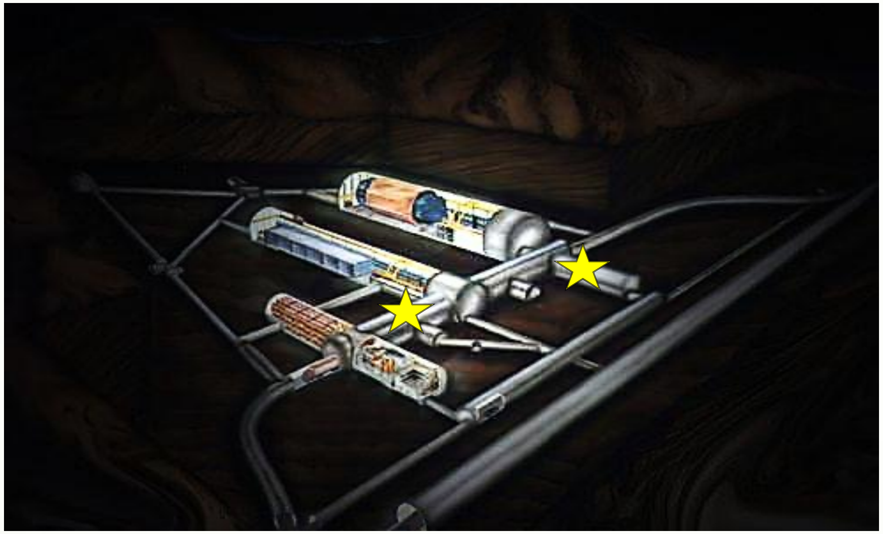
DAMA set-ups

an observatory for rare processes @ LNGS



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

Collaboration:

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

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

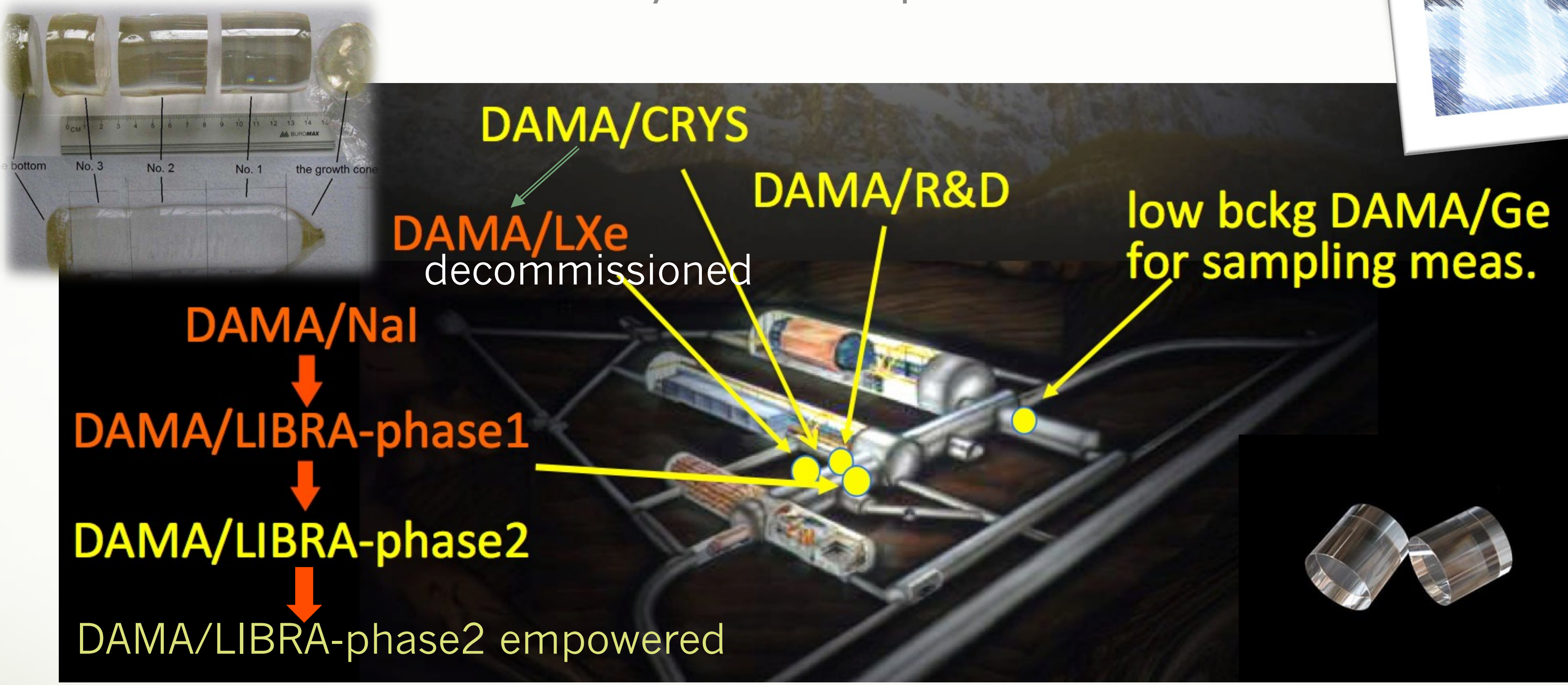
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

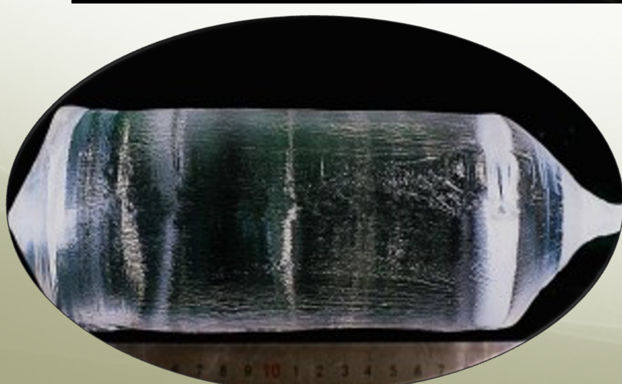
+ in some studies on ββ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

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

DAMA set-ups

an observatory for rare processes @ LNGS





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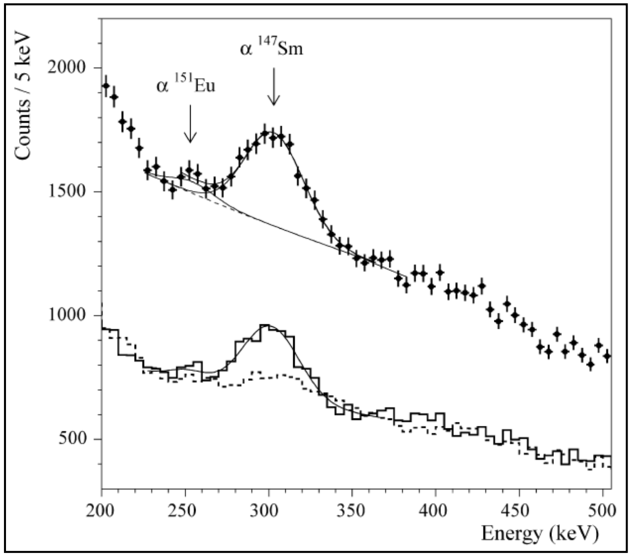
web site: https://dama.web.roma2.infn.it/

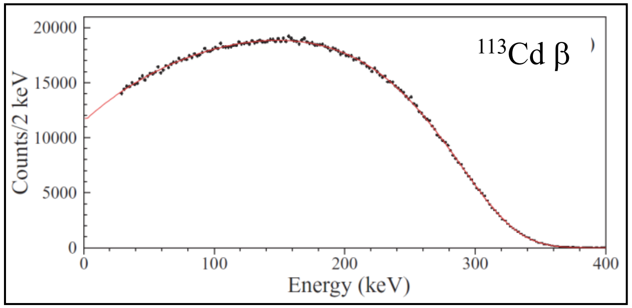
DAMA

- **Processo fisico studiato:**
  - Rivelazione di particelle candidate come materia oscura dell'Universo.
  - Ricerca di vari processi rari, quali:
    - decadimenti 2β in vari isotopi,
    - decadimenti nucleari rari,
    - instabilità nucleare in vari canali invisibili
    - possibili processi CNC,
    - ricerca assioni solari,
    - ricerca di nuclei superpesanti,
    - misure di elevata precisione di spettri di decadimento β rari come ^{113m}Cd ($\rightarrow g_A$ phenomenology),
    - ...
- **Apparato strumentale utilizzato:**
  - Sviluppo ed uso di scintillatori (alcuni dei quali di nuova concezione, altri arricchiti in isotopi vari, …) di basso fondo intrinseco, quali NaI(Tl), $ZnWO_4$, $CdWO_4$, $^{116}CdWO_4$, $^{106}CdWO_4$, LXe, LiF(W), LiI(Eu), $Li_6Eu(BO_3)_3$, $LaCl_3$(Ce), CeF_3, BaF_2, $BaWO_4$, $CeCl_3$, CaF_2(Eu), SrI_2(Eu), Cs_2HfCl_6 (CHC), Cs_2ZrCl_6 (CZC), etc.
  - uso dei setup a basso fondo (DAMA/R&D, DAMA/CRYS, …) o campioni purificati in HPGe

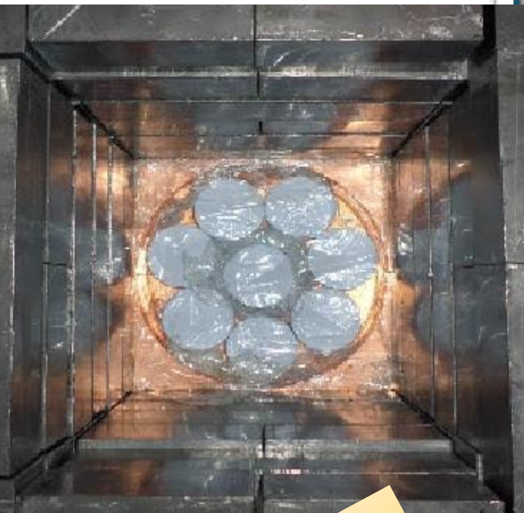
Main results obtained by DAMA in the search for rare processes

- 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
- The best experimental sensitivities in the field for 2β decays with positron emission
- First observation of α decays of ^{151}Eu ($T_{1/2}=5\times10^{18}$yr) with a CaF_2(Eu) scintillator and of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os ($T_{1/2}=3\times10^{14}$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 ($A_{e+e-}/A_\alpha \approx 5\times10^{-9}$)
- CNC processes in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La;
- Search for ^{7}Li solar axions using resonant absorption in LiF crystal
- Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state;
- Search for cluster decays of ^{127}I, ^{138}La and ^{139}La;
- Search for PEP violating processes in sodium and in iodine;
- Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

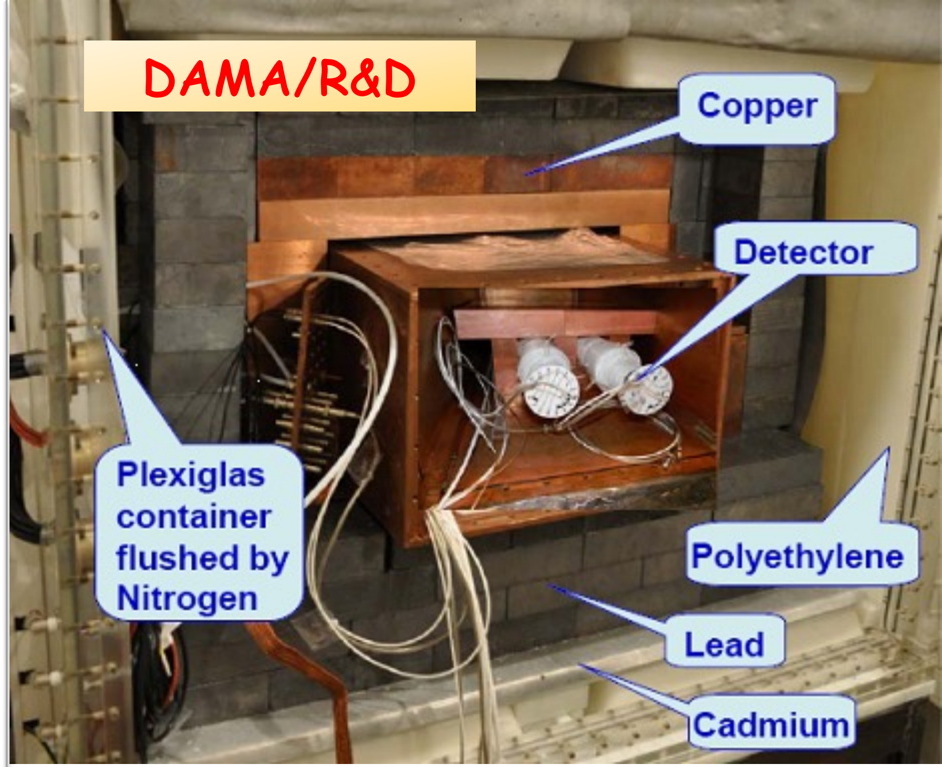


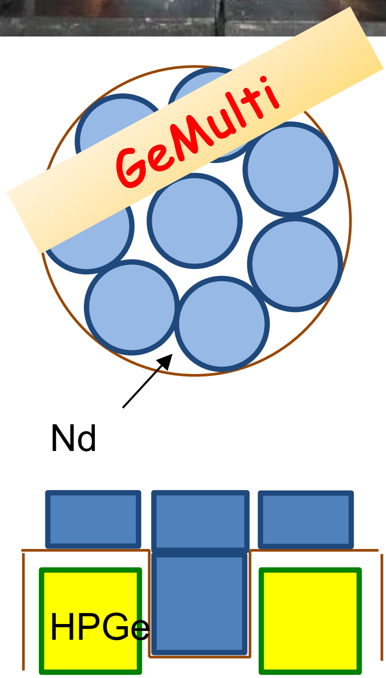


Many others are in progress




DAMA/GeBer

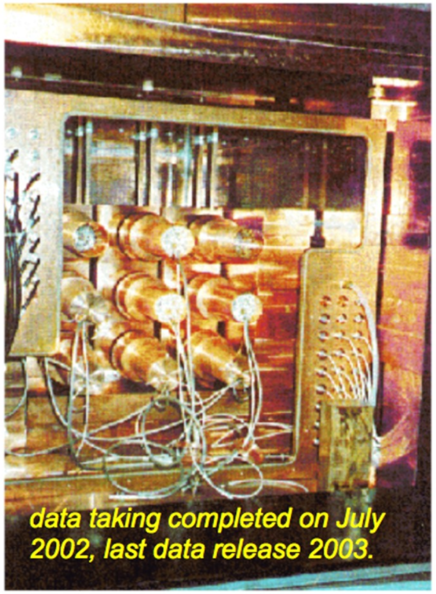

DAMA/R&D
Copper
Detector
Plexiglas container flushed by Nitrogen
Polyethylene
Lead
Cadmium


GeMulti
Nd
HPGe


DAMA/Ge and LNGS
STELLA facility


During mounting 116Cd
DAMA/CRYS

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 pioneer DAMA/NaI:

≈

Pe

Re

Re

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.

The pioneer DAMA/NaI:

≈

Pe

Re

Re

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

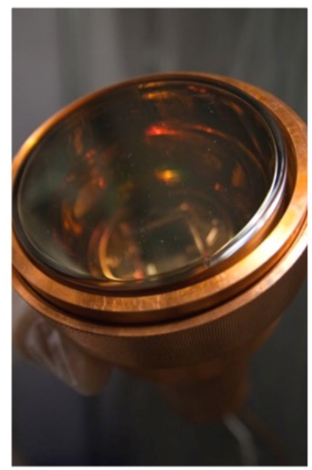
As a result of a 2nd generation R&D for more radiopure NaI(Tl) by

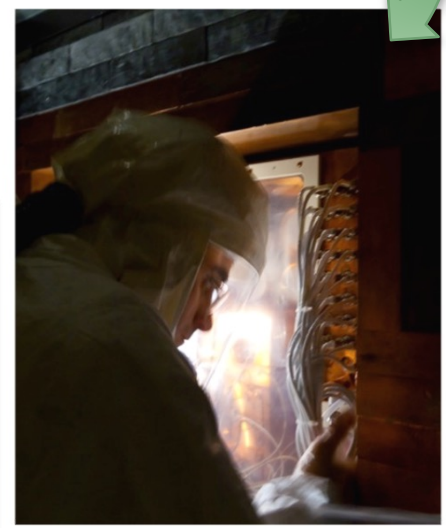
Residual c
DAMA/LIB
^{238}U and ^{40}

DAMA/LIBRA–phase2

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4)(2019)317
PPNP114(2020)103810

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

The pioneer DAMA/NaI:

≈

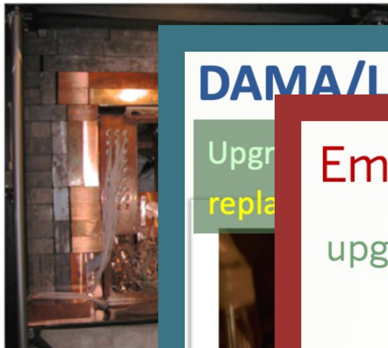
Pe

Re

Re

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

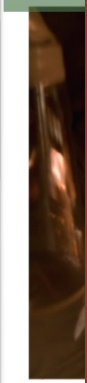


Residual c
DAMA/LIB
^{238}U and ^{40}

DAMA/LIBRA–phase2

JINST 7(2012)03009

Upgr
repla



Empowered DAMA/LIBRA–phase2

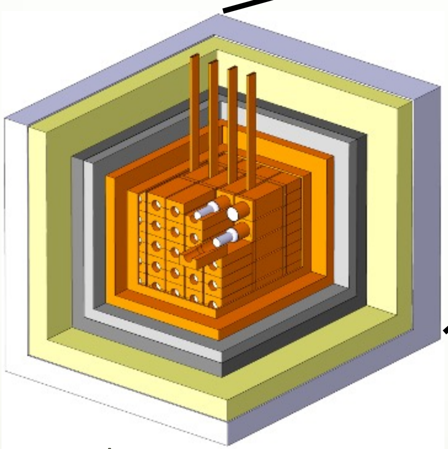
upgrade on fall 2021 to further decrease the software energy threshold

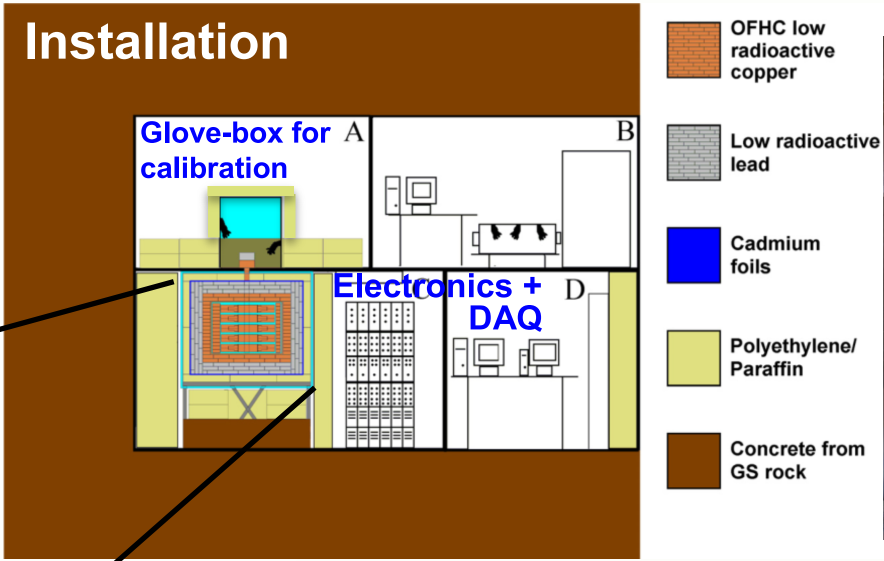
RUNNING

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; 2/1/0.5 keV software energy threshold**





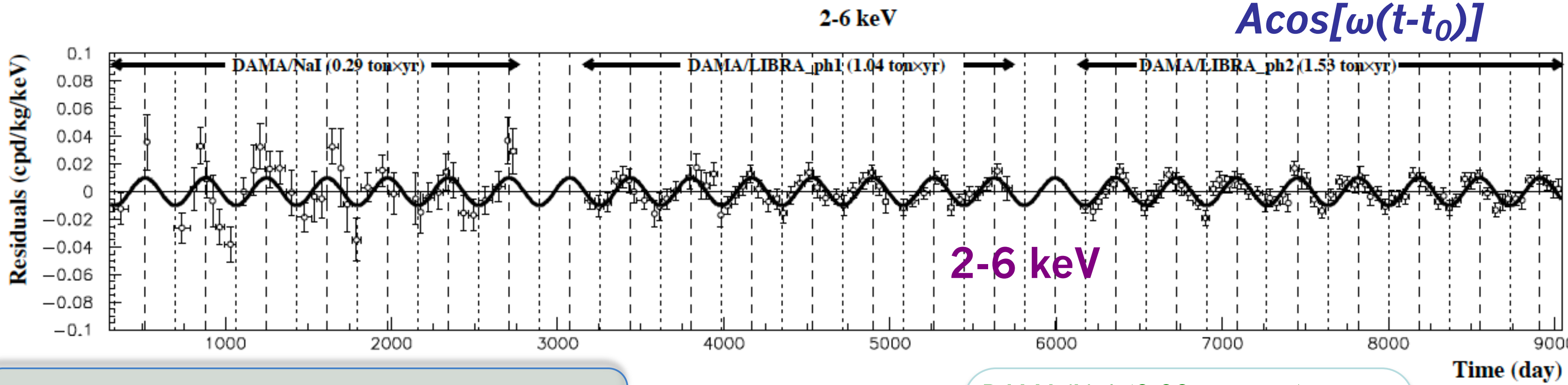
- Whole setup decoupled from ground
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- Dismounting/Installing protocol in HPN_2
- All the materials selected for low radioactivity

- 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

Model-independent Annual Modulation Result

DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr)



DAMA/NaI (0.29 ton x yr)
DAMA/LIBRA-ph1 (1.04 ton x yr)
DAMA/LIBRA-ph2 (1.53 ton x yr)

total exposure = 2.86 ton × yr

Absence of modulation? No

χ^2/dof=311/156 ⇒ P(A=0) =2.3×10^{-12}

continuous lines: t_0 = 152.5 d, T = 1.00 y

A=(0.00996±0.00074) cpd/kg/keV

χ^2/dof = 130/155 **13.4 σ C.L.**

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

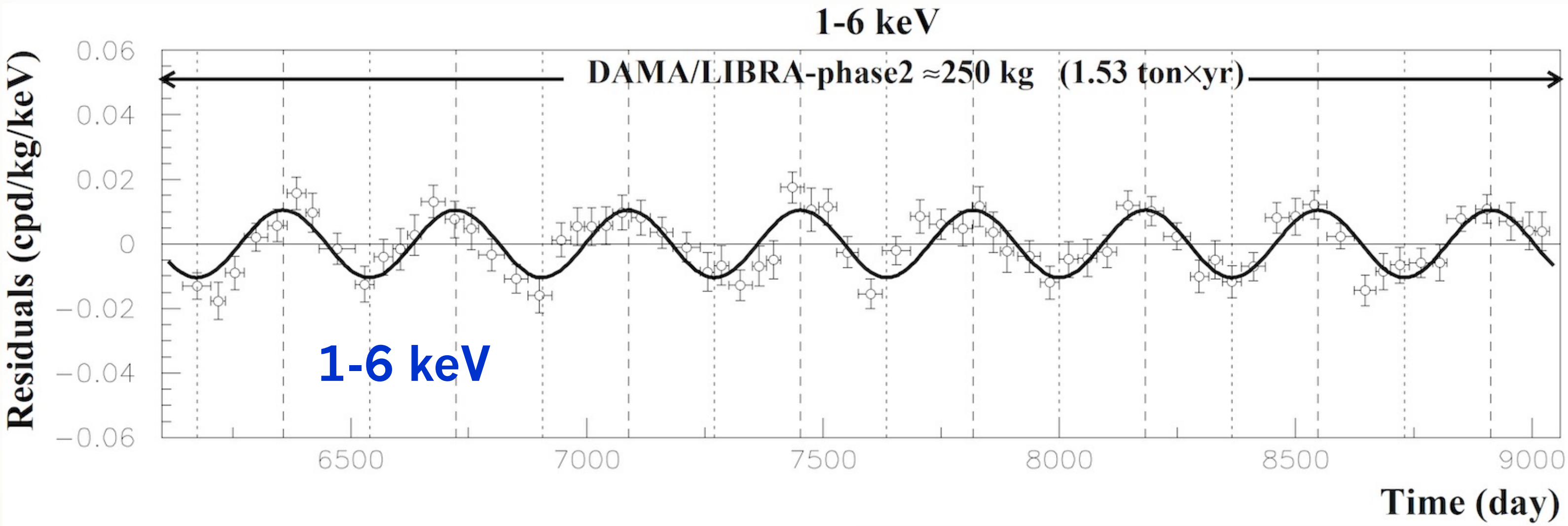
	ΔE	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0191±0.0020	0.99952±0.00080	149.6±5.9	9.6σ
	(1-6) keV	0.01058±0.00090	0.99882±0.00065	144.5±5.1	11.8σ
	(2-6) keV	0.00954±0.00076	0.99836±0.00075	141.1±5.9	12.6σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.00959±0.00076	0.99835±0.00069	142.0±4.5	12.6σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.01014±0.00074	0.99834±0.00067	142.4±4.2	13.7σ

The data of DAMA/NaI + DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favour the presence of a modulated behaviour with proper features at 13.7 σ C.L.

DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (1.53 ton × yr)

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



Absence of modulation? No

χ^2/dof = 202/69 (1-6 keV)

Fit on DAMA/LIBRA-phase2

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

1-6 keV

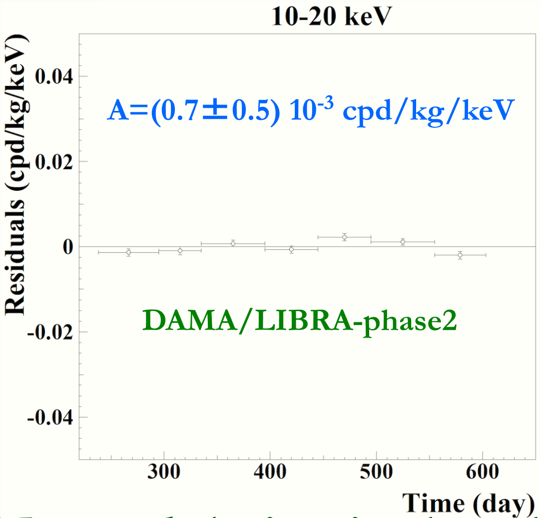
A=(0.01048±0.00090) cpd/kg/keV

χ^2/dof = 66.2/68 **11.6 σ C.L.**

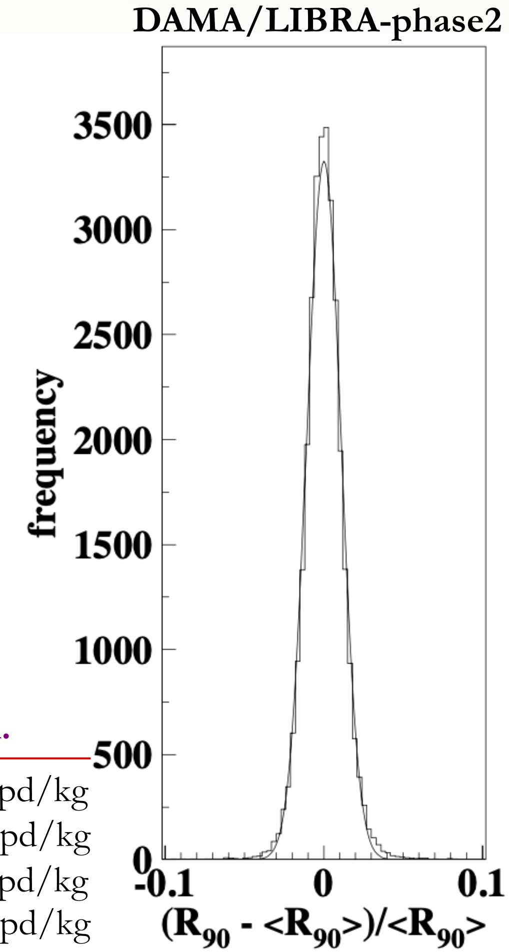
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 11.6σ C.L.

Examples of consistency: 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
-(0.0005 ± 0.0013) DAMA/LIBRA-ph2_8
-(0.0003 ± 0.0014) DAMA/LIBRA-ph2_9
→ 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:

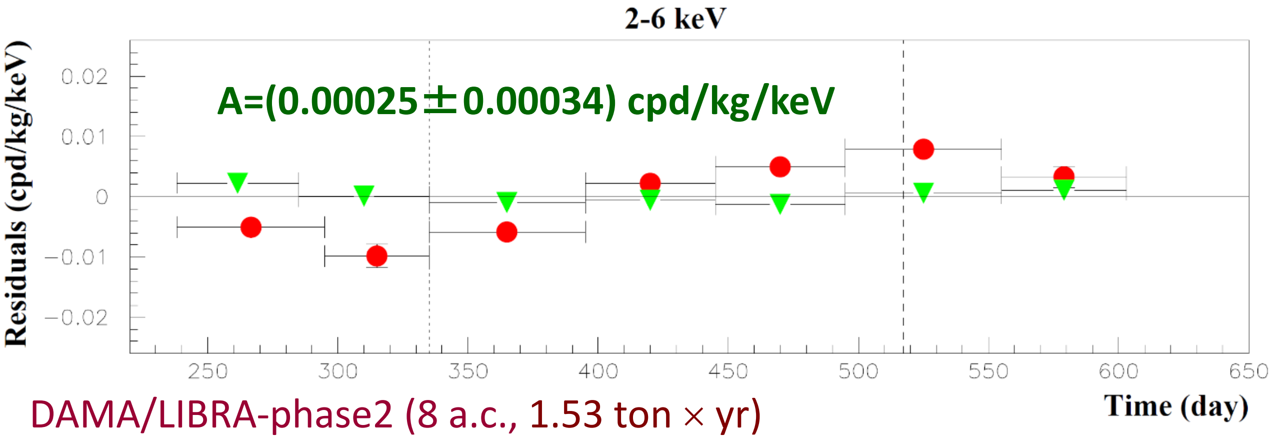
consistent with zero

+ 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
DAMA/LIBRA-ph2_8	-(0.18±0.13) cpd/kg
DAMA/LIBRA-ph2_9	(0.08±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

Model-independent Annual Modulation Result



DAMA/LIBRA-phase2 (8 a.c., 1.53 ton × yr)

Multiple hits events = Dark Matter particle "switched off"

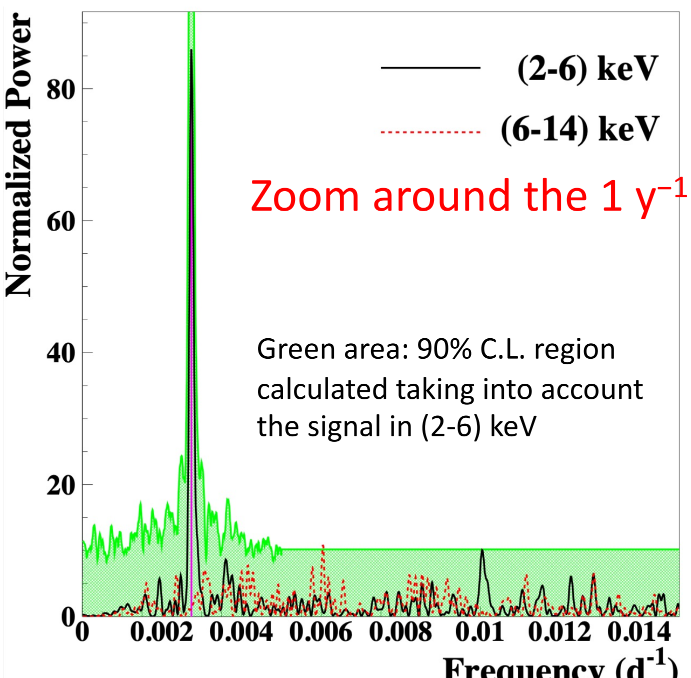
MG16 July 2021, arXiv:2110.04734, to appear on NPAE

Comparison between **single hit residual rate (red)** and **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



DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (22 yr)
total exposure: 2.86 ton×yr

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

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

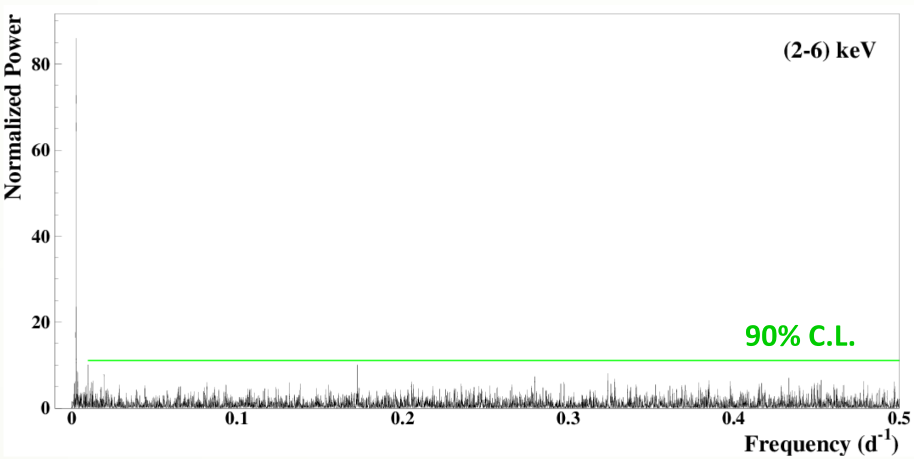
The data of DAMA/NaI + DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favour the presence of a modulated behaviour with proper features at 13.7 σ C.L.

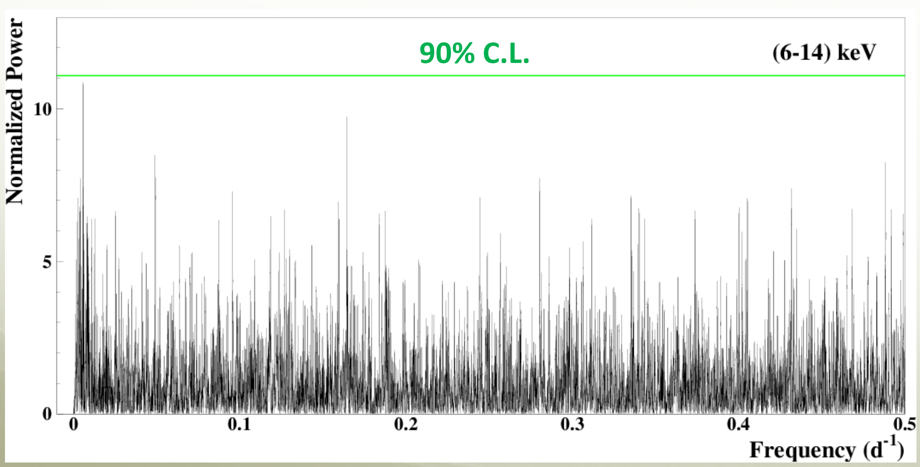
The analysis in frequency

(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

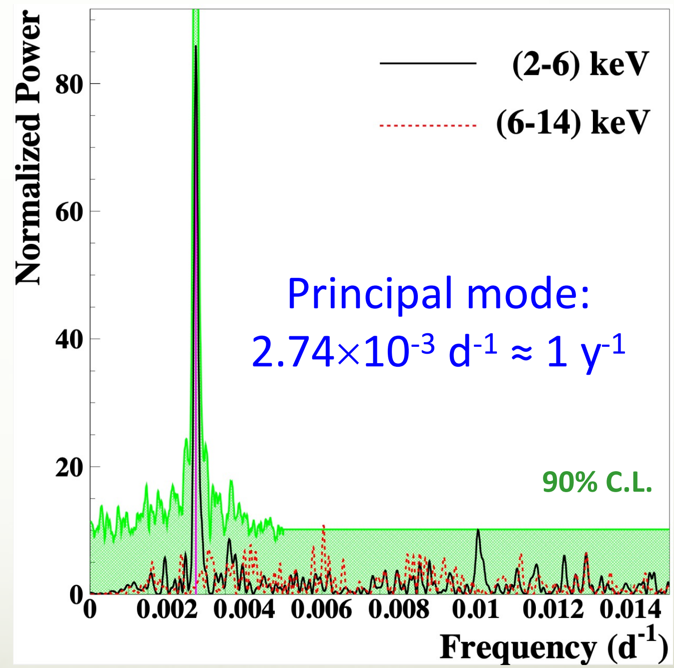
The whole power spectra up to the Nyquist frequency





DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (22 yr)
total exposure: 2.86 ton×yr

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

Modulation amplitudes S_m as function of the energy

The likelihood function of the *single-hit* scintillation events in the *k-th* energy bin is defined as:

$$L_k = \prod_{ij} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!}$$

N_{ijk} is the number of events collected in the *i-th* time interval, by the *j-th* detector and in the *k-th* energy bin.

N_{ijk} follows a Poissonian distribution with expectation value:

$$\mu_{ijk} = \left[b_{jk} + R_k(t)\right] M_j \Delta t_i \Delta E \varepsilon_{jk} = \left[b_{jk} + S_{0,k} + S_{m,k} \cos\omega(t_i - t_0)\right] M_j \Delta t_i \Delta E \varepsilon_{jk}$$

The b_{jk} are the background contributions, M_j is the mass of the *j-th* detector, Δt_i is the detector running time during the *i-th* time interval, ΔE is the chosen energy bin, ε_{jk} is the overall efficiency.

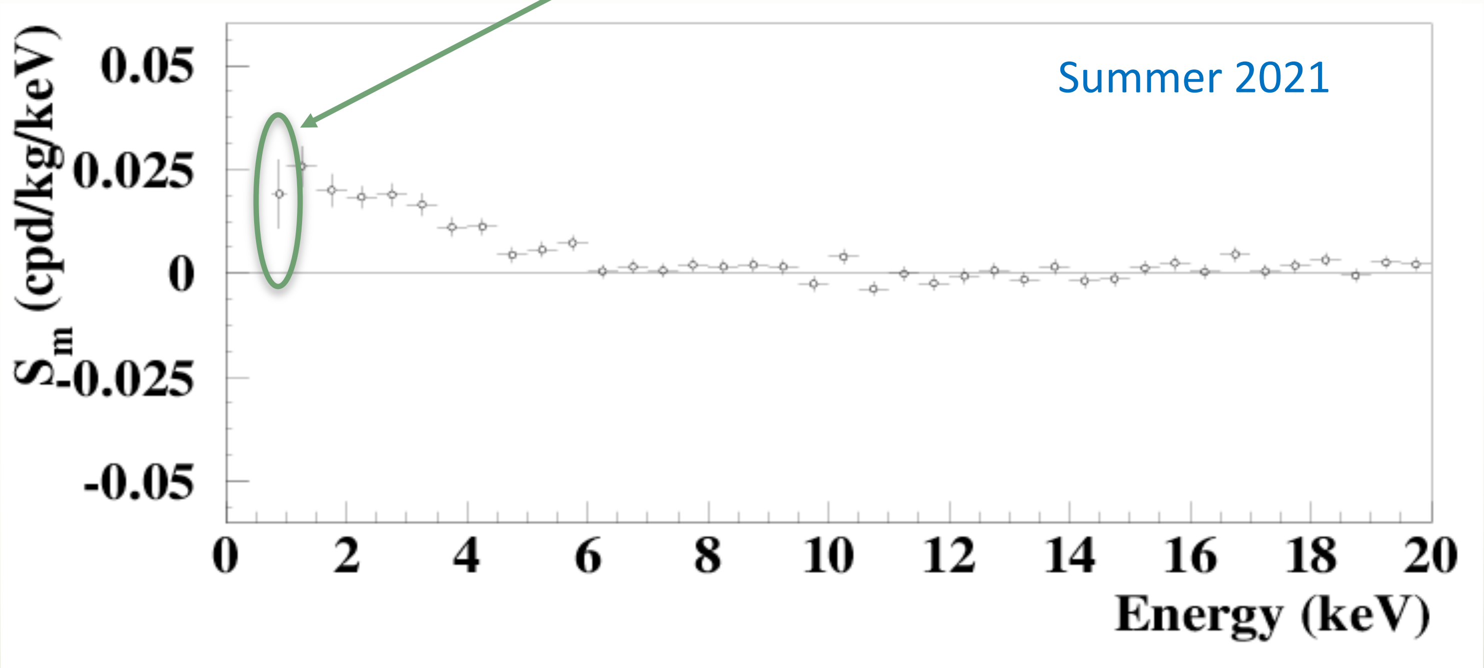
The usual procedure is to minimize the function $y_k=-2ln(L_k) - const$ for each energy bin; the free parameters of the fit are the $(b_{jk} + S_{0,k})$ contributions and the $S_{m,k}$ parameter.

The $S_{m,k}$ is the modulation amplitude of the modulated part of the signal obtained by maximum likelihood method over the data considering $T=2\pi/\omega=1$ yr and $t_0= 152.5$ day.

Efforts towards lower software energy threshold (Summer 2021)

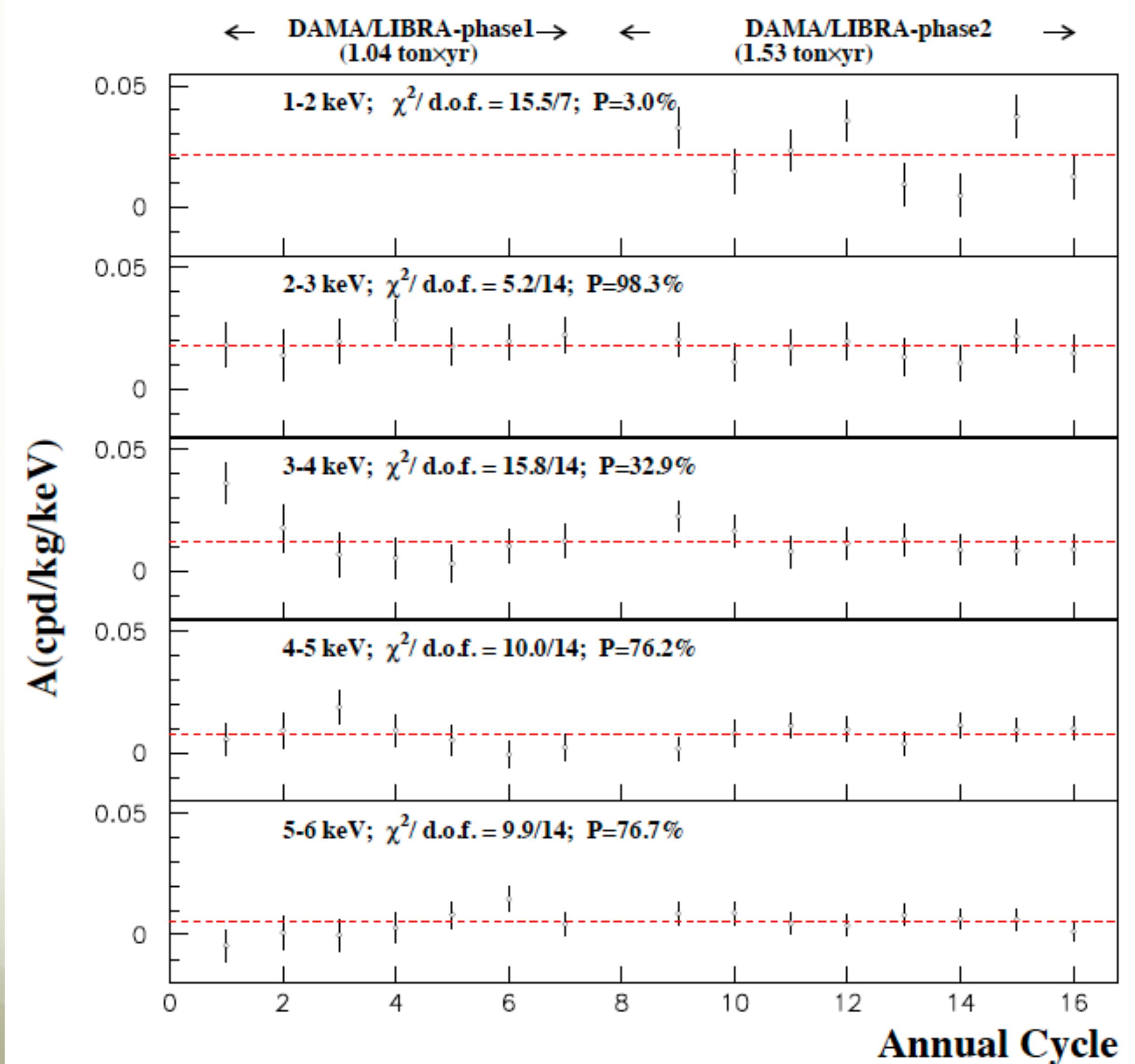
- decreasing the software energy threshold down to 0.75 keV
- using the same technique to remove the noise pulses
- evaluating the efficiency by dedicated studies

New data point with the 8 a.c. of **DAMA/LIBRA-phase2** **(1.53 ton × yr)**



- ❑ A clear modulation is also present below 1 keV, from 0.75 keV, while S_m values compatible with zero are present just above 6 keV
- ❑ This preliminary result suggested the necessity to lower the software energy threshold and to improve the experimental error on the first energy bin

S_m for each annual cycle

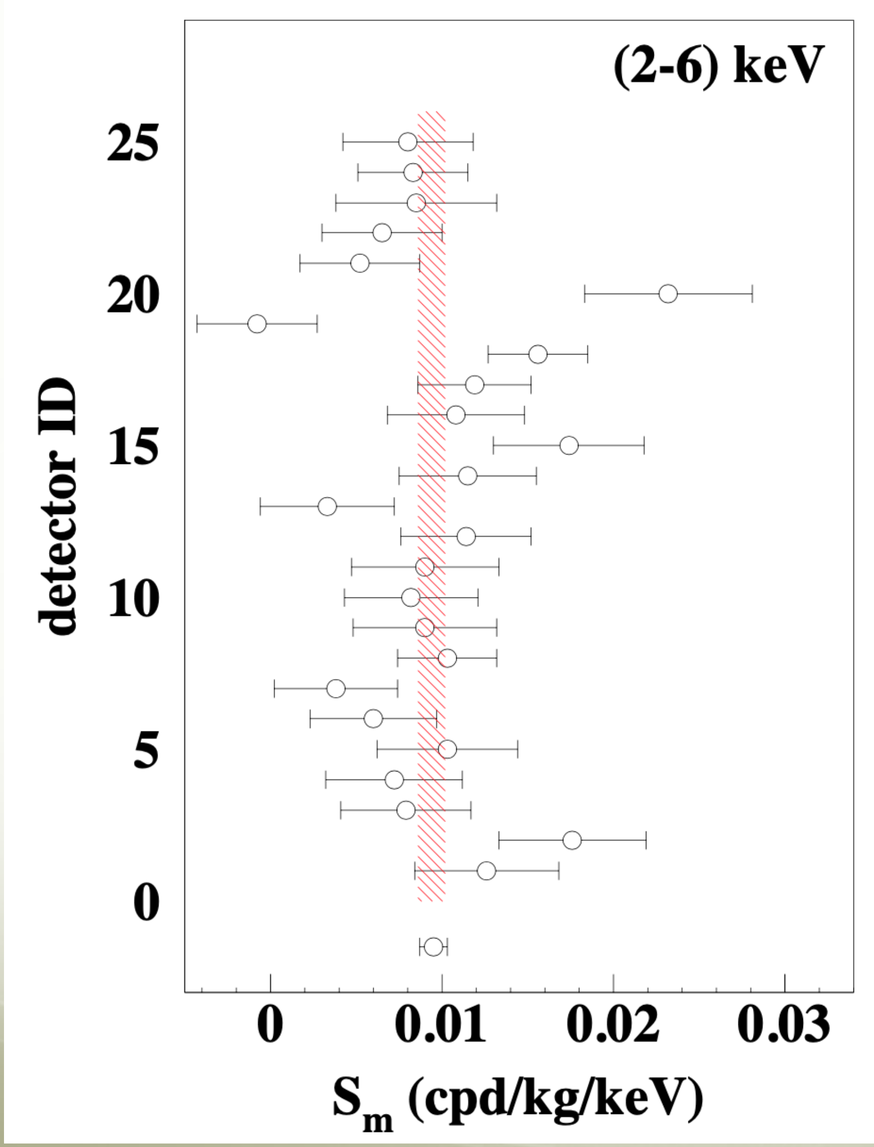


DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2
total exposure: **2.57 ton×yr**

Energy bin (keV)	run test probability	
	Lower	Upper
1-2	89%	37%
2-3	87%	30%
3-4	17%	94%
4-5	17%	94%
5-6	30%	85%

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: **2.57 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

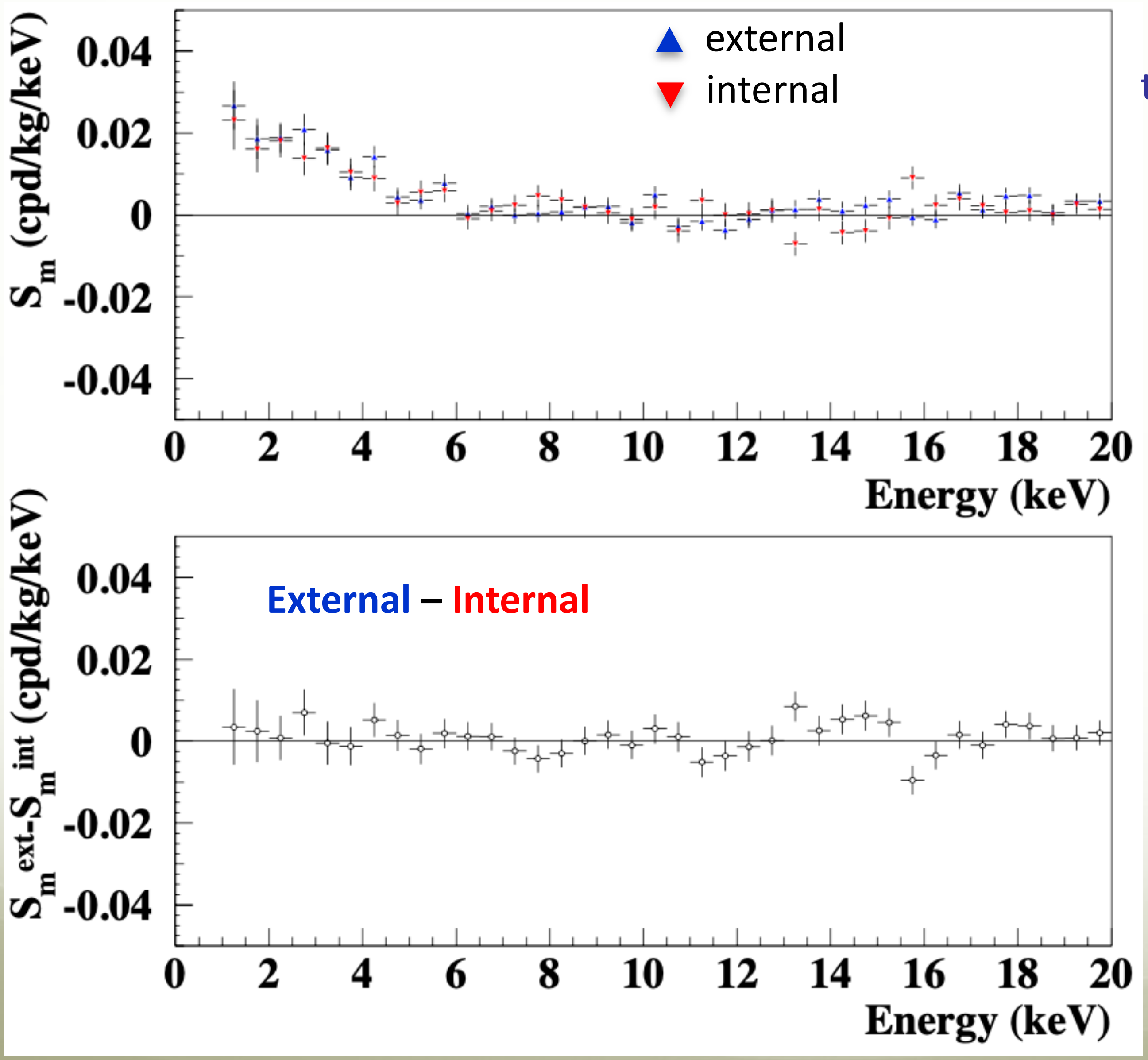
- χ^2/dof = 38.2/24 d.o.f. (P=3.3%)
- removing C19 and C20: χ^2/dof = 22.1/22 d.o.f.

The signal is rather well distributed over all the 25 detectors.

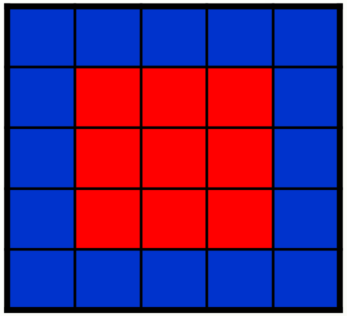
External vs internal detectors:

DAMA/LIBRA-phase1, -phase2 (8.a.c.)

ΔE=0.5 keV



total exposure: **2.57 ton×yr**



1-4 keV χ^2/dof =1.9/6

1-10 keV χ^2/dof =7.6/18

1-20 keV χ^2/dof =36.1/38

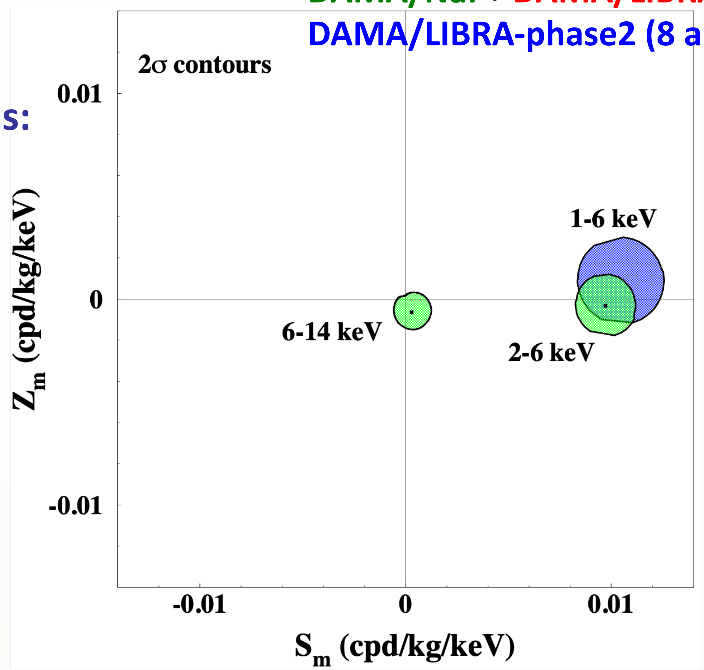
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

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

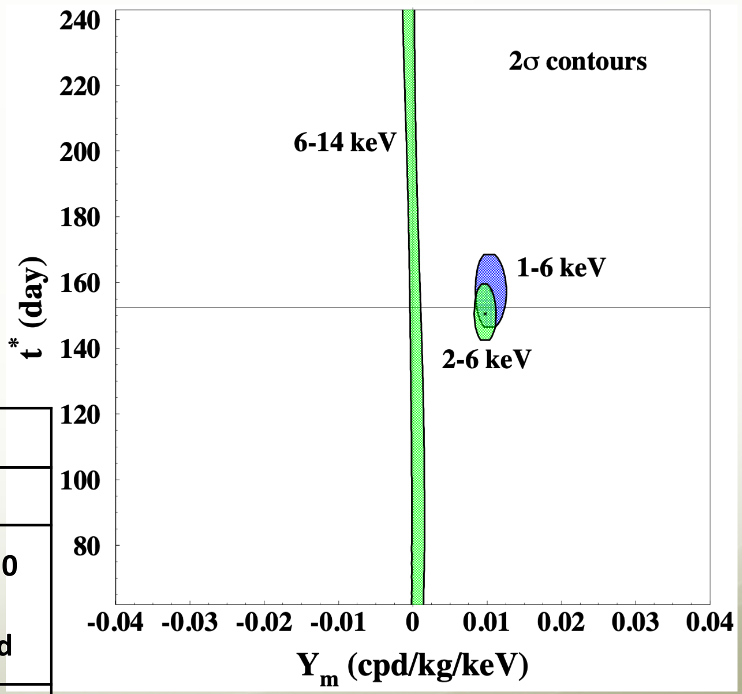
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton × yr]

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



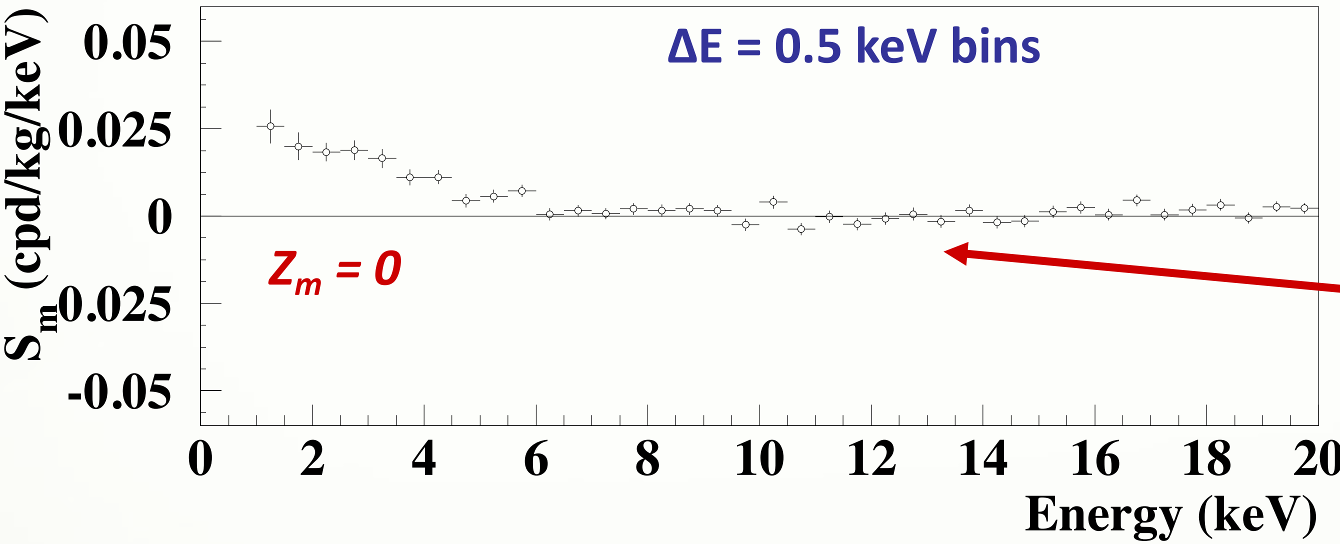
E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0097 ± 0.0007	- 0.0003 ± 0.0007	0.0097 ± 0.0007	150.5 ± 4.0
6-14	0.0003 ± 0.0005	-0.0006 ± 0.0005	0.0007 ± 0.0010	undefined
1-6	0.0104 ± 0.0007	0.0002 ± 0.0007	0.0104 ± 0.0007	153.5 ± 4.0

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

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

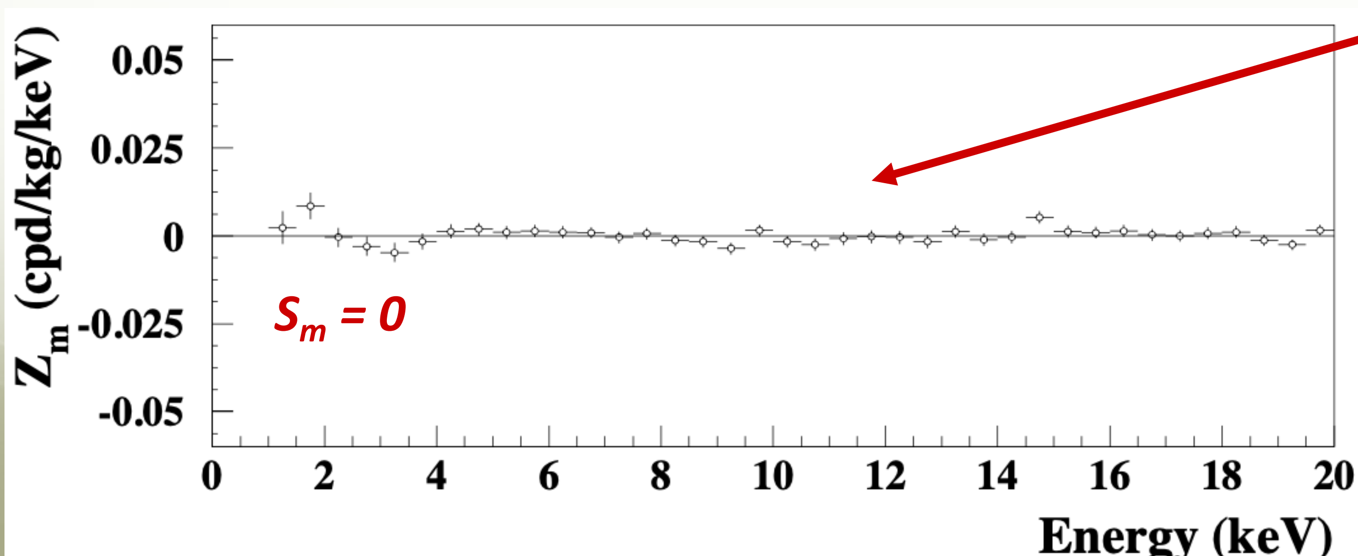
t_0 = *152.5 day* (2^{nd} June)

DAMA/NaI +
DAMA/LIBRA-phase1 +
DAMA/LIBRA-phase2 (8 a.c.)
(2.86 ton × yr)



maximum at 2^{nd} June as for DM particles

maximum at 1^{st} September, that is *T/4* days after 2^{nd} June



The χ^2 test in (1-20) keV energy region (χ^2/dof = 40.6/38 probability of 36%) supports the hypothesis that the Z_m values are simply fluctuating around zero.

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, Universe4(2018)116, Bled19(2018)27, NPAE19(2018)307, PPNP114(2020)103810

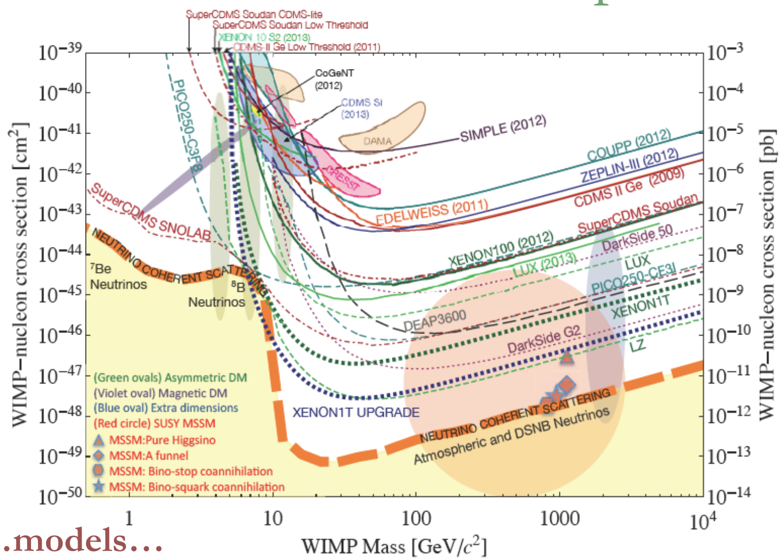
Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<10^{-4} cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**<10^{-4} cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**<1-2 ×10^{-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	**<3×10^{-5} cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

About interpretation: is an "universal" and "correct" way to approach the problem of DM 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, NPAE20(4) (2019)317, PPNP114(2020) 103810



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

…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?
- ...

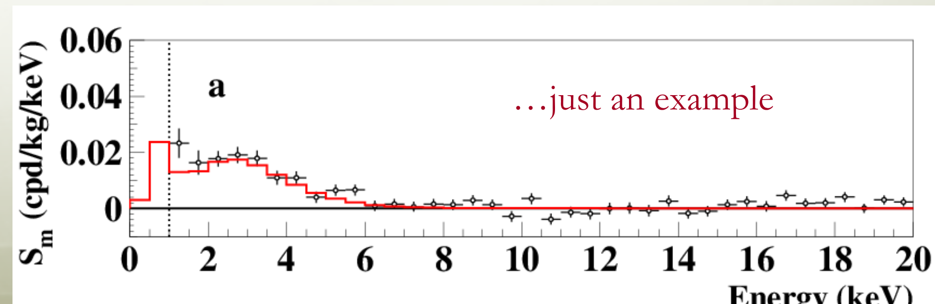
…and experimental aspects…

- Exposures
- Energy threshold
- Calibrations
- Stability of all the operating conditions.
- **Rate and its stability in ann mod**
- Efficiencies
- Detector response (phe/keV)
- Energy scale and energy resolution
- Selections of detectors and of data.
- Definition of fiducial volume and non-uniformity
- Subtraction/rejection procedures and stability in time of all the selected windows
- **Quenching factors, channeling**
- …

Example: 2 keVee of DAMA ≠2 keVee of COSINE-100 for nuclear recoils

No direct model-independent comparison is possible

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

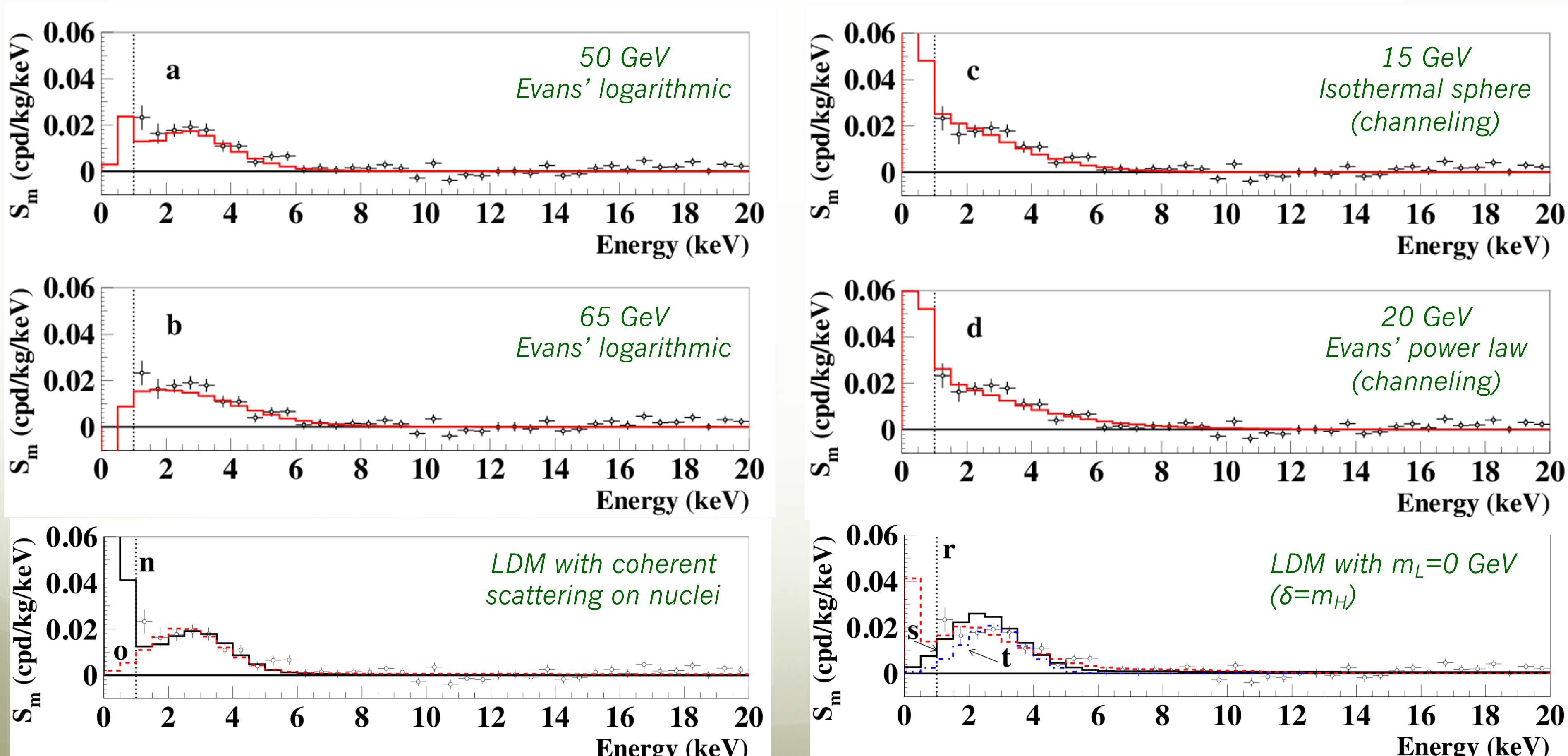


…just an example

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
- E_{th}=1 keV; old data release

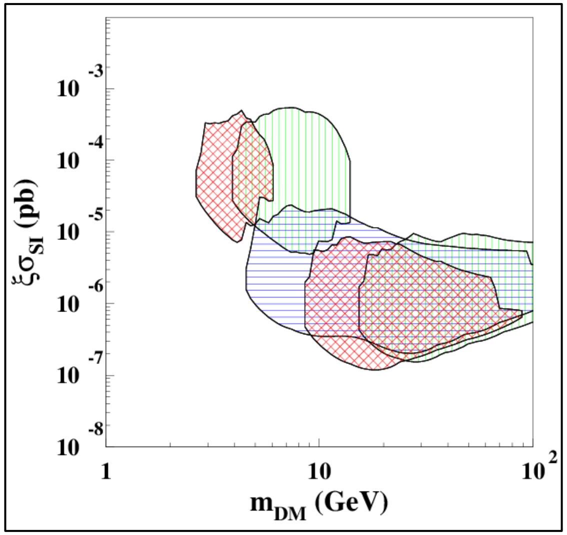


Examples of model-dependent analyses

A large (but not exhaustive) class of halo models and uncertainties are considered

NPAE 20(4) (2019) 317
PPNP114(2020)103810

E_{th}=1 keV; old data release

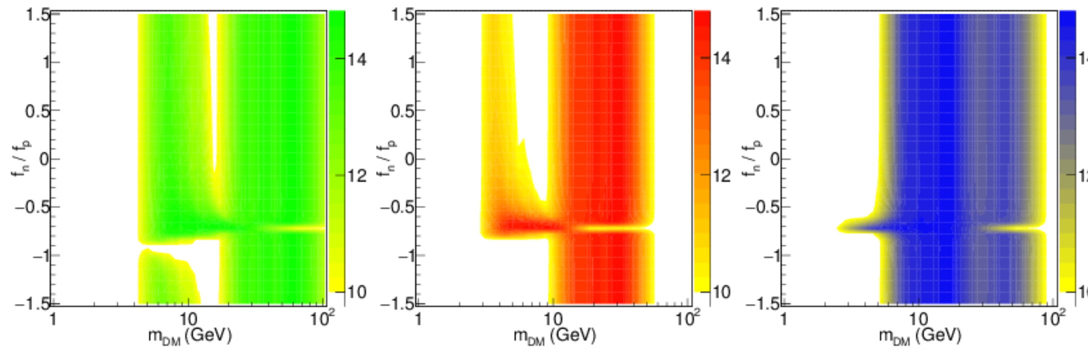


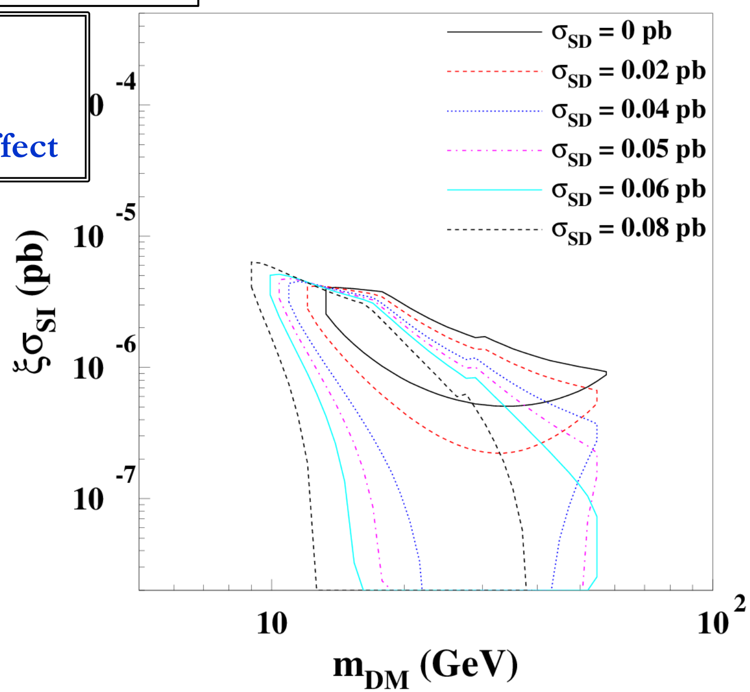
1. Constants q.f.
2. Varying q.f.(E_R)
3. With channeling effect

DM particles elastically scattering off target nuclei – SI interaction

$$\sigma_{SI}(A,Z) \propto m^2_{red}(A,DM)\left[f_p Z + f_n(A-Z)\right]^2$$

Case of isospin violating SI coupling: $f_p \neq f_n$



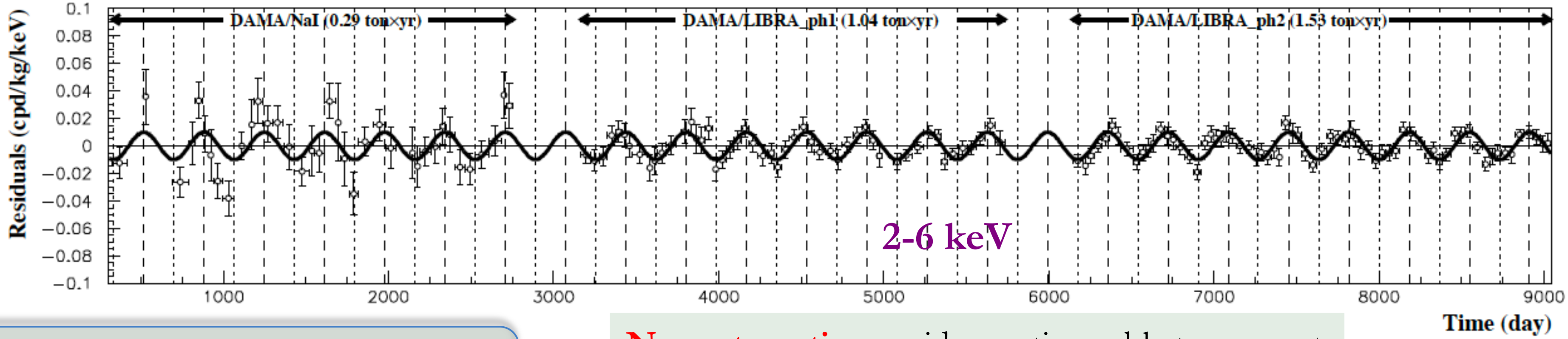


Even a relatively small SD (SI) contribution can drastically change the allowed region in the (m_{DM}, $\xi\sigma_{SI(SD)}$) plane

- Two bands at low mass and at higher mass;
- Good fit for low mass DM candidates at $f_n/f_p \approx$ -53/74 = -0.72 (signal mostly due to ^{23}Na recoils).
- The inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support for f_n/f_p=1 low mass DM candidates either including or not the channeling effect.
- The case of isospin-conserving f_n/f_p=1 is well supported at different extent both at lower and larger mass.

Model-independent Annual Modulation Result

DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr)



Absence of modulation? No

$\chi^2/dof=311/156 \Rightarrow P(A=0) = 2.3\times10^{-12}$

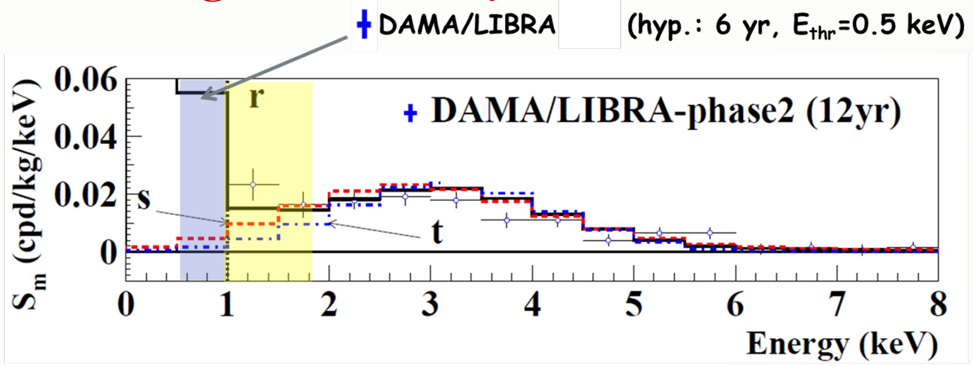
No systematics or side reactions able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

- Several independent analyses consistent
- **Model-independent** evidence for a signal that satisfies all the requirements of the DM annual modulation signature at **13.7σ** C.L. (22 independent annual cycles with 3 different set-ups: 2.86 ton × yr)
- Modulation parameters determined with **increasing precision**
- New investigations on **different peculiarities** of the DM signal in progress
- The result is compatible with many different phenomenological scenarios
- DAMA/LIBRA–phase2 **continuing data taking**
- After a dedicated R&D and data taking (performed at LNGS and here in Tor Vergata), DAMA/LIBRA–phase2 was put in operation with lower software **energy threshold of 0.5 keV**. New divider/amp systems and new 14bit digitizers
- Continuing investigations of **rare processes** other than DM

Running **phase2-empowered** with software energy threshold of **0.5 keV** with suitable high efficiency

Enhancing experimental sensitivities and improving DM corollary aspects, other DM features, second order effects and other rare processes

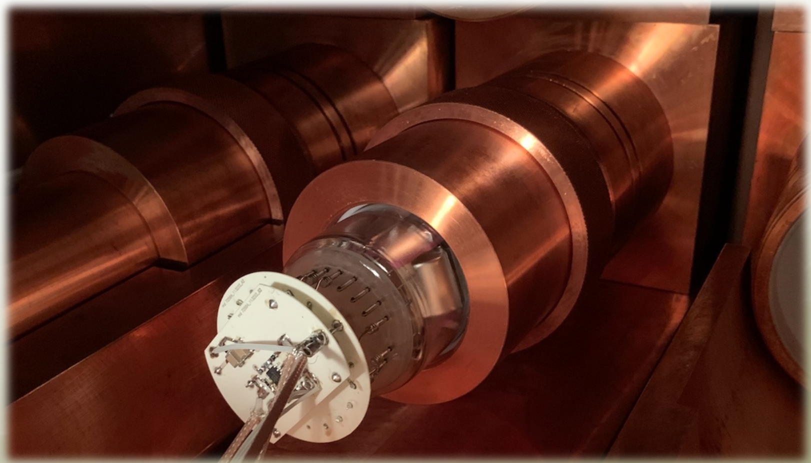
1) During fall 2021, DAMA/LIBRA–phase2 set-up was heavily upgraded
2) The upgrade basically consisted on:
   - new low-background voltage dividers with pre-amps on the same board
   - Transient Digitizers with higher vertical resolution (14 bits)
3) The data taking in this new configuration started on Dec, 1 2021



The features of the voltage divider+preamp system:

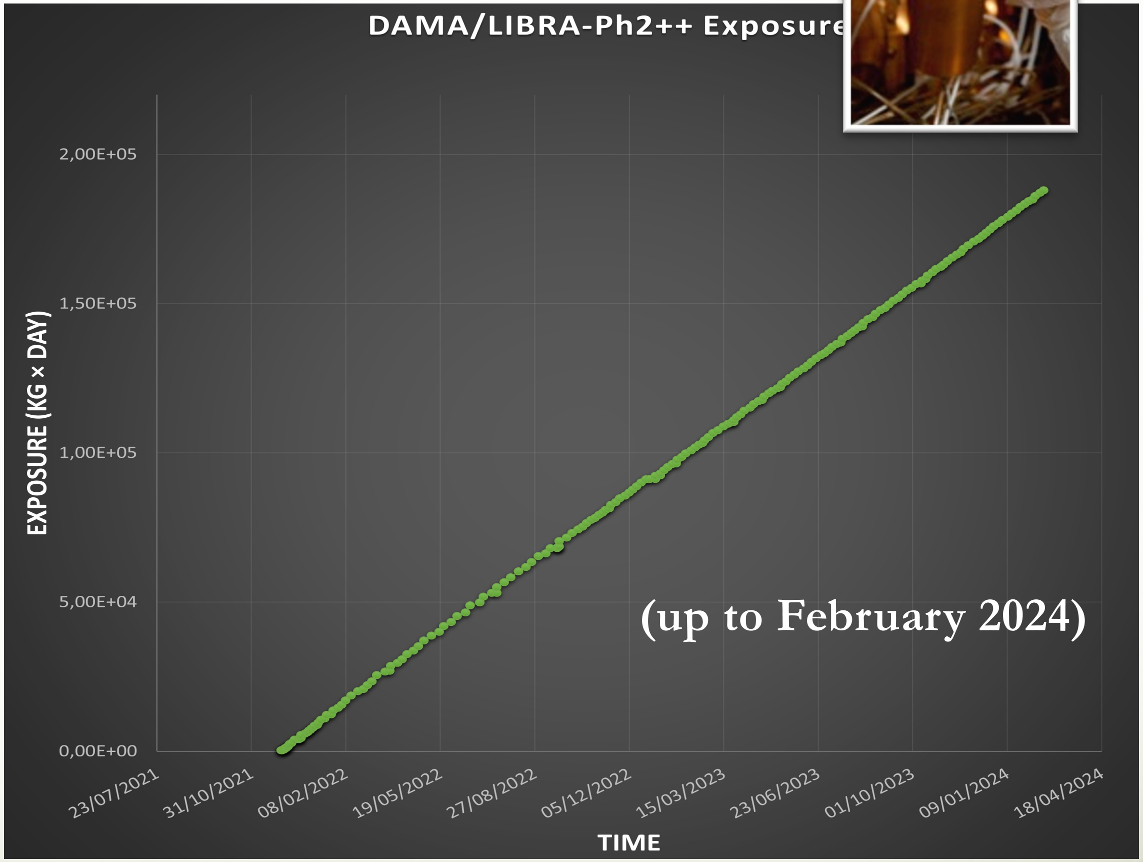
- S/N improvement ≈3.0-9.0;
- discrimination of the single ph.el. from electronic noise: 3 - 8;
- the Peak/Valley ratio: 4.7 - 11.6;
- residual radioactivity lower than that of single PMT

- Higher resolution of TDs makes appreciable the improvements coming from the new voltage-dividers-plus-preamps on the same board
- very stable operational feature
- The baseline fluctuations are more than a factor two lower than those of the previous configuration; RMS of baseline distributions is around 150 μV, ranging between 110 and 190 μV
- Software Trigger Level (**STL) decreased** in the offline analysis
- The "noise" events due to single p.e. with the same energy have evident different structures than the scintillation pulses. This feature is used to discriminate them

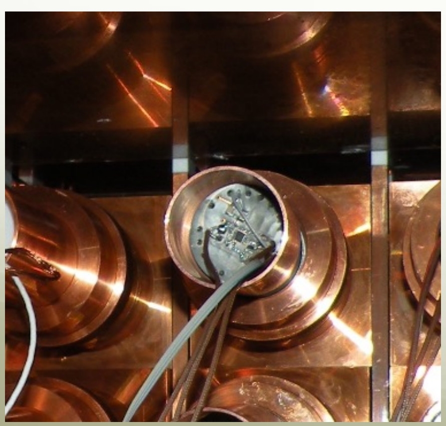


DAMA/LIBRA-phase2-empowered data taking

Data taking in this configuration started on December 2021. The data taking has been continued without interruptions, with regular calibration runs.



- ✓Calibrations: $\approx 6.38 \times 10^7$ events from sources
- ✓Acceptance window eff. per all crystals: $\approx 3.60 \times 10^7$ events ($\approx 1.4 \times 10^6$ events/keV)



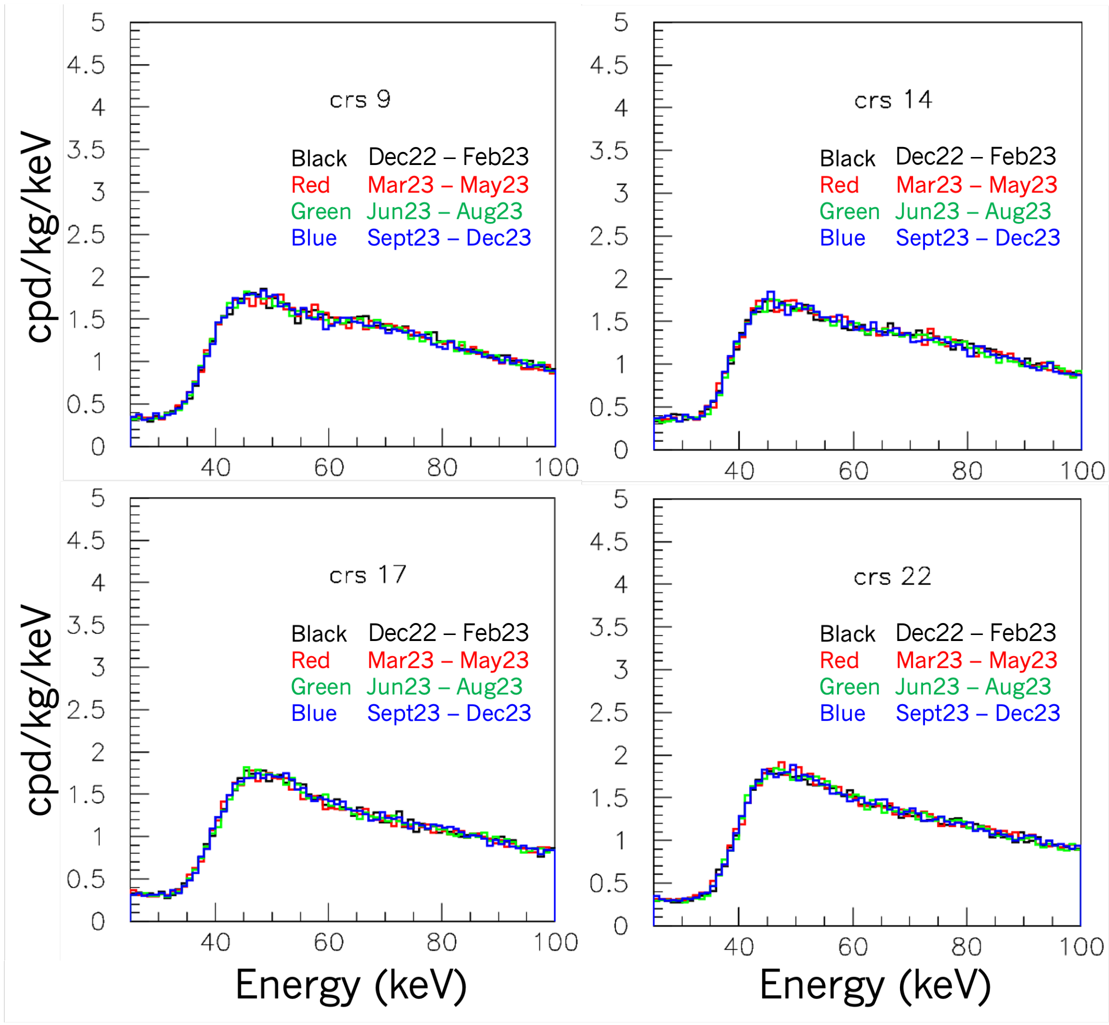
Exposure of DAMA/LIBRA-phase2-empowered up to February 24:

0.478 ton × yr $(\alpha - \beta^2) \approx 0.488$

Measurement quality control and stability verification already presented at CSN2

Example: stability of the energy scale

- Monitor of the energy scale in the region of ^{210}Pb + ^{129}I
- The data in the period dec2022-dec2023 are divided in four time-intervals



- Just few examples
- The detectors are underground since decades (*) and the ^{129}I contribution is dominant in this energy region

- The energy scale is well stable
- The counting rate is well stable

(*) as the other components of the set-up, always kept in HPN_2 and without exposure to neutron sources

Perspectives for the future

Other signatures?

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

Perspectives for the future

Other signatures?

- *Diurnal effects*
- *Shadow effects*
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- *...*

Diurnal effects

EPJC 74 (2014) 2827

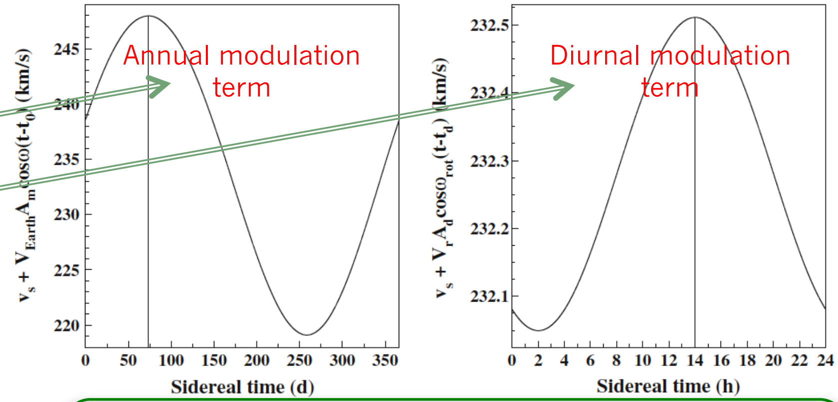
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

Velocity of the detector in the terrestrial laboratory: $\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t),$

Since:

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

$$v_{lab}(t) \simeq v_s + \hat{v}_s \cdot \vec{v}_{rev}(t) + \hat{v}_s \cdot \vec{v}_{rot}(t).$$



Expected signal counting rate in a given k–th energy bin:

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

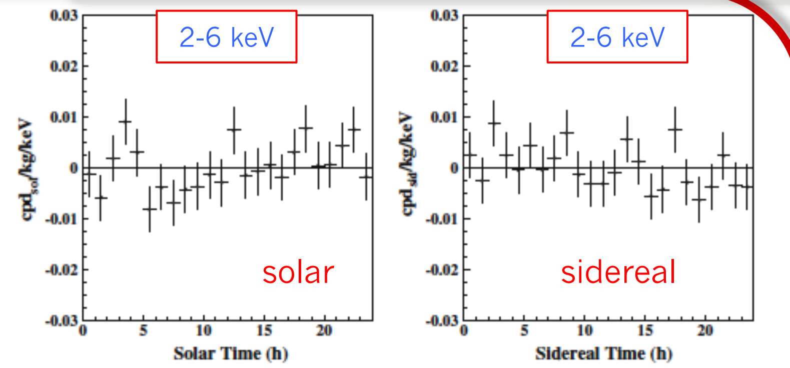
The ratio R_{dy} is a model independent constant:

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

A practical example: the case of DAMA/LIBRA–phase1

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval: (0.0097 ± 0.0013) cpd/kg/keV
- Thus, the expected value of the diurnal modulation amplitude is ≃1.5 × 10^{-4} cpd/kg/keV.
- When fitting the *single-hit* residuals with a cosine function with period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes A_d are compatible with zero at the present level of sensitivity.

A_d (2-6 keV) < 1.2 × 10^{-3} cpd/kg/keV (90%CL)



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

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

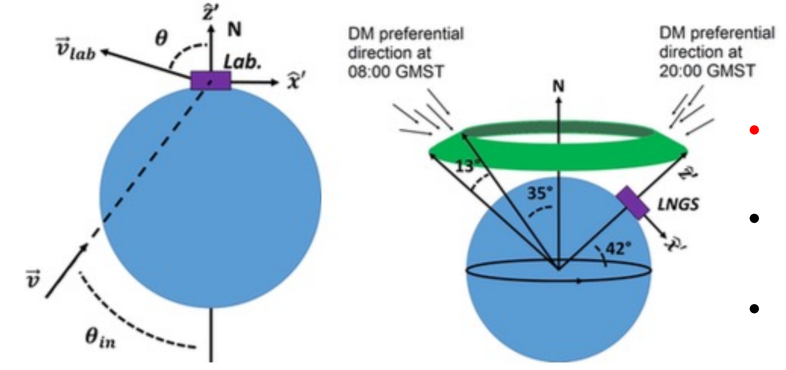
Perspectives for the future

Other signatures?

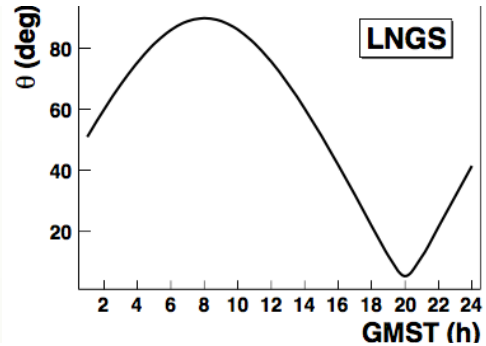
- *Diurnal effects*
- *Shadow effects*
- *Second order effects*
- *Directionality*
- *...*

Earth shadowing effect with DAMA/LIBRA–phase1

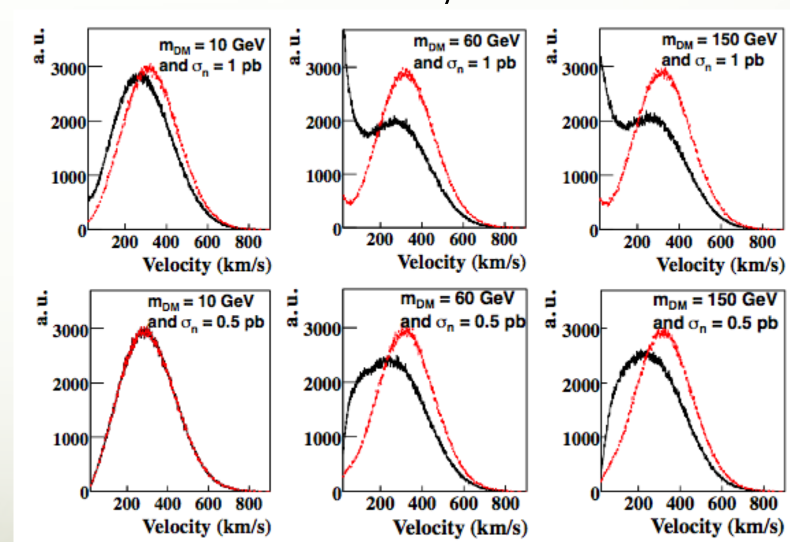
EPJC75(2015)239

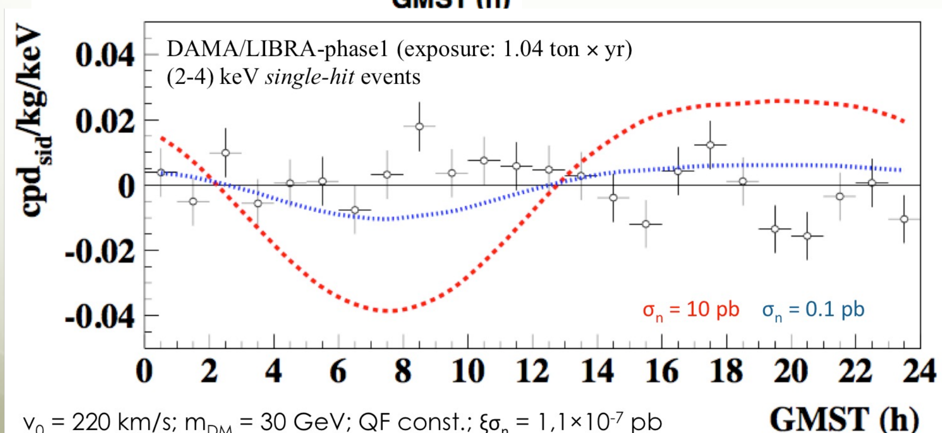


- **Earth Shadow Effect** could be expected for DM candidate particles inducing nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM particle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



- DM particles crossing Earth lose their energy
- DM velocity distribution observed in the laboratory frame is modified as function of time (**GMST 8:00 black**; **GMST 20:00 red**)





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

Perspectives for the future

Other signatures?

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

Features of the DM signal

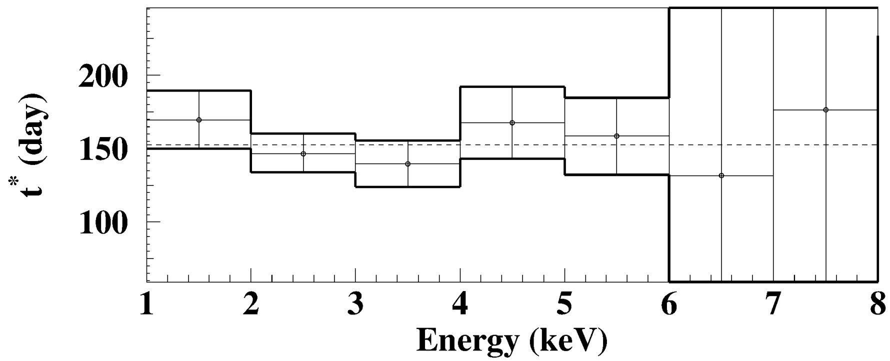
Investigated by the different stages of DAMA; improvements foreseen DAMA/LIBRA-phase2 with the lower energy threshold

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

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

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

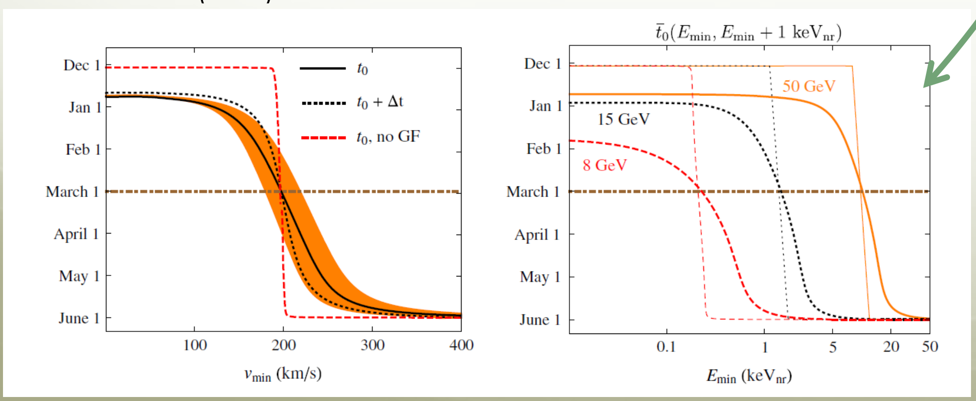
DAMA/NaI+LIBRA-phase2



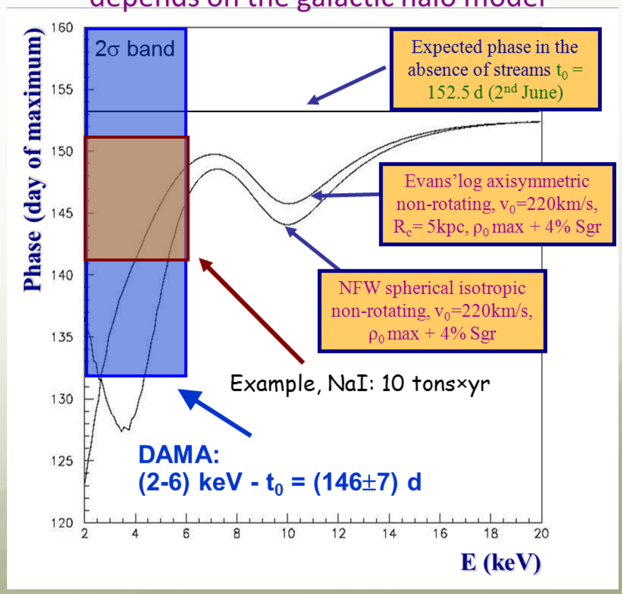
The annual modulation phase depends on :

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

PRL112(2014)011301



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



Perspectives for the future

Other signatures?

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

Directionality technique (at R&D stage)

- Only for candidates inducing recoils
- Identification of the Dark Matter particle by exploiting the non-isotropic recoil distribution correlated to the Earth position with to the Sun

Low pressure Gaseous TPC: DRIFT, MIMAC, DMTPC, NEWAGE, D3, CYGNO ⇒ CYGNUS TPC project

Exp.	V (L)	Gas	P (mbar)	Drift	Threshold (keV)	Location
DRIFT	800	73% CS_2 + 25% CF_4 + 2% O_2	55	ion, 50 cm	20 [24]	Boulby
MIMAC	5.8	70 % CF_4 + 28 % CHF_3 + 2 % C_4H_{10}	50	e^-, 20 cm	2	Modane
NEWAGE	37	CF_4	100	e^-, 41 cm	50	Kamioka
DMTPC	1000	CF_4	40	e^-, 27 cm	20	SNOLAB

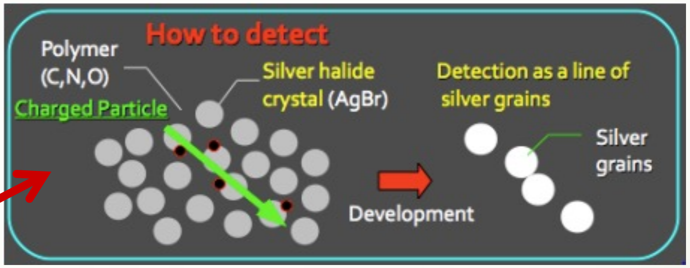
Physics Reports 627(2016)1

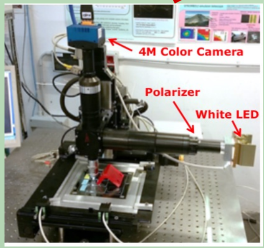
Anisotropic scintillators: DAMA, UK, Japan

R&D on other techniques

NEWSdm at LNGS

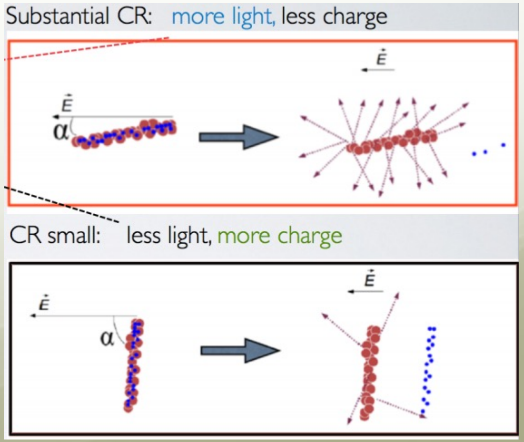
- Nanometric track direction measurement in nuclear emulsions;
- Exploit resonant light scattering using polarised light;
- Measurement of track beyond the optical resolution;
- Shape analysis: threshold 190 nm;
- Polarization analysis: threshold 120 nm





RED

Columnar Recombination (CR) in liquid argon TPC



PTOLEMY

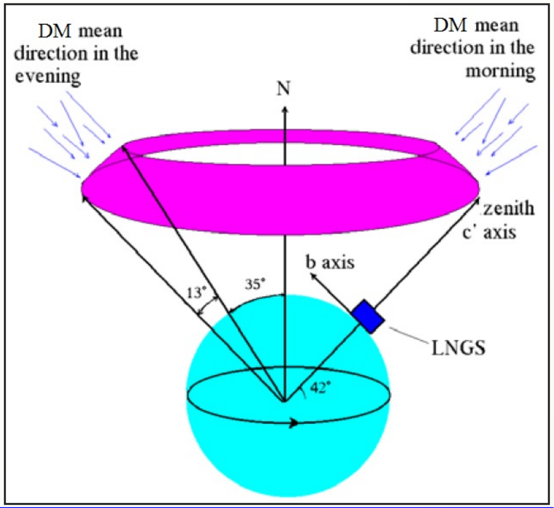
Graphene target (nanoribbon or nanotubes)

Development of detectors with anisotropic response

DAMA - Seminal paper: N.Cim.C15(1992)475; revisited: EPJC28(2003)203); more recently other suitable materials: EPJC73(2013)2276; now: work in progress

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 by exploiting the non-isotropic recoil distribution correlated to the Earth velocity



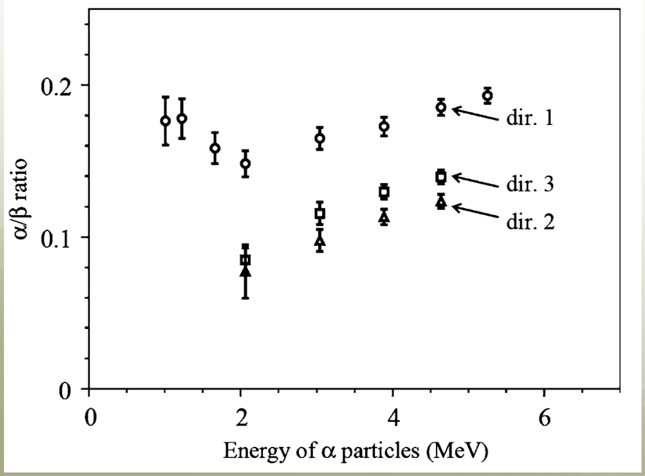
Taking into account:

- 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

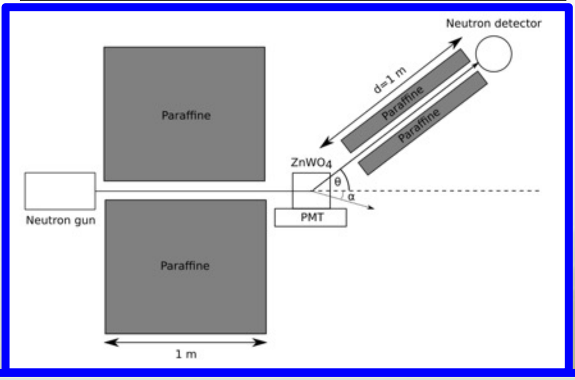
O → light masses
Zn, W → high masses

The ADAMO project: Development of $ZnWO_4$ anisotropic scintillators



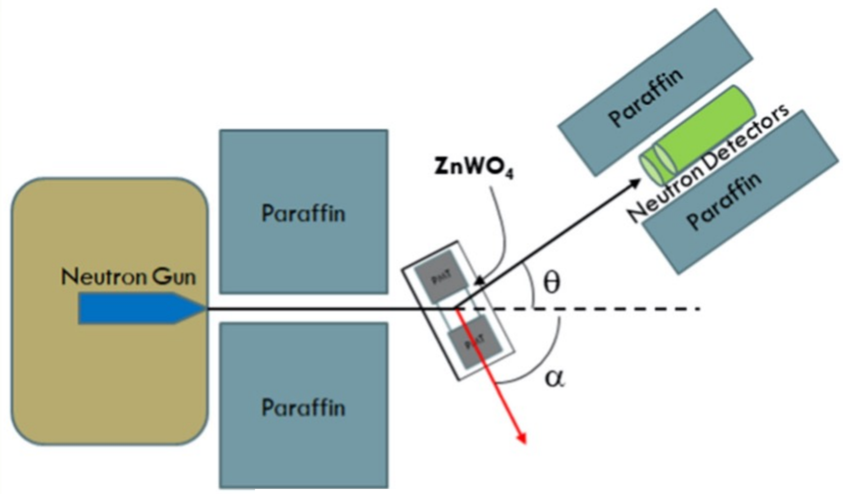
The light output and pulse shape of $ZnWO_4$ depend on the direction of the impinging particles with respect to the crystal axes

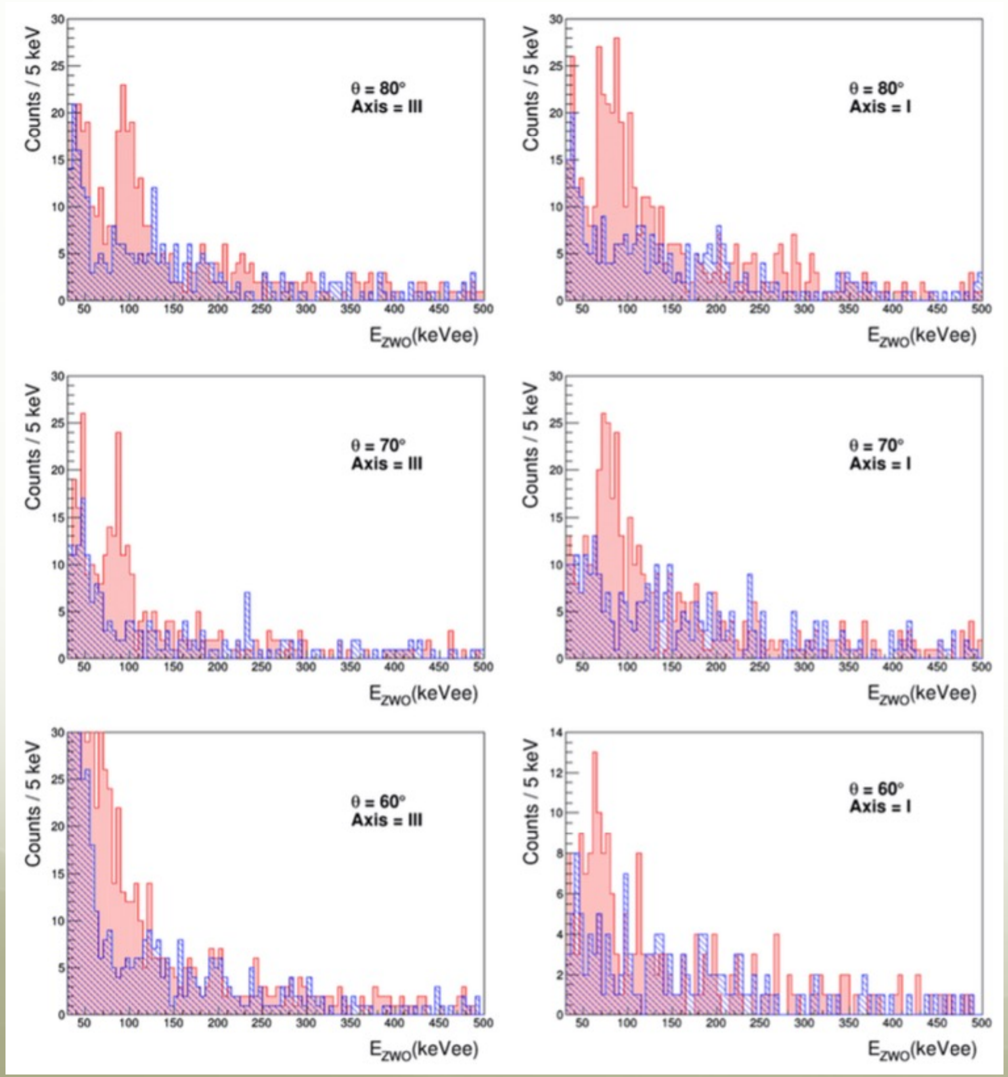
Both these anisotropic features can provide two independent ways to exploit the directionality approach

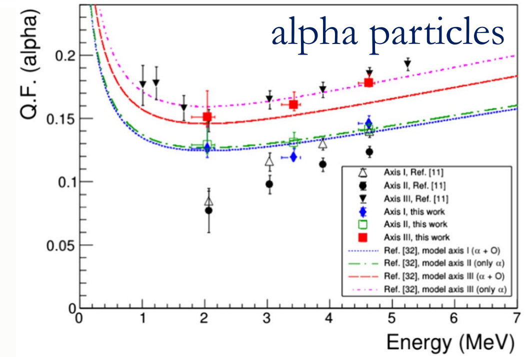


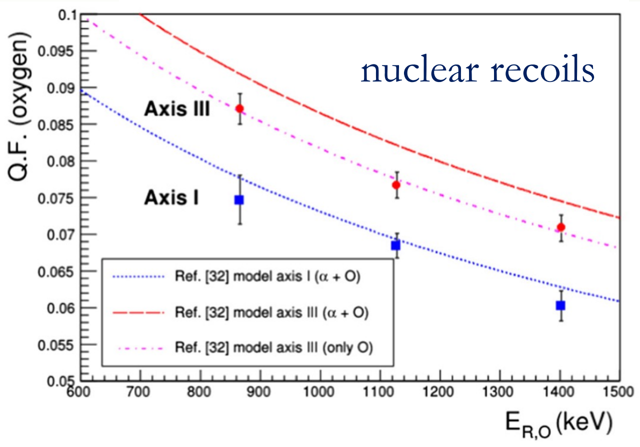
Measurements of anisotropy in keV range by neutron generator done at ENEA-Casaccia

Measurements of $ZnWO_4$ anisotropic response to nuclear recoils (EPJA56(2020)83)







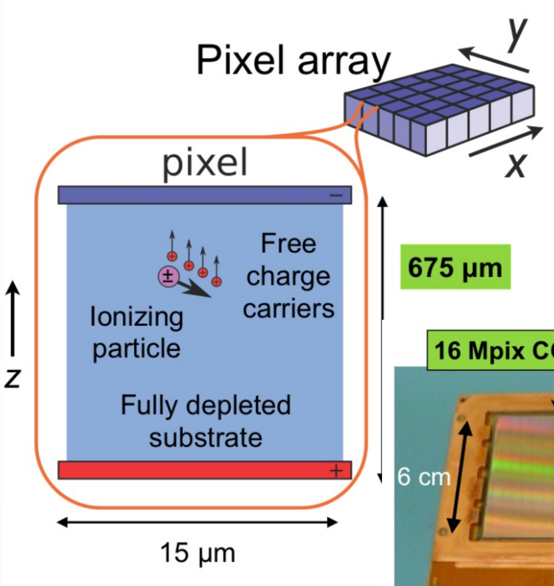


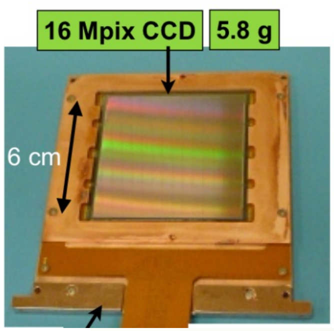
the anisotropy of the light response for nuclear recoils in the $ZnWO_4$ has been determined at 5.4 stnd deviations

Other techniques

DAMIC at SNOLAB

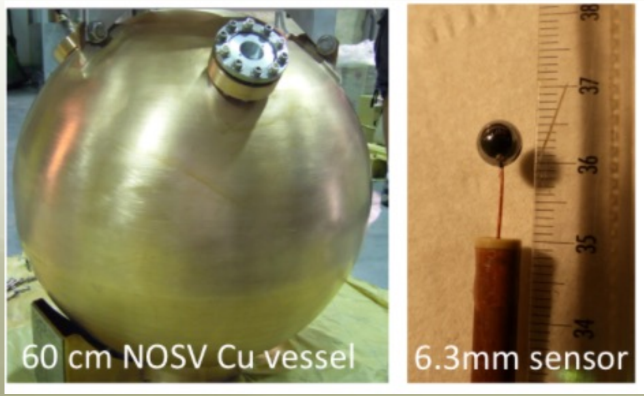
- Charge coupled devices (CCDs) as detectors for **low-energy** particles
- Background suppression techniques
- Ongoing R&D efforts for a **DAMIC-1K**: 1 kg detector, 50 CCDs with 2e$^-$ thr.

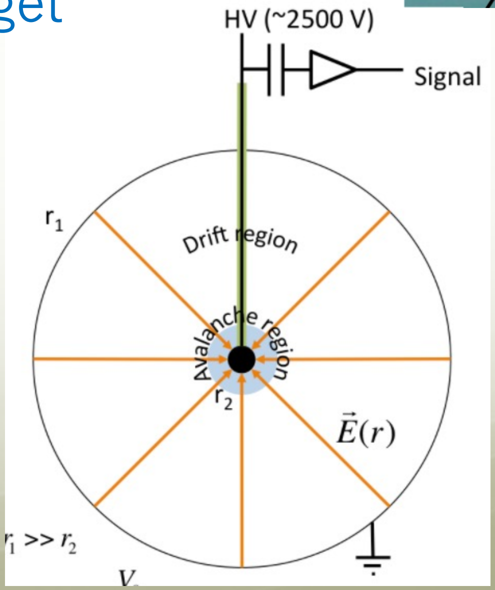




NEWS-G, a spherical TPC with low-A target

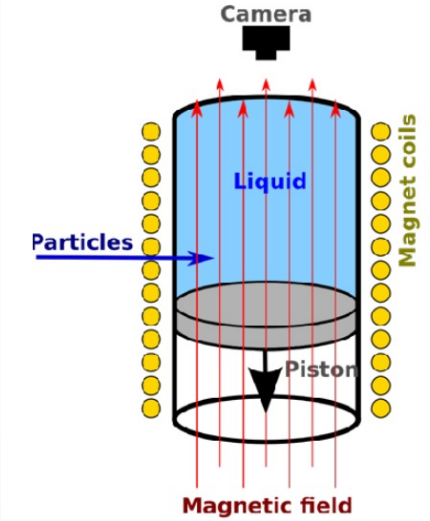
- Sensitive to low mass DM candidate





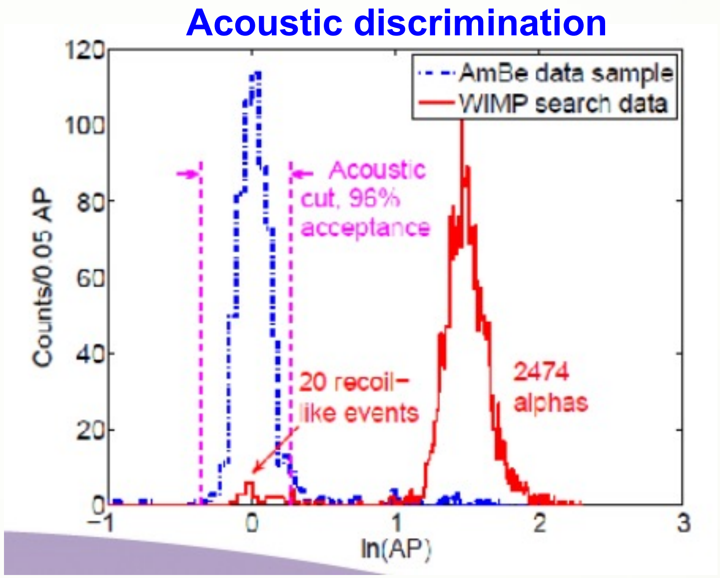
Other techniques

PICO: bubble chamber, using acoustic discrimination, C_3F_8 target



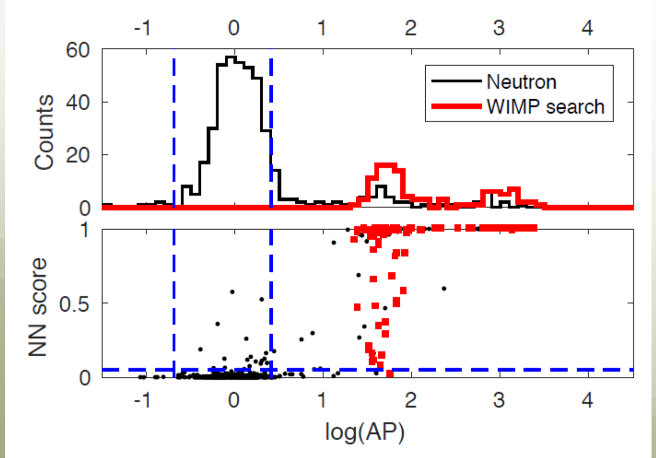
- Any bubble chamber has:
  - optical system with camera, lights
  - expansion system, piston, temperature control

C. Amole *et al.*, Phys. Rev. Lett. 118, 251301



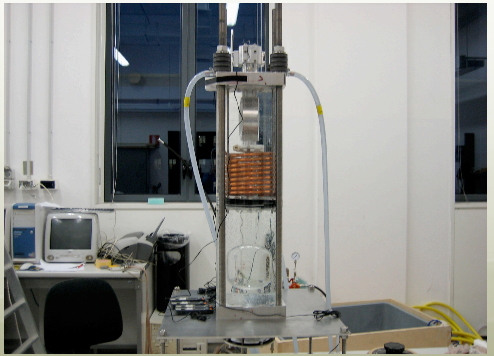
- Alphas deposit their energy over tens of microns
- Nuclear recoils deposit theirs over tens of nanometers

Acoustic Data



- Now: PICO-60
- Next step PICO 500

Bubble Chamber – Geyser



In both cases: technical limitations on the technique (reachable sensitivities, energy thresholds, stability, ...), only DM candidates inducing recoils, tests made at very high energy recoils, what about low energy recoils?

Conclusions

DARK MATTER investigation with direct detection approach

- Different **solid** techniques can give complementary results
  - Some further efforts to demonstrate the **solidity** of some techniques are needed
    - Higher exposed mass not a synonymous of **higher sensitivity**
      - **DAMA** positive evidence (13.7 σ C.L.). The modulation parameters determined with **better precision.**
        full sensitivity to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation.
        - Possible positive hints are compatible with DAMA in many scenarios; null searches not in robust conflict. Also consider the experimental and theoretical uncertainties.

- The **model independent signature** is the definite strategy to investigate the presence of Dark Matter particle component(s) in the Galactic halo