

# Main investigation on rare processes with DAMA experimental set-ups

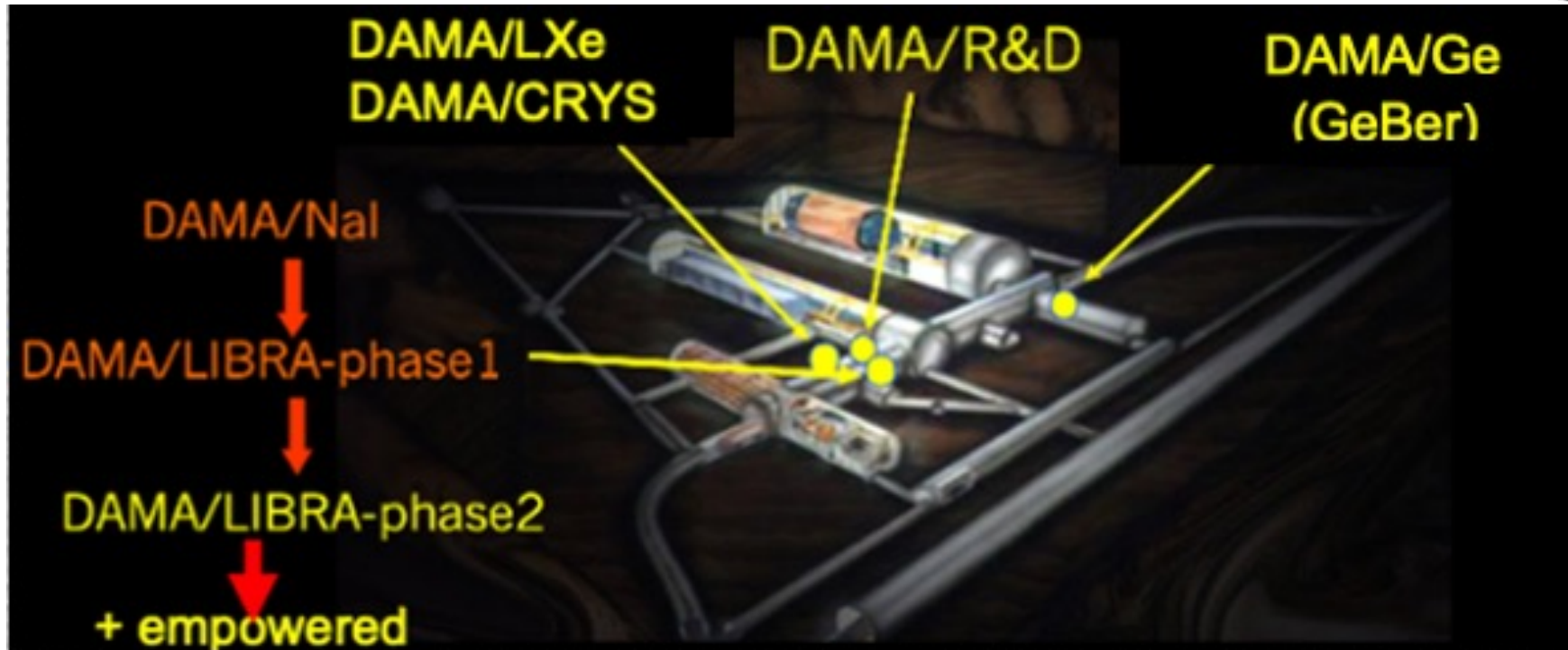


1 experiment for many set-ups  
and measurements since the proposal in April 1990.  
End of running 2024  
Analyses and papers under completion since 2025

**Bled**  
July 13, 2025

**R. Bernabei for DAMA**  
University & INFN Roma Tor Vergata

# Developing and using new and low background crystal scintillators & set-ups for rare events searches



<https://dama.web.roma2.infn.it>

## In numbers:

- 350 (41 in the last five years) publications on international reviews
- 436 (66 in the last five years) talks at conf. and seminars
- DAMA h-index=63
- Theses (various levels): about 30

# Time-line of DAMA/LXe set-up

end '80: **Xelidon** expt in CSN5 to develop LXe detectors - 1<sup>st</sup> prop. on such detectors in INFN

24 April 1990 Italian (Roma Tor Vergata & Roma La Sapienza) Proposal to INFN by R. Bernabei, P. Belli, C. Bacci, A. Incicchitti, R. Marcovaldi and D. Prosperi on large mass NaI(Tl) and liquid Xenon experiments  
LXe only Italian + later C.J. Dai

1<sup>o</sup> experiment proposed and funded specifically for DM direct detection deep underground, and with LXe detector exploiting also the DM annual mod. Signature and other rare processes mainly Xenon enriched in  $^{129}\text{Xe}$  or  $^{136}\text{Xe}$ ,  $^{134}\text{Xe}$

1990- ~1994 **prototypes** for LB + installation deep underground of the LB set-up+ running  $^{\text{nat}}\text{Xe}$

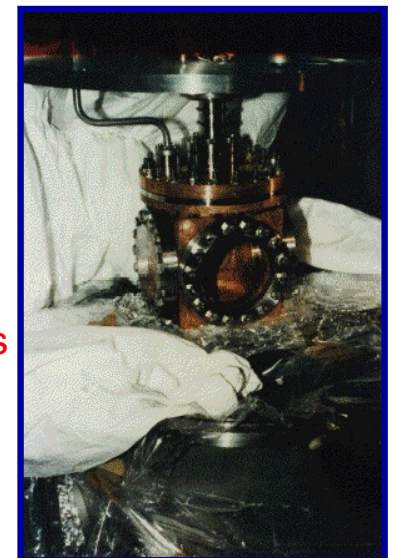
Around ~1995 we pointed out to the INFN-CSN2 the intrinsic limitations of this detector medium (see e.g. some arguments in our more recent monography in Exorma ed. (2009) ISBN: 978-88-95688-12-1 and IJMPA30(2015)153005) and agreed to pursue the activity with a set-up with a full block of Cu inner vessel by using ~ 6.5 kg Kr-free Xenon enriched either in  $^{129}\text{Xe}$  at 99.5% or in  $^{136}\text{Xe}$  at 68.8% and in  $^{134}\text{Xe}$  at 17.1% (the largest LXe detector underground at time)

1996-2018 **Several upgrades occurred with time** + a period of stopping due to the Borexino accident that caused the stop of using liquids underground.

**Published results on: DM elastic- and inelastic-scattering, on response of a similar pure LXe scintillator to recoil nuclei as well as its pulse shape discrimination capability, on possible charge non-conserving processes, on nucleon and di-nucleon stability, on  $\beta\beta$  decay modes:  $^{136}\text{Xe}$  enriched at 68.8% or  $^{134}\text{Xe}$  enriched at 17.1%, etc.+ detector details and performances**

Astrop.Phys5(1996)217, NCim19(1996)537, PLB436(1998)379, PLB387(1996)222 + PLB389(1996)783, PLB465(1999)315, PLB493(2000)12, PRD61(2000)117301, NJP2(2000)15.1, EPJdirectC11(2001)1, PLB527(2002)182, PLB546(2002)23, NIMA482(2002)728, Beyond the Desert (2003) 365, EPJA27 s01 (2006) 35]

2018 Out of operation as in the plans



# Time-line of ULB NaI(Tl) DAMA set-ups

end '80-beginning 90      underground tests with commercial NaI(Tl) of the LADON 100 kg sphere; search for the best manufacture for ULB: Harshaw chosen, then acquired by Crismatec

24 April 1990

only italians (Roma Tor Vergata & Roma La Sapienza): Proposal to INFN by R. Bernabei, P. Belli, C. Bacci, A. Incicchitti, R. Marcovaldi and D. Prospero on large mass NaI(Tl) and liquid Xenon experiments for Dark Matter search, and first funding

1<sup>o</sup> experiment proposed and funded specifically for DM direct detection deep underground, with ULB NaI(Tl) and with LXe exploiting also the DM annual modulation signature

1990-end 1995

R&D by a joint coll. between DAMA members and companies for crystal detectors and dedicated EMI-Thorn B53 PMTs realization

Chinese colleagues joined @LNGS in 1992

end 1995/96 to July 2002      100 kg DAMA/NaI installation + running + 1998 minimal upgrade + July 2000 new DAQ and new electronic chain

Fall 1996

Italian DAMA proposed (for insertion in the Piano Triennale) to INFN DAMA/1ton; get DAMA/LIBRA-phase1 as intermediate step and - with time - some additional R&Ds funded and carried out

1996/97 to 2003

R&D and realization of the new DAMA/LIBRA detectors by Quartz & Silice (former Crismatec) → DAMA/R&D setup realized for tests of this R&D and then to be used for small scale expts.

Sept 2003

start 250 kg DAMA/LIBRA-phase 1 + upgrade on Sept/Oct 2008

Fall 2010

2<sup>nd</sup> DAMA/LIBRA upgrade → DAMA/LIBRA-phase2 + preamp upgrade in Fall 2012

Dec 2010 – 2021

DAMA/LIBRA-phase2 running

2019 – 2021

R&Ds towards DAMA/LIBRA-phase2-empowered

Fall 2021

Start DAMA/LIBRA-phase2-empowered

2021 – fall 2024

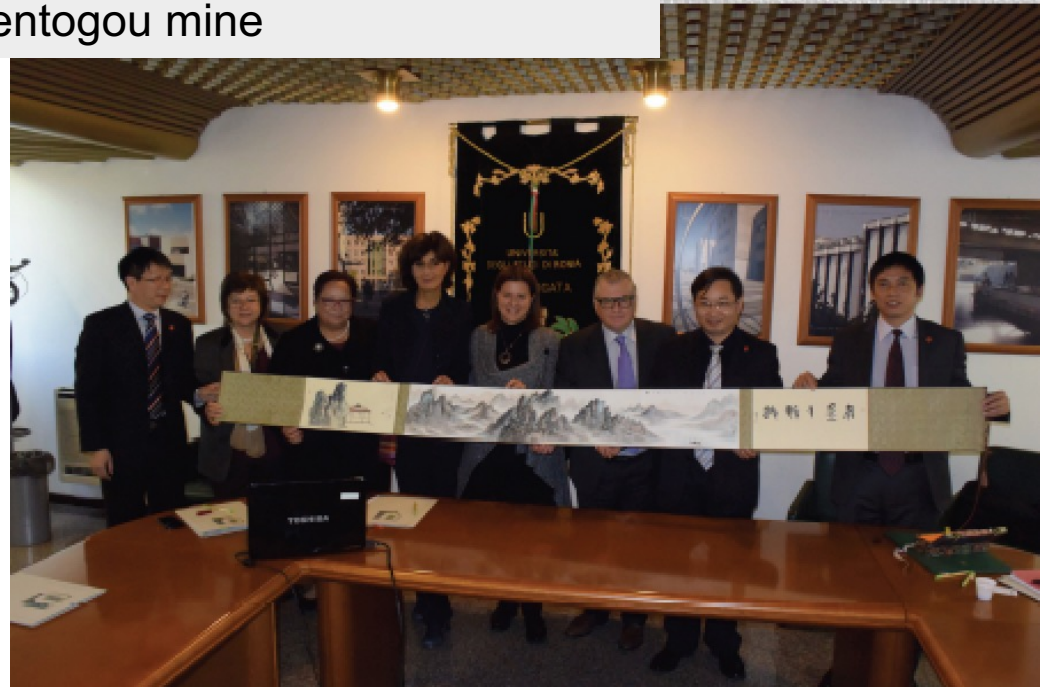
DAMA/LIBRA-phase2-empowered running



Just two historical pictures  
from a long and fruitful  
collaboration and exchanges



**1992:** Visiting the Ge installation of the Chinese colleagues in the Mentogou mine



**2015:** Signing of a MOU by the two Rectors of the Rome Tor Vergata University and the Jinggangshan University

# 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
- CNC processes
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
- Search for solar axions
- Exotic Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

PLB408(1997)439  
PRC60(1999)065501

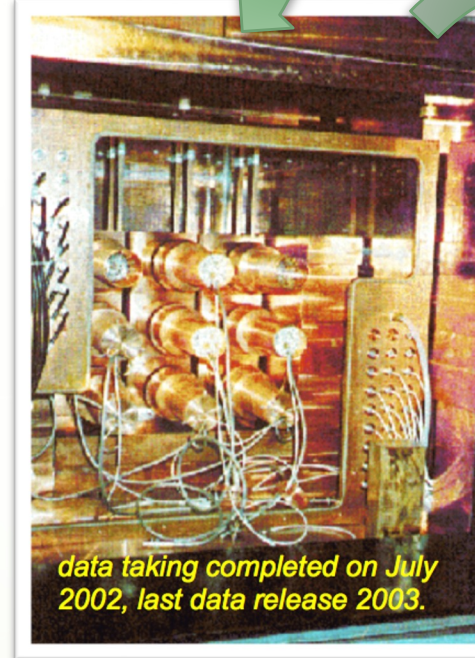
PLB460(1999)235  
PLB515(2001)6  
EPJdirect C14(2002)1  
EPJA23(2005)7  
EPJA24(2005)51

## Results on DM particles:

- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- **Annual Modulation Signature**

PLB389(1996)757  
N.Cim.A112(1999)1541  
PRL83(1999)4918

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  $6.3\sigma$  C.L.**

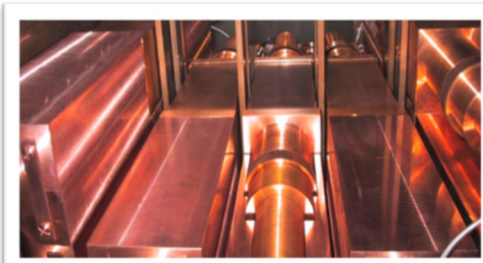
total exposure (7 annual cycles) 0.29 ton×yr

# The pioneer DAMA/NaI:

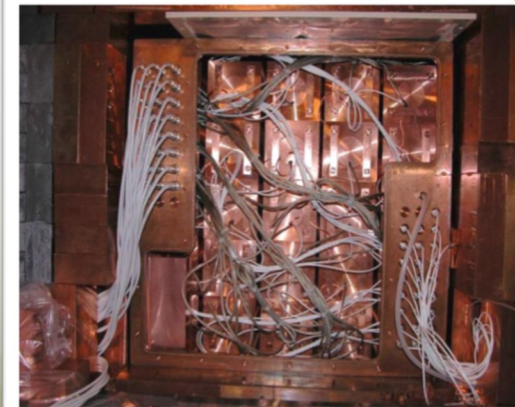
## The DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RARE processes)



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)



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



- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles,
  - Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, 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  $^{241}\text{Am}$ : EPJA49(2013)64

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

# The pioneer DAMA/NaI:

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As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques

### DAMA/LIBRA-phase2

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

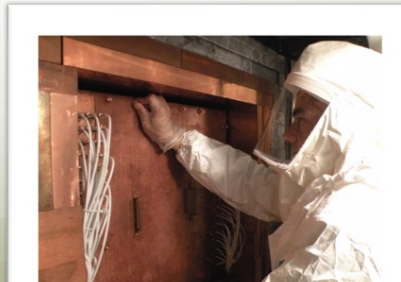
JINST 7(2012)03009  
Universe 4 (2018) 116  
NPAE 19 (2018) 307  
Bled 19 (2018) 27  
NPAE 20(4)(2019)317  
PPNP114(2020)103810



Residual of DAMA/LIBRA  
 $^{238}\text{U}$  and  $^{232}\text{Th}$



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



# The pioneer DAMA/NaI:

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

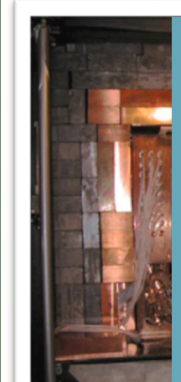
As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques

### DAMA/LIBRA-phase2

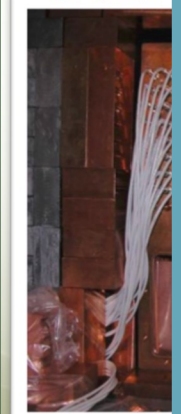
Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

- JINST 7(2012)03009
- Universe 4 (2018) 116
- NPAE 19 (2018) 307
- Bled 19 (2018) 27
- NPAE 20(4)(2019)37
- PPNP114(2020)10-110

A new stage of the experiment:  
**DAMA/LIBRA-phase2- empowered with 0.5 keV**  
software energy threshold from Dec 1, 2021 to 2024

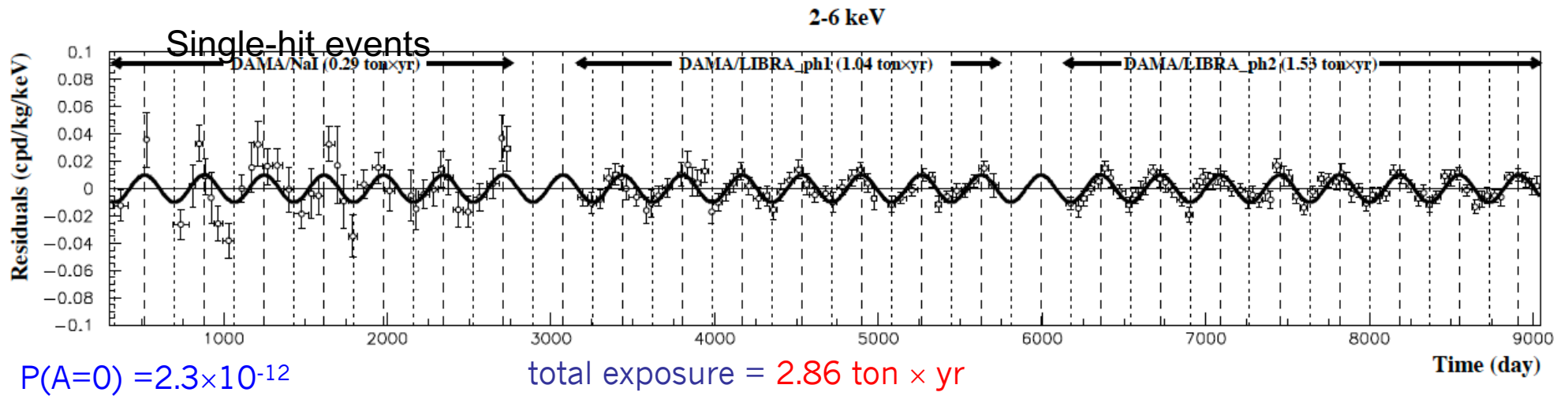


Residual of DAMA/LIBRA  $^{238}\text{U}$  and  $^{232}\text{Th}$



Q.E. of the new PMTs:  
33 – 39% @ 420 nm  
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phase and period well compatible with expectations for DM annual modulation

- Multiple different and independent analyses give completely consistent results
- All the many peculiarities of the DM annual modulation signature satisfied
- No competing systematics or reactions capable of mimicking the signature
- Result compatible with many different phenomenological scenarios

Further exposure and lower software thresholds increased with time the sensitivity and allowed a more precise determination of the parameters to investigate:

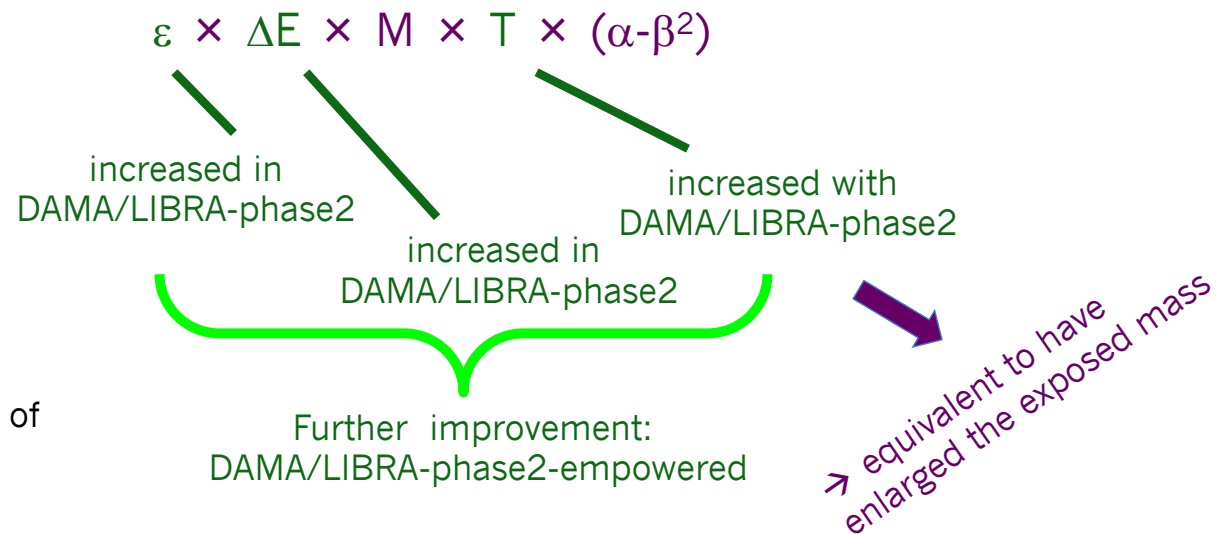
- The nature of Dark Matter particles
- Possible diurnal effects with sidereal time
- Astrophysical models

## Increasing sensitivity in the model-independent DM annual modulation signature → lowering the software energy threshold ...

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

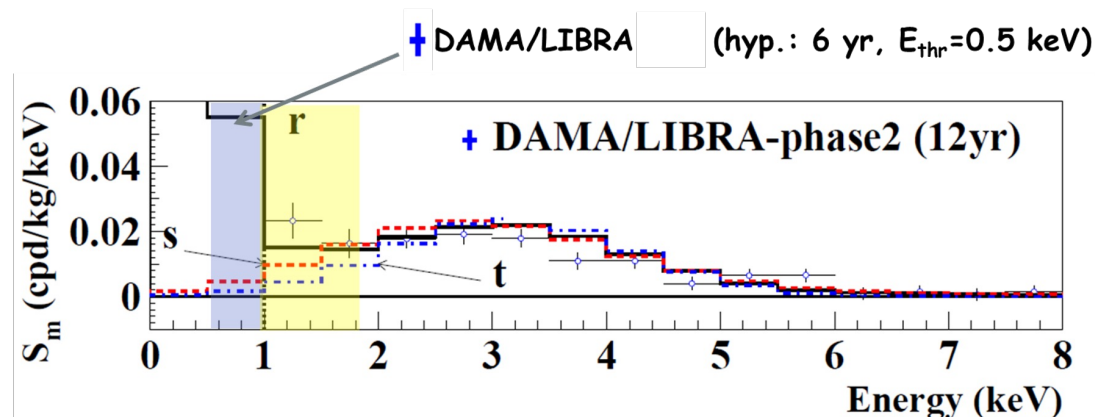
&: this signature acts itself as a strong bckg reduction strategy as pointed out in the original paper by Freese et al.

&: No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available



## .... and improvement in model-dependent corollary analyses

Just an example

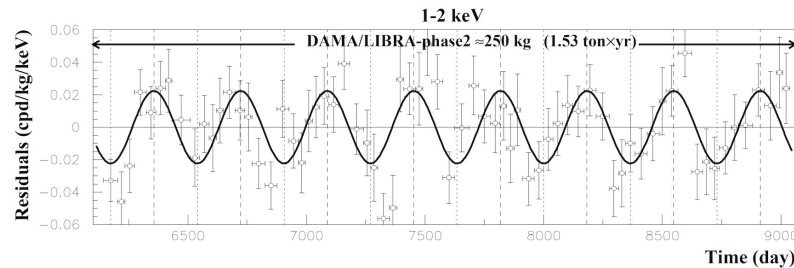


# DM model-independent Annual Modulation Result

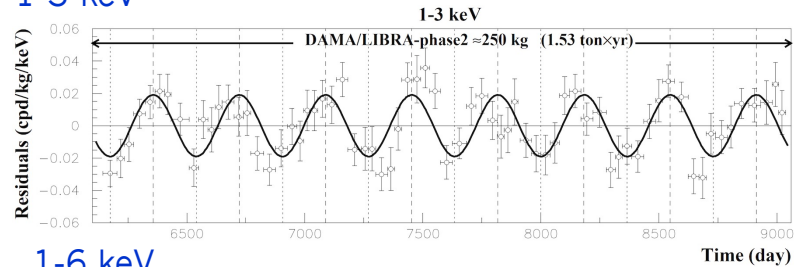
DAMA/LIBRA-phase2 (1.53 ton × yr)

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

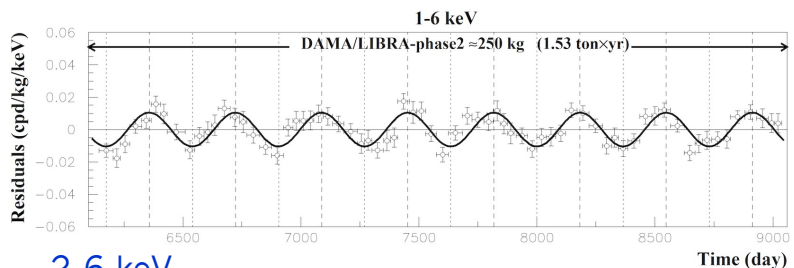
1-2 keV



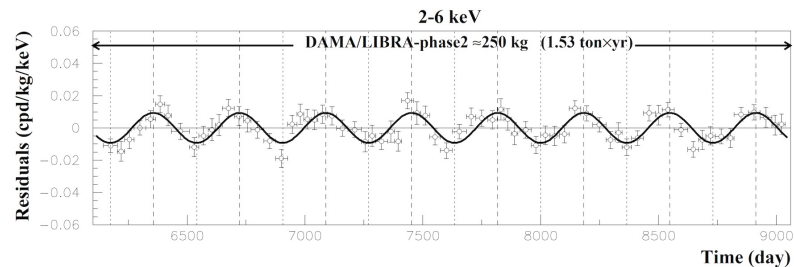
1-3 keV



1-6 keV



2-6 keV



Absence of modulation? No

$\chi^2/\text{dof} = 130/69$  (1-2 keV);  $176/69$  (1-3 keV);  
 $202/69$  (1-6 keV);  $157/69$  (2-6 keV)

Fit on DAMA/LIBRA-phase2  
 $\text{Acos}[\omega(t-t_0)]$ ;  $t_0 = 152.5$  d,  $T = 1.00$  y

**1-2 keV**

$A = (0.0224 \pm 0.0030)$  cpd/kg/keV  
 $\chi^2/\text{dof} = 75.8/68$  **7.4  $\sigma$  C.L.**

**1-3 keV**

$A = (0.0191 \pm 0.0020)$  cpd/kg/keV  
 $\chi^2/\text{dof} = 81.6/68$  **9.7  $\sigma$  C.L.**

**1-6 keV**

$A = (0.01048 \pm 0.00090)$  cpd/kg/keV  
 $\chi^2/\text{dof} = 66.2/68$  **11.6  $\sigma$  C.L.**

**2-6 keV**

$A = (0.00933 \pm 0.00094)$  cpd/kg/keV  
 $\chi^2/\text{dof} = 58.2/68$  **9.9  $\sigma$  C.L.**

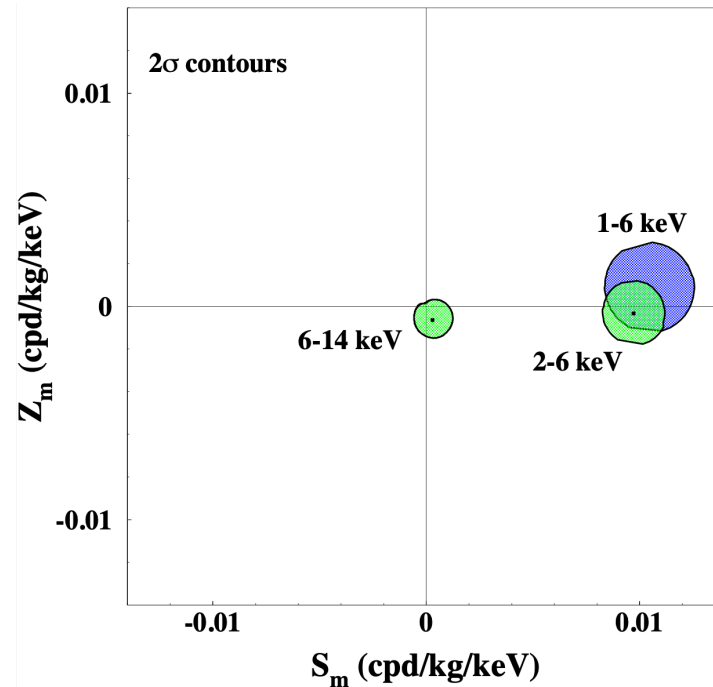
The data of DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at **11.6  $\sigma$  C.L.**

## Is there a sinusoidal contribution in the signal? Phase $\neq 152.5$ day?

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

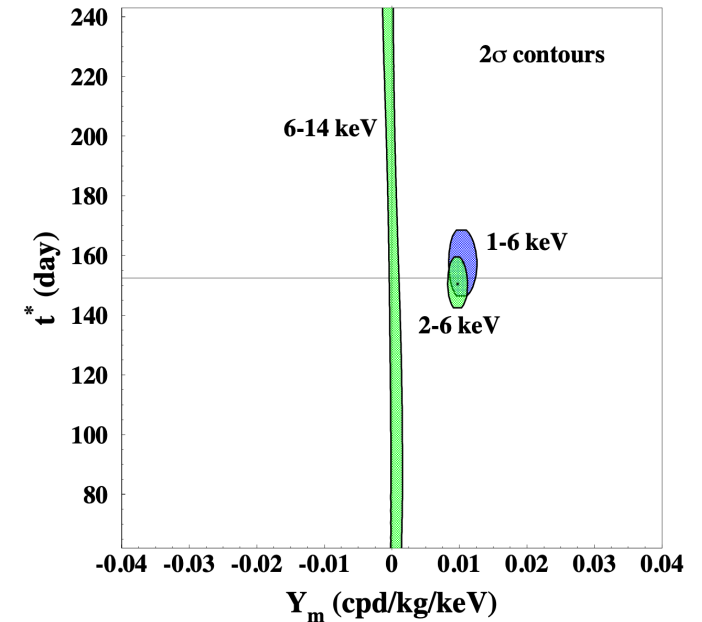
For Dark Matter signals:

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



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

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

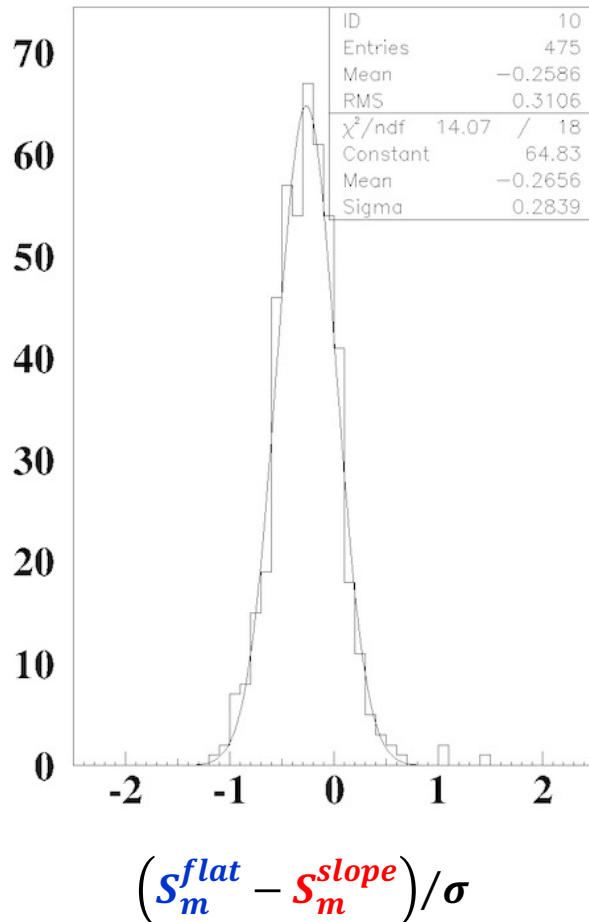
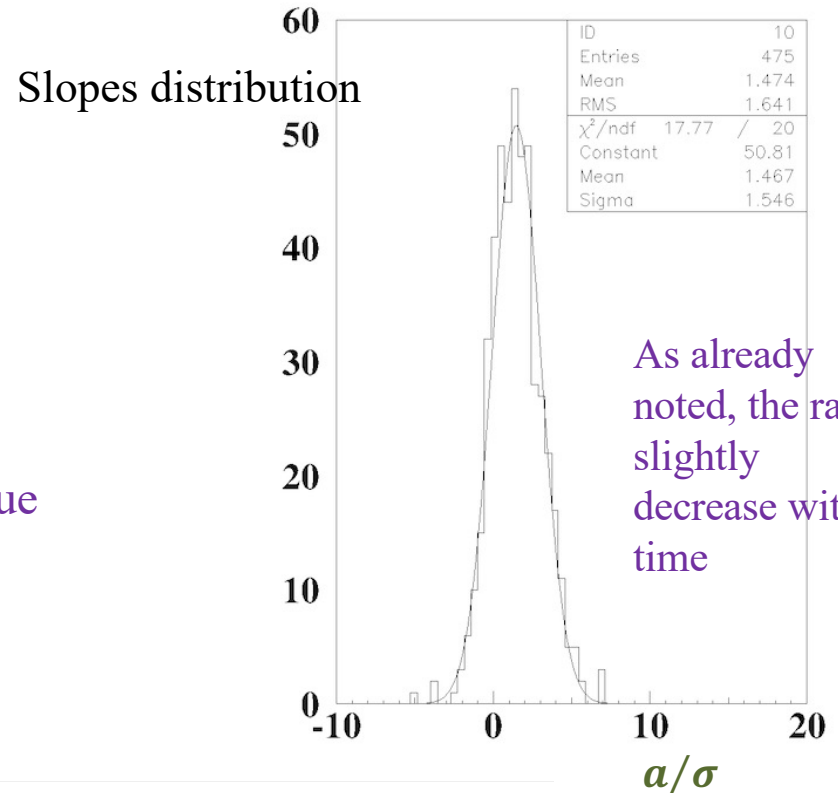


E (keV)	$S_m$ (cpd/kg/keV)	$Z_m$ (cpd/kg/keV)	$Y_m$ (cpd/kg/keV)	$t^*$ (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	$0.0097 \pm 0.0007$	$-0.0003 \pm 0.0007$	$0.0097 \pm 0.0007$	$150.5 \pm 4.0$
6-14	$0.0003 \pm 0.0005$	$-0.0006 \pm 0.0005$	$0.0007 \pm 0.0010$	undefined
1-6	$0.0104 \pm 0.0007$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

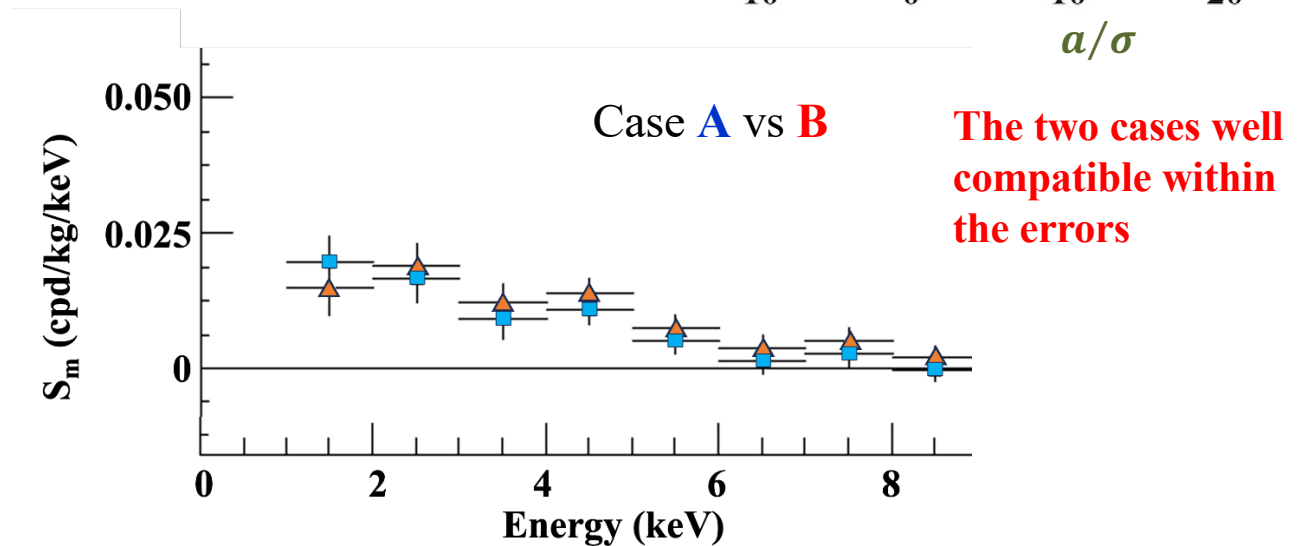
# Rate time dependence?

The general case: last three published years of DAMA/LIBRA-phase2 (0.61 ton×yr)

- For each detector the rates are fitted by MaxLik by case **A**:  $b + S_m^{flat} \cos$
- and by case **B**:  $b - a \times time + S_m^{slope} \cos$
- 475 entries = 25 detectors × 19 energy bins

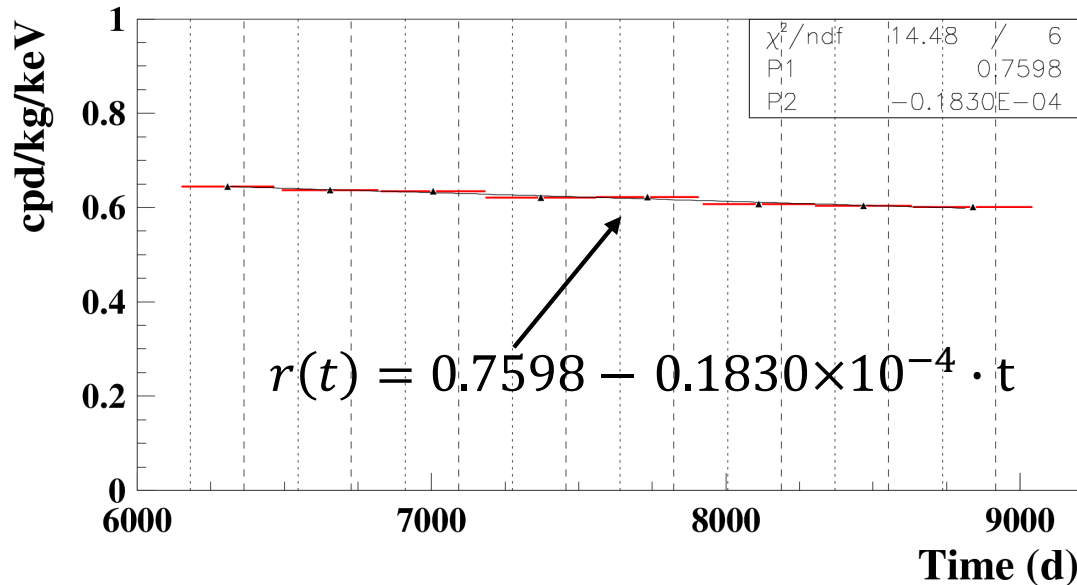


- The mean shift of the modulation amplitudes due to the introduction in the fit of a slope is  $\approx 0.27\sigma$



# Flat in DAMA/LIBRA-phase2

Rate in low-energy [2,6] keV interval, averaged over the detectors, for each annual cycle



In DAMA:

[arXiv:2209.00882](https://arxiv.org/abs/2209.00882)

- Data taking of each annual cycle starts before the expected **minimum** (Dec) of the DM signal and ends after its expected **maximum** (June)
- Thus, assuming a **constant background** within each annual cycle:
  - ✓ any possible decay of **long-term-living isotopes** cannot mimic a DM positive signal with all its peculiarities
  - ✓ it may only lead to **underestimate** the observed  $S_m$ , depending on the radio-purity of the set-up

- the rate **slightly decreases** with time

- simplest behaviour:  $r(t, \text{cpd/kg/keV}) = 0.7598 - 0.1830 \times 10^{-4} \cdot t(\text{day})$

$$\text{faked } S_m \approx \text{slope} \times \frac{(t_{\max} - t_{\min})}{2} = -1.6 \times 10^{-3} \text{ cpd/kg/keV}$$

Remind:

$$S_m(2-6 \text{ keV; phase2}) \approx 10^{-2} \text{ cpd/kg/keV}$$

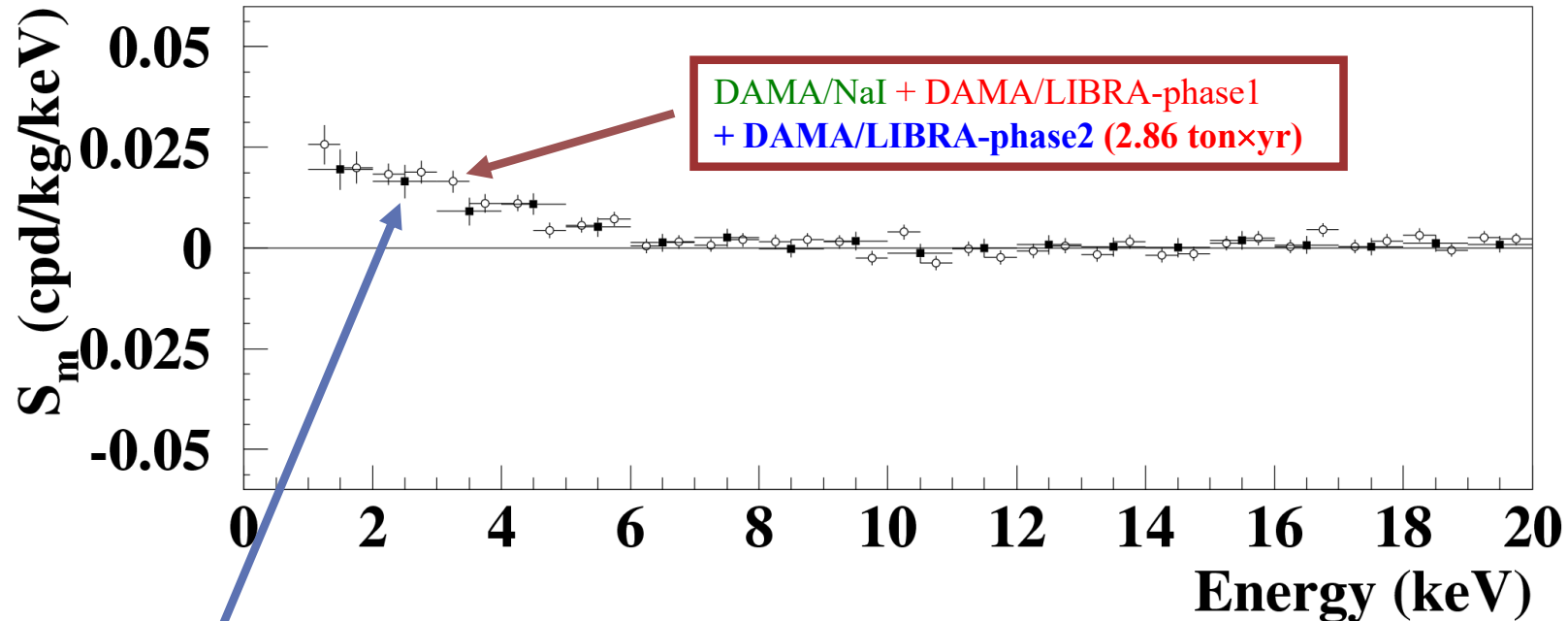


Thus, positive faked  $S_m$  excluded; only possible **underestimate**: about 16% of  $S_m$

## Max-likelihood analysis

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

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



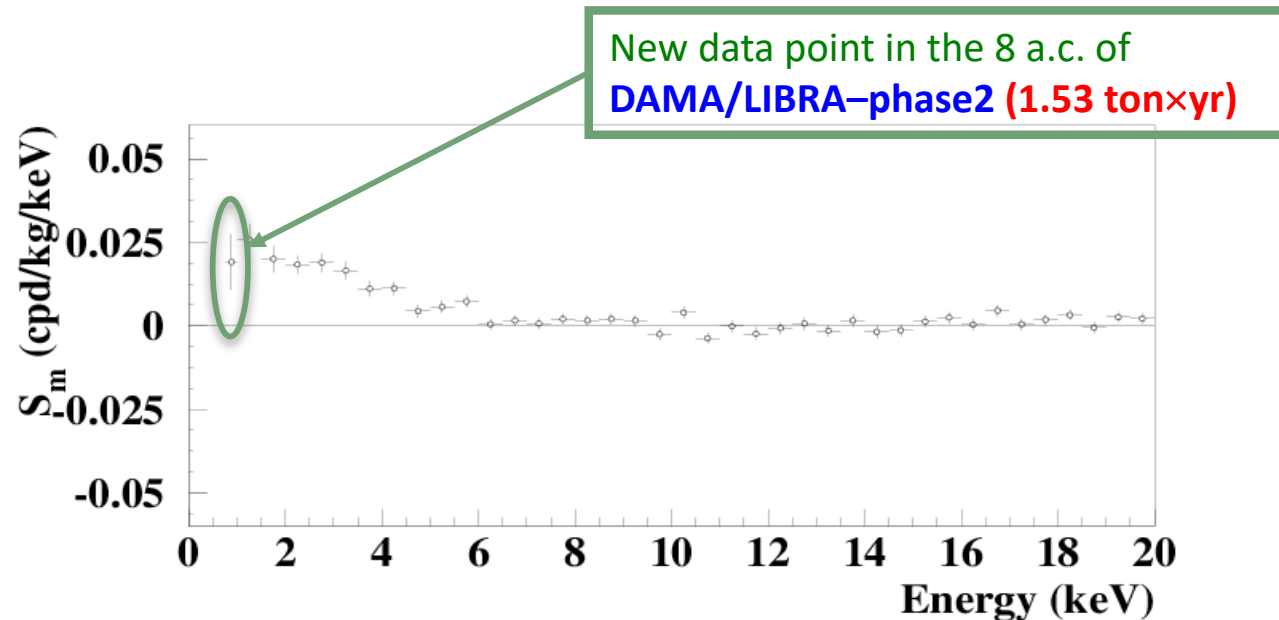
Black squared data points: the **last three published years of DAMA/LIBRA-phase2 (0.61 ton×yr)**, with common (**constant**) background

$$\mu_{ijk} = b_{jk} + S_{0,k} + S_{m,k} \cos[\omega(t_i - t_0)]$$

Thus, the evaluation of the modulation amplitudes does NOT depend on the methods

## First attempt towards further lowering of the software energy threshold

- decreasing the software energy threshold down to 0.75 keV in the already published exposure of DAMA/LIBRA-phase2
- using the same technique to remove the noise pulses
- evaluating the efficiency by dedicated studies



- ❑ 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 suggests the necessity to lower the software energy threshold and to improve the experimental error on the first energy bin

## DAMA/LIBRA-phase2-empowered: software energy threshold below 1 keV with suitable efficiency

After some years of developments, [in Fall 2021](#), DAMA/LIBRA-phase2 has been heavily upgraded:

- a. equipping all the PMTs with new low-background [voltage dividers with pre-amps](#) on the same board
- b. using [Transient Digitizers](#) with higher vertical resolution (14 bits).

### The features of the voltage divider+preamp system:

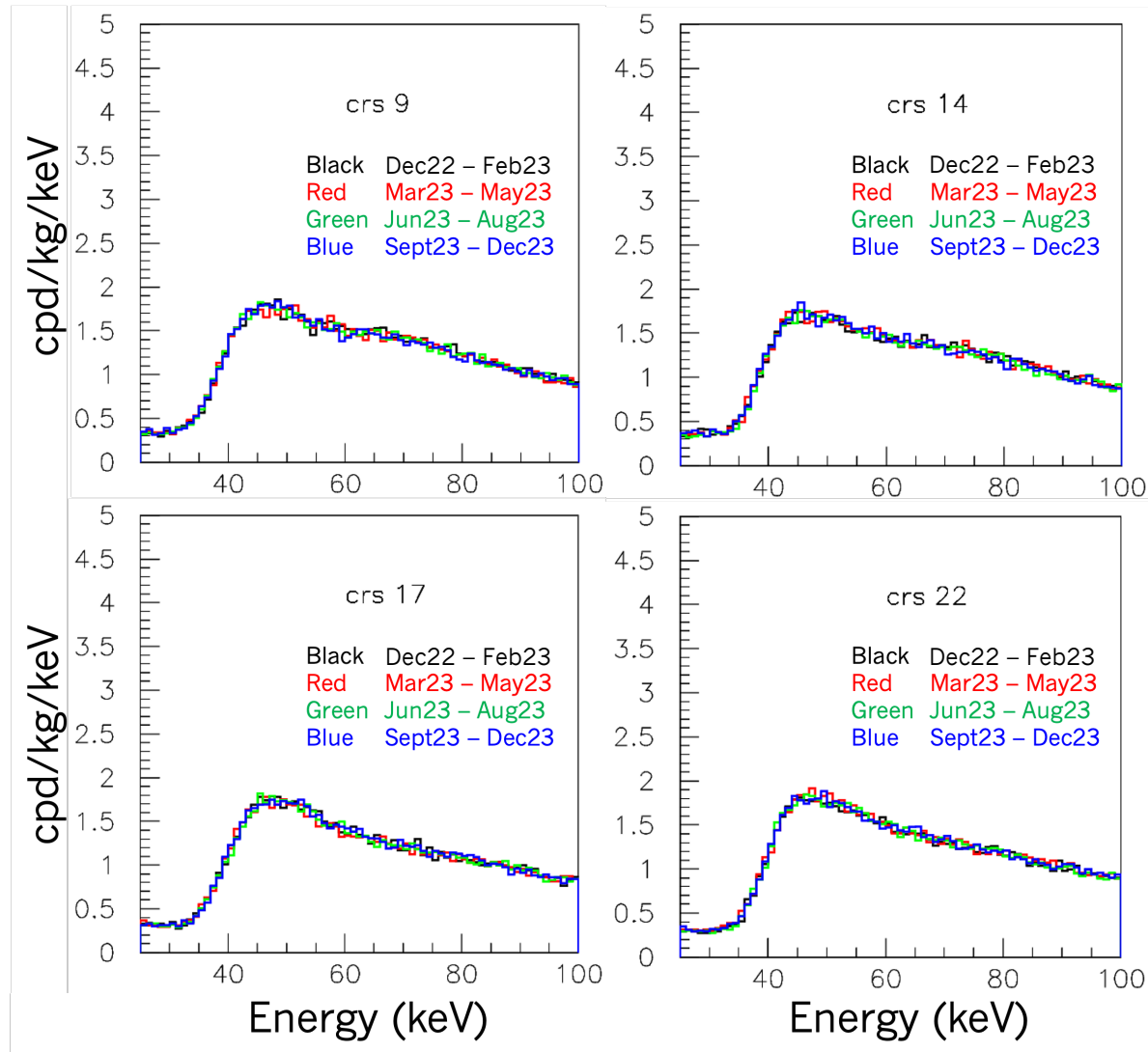
- S/N improvement  $\approx 3.0-9.0$ ;
- discrimination of the single ph.el. from electronic noise: 3 - 8;
- the Peak/Valley ratio: 4.7 - 11.6;
- residual radioactivity lower than that of single PMT



- 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  \$\mu\text{V}\$](#) , ranging between 110 and 190  $\mu\text{V}$
- Software Trigger Level (**STL**) **decreased** in the offline analysis
- “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

## Example: stability of the energy scale in -empowered

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



- Just few examples
- The detectors are underground since decades (\*) and the  $^{129}\text{I}$  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  $\text{HPN}_2$  and without exposure to neutron sources

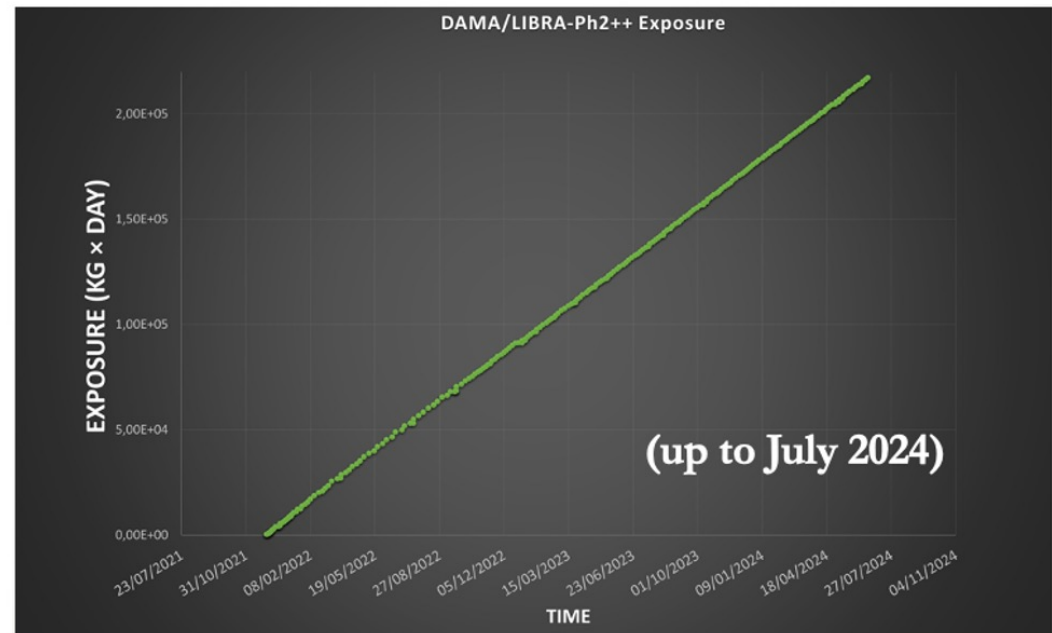
Full empowered data under analyses, paper in preparation – wait for more

Data taking has been continued without interruptions, with regular calibration runs

- ✓ Calibrations:  $\approx 7.75 \times 10^7$  evts from sources
- ✓ Acceptance window eff. per all crystals:  $\approx 4.35 \times 10^7$  evts ( $\approx 1.74 \times 10^6$  evts/keV)

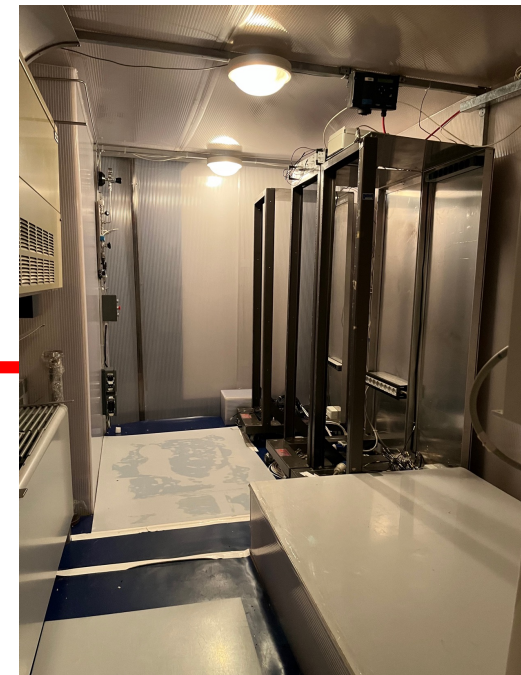
Exposure of DAMA/LIBRA-phase2-empowered up to July 24:

**0.558 ton  $\times$  yr**      **$(\alpha - \beta^2) \approx 0.501$**



- Dismounted read-out, electronics, cables, etc. at end of Sept. 2024
- Data analysis in progress in 2025 for data collected up to July 2024

Low-level of DAMA/LIBRA empty



## Model independent experimental result from DAMA/NaI+DAMA/LIBRA-phase1+phase2 (2.46 ton × yr )

Presence of modulation over 20 annual cycles at about 13  $\sigma$  C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 20 independent experiments of 1 year each one

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

1)

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

2)

Measured period is equal to  $(0.999 \pm 0.001)^*$  yr, well compatible with the 1 yr period, as expected for the DM signal

3)

Measured phase  $(145 \pm 5)^*$  days is well compatible with the roughly about 152.5 days as expected for the DM signal

4)

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

5)

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

6)

The measured modulation amplitude in NaI(Tl) of the *single-hit* events is:  $(0.0103 \pm 0.0008)^*$  cpd/kg/keV (about 13  $\sigma$  C.L.).

\* Here 2-6 keV energy interval

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available



.. And more:  
Phase2- empowered data under  
analyses, paper in preparation

## Model independent experimental result from DAMA/NaI+DAMA/LIBRA-phase1+phase2 (2.46 ton × yr )

Presence of modulation over 20 annual cycles at about 13  $\sigma$  C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 20 independent experiments of 1 year each one

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

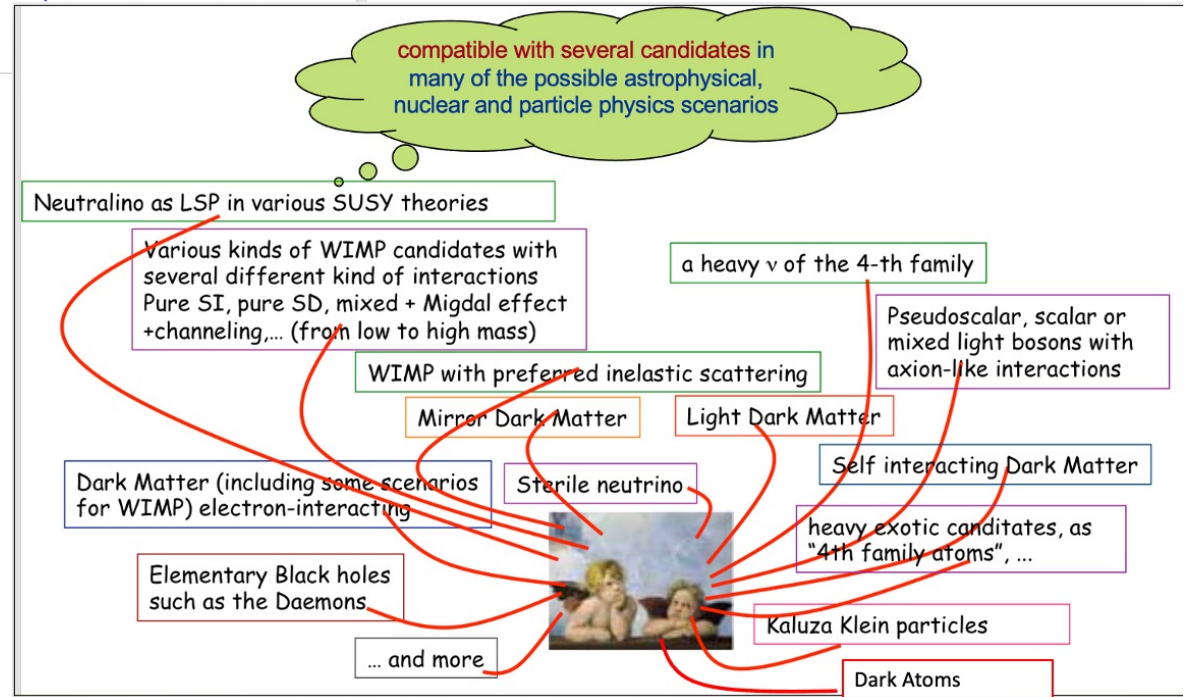
- 1) 1) The *single-hit* events show a clear cosine-like modulation, as expected for the DM signal
- 2) 2) Measured period is equal to  $(0.999 \pm 0.001)^* \text{ yr}$ , well compatible with the 1 yr period, as expected for the DM signal
- 3) 3) Measured phase  $(145 \pm 5)^* \text{ days}$  is well compatible with the roughly about 152.5 days as expected for the DM signal
- 4) 4) The modulation is present only in the low energy (2–6) keV energy interval and not in other higher energy regions, consistently with expectation for the DM signal
- 5) 5) The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal
- 6) 6) The measured modulation amplitude in NaI(Tl) of the *single-hit* events is:  $(0.0103 \pm 0.0008)^* \text{ cpd/kg/keV}$  (about 13  $\sigma$  C.L.).

\* Here 2–6 keV energy interval

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available



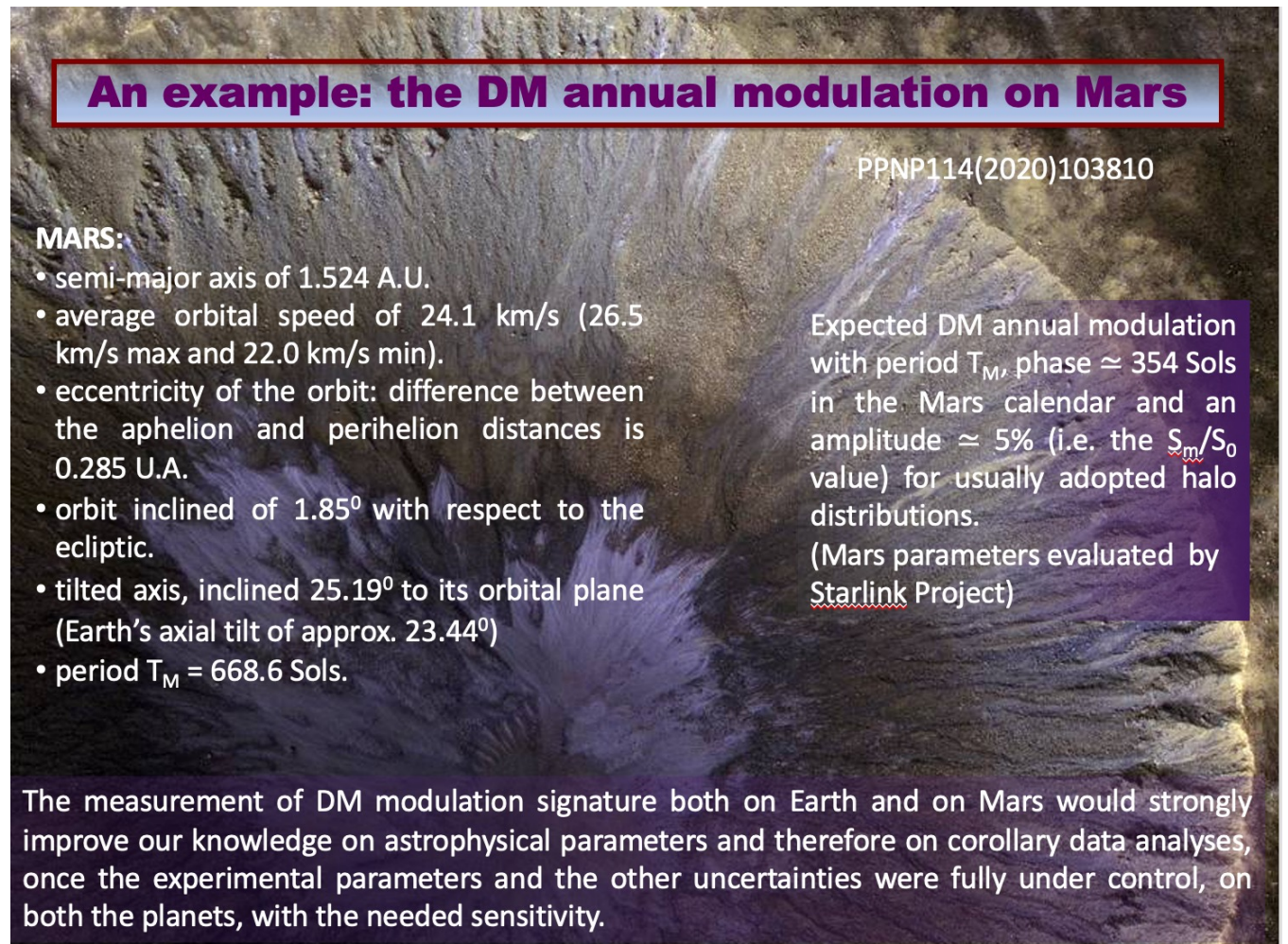
.. And more:  
Phase2- empowered data under  
analyses, paper in preparation



## Other signatures for DM?

- *Second order effects* EPJC 74 (2014)2827
- *Diurnal effects* EPJC74(2014)2827
- *Shadow effects* EPJC75 (2015) 239 (only for high cross section candidates)
- *Directionality* N.Cim.C15(1992)475; EPJC28(2003)203; EPJC73(2013)2276,  
IJMPA 32(2017)1743009, IJMPA**37**(2022)2240013, etc.  
(only for DM candidates inducing just nuclear recoils)

... and long-term future:



**An example: the DM annual modulation on Mars**

PPNP114(2020)103810

**MARS:**

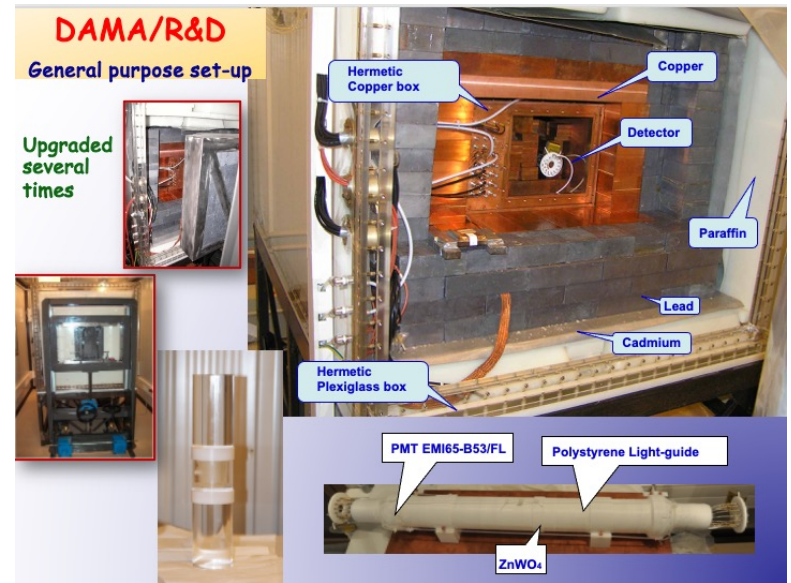
- semi-major axis of 1.524 A.U.
- average orbital speed of 24.1 km/s (26.5 km/s max and 22.0 km/s min).
- eccentricity of the orbit: difference between the aphelion and perihelion distances is 0.285 U.A.
- orbit inclined of  $1.85^\circ$  with respect to the ecliptic.
- tilted axis, inclined  $25.19^\circ$  to its orbital plane (Earth's axial tilt of approx.  $23.44^\circ$ )
- period  $T_M = 668.6$  Sols.

Expected DM annual modulation with period  $T_M$ , phase  $\simeq 354$  Sols in the Mars calendar and an amplitude  $\simeq 5\%$  (i.e. the  $S_m/S_0$  value) for usually adopted halo distributions.  
(Mars parameters evaluated by Starlink Project)

The measurement of DM modulation signature both on Earth and on Mars would strongly improve our knowledge on astrophysical parameters and therefore on corollary data analyses, once the experimental parameters and the other uncertainties were fully under control, on both the planets, with the needed sensitivity.

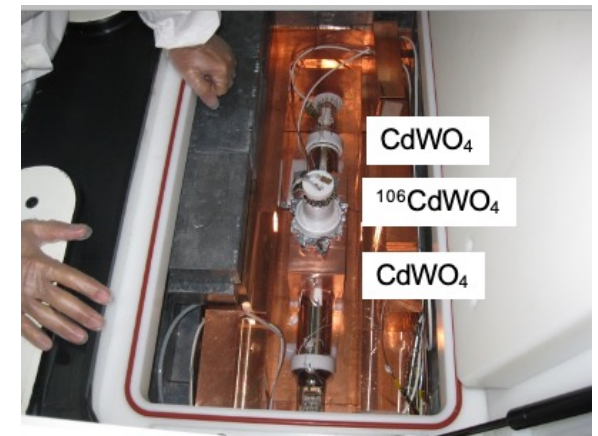
## Time-line of DAMA/R&D set-up

- proposed 1996-1997: setup for testing the prototypes of the R&D-I, -II for the new DAMA/LIBRA detectors and up to R&D-V for DAMA/1ton (proposed in 1996; other 3 replicas of DAMA/LIBRA) but abandoned later because: i) no similar materials and protocols (as e.g. no Pt crucibles and Kyropoulos growth); ii) possibility to increase DAMA/LIBRA sensitivity acting on other parameters
- to 2024: several measurements on various rare processes mainly within signed coll agreements INFN - INR-Kiev + others



## Time-line of DAMA/CRYS set-up

- proposed end 2012: DAMA/CRYS set-up was installed in the same barrack of VIP. This set-up allowed the study of several rare processes in different low-bckg scintillators. The passive shield of the set-up was made of high purity copper, lead, cadmium, and polyethylene. Also this set-up was sealed and continuously flushed by HP-N<sub>2</sub> gas to prevent the detector and other materials to be in contact with the environmental air.
- March 2020: DAMA/CRYS set-up moved to the inner part of the ground floor level of the dismantled DAMA/LXe; the previous DAMA/CRYS site was returned to LNGS
- to 2024: several measurements on small scale experiments and the <sup>106</sup>CdWO<sub>4</sub> expt. whose final results have been published in last days



- Fruitful long collaboration since early 90 to 2025 (regular signed agreements) with INR-Kiev for measurements on many rare processes (leader: Y. Zdesenko<sup>+</sup>, and then F. Danevich)

+ deceased on Sept. 2004

- & more coll. depending on the measurement.

Their first time visiting LNGS



V. Tretyak



## Time-line of GEBER also indicated as DAMA/Ge set-up always sited in the Stella Laboratory

- end '80- beginning '90

Low Z window low-background HPGe realized by company with exchanges with R. Bernabei (suggestions from C. Arpesella and G. Heusser) with funding from Tor Vergata section other than DAMA



- 2003-2004

upgrade of shielding and protocol mainly coordinated by Roma La Sapienza



Measurements for qualifications of powders and samples, for materials for RD-I to RD-V, for other scintillator materials and for some of the RDs on PMTs and new scintillators + small scale experiments

**Over all years also measurements in the  
HPGe of the LNGS Stella Laboratory  
(headed by Dr. M. Laubenstein)**



## In addition to ULB NaI(Tl): developments/measurements in the low-bckg DAMA set-ups

ZnWO <sub>4</sub>	Ukraine	NIMA1029(2022)166400, J. of Lumin. 249 (2022) 119028, EPJA56(2020)83, NIMA935(2019)89, NIMA833(2016)77, PS90(2015)085301, EPJC73(2013)2276, JPG:NPP38(2011)115107, NIMA626-627(2011)31, NPA826(2009)256, PLB658(2008)193	
CdWO <sub>4</sub>	Ukraine	EPJA36(2008)167, PRC76(2007)064603	
}	<sup>106</sup> CdWO <sub>4</sub>	Ukraine	Universe in publ. (2025), NPAE24(2023)193, Univ.6(2020)182, PRC93(2016)045502, PRC85(2012)044610, NIMA615(2010)301, AstroPhys10(1999)115
	<sup>116</sup> CdWO <sub>4</sub>	Ukraine	Phys.Scr.97(2022)085302, PRD98(2018)092007, NIMA833(2016)77, JINST6(2011)08011
Cs <sub>2</sub> HfCl <sub>6</sub>	Canada (by S. Nagorny)	NPA1053(2025)122976, NPA1002(2020)121941	
Cs <sub>2</sub> ZrCl <sub>6</sub>	Canada (by S. Nagorny)	JINST19(2024)P05037, EPJA59(2023)176	
SrI <sub>2</sub>	Ukraine, USA	NIMA670(2012)10, analysis in progress	
CaF <sub>2</sub> (Eu)	Bicron/Crismatec(Saint Gobain)	NPA789(2007)15, NPA705(2002)29, NPB563(1999)97, AstroPhys7 (1997)73	
CeF <sub>3</sub>	Crystal Clear coll. or China	NIMA498(2003)352, NCIM 110A (1997) 189	
BaF <sub>2</sub>	China or Bicron/Saint Gobain	EPJA50(2014) 134, NIMA525(2004)535	
LiF(W)	Ukraine	NPA806(2008)388	
<sup>7</sup> LiI(Eu)	Ukraine	NIM704(2013)40	
LaCl <sub>3</sub> (Ce)	Saint Gobain	Ukr. J. of Phys.51(2006)1037, NIMA555(2005)270	
CeCl <sub>3</sub>	Iltis/Saint Gobain	JPG:NPP38(2011)015103, NPA824 (2009)101	
Li <sub>2</sub> MoO <sub>4</sub>	Ukraine	NIMA607(2009)573	
Li <sub>6</sub> Eu(BO <sub>3</sub> ) <sub>3</sub>	Ukraine	NIMA572(2007)734	
BaWO <sub>4</sub>	Canada (by S. Nagorny)	NIMA901(2018)150	
Rb <sub>2</sub> ZrCl <sub>6</sub>	Canada (by S. Nagorny)	paper in preparation	
GAGG:Ce	Epjc-crystal	analysis in progress	
and polycrystalline powder:	ZnS(Ag)	Saint-Gobain MPLA27, No. 8 (2012)1250031	



# Main results obtained by DAMA in the search for rare processes

- First or improved results in the search for  $2\beta$  decays of  $\sim 30$  candidate isotopes:  $^{40}\text{Ca}$ ,  $^{46}\text{Ca}$ ,  $^{48}\text{Ca}$ ,  $^{64}\text{Zn}$ ,  $^{70}\text{Zn}$ ,  $^{100}\text{Mo}$ ,  $^{96}\text{Ru}$ ,  $^{104}\text{Ru}$ ,  $^{106}\text{Cd}$ ,  $^{108}\text{Cd}$ ,  $^{114}\text{Cd}$ ,  $^{116}\text{Cd}$ ,  $^{112}\text{Sn}$ ,  $^{124}\text{Sn}$ ,  $^{134}\text{Xe}$ ,  $^{136}\text{Xe}$ ,  $^{130}\text{Ba}$ ,  $^{136}\text{Ce}$ ,  $^{138}\text{Ce}$ ,  $^{142}\text{Ce}$ ,  $^{144}\text{Sm}$ ,  $^{154}\text{Sm}$ ,  $^{150}\text{Nd}$ ,  $^{156}\text{Dy}$ ,  $^{158}\text{Dy}$ ,  $^{162}\text{Er}$ ,  $^{168}\text{Yb}$ ,  $^{180}\text{W}$ ,  $^{186}\text{W}$ ,  $^{184}\text{Os}$ ,  $^{192}\text{Os}$ ,  $^{190}\text{Pt}$  and  $^{198}\text{Pt}$  (observed  $2\nu 2\beta$  decay in  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ ,  $^{150}\text{Nd}$ )
- One of the best experimental sensitivities in the field for  $2\beta$  decays with positron emission ( $^{106}\text{Cd}$ )

First observation of  $\alpha$  decays of  $^{151}\text{Eu}$  with a  $\text{CaF}_2(\text{Eu})$  scintillator

First observation of  $\alpha$  decay of  $^{190}\text{Pt}$  to the first excited level ( $E_{\text{exc}} = 137.2$  keV) of  $^{186}\text{Os}$

First observation of  $\alpha$  decays of  $^{174}\text{Hf}$  the measured half-life is in good agreement with the theoretical predictions

Investigations of rare  $\beta$  decays of  $^{113}\text{Cd}$  and  $^{113\text{m}}\text{Cd}$  with  $\text{CdWO}_4$  scintillators and of  $^{48}\text{Ca}$  with a  $\text{CaF}_2(\text{Eu})$  detector

Observation of correlated  $e^+e^-$  pairs emission in  $\alpha$  decay of  $^{241}\text{Am}$  ( $A_{e^+e^-}/A_\alpha \approx 5 \times 10^{-9}$ )

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

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

Search for solar axions by Primakoff effect

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

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

Search for PEP violating processes in Sodium and in Iodine

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

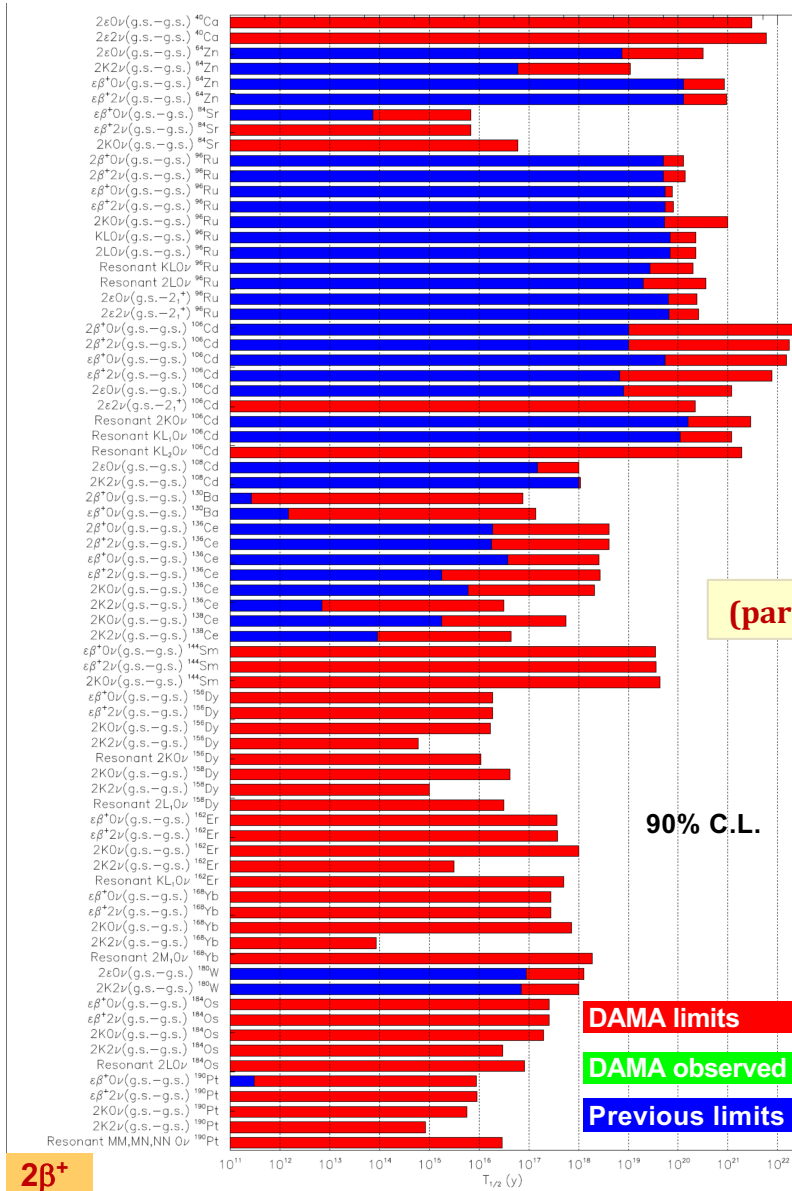
Search for long-lived super-heavy eka-tungsten with  $\text{ZnWO}_4$  and  $\text{CdWO}_4$

Best sensitive meas. of  $2\beta$  decays of  $^{150}\text{Nd}$  to  $0^+_1$  level and first observation to  $2^+_1$  level of  $^{150}\text{Sm}$

Dark Matter model-indep & model-dep investigations with several methodologic approaches

... and many others

# Searches for $2\beta^-$ decay modes in various isotopes at DAMA set-ups and in STELLA HPGe facility

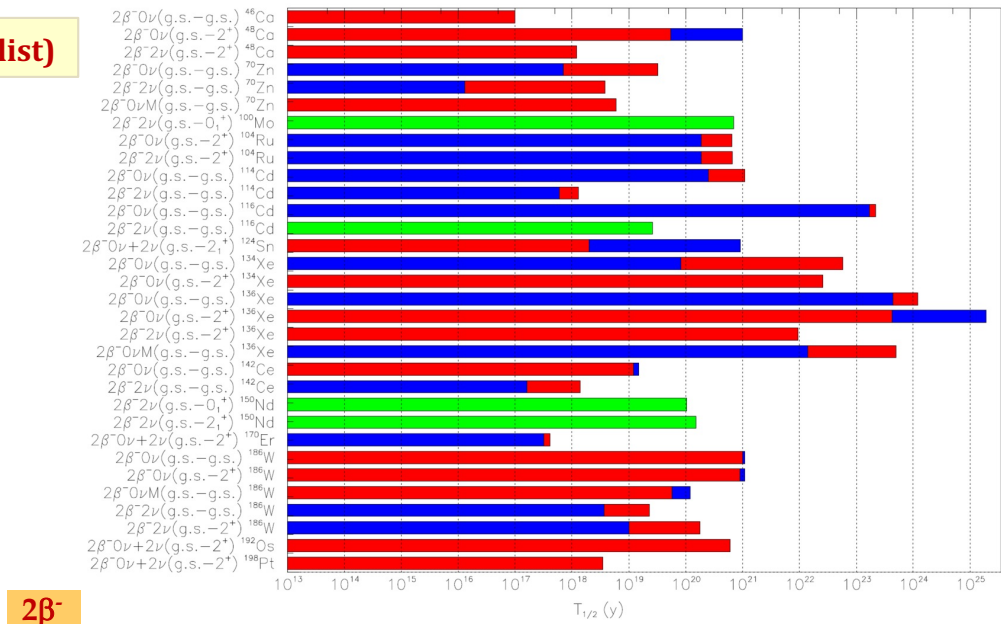


**New observations:**

Experiment	Decay Mode	Reference
ARMONIA	$2\nu 2\beta^-$ decay $^{100}\text{Mo} \rightarrow ^{100}\text{Ru}(0_1^+)$	NPA846(2010)143
AURORA	$2\nu 2\beta^-$ decay $^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	PRD98(2018)092007
Nd <sub>2</sub> O <sub>3</sub> -HPGe	$2\nu 2\beta^-$ decay $^{150}\text{Nd} \rightarrow ^{150}\text{Sm}(0_1^+)$	EPJC85(2025)174
	$2\nu 2\beta^-$ decay $^{150}\text{Nd} \rightarrow ^{150}\text{Sm}(2_1^+)$	EPJC85(2025)174

DAMA and DAMA-Kiev

$^{40}\text{Ca}$ ,  $^{48}\text{Ca}$ ,  $^{64}\text{Zn}$ ,  $^{70}\text{Zn}$ ,  $^{100}\text{Mo}$ ,  $^{96}\text{Ru}$ ,  $^{104}\text{Ru}$ ,  $^{106}\text{Cd}$ ,  $^{108}\text{Cd}$ ,  $^{114}\text{Cd}$ ,  $^{116}\text{Cd}$ ,  $^{112}\text{Sn}$ ,  $^{124}\text{Sn}$ ,  $^{134}\text{Xe}$ ,  $^{136}\text{Xe}$ ,  $^{130}\text{Ba}$ ,  $^{136}\text{Ce}$ ,  $^{138}\text{Ce}$ ,  $^{142}\text{Ce}$ ,  $^{148}\text{Nd}$ ,  $^{150}\text{Nd}$ ,  $^{144}\text{Sm}$ ,  $^{154}\text{Sm}$ ,  $^{156}\text{Dy}$ ,  $^{158}\text{Dy}$ ,  $^{162}\text{Er}$ ,  $^{170}\text{Er}$ ,  $^{168}\text{Yb}$ ,  $^{176}\text{Yb}$ ,  $^{180}\text{W}$ ,  $^{186}\text{W}$ ,  $^{184}\text{Os}$ ,  $^{192}\text{Os}$ ,  $^{190}\text{Pt}$ ,  $^{198}\text{Pt}$



Thanks to the developments on **crystal scintillators**, **competitive results** obtained on lifetime of  $2\beta^+$ ,  $\epsilon\beta^+$  and  $2\epsilon$  processes; **first searches** for **resonant  $0\nu 2\epsilon$**  decays in some isotopes

## Just some most recent published results other than DM

*Eur. Phys. J. C* **85** (2025) 174

**A) The  $2\nu 2\beta$  decay of  $^{150}\text{Nd}$**  to the first excited 740.5 keV  $0_1^+$  level of  $^{150}\text{Sm}$  measured **over 5.845 yr** with the help of a 4-crystal low-background HPGe  $\gamma$  spectrometry system in the STELLA laboratory, with indication of  $2\nu 2\beta$  decay the  $2^+_{1}$  excited level of  $^{150}\text{Sm}$

3 kg of  $\text{Nd}_2\text{O}_3$  used in the previous measurements [JETP-Lett.79(2004)52] additionally purified with liquid-liquid extraction (First, the oxide was converted to chloride:  
 $\text{Nd}_2\text{O}_3 + 6\text{HCl} \rightarrow 2\text{NdCl}_3 + 3\text{H}_2\text{O}$ )

# Just some most recent published results other than DM

*Eur. Phys. J. C* **85** (2025) 174

**A) The  $2\nu 2\beta$  decay of  $^{150}\text{Nd}$  to the first excited  $740.5 \text{ keV } 0^+_{1st}$  level of  $^{150}\text{Sm}$  measured over 5. background HPGe  $\gamma$  spe with indication of  $2\nu 2\beta$  de**

3 kg of  $\text{Nd}_2\text{O}_3$  used in the measurements [JETP-Let additionally purified with liquid-liquid extraction (f converted to chloride:  
 $\text{Nd}_2\text{O}_3 + 6\text{HCl} \rightarrow 2\text{NdCl}_3 + 3\text{H}_2\text{O}$

Chain	Nuclide	Activity (mBq/kg)	
		Before purification	After purification
	$^{40}\text{K}$	$16 \pm 8$	$3.4 \pm 0.7$
	$^{138}\text{La}$		$0.095 \pm 0.007$
	$^{150}\text{Eu}$		$\leq 0.037$
	$^{176}\text{Lu}$	$1.1 \pm 0.4$	$0.30 \pm 0.02$
$^{232}\text{Th}$	$^{228}\text{Ra}$	$\leq 2.1$	$0.13 \pm 0.08$
	$^{228}\text{Th}$	$\leq 1.3$	$0.37 \pm 0.06$
$^{235}\text{U}$	$^{235}\text{U}$	$\leq 1.7$	$0.8 \pm 0.2$
	$^{231}\text{Pa}$		$\leq 0.29$
	$^{227}\text{Ac}$		$0.46 \pm 0.08$
$^{238}\text{U}$	$^{238}\text{U}$	$\leq 28$	$\leq 3.8$
	$^{226}\text{Ra}$	$15 \pm 0.8$	$\leq 0.18$
	$^{210}\text{Pb}$		$\leq 178$

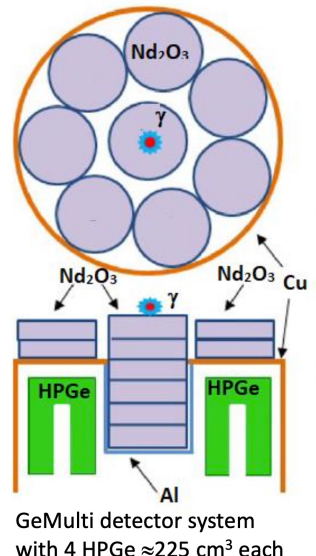
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*Eur. Phys. J. C* **85** (2025) 174

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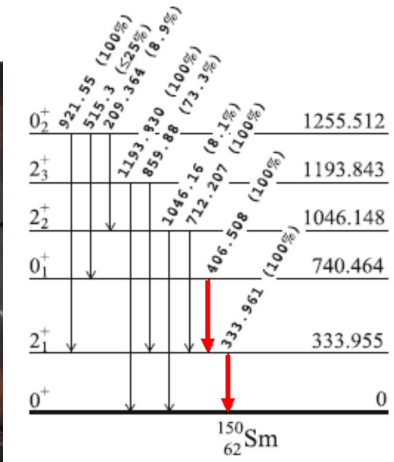
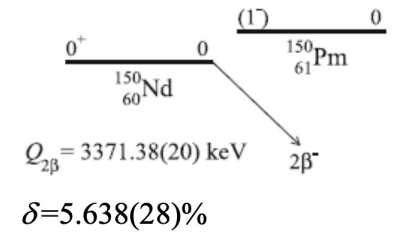
3 kg of  $\text{Nd}_2\text{O}_3$  used in the previous measurements [JETP-Lett.79(2004)52] additionally purified with liquid-liquid extraction (First, the oxide was converted to chloride:  
 $\text{Nd}_2\text{O}_3 + 6\text{HCl} \rightarrow 2\text{NdCl}_3 + 3\text{H}_2\text{O}$ )

Nd concentration:  $(73.1 \pm 1.2)\%$   
 In the sample also Cl and  $\text{CO}_2$  (few %), while Eu concentration of Eu <5 ppb



2.381 kg of Nd-containing material  $\Rightarrow$   
 1.74 kg of Nd  $\Rightarrow$   
**98 g of  $^{150}\text{Nd}$**

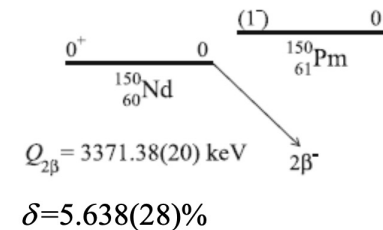
10 cm HP-Cu 20 cm PB in a Plexiglas box continuously flushed by HP-N<sub>2</sub> gas; LNGS underground laboratory ( $\sim 3.8\text{ km w.e.}$ )



# Just some most recent published results other than DM

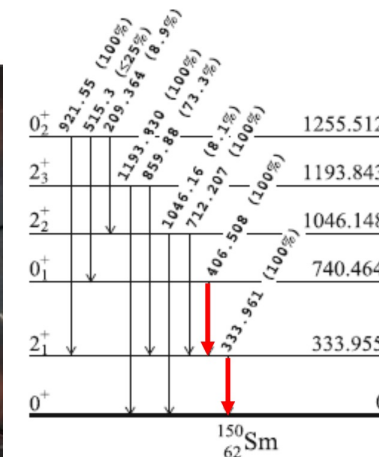
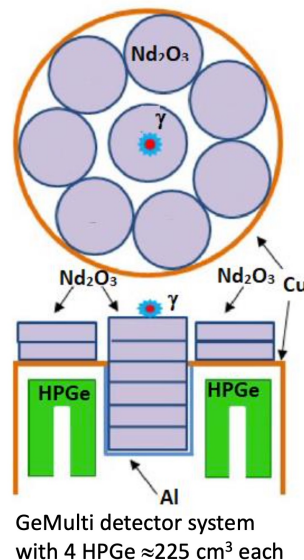
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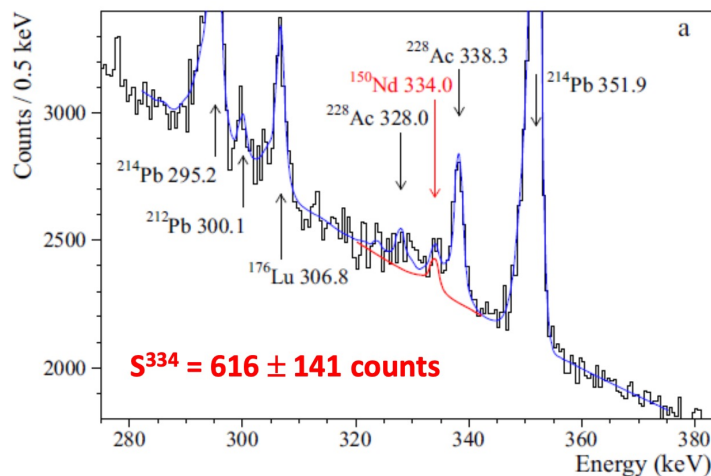
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Nd concentration:  $(73.1 \pm 1.2)\%$   
 In the sample also Cl and  $\text{CO}_2$  (few %), while Eu concentration of Eu <5 ppb

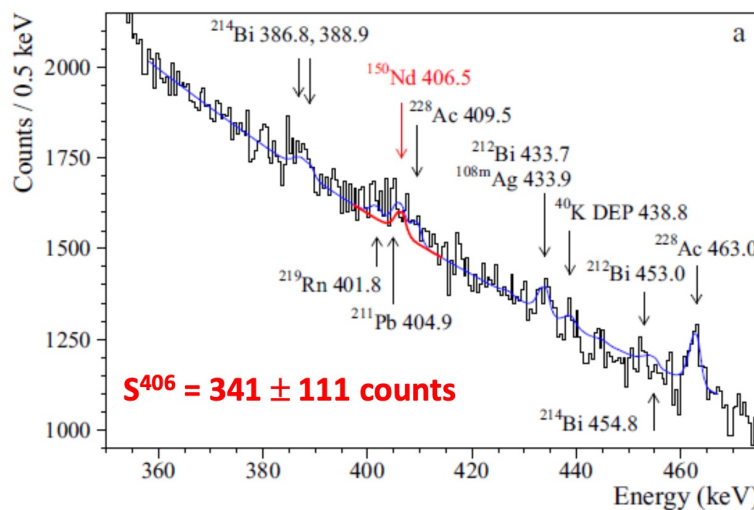


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10 cm HP-Cu 20 cm PB in a Plexiglas box continuously flushed by HP-N<sub>2</sub> gas; LNGS underground laboratory ( $\sim 3.8\text{ km w.e.}$ )

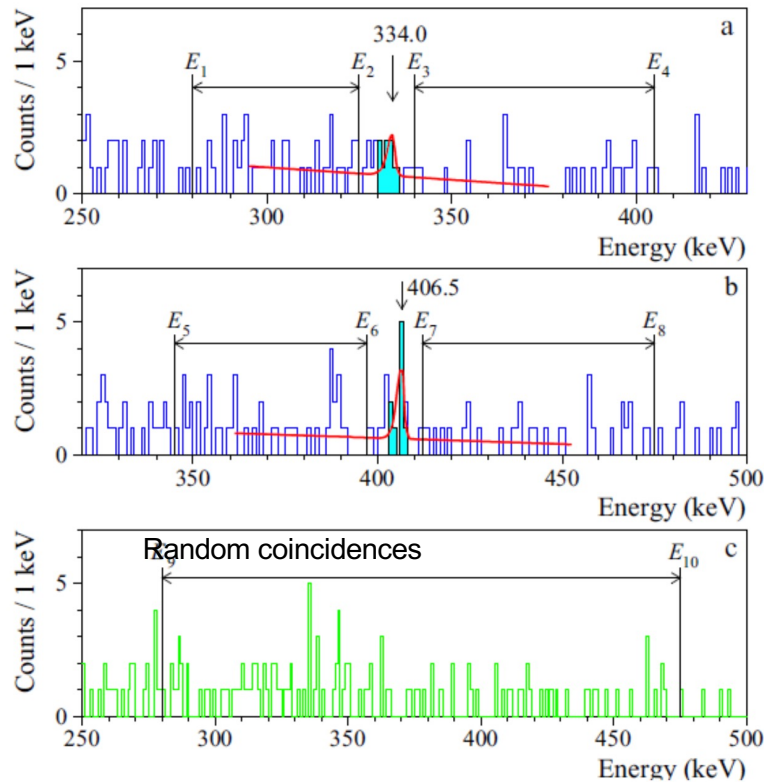


$\gamma$  peak at 334 keV observed in 1-dimensional data



$\gamma$  peak at 406 keV observed in 1-dimensional data

For residual contaminations, bckg model and details see ref. above



Expected  $\gamma$ 's from the  $0_1^+$  level with 334.0 keV and 406.5 keV were observed both in one-dimensional spectrum and in coincidence data resulting in

$$T_{1/2} = [0.83_{-0.13}^{+0.18}(\text{stat})_{-0.19}^{+0.16}(\text{syst})] \times 10^{20} \text{ yr}$$

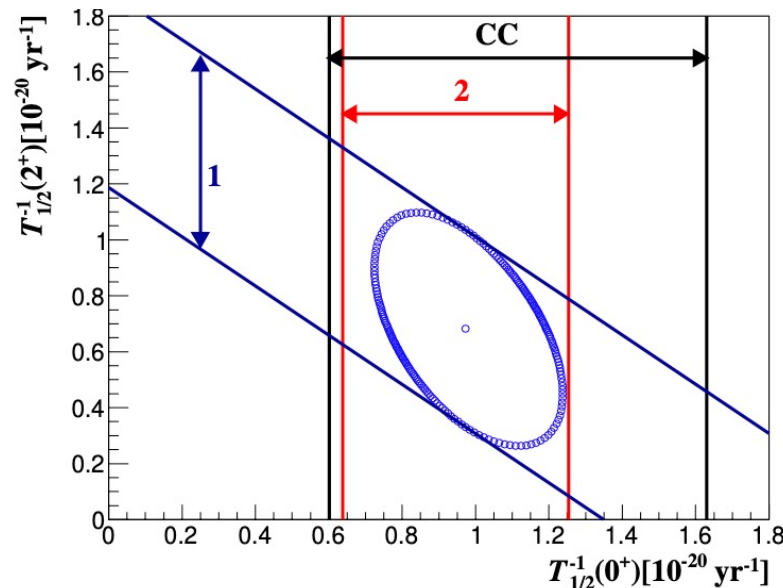
Interpreting the excess of the 334.0-keV peak area as an indication of the  $2\beta$  decay of  $^{150}\text{Nd}$  to the 334.0 keV  $2_1^+$  excited level of  $^{150}\text{Sm}$  with a half-life:

$$T_{1/2} = [1.5_{-0.6}^{+2.3}(\text{stat}) \pm 0.4(\text{syst})] \times 10^{20} \text{ yr}$$

the  $2\nu 2\beta$  half-life of  $^{150}\text{Nd}$  for the transition to the  $0_1^+$  level:

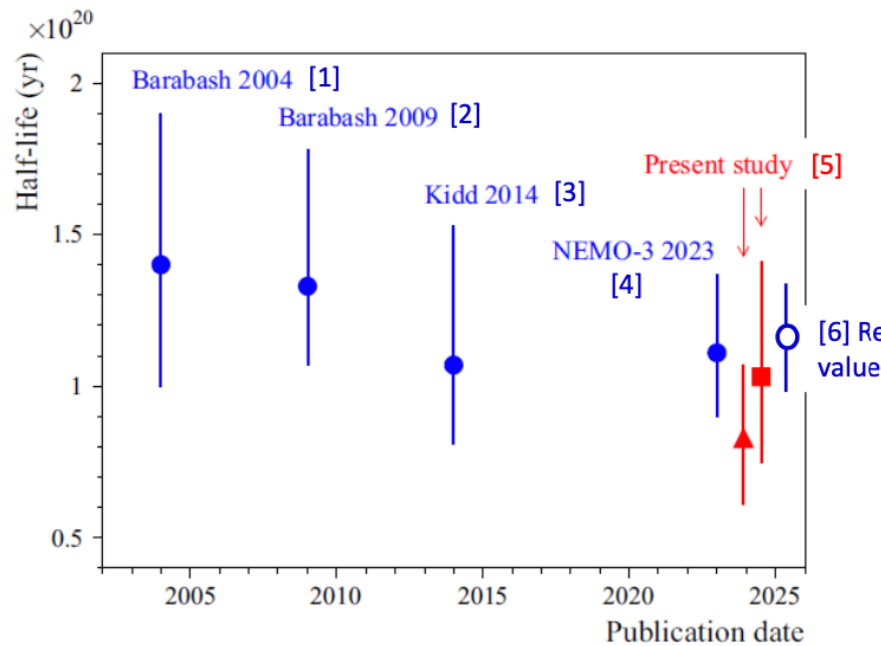
$$T_{1/2} = [1.03_{-0.22}^{+0.35}(\text{stat})_{-0.19}^{+0.16}(\text{syst})] \times 10^{20} \text{ yr}$$

in agreement with the previous experiments.



1- $\sigma$  contour and best fit value in the plane with coordinates equal to the inverses of the half-lives of the two processes:  $2\nu 2\beta$  decay of  $^{150}\text{Nd}$  to the  $0_1^+$  and to the  $2_1^+$  excited levels of  $^{150}\text{Sm}$ . The 1- $\sigma$  bands that are achievable when considering only either the 1, or 2, or CC method of analysis

For  $2\nu 2\beta$  and  $0\nu 2\beta$  transitions of  $^{150}\text{Nd}$  and  $^{148}\text{Nd}$  to several excited levels of  $^{150}\text{Sm}$  and  $^{148}\text{Sm}$ , limits were set at level of  $T_{1/2} > 10^{20} - 10^{21} \text{ yr}$



[1] A.S. Barabash et al., JETP Lett. 79, 10 (2004) 52  
 [2] A.S. Barabash et al., Phys. Rev. C 79 (2009) 045501  
 [3] M.F. Kidd et al., Phys. Rev. C 90 (2014) 055501 (2014)  
 [4] X. Aguerre et al., Eur. Phys. J. C 83 (2023) 1117  
 [5] P. Belli et al., Eur. Phys. J. C 85 (2025) 174  
 [6] B. Pritychenko, V.I. Tretyak, At. Data Nucl. Data Tables. 161 (2025) 101694

Both  $T_{1/2}$  reasonably agree with the theoretical calculations in the framework of proton-neutron QRPA with isospin restoration combined with like nucleon QRPA for description of excited states in the final nuclei:

Transition $^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	$g_A^{\text{eff}}$	Theoretical $T_{1/2}$ (yr)	Experiment (yr)
$0^+ \rightarrow 0^+$	1.276	$9.34 \times 10^{18}$	$9.3(7) \times 10^{18}$ yr [1]
	0.957	$9.31 \times 10^{18}$	
$0^+ \rightarrow 0^+_1$	1.276	$0.43 \times 10^{20}$	$1.03^{+0.38}_{-0.29} \times 10^{20}$
	0.957	$1.19 \times 10^{20}$	
$0^+ \rightarrow 2^+_1$	1.276	$1.32 \times 10^{20}$ *)	$1.5^{+2.3}_{-0.7} \times 10^{20}$
	0.957	$4.18 \times 10^{20}$	

[1] X. Aguerre et al., Eur. Phys. J. C 83 (2023) 1117

The experimental sensitivity can be improved with a sample of about 40 g of enriched  $^{150}\text{Nd}$  between two ultra-low background HPGe detectors.

**$\alpha$  decay:** From 7 naturally occurring Nd isotopes, 5 are unstable for  $\alpha$  decay ( $^{143}\text{Nd}$ ,  $^{144}\text{Nd}$ ,  $^{145}\text{Nd}$ ,  $^{146}\text{Nd}$ ,  $^{148}\text{Nd}$ ). If these decays are accompanied by  $\gamma$  quanta, we can search for them:

1.  $^{143}\text{Nd}$  and  $^{145}\text{Nd}$ : previously known  $T_{1/2}$  limits of  $\sim 10^{17}$  yr improved by 2 – 3 orders of magnitude;
2.  $^{144}\text{Nd}$ : the **first limit** for the decay to the first excited  $^{140}\text{Ce}$  level at 1596.2 keV set at  $9.3 \times 10^{20}$  yr;
3.  $^{146}\text{Nd}$ : the previous best limit of  $\sim 10^{18}$  yr for the decay to the first excited  $^{142}\text{Ce}$  level at 641.3 keV **improved** by 3 orders of magnitude;
4.  $^{148}\text{Nd}$ : the **first experimental  $T_{1/2}$  limit** set:  $4.2 \times 10^{18}$  yr

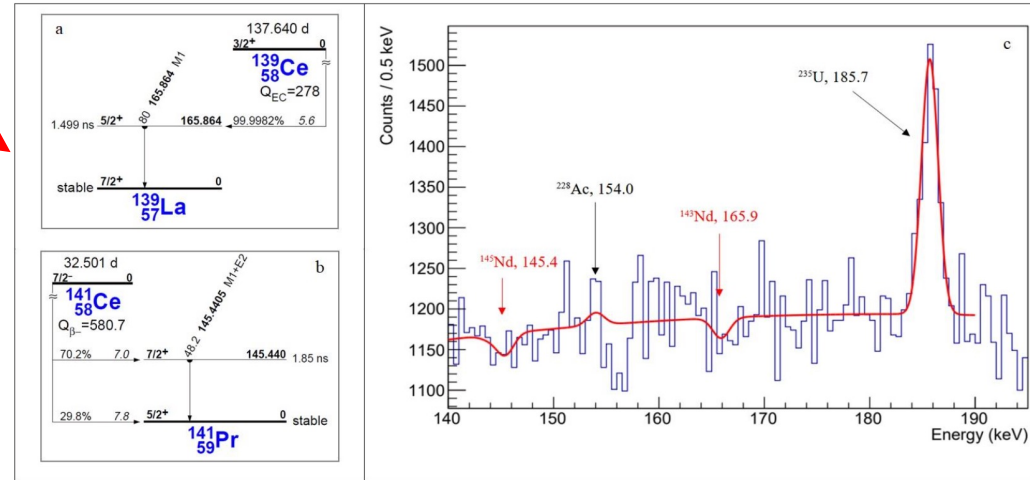


Fig. 3. Left: Schemes of the decay of  $^{139}\text{Ce}$  (a) and  $^{141}\text{Ce}$  (b) [50]. Right: Part of the energy spectrum of the detector 2 at low energies measured during 51237 h, and its fit (c).

**$2\alpha$  decay.** New mode of nuclear decay, “reopened” in [3]. Theoretical estimations are very different (up to 50 orders of magnitude, see [3,4,5]). However, for symmetric  $2\alpha$  decay (2  $\alpha$  emitted in opposite directions with equal energies),  $T_{1/2}$  are lower, sometimes by many orders of magnitude.

4 natural Nd isotopes are theoretically unstable in relation to  $2\alpha$  decay ( $^{144}\text{Nd}$ ,  $^{145}\text{Nd}$ ,  $^{146}\text{Nd}$ ,  $^{148}\text{Nd}$ ). For  $^{146}\text{Nd}$ ,  $2\alpha$  decay is estimated as faster than usual  $\alpha$  decay [5]. Only for  $^{148}\text{Nd}$  the process is accompanied by  $\gamma$ :

5. Also for  $^{148}\text{Nd}$ , we set the **first experimental limit** for  $2\alpha$  decay as  $2.1 \times 10^{20}$  yr (this can be compared with the only known limit for  $^{209}\text{Bi}$   $T_{1/2} > 2.9 \times 10^{20}$  yr [28]).

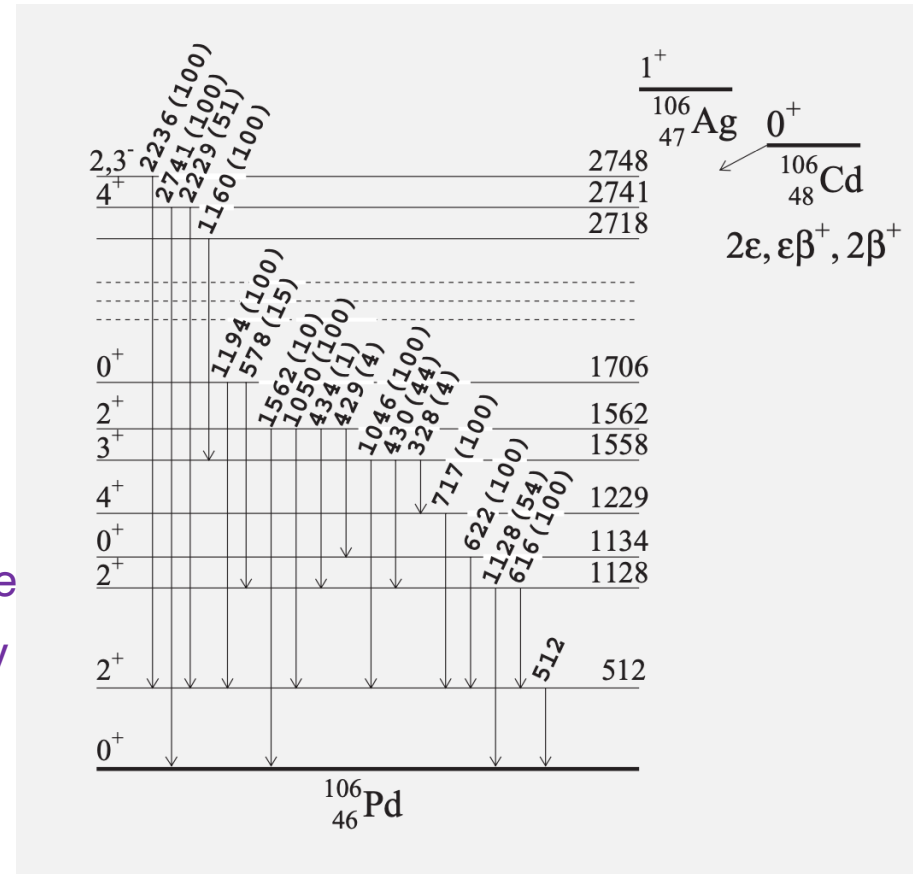
**Nevertheless, we have to note that the obtained  $T_{1/2}$  limits are still very far from the theoretical predictions, with exception of  $^{145}\text{Nd}$ , whose  $\alpha$  decay could be registered in future experiments.**

[1] G. Kauw, Landes Nordrhein-Westfalen No.1640 (1966).  
 [2] C. Stengl et al., Int. J. Mod. Phys. E 24 (2015) 1550043.  
 [3] V.I. Tretyak, Nucl. Phys. At. Energy 22 (2021) 121.  
 [4] K.P. Santhosh et al., Phys. Rev. C 104 (2021) 064604.  
 [5] V.Yu. Denisov, Phys. Lett. B 835 (2022) 137569.

**B) New stage of the search for  $2\beta$  decay of  $^{106}\text{Cd}$**  with a  $\text{CdWO}_4$  scintillator enriched (66%) in  $^{106}\text{Cd}$  ( $^{106}\text{CdWO}_4$ ) in coincidence and anticoincidence with two  $\text{CdWO}_4$  scintillation counters scintillator at the DAMA/R&D set-up



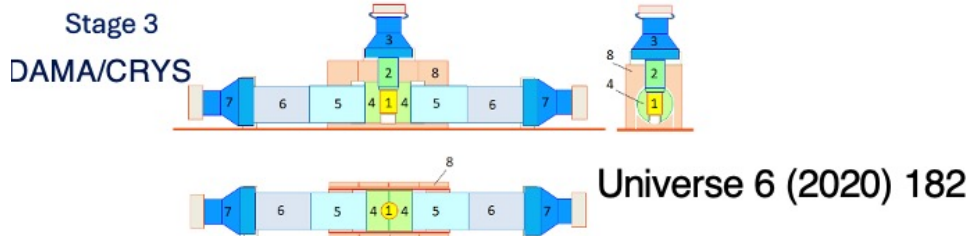
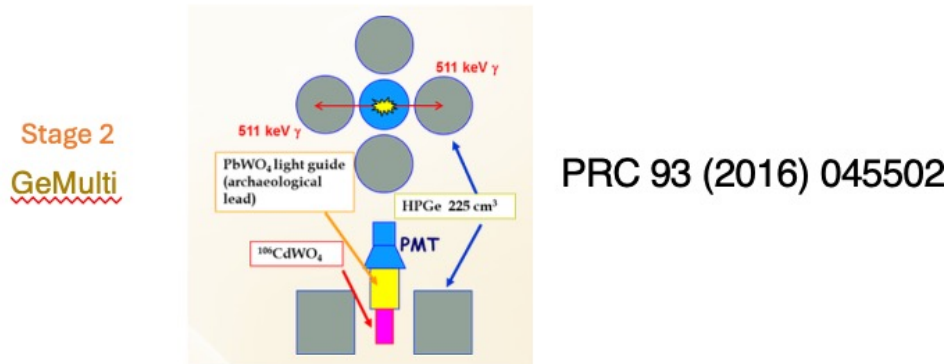
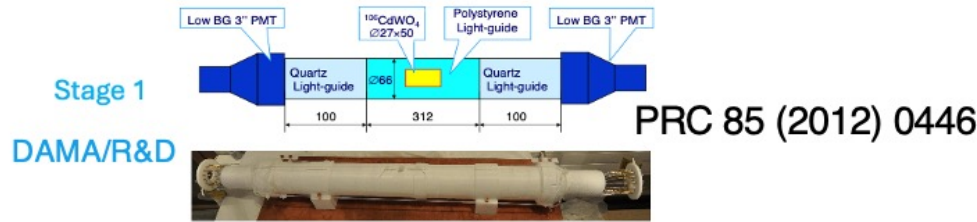
- One of the highest  $2\beta^+$  decay energy:  
 $Q_{2\beta} = 2775.39 (0.10) \text{ keV}$ ;
- Relatively high isotopic abundance:  $\delta = 1.245(22) \%$   
+ Possibility of enrichment by gas centrifugation;
- Favorable theoretical predictions for half-lives for some  $2\nu$  modes ( $T_{1/2} \sim 10^{21} - 10^{22} \text{ yr}$ ) that could be reached by modern techniques;
- Possibility of «near resonant»  $0\nu 2\varepsilon$  to excited levels of  $^{106}\text{Pd}$ ;
- Existing technologies of Cd purification and availability of Cd-based calorimetric detectors with high detection efficiency.



**Positive channels:**

**less studied but easier to identify  $\rightarrow$  complementary information to  $0\nu 2\beta^-$  + resonant effect**

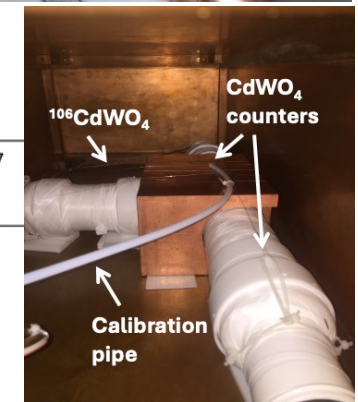
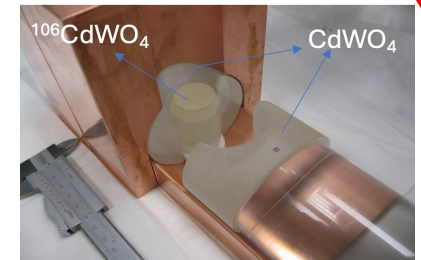
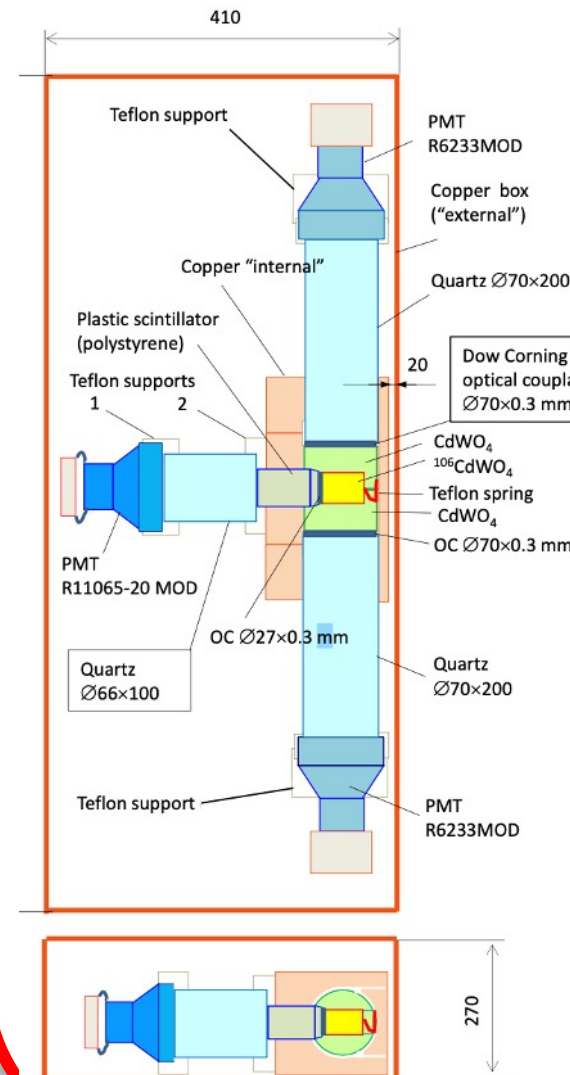
A  $^{106}\text{CdWO}_4$  crystal (approximate sizes  $\varnothing 27 \text{ mm} \times 50 \text{ mm}$ , mass 215 g) enriched in  $^{106}\text{Cd}$  at 66% was grown [NIMA 615 (2010) 301] and already used in three previous stages of the experiment:



Efforts in this project with enriched  $^{106}\text{CdWO}_4$  since 2008

## New stage in DAMA/R&D

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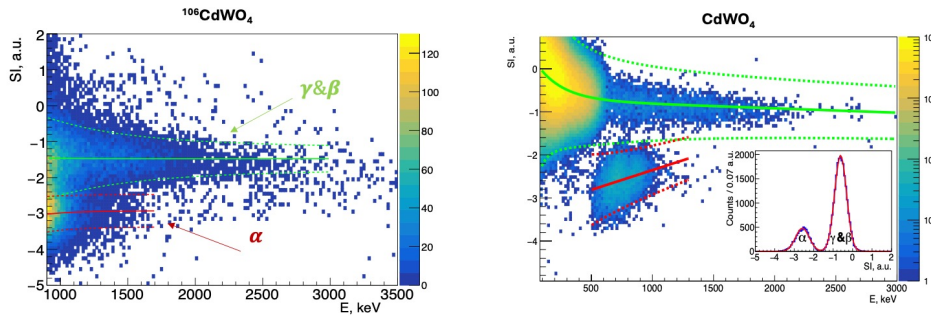
$^{106}\text{CdWO}_4$  housed in a cylindrical cut-out of 2  $\text{CdWO}_4$  almost completely enveloping it

# Pulse shape discrimination of $\alpha$ and $\gamma$ & $\beta$ events

$$SI = \sum f(t_k) \times P(t_k) / \sum f(t_k)$$

$$\text{with } P(t) = \frac{f_\alpha(t) - f_\gamma(t)}{f_\alpha(t) + f_\gamma(t)}$$

$f_\alpha(t), f_\gamma(t)$  - reference pulse shapes  
 $f(t_k)$  - amplitude at  $t_k$   
 $P(t_k)$  - weight function



$$SI = \sum f(t_k) \times P(t_k) / \sum f(t_k)$$

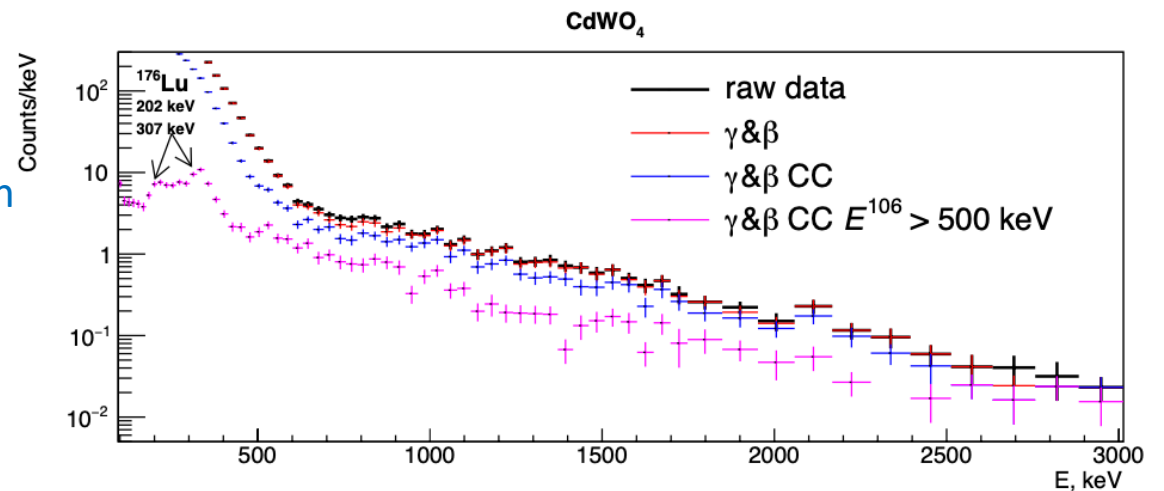
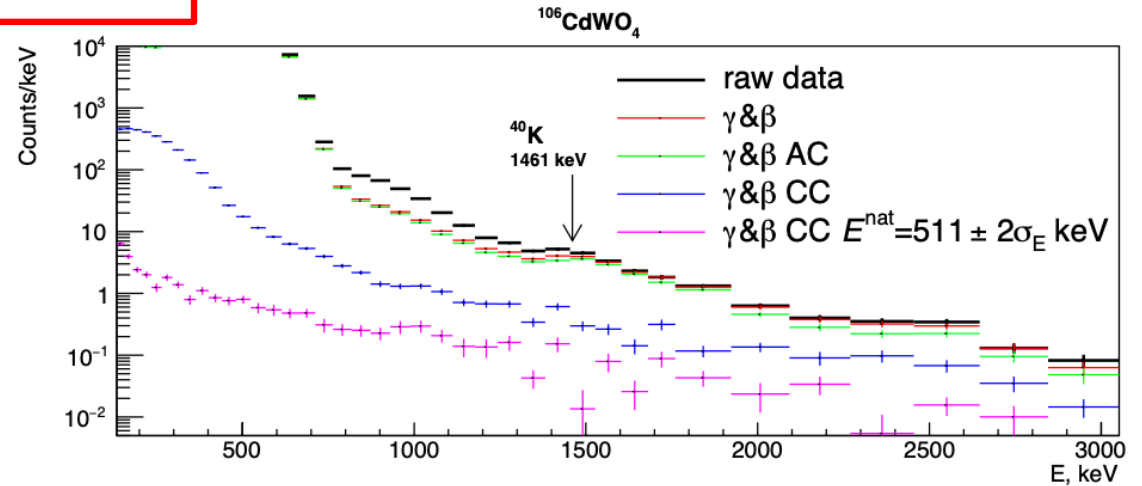
$$\text{with } P(t) = \frac{f_\alpha(t) - f_\gamma(t)}{f_\alpha(t) + f_\gamma(t)}$$

$f_\alpha(t), f_\gamma(t)$  - reference pulse shapes  
 $f(t_k)$  - amplitude at  $t_k$   
 $P(t_k)$  - weight function

## Experimental energy spectra (1075 days of data taking)

under different selection conditions.

- $\gamma$ & $\beta$   $\rightarrow$  spectrum of  $\gamma$ & $\beta$ -events.
- AC (CC)  $\rightarrow$  anti-coincidence (coincidence) mode.
- $E_{nat} = 511 \pm 2\sigma E$  keV  $\rightarrow$  energy deposit in at least one of the CdWO<sub>4</sub> detectors
- $E_{106} > 500$  keV  $\rightarrow$  energy deposit in <sup>106</sup>CdWO<sub>4</sub> detector more than 500 keV.



## Radioactive contamination of the experimental set-up

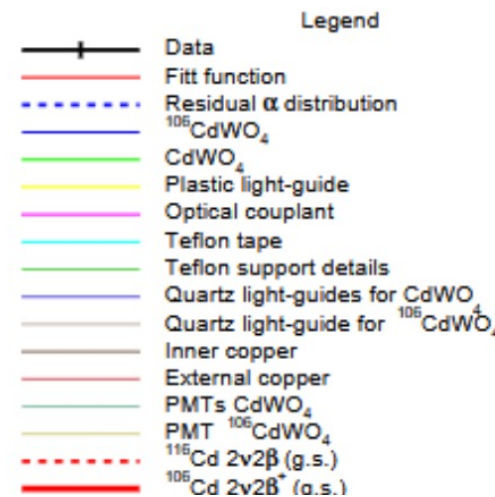
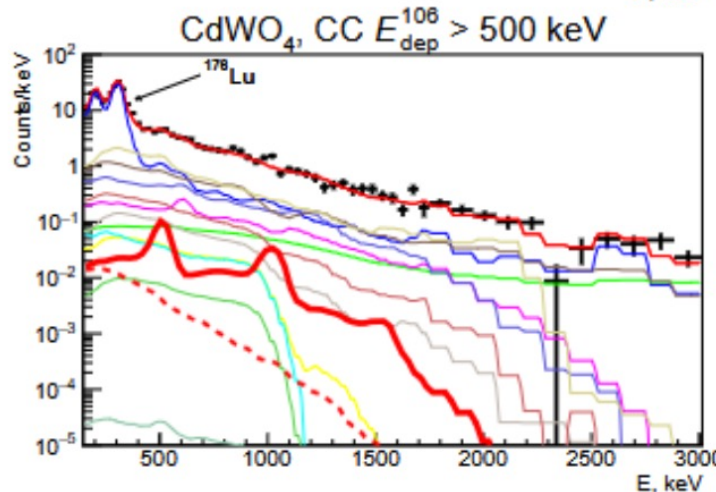
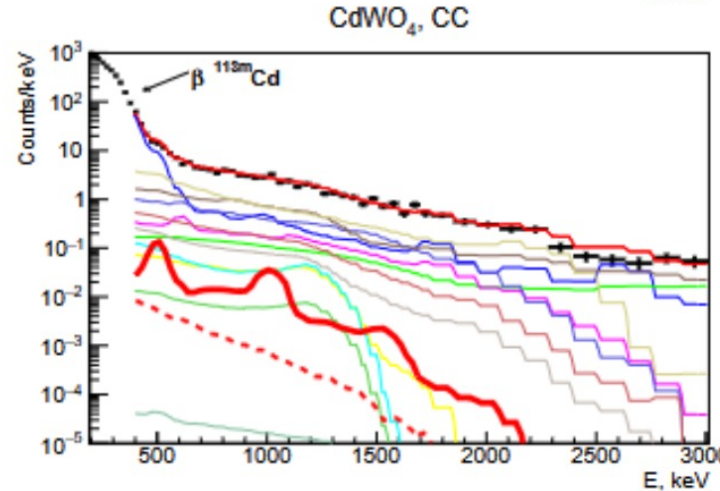
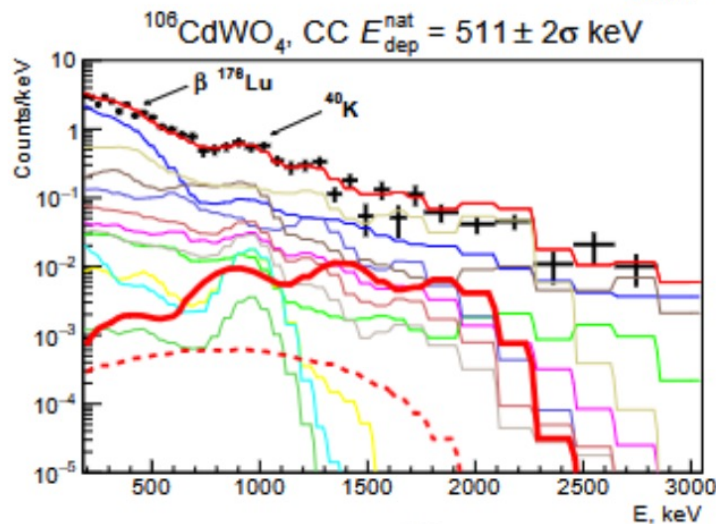
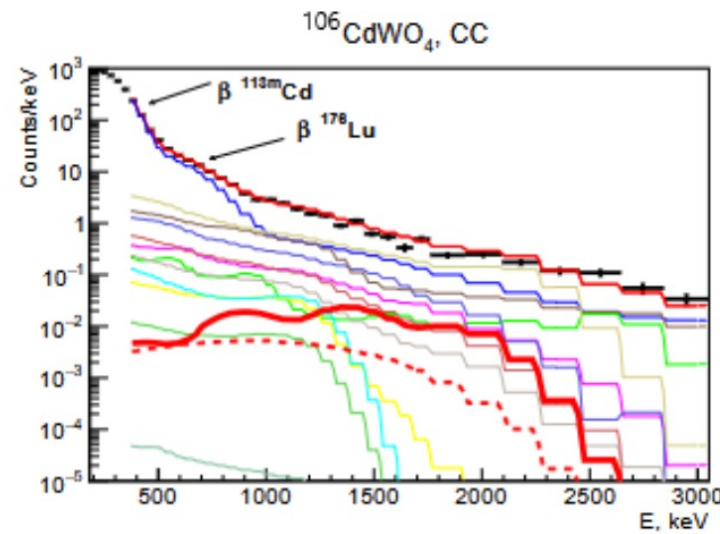
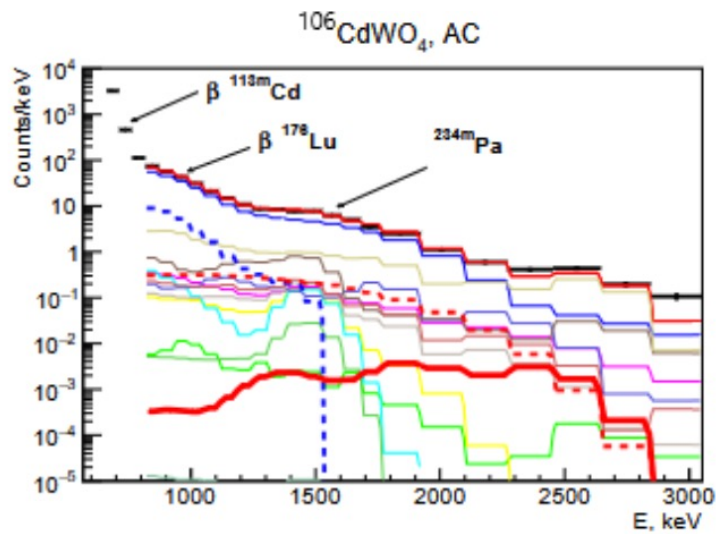
Setup Component	$^{238}\text{U}$	$^{234}\text{U}$	$^{230}\text{Th}$	$^{226}\text{Ra}$	$^{210}\text{Pb}$	$^{232}\text{Th}$	$^{228}\text{Ra}$	$^{228}\text{Th}$	$^{40}\text{K}$	$^{176}\text{Lu}$	$^{56}\text{Co}$	$^{60}\text{Co}$
$^{106}\text{CdWO}_4$	0.65(3)			<0.04	<0.4		<0.02	0.0174(14) *	<0.24	1.68(3)		
$\text{CdWO}_4$	0.29(7) †	<0.2 †	1.40(7) †	<0.002 †	0.89(4) †	<0.01 †	<0.03	0.012(2) *	<2			
Plastic scintillator	<8.9			<1.1	<11.8		<2.8	<1.1	<8.7			
Optical couplant	<59			<79	<32		<13	<9.5	<260			
Teflon tape	<4.1			<2.0	<31		<6.4	<2.8	<12			
Teflon support details	<1.4			<1.3	<7.3		<5.0	<5.2	<9.7			
Q. lg. for $\text{CdWO}_4$	<1.0			<3.4	<3.2		<0.6	<0.4	<1.2			
Q. lg. for $^{106}\text{CdWO}_4$	<3.5			<9.3	<20		<9.1	<14.7	<40			
Internal copper	<4.2			<0.09	<28		<0.16	<0.04	<2.4		<0.08	<0.07
External copper	<17			<0.46			<0.39	<0.08	<0.73			
PMTs for $\text{CdWO}_4$	<920			<1530			<1500	<1420	<1630			
PMTs for $^{106}\text{CdWO}_4$	<1400			<2500			<2500	<450	<2320			

- (\*) determined using the time-amplitude analysis
- (†) determined by analysis of the  $\alpha$  distribution

### Main components of the background considered in the fit:

- 1)  $^{40}\text{K}$  and  $^{232}\text{Th}$ ,  $^{238}\text{U}$  with their daughters in all the setup components;
- 2) Residual  $\alpha$  distribution in the  $^{106}\text{CdWO}_4$  crystal (7.3% of the alpha distribution);
- 3) Beta decay of  $^{176}\text{Lu}$  and  $^{113\text{m}}\text{Cd}$  ( $Q_\beta = 587$  keV), and  $2\nu 2\beta$  decay of  $^{116}\text{Cd}$  with  $T_{1/2} = 2.63 \times 10^{19}$  yr in the  $^{106}\text{CdWO}_4$
- 4)  $^{113}\text{Cd}$  ( $Q_\beta = 324$  keV) in the  $\text{CdWO}_4$  and  $^{106}\text{CdWO}_4$  crystal scintillators.
- 5)  $^{56}\text{Co}$  and  $^{60}\text{Co}$  in the internal copper.

# $\gamma$ & $\beta$ spectra



Results of the combined approximation of the  $\gamma$ & $\beta$  spectra measured by the  $^{106}\text{CdWO}_4$  and two  $\text{CdWO}_4$  detectors under different selection conditions.

The fit function represents the approximation result.

The contributions from the contamination of the setup are shown separately (see legend).

An excluded distribution of the  $2\nu 2\beta^+$  decay of  $^{106}\text{Cd}$  to the ground state of  $^{106}\text{Pd}$  with a half-life  $T_{1/2} = 1.7 \times 10^{22}$  yr is shown by solid red line in all the spectra.

# Results

$$\lim T_{1/2} = N \cdot \eta_{det} \cdot \eta_{sel} \cdot \ln 2 \cdot t / \lim S$$

Decay	Level of $^{106}\text{Pd}$ , keV	Theoretical $T_{1/2}$ , Years	$\lim T_{1/2}$ , Years	
			Previous Result	Present Work
$2\nu 2\beta^+$	g.s.	$(5.4 - 880) \times 10^{25}$ [47,48,50], $>2.4 \times 10^{27}$ [49]	$4.4 \times 10^{21}$ [54]	$1.7 \times 10^{22}$
	512	$(1.5 - 25) \times 10^{27}$ [47,55,56]	$4.1 \times 10^{21}$ [54]	$1.5 \times 10^{22}$
$0\nu 2\beta^+$	g.s.	$(1.4 - 32) \times 10^{27}$ [47,55-61]	$5.9 \times 10^{21}$ [62]	$2.2 \times 10^{22}$
	512		$4.1 \times 10^{21}$ [54]	$1.5 \times 10^{22}$
<u><math>2\nu\text{EC}\beta^+</math></u>	g.s.	$(1.4 - 240) \times 10^{21}$ [47,48,50-53], $>2.7 \times 10^{22}$ [49]	$2.1 \times 10^{21}$ [62]	$7.7 \times 10^{21}$
	512	$(5.3 - 24) \times 10^{25}$ [51,52], $>1.1 \times 10^{25}$ [49]	$3.3 \times 10^{21}$ [54]	$9.9 \times 10^{21}$
	1128	$3.7 \times 10^{30}$ [51]	$2.0 \times 10^{21}$ [54]	$1.2 \times 10^{22}$
	1134	$(1.3 - 13) \times 10^{26}$ [51,52], $>1.1 \times 10^{27}$ [49]	$2.5 \times 10^{21}$ [54]	$1.3 \times 10^{22}$
$0\nu\text{EC}\beta^+$	g.s.	$(1.0 - 17) \times 10^{26}$ [32,47,55,56]	$1.4 \times 10^{22}$ [62]	$1.5 \times 10^{22}$
	512		$9.7 \times 10^{21}$ [62]	$2.1 \times 10^{22}$
	1128		$1.0 \times 10^{22}$ [62]	$1.9 \times 10^{22}$
	1134	$(1.0 - 21) \times 10^{29}$ [32,55,57,58]	$2.7 \times 10^{21}$ [54]	$2.1 \times 10^{22}$
$2\nu 2\text{EC}$	g.s.	$(2.0 - 230) \times 10^{20}$ [47,48,50-53]	$1.7 \times 10^{21}$ [63]	–
	512	$(1.5 - 9.4) \times 10^{27}$ [51,52], $>4.0 \times 10^{26}$ [49]	$9.9 \times 10^{20}$ [64]	$2.2 \times 10^{20}$
	1128	$9.9 \times 10^{28}$ [51]	$6.6 \times 10^{20}$ [62]	$9.3 \times 10^{20}$
	1134	$(1.1 - 11) \times 10^{23}$ [51,52]	$1.0 \times 10^{21}$ [64]	$1.4 \times 10^{21}$
	1562	$(2.4 - 4.3) \times 10^{28}$ [52], $>5.4 \times 10^{28}$ [49]	$7.8 \times 10^{20}$ [62]	$7.9 \times 10^{20}$
	1706	$>1.9 \times 10^{25}$ [49]	$7.1 \times 10^{20}$ [64]	$4.6 \times 10^{21}$
	2001	$>8.9 \times 10^{24}$ [49]	$1.5 \times 10^{21}$ [62]	$1.4 \times 10^{21}$
	2278	$>2.1 \times 10^{27}$ [49]	$1.0 \times 10^{21}$ [64]	$1.8 \times 10^{21}$
$0\nu 2\text{EC}$	g.s.		$1.0 \times 10^{21}$ [39]	$1.2 \times 10^{21}$
	512		$5.1 \times 10^{20}$ [39]	$1.9 \times 10^{21}$
	1128		$5.1 \times 10^{20}$ [64]	$1.7 \times 10^{21}$
	1134		$1.1 \times 10^{21}$ [64]	$2.2 \times 10^{21}$
	1562		$1.4 \times 10^{21}$ [62]	$2.0 \times 10^{21}$
	1706		$2.0 \times 10^{21}$ [62]	$1.7 \times 10^{21}$
	2001		$1.2 \times 10^{21}$ [64]	$3.3 \times 10^{21}$
	2278		$1.2 \times 10^{21}$ [62]	$1.2 \times 10^{21}$
Res. $0\nu 2\text{EC}$	2718	$(3.2 - 9.7) \times 10^{22}$ [57], $>5.2 \times 10^{24}$ [65,66], $>7.9 \times 10^{23}$ [32]	$2.9 \times 10^{21}$ [62]	$2.0 \times 10^{21}$
	2741	$>5.2 \times 10^{24}$ [66]	$9.5 \times 10^{20}$ [39]	$1.2 \times 10^{21}$
	2748	$2 \times 10^{29} - 2 \times 10^{34}$ [29]	$1.4 \times 10^{21}$ [64]	$1.9 \times 10^{21}$

[32] J. Phys. Lett. B 2011, 701, 490  
 [47] Eur. Phys. J. A 2003, 17, 529  
 [48] Eur. Phys. J. A 2005, 23, 235  
 [49] Nucl. Phys. A 2005, 753, 337  
 [50] Eur. Phys. J. A 2006, 28, 27  
 [51] J. AIP Conf. Proc. 2011, 1417, 115  
 [52] J. Phys. Rev. C 2015, 91, 054309.

[53] J. Phys. G 2017, 44, 115201.  
 [54] Phys. Scr. 2022, 97, 064006.  
 [55] Nucl. Phys. A 2003, 723, 271-288.  
 [56] Phys. Rev. C 2009, 80, 044303.  
 [57]. J. Phys. Conf. Ser. 2012, 338, 012030.  
 [58] J. Phys. Scripta T 2012, 150, 014039.  
 [62] Universe 2020, 6, 182.

[39] Phys. Rev. C 2012, 85, 044610.  
 [64] Phys. Rev. C 2016, 93, 045502.  
 [65] AIP Conf. Proc. 2010, 1304, 85-93.  
 [66] AIP Conf. Proc. 2010, 1304, 354-358

## Summarizing

- After 1075 days of data taking, we were able to provide new improved half-life limits on the different channels and modes of  $^{106}\text{Cd}$   $2\beta$  decay at the level of  $\lim T_{1/2} = 10^{20} - 10^{22}$  yr.
- A new half-life limit on  $2\nu EC\beta^+$  decay to the g.s. of  $^{106}\text{Pd}$  was set as  $\lim T_{1/2}^{2\nu EC\beta^+ \text{ g.s.}} = 7 \times 10^{21}$  yr, in region of theoretical predictions:  $10^{21} - 10^{23}$  yr.
- The half-life limits on near resonant  $0\nu 2EC$  decay transitions to the 2718 keV, 2741 keV, and 2748 keV excited levels of  $^{106}\text{Pd}$  have been set at the level  $\lim T_{1/2}^{Res.0\nu 2EC} = (1.2 - 2.0) \times 10^{21}$  yr.

Analysis of the complete data set of all the stages of  $^{106}\text{Cd}$  experiment in progress

... more

- Completion of data analysis on available statistics of DAMA/LIBRA-phase2-empowered
- Other kinds of DM candidates and interactions
- Other processes investigated with available data
- Beta spectrum of  $^{113}\text{Cd}$  and  $^{113\text{m}}\text{Cd}$  (submitted)
- Beta spectrum of  $^{87}\text{Rb}$  (submitted)
- Data analyses in progress on several rare processes
- Phenomenological studies
- ...



# Main original ideas and/or legacy of DAMA

- First use of new low-background scintillators (NaI, LXe, and others) for DM investigation
- First exploitation of the DM annual mod. signature following Drukier et al. in 1986
- First idea of use of anisotropic scintillators for DM directionality
- First addressing of the Migdal effect in DM field
- First addressing of the Channeling effect in DM field
- E.m. signals due to DM interactions
- Other kinds of DM candidates
- Impact of Galactic and SagDEG streams
- DM Diurnal modulation
- DM Shadow effects
- First measurements of anisotropic response to nuclear recoils in anisotropic scintillators ( $\text{ZnWO}_4$ )
- R&D of several scintillators
- Many nuclides available for  $2\beta$  decay investigations
- Many nuclear, rare, exotic, processes studied
- Axions investigation in underground expts
- ...

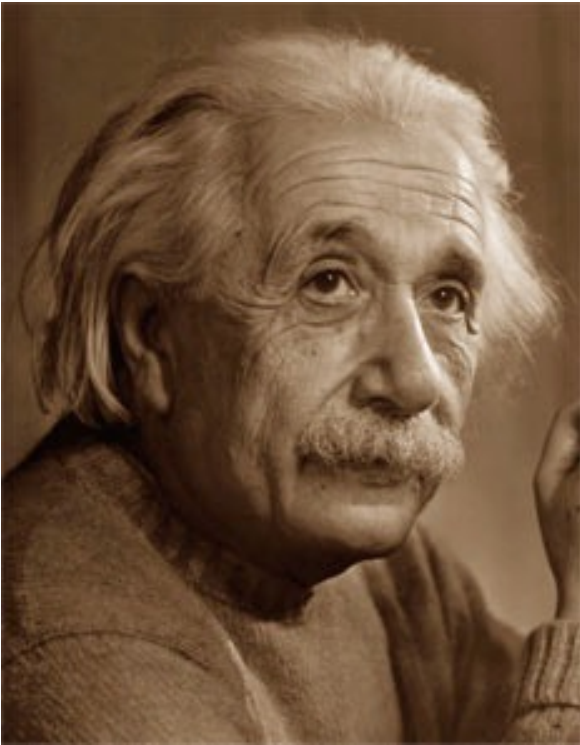


# Conclusions

- The DAMA set-ups and measurements have been realized by the DAMA coll. over several decades
- Many new/improved results have been obtained both on Dark Matter and on many other rare processes
- All the DAMA set-ups have been dismantled at fall 2024 while DAMA/Ge (GeBer) detector still operating in the LNGS STELLA facility

- Thus, the experimental activities of the DAMA project are concluded within 2024 as in the plans, while model independent and model dependent analyses on several rare processes are continuing also with various other collaborators, and several other results and papers are in preparation.





"... The one who follows the crowd will usually get no further than the crowd. The one who walks alone, is likely to find himself in places no one has ever been."

*Thanks for attention*