New results of the experiment to search for 2β decay of ^{106}Cd using $^{106}CdWO_4$ scintillator

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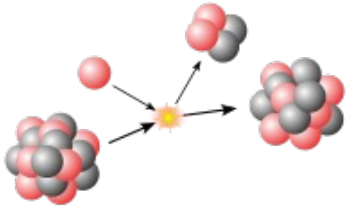
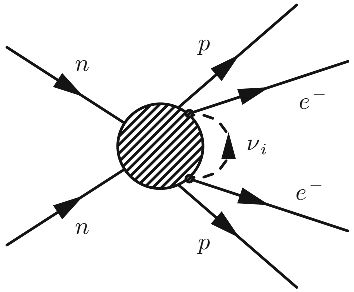
MEDEX’25
Matrix Elements for Double beta decay EXperiments
Prague, 23 – 27 June 2025



The 2β decay

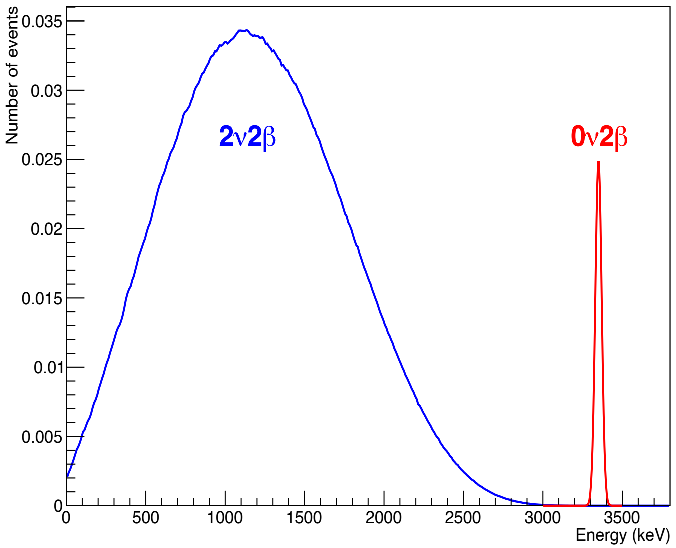


(Neutrino oscillations)

- **2ν2β** decay is a rare process allowed in the SM → lepton number L conserved
- **0ν2β**, if observed, could open a new window beyond the SM → L violated ($\Delta L = 2$) → massive Majorana neutrino

$$\begin{aligned} 2\nu2\beta^- &: {}^A_ZX \to {}^A_{Z+2}Y + 2e^- + 2\bar{\nu}_e \\ 2\nu2\beta^+ &: {}^A_ZX \to {}^A_{Z-2}Y + 2e^+ + 2\nu_e \\ 2\nu\varepsilon\beta^+ &: e^- + {}^A_ZX \to {}^A_{Z-2}Y + e^+ + 2\nu_e \\ 2\nu2\varepsilon &: 2e^- + {}^A_ZX \to {}^A_{Z-2}Y + 2\nu_e \end{aligned}$$

$$\begin{aligned} 0\nu2\beta^- &: {}^A_ZX \to {}^A_{Z+2}Y + 2e^- \\ 0\nu2\beta^+ &: {}^A_ZX \to {}^A_{Z-2}Y + 2e^+ \\ 0\nu\varepsilon\beta^+ &: e^- + {}^A_ZX \to {}^A_{Z-2}Y + e^+ \\ 0\nu2\varepsilon &: 2e^- + {}^A_ZX \to {}^A_{Z-2}Y + \gamma \end{aligned}$$



Current sensitivity for **2ν2β⁻** decay: $T_{1/2} \sim 10^{18}$-10^{24} yr; for **0ν2β⁻** : $T_{1/2} > 10^{24}$ - 10^{26} yr

Positive channels: less studied but easier to identify. Current experimental sensitivities: $T_{1/2} \sim 10^{16}$-10^{22} yr.

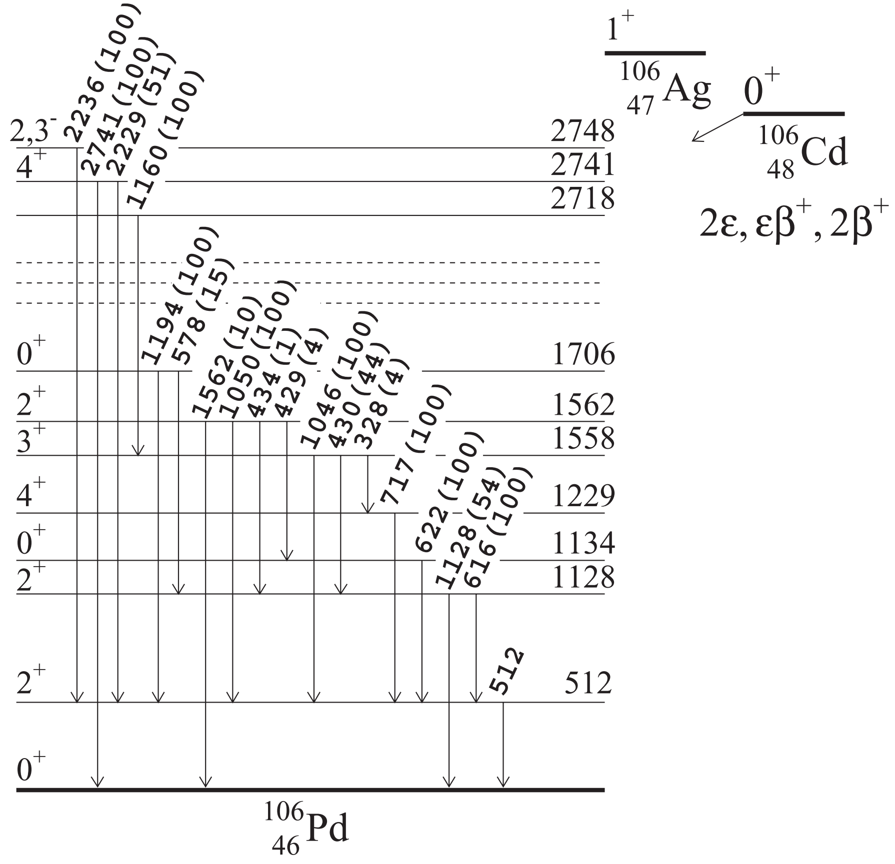
→ **Complementary information to 0ν2β⁻ + resonant effect**

$$(T^{0\nu}_{1/2})^{-1} = g_A^4 G^{0\nu}(Q,Z) \left| M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_F \right|^2 |m_{\beta\beta}|^2$$

where: $m_{\beta\beta} = \sum_i U^2_{ei} m_i$

Advantages of ^{106}Cd for 2β decay searches

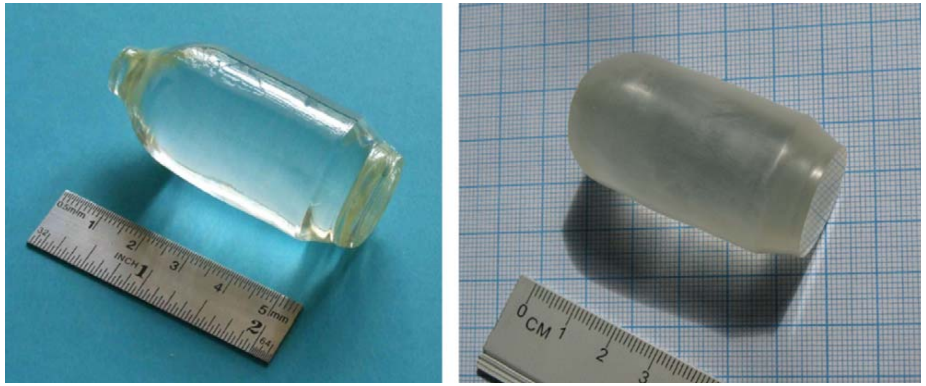
- One of the highest $2\beta^+$ decay energy: $Q_{2\beta} = 2775.39(10)$ keV;
- Relatively high isotopic abundance: $\delta = 1.245(22)$ %;
- Possibility of enrichment by gas centrifugation;
- Favorable theoretical predictions for half-lives for some 2ν modes ($T_{1/2} \sim 10^{21}–10^{22}$ yr) that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



$CdWO_4$ crystal scintillators

Some general properties	$CdWO_4$
Effective atomic number	66
Density (g/cm^3)	7.9
Melting point (°C)	1325
Refractive index	2.2 – 2.3
Emission maximum (nm)	475 – 490
Scintillation time constants (μs)	**~15** (89%), ~4.6 (9%), ~0.8 (2%), ~0.15 (0.5%) [1]
Light Yield	≈ 15000 photons/MeV
Linearity of the energy response	Excellent, down to ~100 keV
Energy resolution (FWHM, %) @ 662 keV	~ 7.0 – 10
Pulse-shape discrimination ability	Excellent

Boule of $^{106}CdWO_4$ single crystal grown by low-thermal-gradient Czochrlaski technique and crystal scintillator obtained by cutting a boule and grinding its surface.

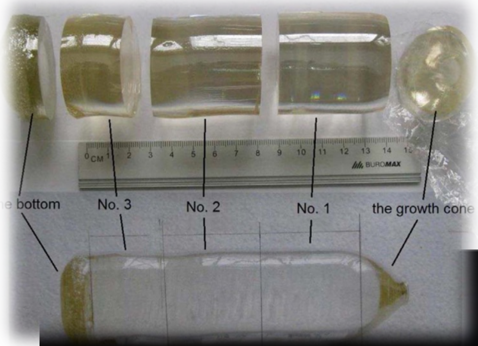


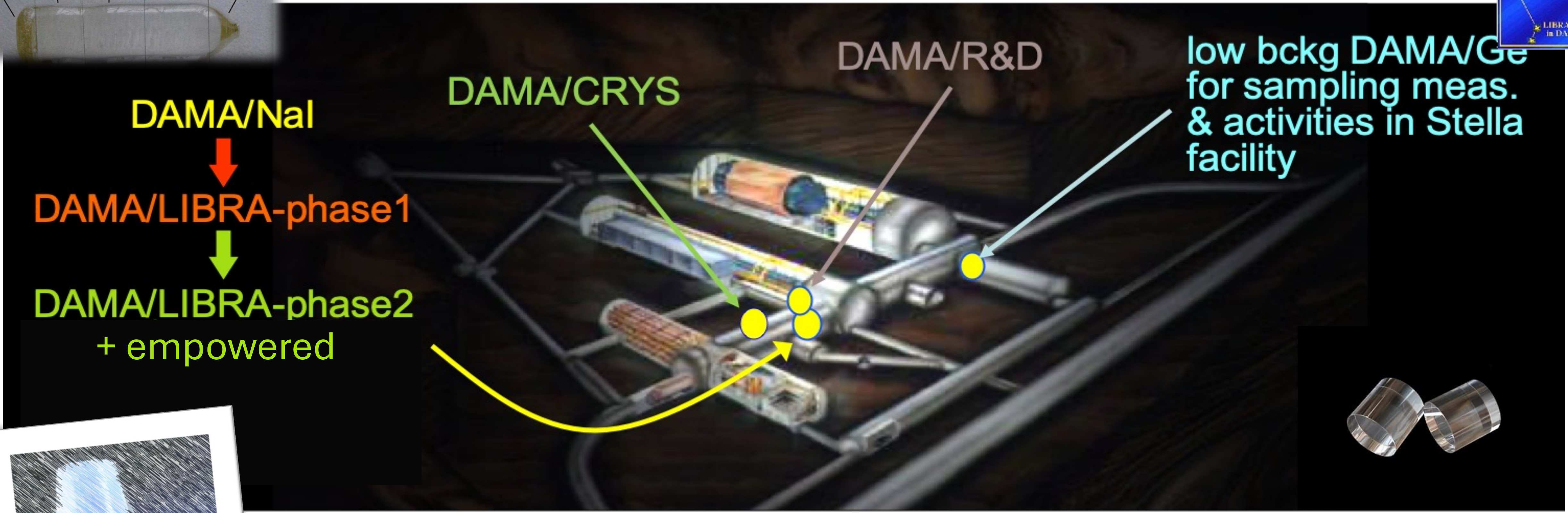
[2] Belli, P. et al., NIMA 2010, 615, 301-306.

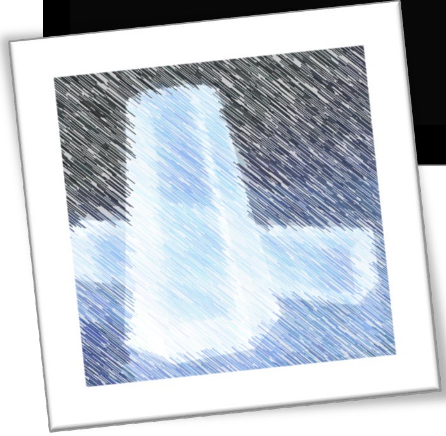
[1] Bardelli, L. et al. Nucl. Instrum. Meth. A 2006, 569, 743–753.

DAMA set-ups

an observatory for rare processes @ LNGS







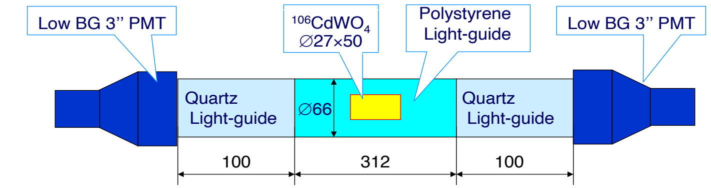
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

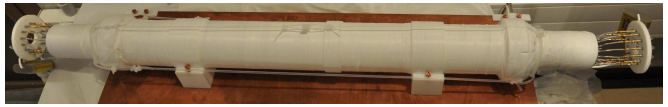
+ by-products and small scale expts.: INR-Kiev + other institutions
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia
+ in some studies on 2β decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

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

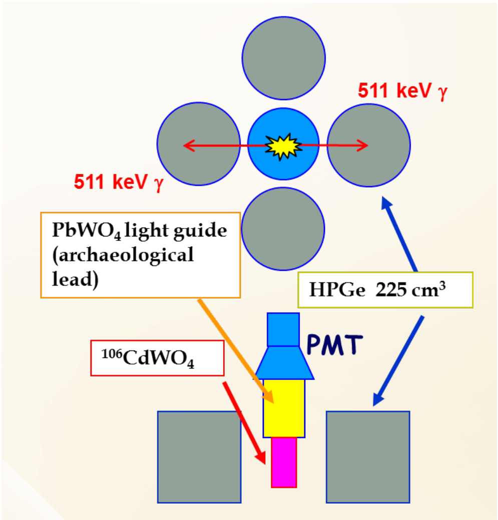
Searches for 2β decay of ^{106}Cd at LNGS: previous stages of the experiment

Stage 1

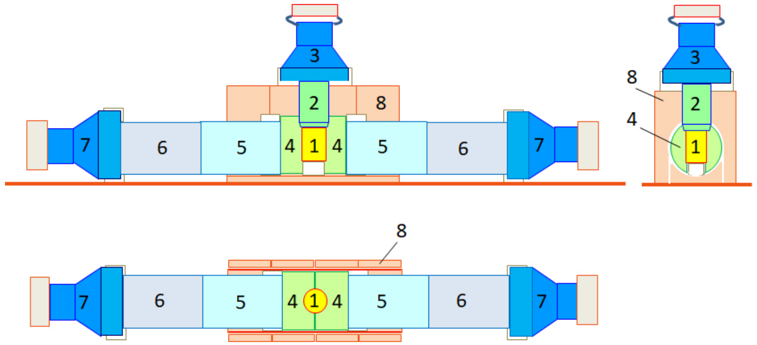




Stage 2



Stage 3



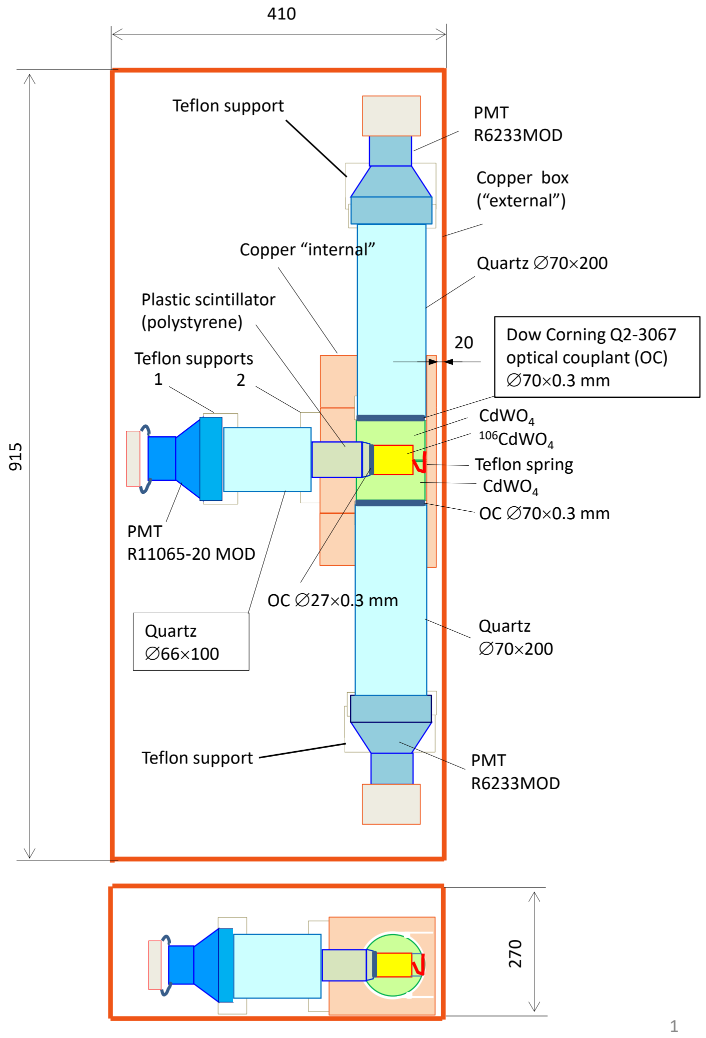
A ^{106}CdWO$_4$ crystal (approximate sizes ⌀ 27 mm x 50 mm, mass 215 g) enriched in ^{106}Cd at 66 % was developed **[NIMA 615 (2010) 301]** and used in the experiment:

- **Stage 1** (2012) **[PRC 85 (2012) 044610]:** ^{106}CdWO$_4$ crystal was fixed inside a cavity in the central part of a polystyrene light-guide. The experimental apparatus was located in the **DAMA/R&D** setup.

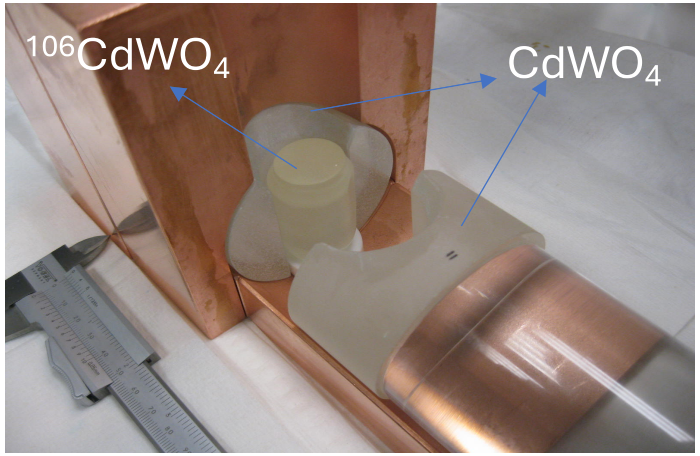
- **Stage 2** (2016) **[PRC 93 (2016) 045502]:** ^{106}CdWO$_4$ crystal in coincidence with 4 ultra-low-background HPGe detectors of the GeMulti setup of the **STELLA** (SubTErranean Low Level Assay) facility.

- **Stage 3** (2020) **[Universe 6 (2020) 182]:** ^{106}CdWO$_4$ detector in coincidence with two large-volume CdWO$_4$ scintillator detectors in the **DAMA/CRYS** set-up to improve the detection efficiency to γ quanta emitted in the 2β processes in ^{106}Cd.

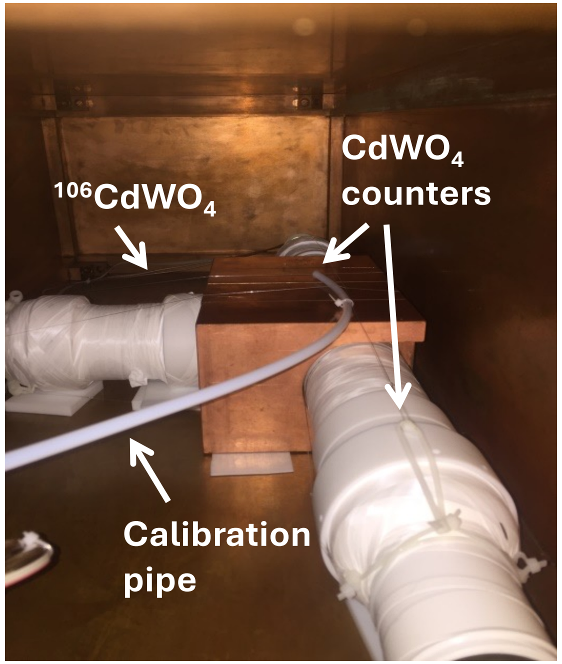
The new experiment installed in the DAMA/R&D setup at LNGS

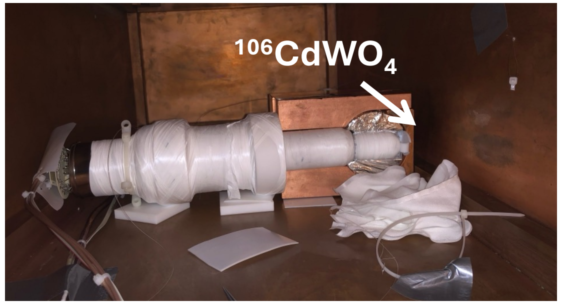


- **DAMA/R&D**: high-purity copper 10 cm thick, 15 cm of low-radioactive lead, a 1.5 mm layer of cadmium and from 4 to 10 cm of polyethylene/ paraffin.
- **$^{106}CdWO_4$** is housed in a cylindrical cut-out of the two $CdWO_4$ (⌀70 mm x 38 mm) scintillators which almost completely envelop the enriched crystal.



DAMA/R&D setup at LNGS





[Universe 11 (2025), 123]

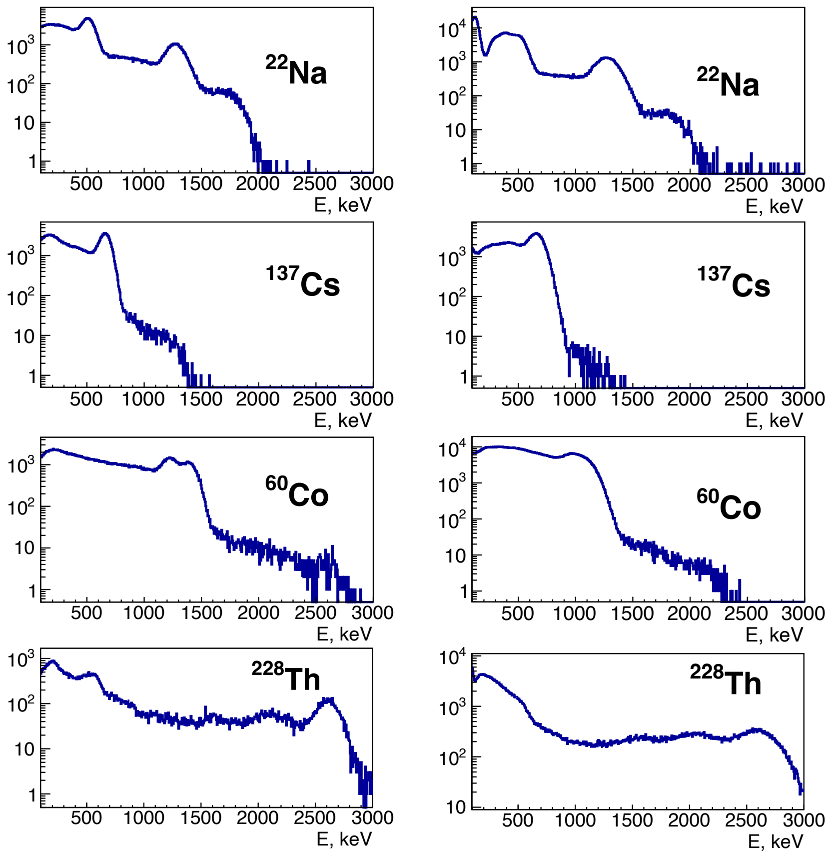
Energy and time resolutions

The energy scale was calibrated using ^{22}Na, ^{60}Co, ^{133}Ba, ^{137}Cs, and ^{228}Th γ sources.

$$\mathrm{FWHM} = \mathrm{A} \times \sqrt{\mathrm{E}_\gamma}$$

A = 4.92 for $^{106}CdWO_4$
A = 3.65 for $CdWO_4$ – 1
A = 3.20 for $CdWO_4$ – 2

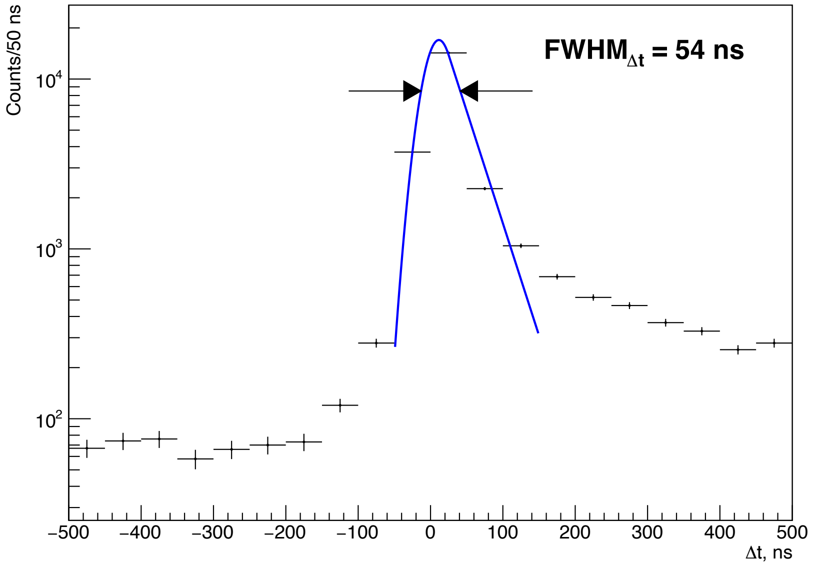
$CdWO_4$ **$^{106}CdWO_4$**



Distribution of time intervals Δt between signals of $^{106}CdWO_4$ and one of the $CdWO_4$ counters with energy $511 \pm 2\sigma_E$ keV:

$$f(\Delta t) = A \times \begin{cases} \exp\left(-\frac{1}{2}\left(\frac{\Delta t - \mu}{\sigma}\right)^2\right), & \frac{\Delta t - \mu}{\sigma} \le k; \\ \exp\left(\frac{k^2}{2} - k\,\frac{\Delta t - \mu}{\sigma}\right), & \frac{\Delta t - \mu}{\sigma} > k; \end{cases}$$

where A, μ, σ and k are free parameters of the fit.

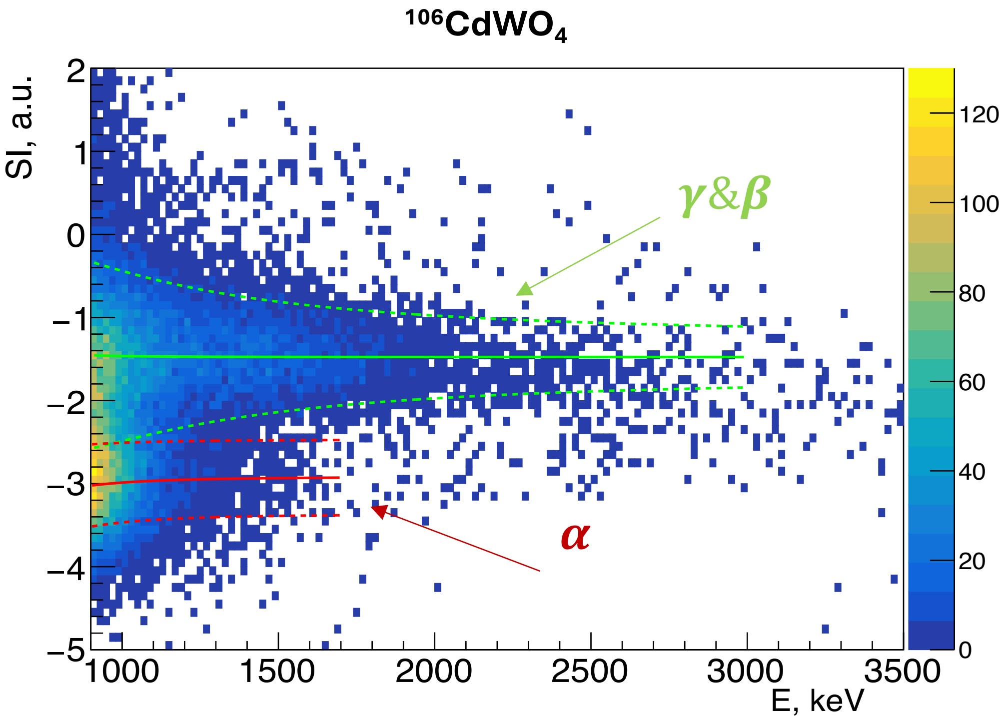


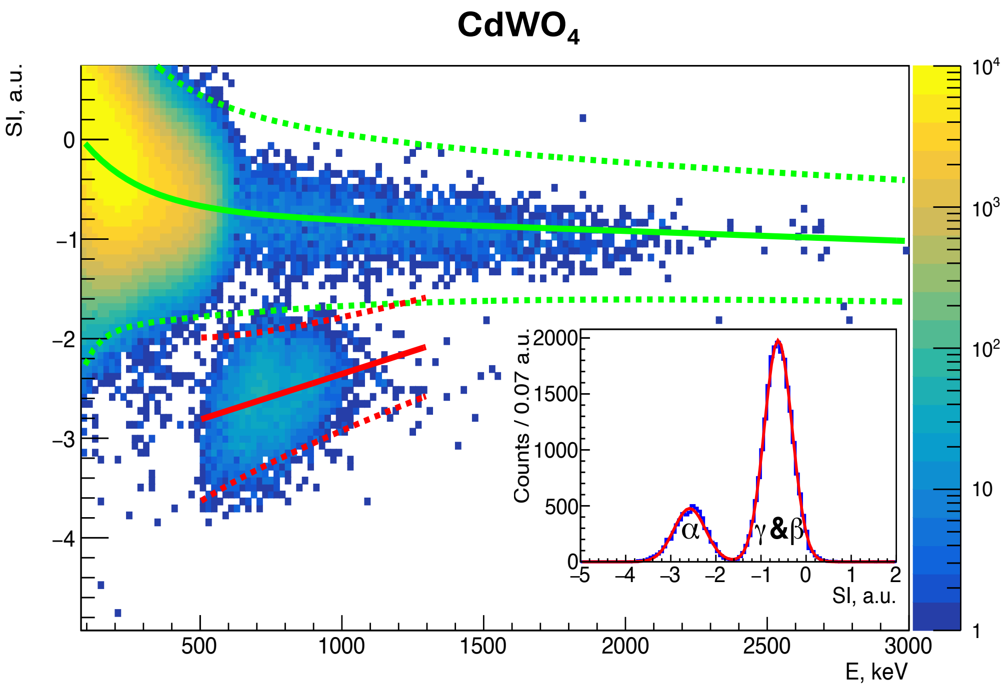
Pulse shape discrimination of α and $\gamma\&\beta$ events

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

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

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





[Universe 11 (2025), 123]

Experimental energy spectra

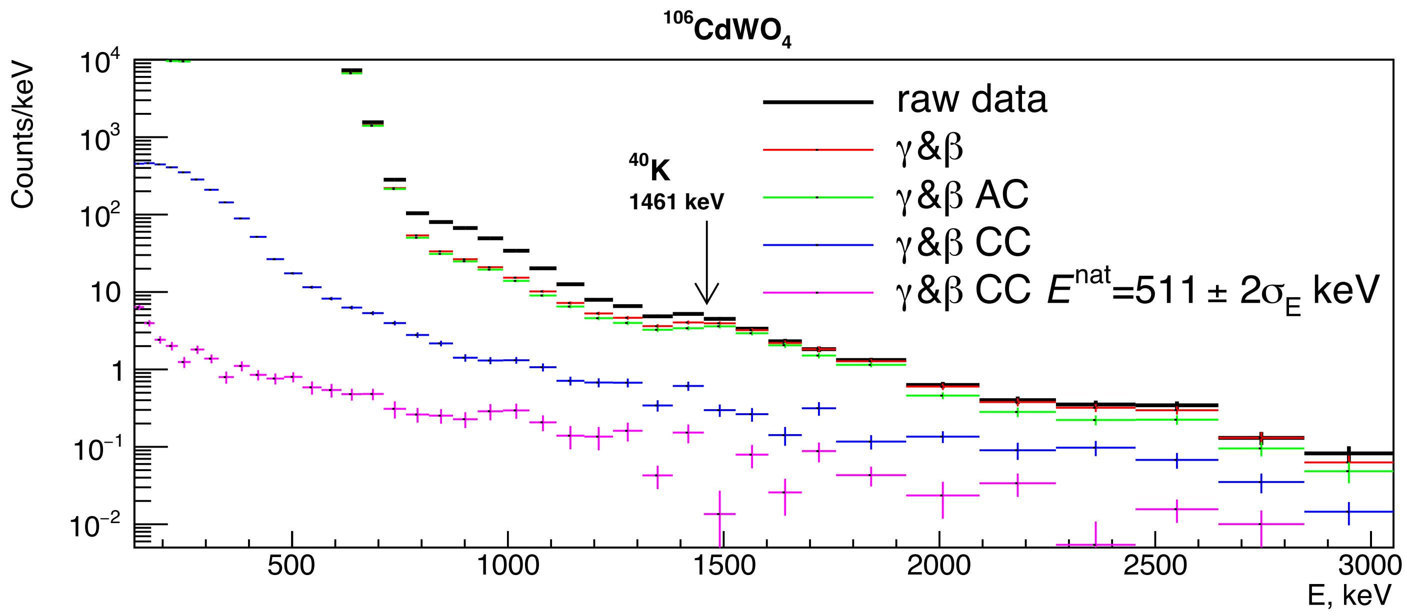
✓ 1075 days of data taking

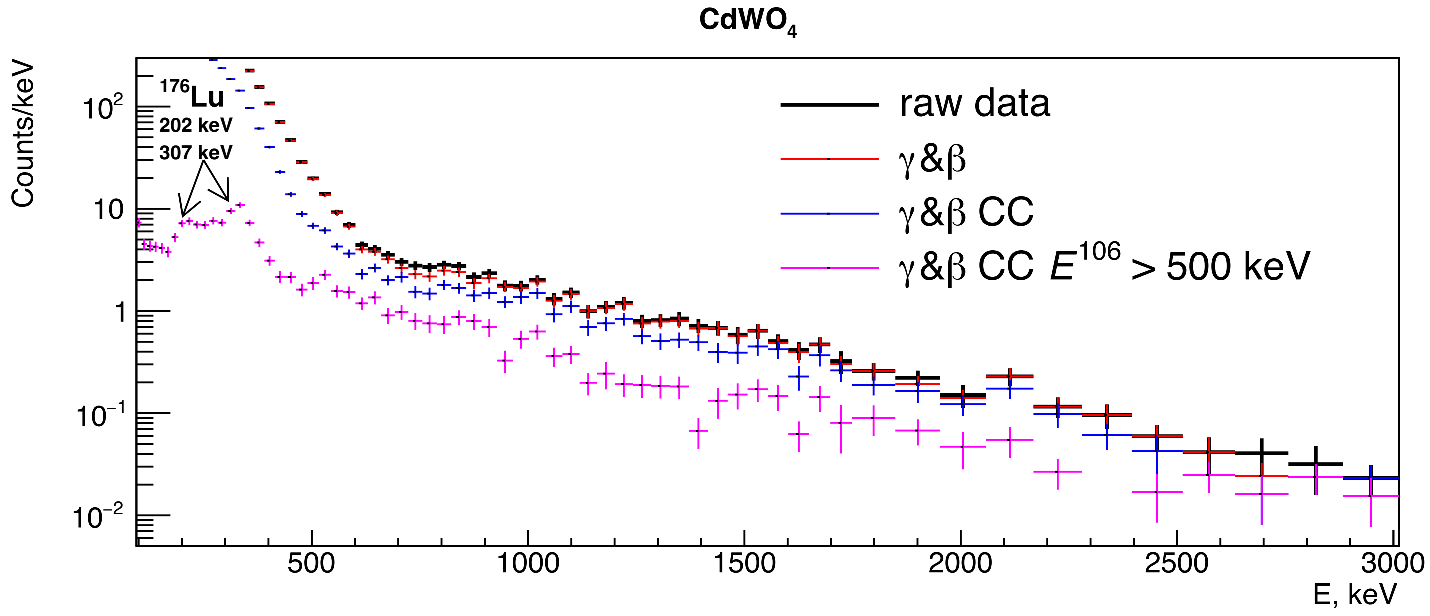
Anticoincidence mode (AC):

An event in the $^{106}CdWO_4$ detector with an energy > 500 keV.

Coincidence mode (CC):

An event in the $^{106}CdWO_4$ detector with an energy > 50 keV in coincidence with at least one of the $CdWO_4$ counters with E > 50 keV.





Radioactive contamination of the experimental setup

Setup Component	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{232}Th	^{228}Ra	^{228}Th	^{40}K	^{176}Lu	^{56}Co	^{60}Co
$^{106}CdWO_4$	0.65(3)			<0.04	<0.4		<0.02	0.0174(14) *	<0.24	1.68(3)		
$CdWO_4$	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 $CdWO_4$	<1.0			<3.4	<3.2		<0.6	<0.4	<1.2			
Q. lg. for $^{106}CdWO_4$	<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 $CdWO_4$	<920			<1530			<1500	<1420	<1630			
PMTs for $^{106}CdWO_4$	<1400			<2500			<2500	<450	<2320			

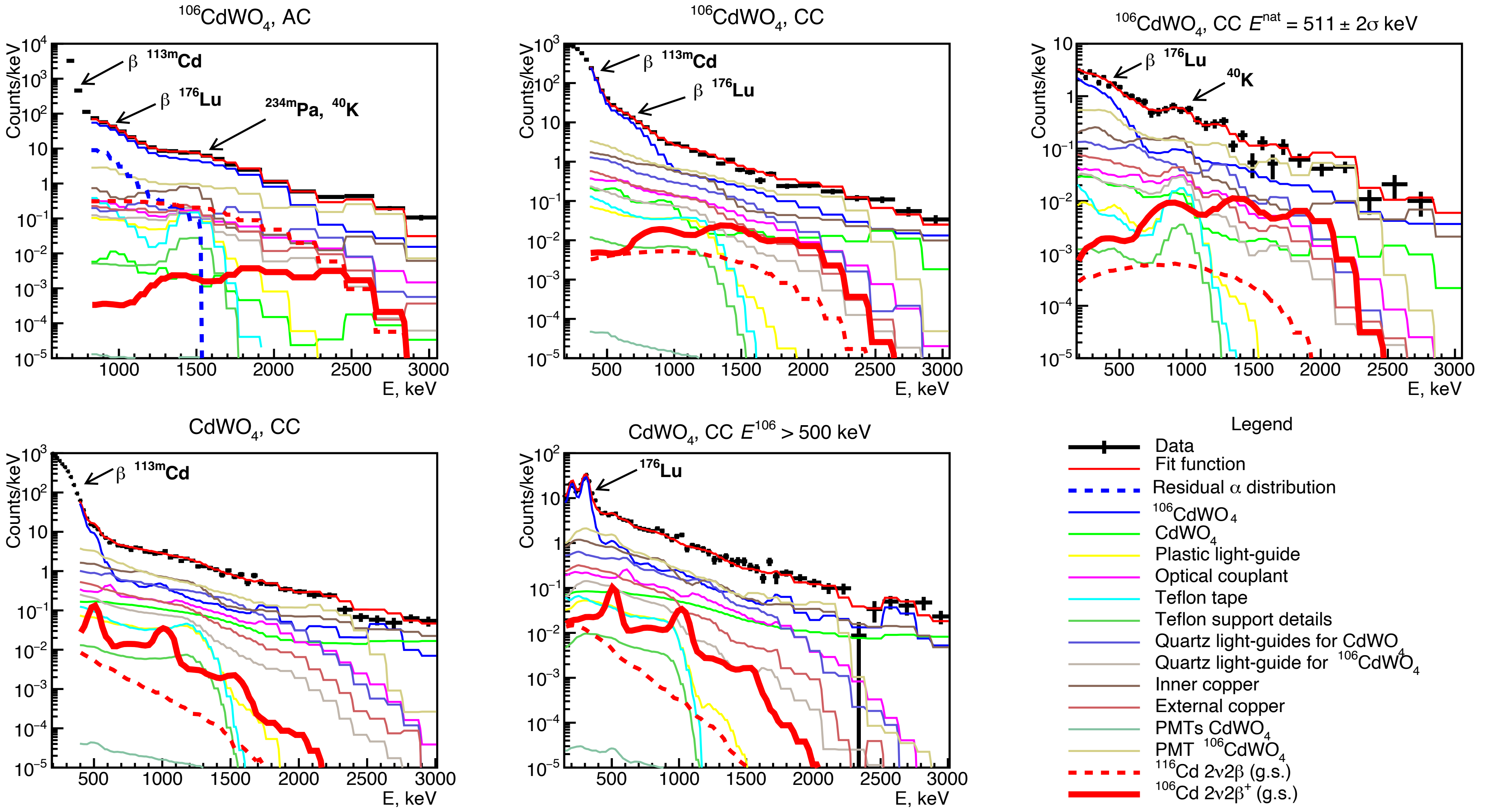
- Activities are in mBq/kg
- (*) determined using the time-amplitude analysis
- (†) determined by analysis of the α distribution

Main components of the background considered in the fit:

1) ^{40}K and ^{232}Th, ^{238}U with their daughters in all the setup components;
2) Residual α distribution in the $^{106}CdWO_4$ crystal (7.3% of the alpha distribution);
3) Beta decay of ^{176}Lu and ^{113m}Cd (Q_β = 587 keV), and $2\nu2\beta$ decay of ^{116}Cd with a half-life of $T_{1/2} = 2.63 \times 10^{19}$ yr in the $^{106}CdWO_4$ crystal.
4) ^{113}Cd (Q_β = 324 keV) in the $CdWO_4$ and $^{106}CdWO_4$ crystal scintillators.
5) ^{56}Co and ^{60}Co in the internal copper.

[Universe 11 (2025), 123]

$\gamma\&\beta$ spectra in different modes



- The main background contributions arise from the PMT, the light guide and the internal contamination of the ^{106}CdWO$_4$ crystal.

Half-life limits on 2β decay processes in ^{106}Cd

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

- N is the number of ^{106}Cd nuclei in the $^{106}CdWO_4$ crystal ($N = 2.42 \times 10^{23}$);
- η_{det} is the detection efficiency for the process of decay and η_{sel} is the selection efficiency;
- t is the measurement live time (1075 days);
- $\lim S$ is the number of events of the effect searched for, which can be excluded at a given confidence level (C.L.; in the present study all limits are given at the 90% C.L.).

$$\Longrightarrow \lim T_{1/2} = N \cdot \ln 2 \cdot t/\lim N_{dec}$$

- $\lim N_{dec} = \lim S/(\eta_{det} \cdot \eta_{sel})$ is the number of decays of the process searched for.

[Universe 11 (2025), 123]

Results

Decay	Level of ^{106}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]	4.4×10^{21} [54]	1.7×10^{22}
	512	$(1.5 - 25) \times 10^{27}$ [47,55,56]	4.1×10^{21} [54]	1.5×10^{22}
$0\nu 2\beta^+$	g.s.	$(1.4 - 32) \times 10^{27}$ [47,55–61]	5.9×10^{21} [62]	2.2×10^{22}
	512		4.1×10^{21} [54]	1.5×10^{22}
$2\nu EC\beta^+$	g.s.	$(1.4 - 240) \times 10^{21}$ [47,48,50–53], $>2.7 \times 10^{22}$ [49]	2.1×10^{21} [62]	7.7×10^{21}
	512	$(5.3 - 24) \times 10^{25}$ [51,52], $>1.1 \times 10^{25}$ [49]	3.3×10^{21} [54]	9.9×10^{21}
	1128	3.7×10^{30} [51]	2.0×10^{21} [54]	1.2×10^{22}
	1134	$(1.3 - 13) \times 10^{26}$ [51,52], $>1.1 \times 10^{27}$ [49]	2.5×10^{21} [54]	1.3×10^{22}
$0\nu EC\beta^+$	g.s.	$(1.0 - 17) \times 10^{26}$ [32,47,55,56]	1.4×10^{22} [62]	1.5×10^{22}
	512		9.7×10^{21} [62]	2.1×10^{22}
	1128		1.0×10^{22} [62]	1.9×10^{22}
	1134	$(1.0 - 21) \times 10^{29}$ [32,55,57,58]	2.7×10^{21} [54]	2.1×10^{22}

[32] Suhonen, J. Phys. Lett. B 2011, 701, 490–495.
[47] Stoica, S.; Klapdor-Kleingrothaus, H.V. Eur. Phys. J. A 2003, 17, 529–536.
[48] Shukla, A. et al. Eur. Phys. J. A 2005, 23, 235–242.
[49] Domin, P. et al. Nucl. Phys. A 2005, 753, 337–363.
[50] Raina, P.K. et al. Eur. Phys. J. A 2006, 28, 27–36.
[51] Suhonen, J. AIP Conf. Proc. 2011, 1417, 115–119.
[52] Pirinen, P.; Suhonen, J. Phys. Rev. C 2015, 91, 054309.
[53] Ejiri, H. J. Phys. G 2017,44, 115201.
[54] Leoncini, A. et al. Phys. Scr. 2022, 97, 064006.
[55] Suhonen, J.; Aunola, M. Nucl. Phys. A 2003, 723, 271–288.
[56] Rath, P.K. et al. Phys. Rev. C 2009, 80, 044303.
[57] Suhonen, J. J. Phys. Conf. Ser. 2012, 338, 012030.
[58] Suhonen, J. Phys. Scripta T 2012, 150, 014039.
[62] Belli, P. et al. Universe 2020, 6, 182.

Results

Decay	Level of ^{106}Pd, keV	Theoretical $T_{1/2}$, Years	lim$T_{1/2}$, Years Previous Result	lim$T_{1/2}$, Years Present Work
2ν2EC	g.s.	$(2.0-230)\times10^{20}$ [47,48,50–53]	1.7×10^{21} [63]	–
	512	$(1.5-9.4)\times10^{27}$ [51,52], $>4.0\times10^{26}$ [49]	9.9×10^{20} [64]	2.2×10^{20}
	1128	9.9×10^{28} [51]	6.6×10^{20} [62]	9.3×10^{20}
	1134	$(1.1-11)\times10^{23}$ [51,52]	1.0×10^{21} [64]	1.4×10^{21}
	1562	$(2.4-4.3)\times10^{28}$ [52], $>5.4\times10^{28}$ [49]	7.8×10^{20} [62]	7.9×10^{20}
	1706	$>1.9\times10^{25}$ [49]	7.1×10^{20} [64]	4.6×10^{21}
	2001	$>8.9\times10^{24}$ [49]	1.5×10^{21} [62]	1.4×10^{21}
	2278	$>2.1\times10^{27}$ [49]	1.0×10^{21} [64]	1.8×10^{21}
0ν2EC	g.s.		1.0×10^{21} [39]	1.2×10^{21}
	512		5.1×10^{20} [39]	1.9×10^{21}
	1128		5.1×10^{20} [64]	1.7×10^{21}
	1134		1.1×10^{21} [64]	2.2×10^{21}
	1562		1.4×10^{21} [62]	2.0×10^{21}
	1706		2.0×10^{21} [62]	1.7×10^{21}
	2001		1.2×10^{21} [64]	3.3×10^{21}
	2278		1.2×10^{21} [62]	1.2×10^{21}
Res. 0ν2EC	2718	$(3.2-9.7)\times10^{22}$ [57], $>5.2\times10^{24}$ [65,66], $>7.9\times10^{23}$ [32]	2.9×10^{21} [62]	2.0×10^{21}
	2741	$>5.2\times10^{24}$ [66]	9.5×10^{20} [39]	1.2×10^{21}
	2748	$2\times10^{29}-2\times10^{34}$ [29]	1.4×10^{21} [64]	1.9×10^{21}

[39] Belli, P. et al. Phys. Rev. C 2012, 85, 044610.
[64] Belli, P. et al. Phys. Rev. C 2016, 93, 045502.
[65] Suhonen, J. AIP Conf. Proc. 2010, 1304, 85–93.
[66] Belli, P. et al. AIP Conf. Proc. 2010, 1304, 354–358.

Conclusions

- One of the most sensitive $2\beta^+$ experiments to search for 2β decay of ^{106}Cd with an enriched $^{106}CdWO_4$ scintillator in coincidence with two large volume $CdWO_4$ counters was carried out at the LNGS (Italy).

- After 1075 days of data taking, we provide new improved half-life limits on the different channels and modes of ^{106}Cd 2β decay at the level of $\lim T_{1/2} = 10^{20}$– 10^{22} years.

- A new half-life limit on $2\nu EC\beta^+$ decay to the g.s. of ^{106}Pd was set as $\lim T_{1/2}^{2\nu EC\beta^+\ g.s.} = 7.7 \times 10^{21}$ years, in the region of the theoretical predictions of 10^{21}–10^{23} years.

- 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}Pd have been set at the level $\lim T_{1/2}^{Res.0\nu 2EC} = (1.2 - 2.0) \times 10^{21}$ years.

- The main sources of background are the PMT, the light-guide and the internal contamination of the $^{106}CdWO_4$ crystal, which affect the sensitivity to 2β decay processes.

- <u>Analysis of the complete data set of the experiment is in progress.</u>

BACKUP

Past experiments on the search of 2β decay processes in ^{106}Cd

[252] Danevich, F. A. et al. Phys. Rev. C 68, 2003, 035501.
[292] Belli, P. et al. Phys. Rev. C 85, 2012, 044610.
[293] Belli, P. et al. Phys. Rev. C 93, 2016, 045502.
[294] Fremlin, J. H. et al. Proc. Phys. Soc. Lond. A 65, 1952, 911.
[295] Winter, R. G.; Phys. Rev. 99, 1955, 88.
[296] Norman, E. B.; DeFaccio, M.A. Phys. Lett. B 148, 1984, 31.
[297] Georgadze, A. Sh. et al. Phys. At. Nucl. 58, 1995, 1093
[298] Danevich, F.A. et al. Z. Phys. A 355, 1996, 433.
[299] Barabash, A.S.et al. Nucl. Phys. A 604, 1996, 115.
[300] Ito, Y. et al. Nucl. Instr. and Meth. A 386, 1997, 439.
[301] Belli, P. et al. Astropart. Phys. 10, 1999, 115.
[302] Dawson, J. V. et al. Phys. Rev. C 80, 2009, 025502.
[303] Kiel, H.; Munstermann, D.; Zuber, K. Nucl. Phys. A 723, 2003, 499-514.
[304] Ebert, J. et al. Adv. High Energy Phys. 2013, 2013, 703572.
[305] Ebert, J. et al. Phys. Rev. C 94, 2016, 024603.
[306] Rukhadze, N. I. et al. Nucl. Phys. A 852, 2011, 197-206.
[307] Rukhadze, N.I. et al. Bull. Russ. Acad. Sci. Phys. 75, 2011, 879-882.
[308] Polischuk, O.G. et al. AIP Conf. Proc. 2165, 2019, 020020.

Description	$T_{1/2}$ limit (yr)	Year[Ref. No]
Cd samples between photographic emulsions	$\sim 10^{15}(0\nu 2\beta^+, 0\nu\varepsilon\beta^+)$	1952 [294]
Cd foil in a Wilson cloud chamber	$6\times 10^{16}(0\nu 2\beta^+)$	1955 [295]
Cd sample between two NaI(Tl) scintillators in coincidence	$(2.2-2.6)\times 10^{17}((0\nu+2\nu)2\beta^+)$ $(4.9-5.7)\times 10^{17}((0\nu+2\nu)\varepsilon\beta^+)$ $1.5\times 10^{17}(2\nu 2\varepsilon)$	1984 [296]
$^{116}CdWO_4$ crystal scintillator	$(0.5-1.4)\times 10^{18}(0\nu 2\beta^+)$ $(0.3-1.1)\times 10^{19}(0\nu\varepsilon\beta^+)$ $5.8\times 10^{17}(2\nu 2\varepsilon)$	1995 [297]
$CdWO_4$ crystal scintillator	$2.2\times 10^{19}(0\nu 2\beta^+)$ $9.2\times 10^{17}(2\nu 2\beta^+)$ $5.5\times 10^{19}(0\nu\varepsilon\beta^+)$ $2.6\times 10^{17}(2\nu\varepsilon\beta^+)$	1996 [298]
Cd sample measured by HPGe detector	$1.0\times 10^{19}((0\nu+2\nu)2\beta^+)$ $(6.6-8.1)\times 10^{18}((0\nu+2\nu)\varepsilon\beta^+)$ $(3.5-6.2)\times 10^{18}((0\nu+2\nu)2\varepsilon)$	1996 [299]
CdTe cryogenic bolometer	$1.4\times 10^{16}(0\nu\varepsilon\beta^+)$	1997 [300]
^{106}Cd sample between two NaI(Tl) scintillators in coincidence	$(1.6-2.4)\times 10^{20}((0\nu+2\nu)2\beta^+)$ $(1.1-4.1)\times 10^{20}((0\nu+2\nu)\varepsilon\beta^+)$ $(3.0-7.3)\times 10^{19}((0\nu+2\nu)2\varepsilon\beta)$	1999 [301]
$^{116}CdWO_4$ crystal scintillator	$(0.5-1.4)\times 10^{19}((0\nu+2\nu)2\beta^+)$ $(0.1-7.0)\times 10^{19}((0\nu+2\nu)\varepsilon\beta^+)$ $(0.6-8.0)\times 10^{18}((0\nu+2\nu)2\varepsilon)$	2003 [252]
CdZnTe semiconductor detectors (COBRA)	$(0.9-2.7)\times 10^{18}((0\nu+2\nu)2\beta^+)$ $(4.9-4.7)\times 10^{18}((0\nu+2\nu)\varepsilon\beta^+)$ $1.6\times 10^{17}((0\nu+2\nu)2\varepsilon)$	2009 [302–305]
Cd samples between planar HPGe detectors(TGV)	$3.6\times 10^{20}(2\nu 2\varepsilon)$ $1.1\times 10^{20}(0\nu 2\varepsilon, 2741\ \text{keV})$	2011 [306]
	$(1.4-1.7)\times 10^{20}((0\nu+2\nu)2\beta^+)$ $(1.1-1.6)\times 10^{20}((0\nu+2\nu)\varepsilon\beta^+)$ $1.6\times 10^{20}(0\nu 2\varepsilon, 2718\ \text{keV})$	2011 [307]
$CdWO_4$ enriched in ^{106}Cd up to 66%	$(2.1)\times 10^{20}(2\nu\varepsilon\beta^+)$ $(4.3)\times 10^{20}(2\nu 2\beta^+)$ $(1.0)\times 10^{21}(0\nu 2\varepsilon)$	2012 [292]
$^{106}CdWO_4$ enriched in ^{106}Cd up to 66% in coincidence with HPGe detectors with four Ge crystals	$1.1\times 10^{21}(2\nu\varepsilon\beta^+)$	2016 [293]
$^{106}CdWO_4$ in coincidence with two large volume $CdWO_4$	$4\times 10^{21}(2\nu\varepsilon\beta^+)$	2019 [308]