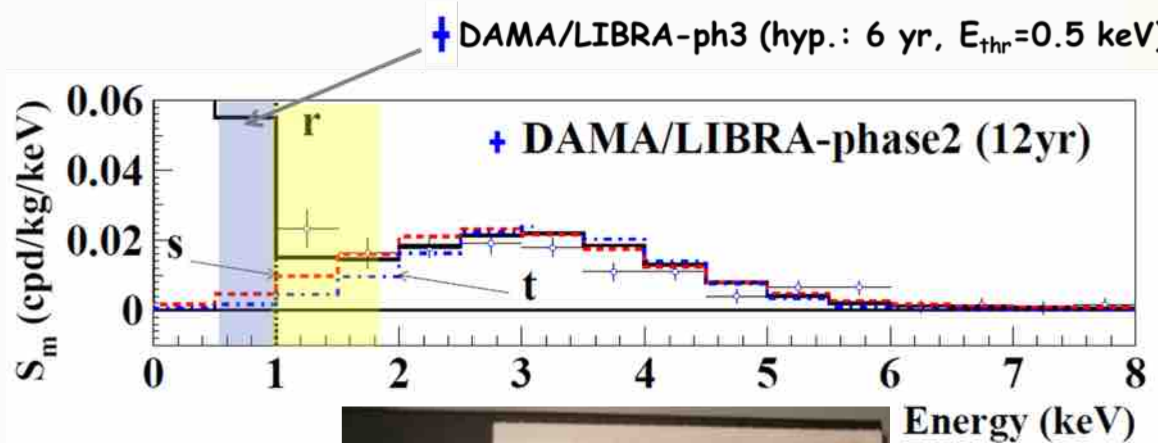
$\sqrt{f} \cdot \epsilon$ coupling const. and fraction of mirror atom



Running phase2 and towards future DAMA/LIBRA–phase3 with software energy threshold below 1 keV

Enhancing sensitivities for DM corollary aspects, other DM features, second order effects and other rare processes:

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



- R&D towards possible DAMA/LIBRA-phase3 continuing:
  1. new development of high Q.E. PMTs with increased radio-purity to directly couple them to the crystals.
  2. new protocols for possible modifications of the detectors;
  3. alternative strategies under investigation.
  4. **Other possible option**: new ULB crystal scintillators (e.g. $ZnWO_4$) placed in between the DAMA/LIBRA detectors to add also a high sensitivity directionality measurement.

The presently-reached metallic PMTs features:

- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- Radio-purity at level of 5 mBq/PMT (^{40}K), 3-4 mBq/PMT (^{232}Th), 3-4 mBq/PMT (^{238}U), 1 mBq/PMT (^{226}Ra), 2 mBq/PMT (^{60}Co).

4 prototypes from a dedicated R&D with HAMAMATSU at hand

Conclusions

- Model-independent positive evidence for the presence of DM particles in the galactic halo at **12.9σ** C.L. (20 independent annual cycles with 3 different set-ups: 2.46 ton × yr)
- Modulation parameters determined with increasing precision
- New investigations on different peculiarities of the DM signal exploited in progress
- Full sensitivity to many kinds of DM candidates and interactions types (both inducing recoils and/or e.m. radiation), **full sensitivity to low and high mass candidates**

- DAMA/LIBRA–phase2 **continuing data taking**
- DAMA/LIBRA–phase3 **R&D in progress**
- R&D for a possible DAMA/1ton - full sensitive mass - set-up, proposed to INFN by DAMA since 1996, **continuing at some extent** as well as **some other R&Ds**
- New corollary analyses **in progress**
- Continuing investigations of **rare processes** other than DM