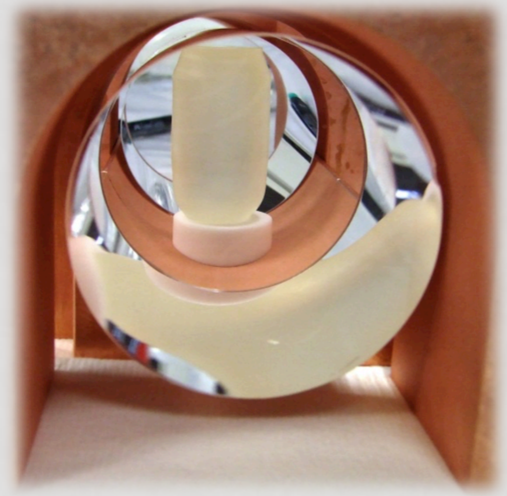


Search for double beta decay in ^{106}Cd in the DAMA/Crys setup

Belli P., Bernabei R., Brudanin V.B., Cappella F., Caracciolo V., **Cerulli R.**, Danevich F.A., Incicchitti A., Kasperovych D.V., Kobychev V.V., Mokina V.M., Polischuk O.G., Tretyak V.I., Zarytskyy M.M.

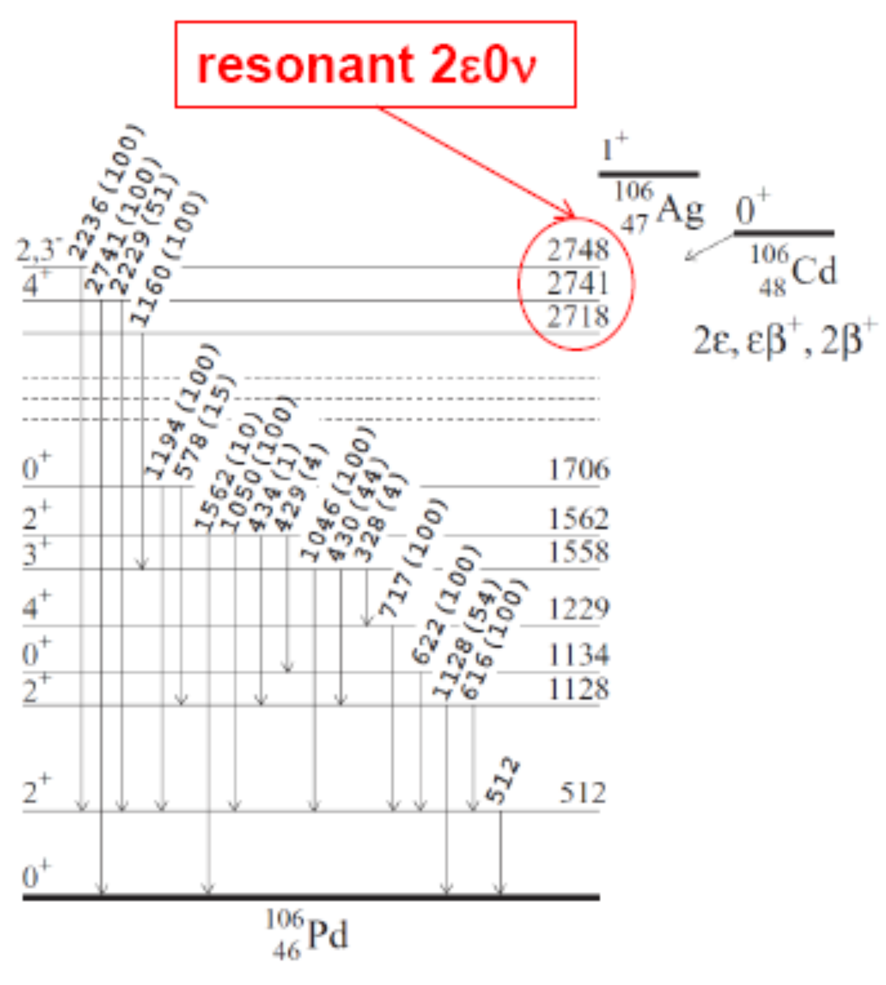
R. Cerulli
INFN – Roma Tor Vergata

MEDEX'17 Conference
Prague (Czech Republic)
May 29 –June 2, 2017

^{106}Cd for 2β decay

^{106}Cd, a promising isotope:

1) One of the six isotopes candidate for $2\beta^+$ decay
2) High natural abundance δ=(1.25±0.06)%; possible enrichment up to 100%;
3) $Q_{2\beta}$= (2775.39±0.10) keV; $2\beta^+$, $\varepsilon\beta^+$ and 2ε decay modes possible
4) Possible resonant $2\varepsilon0\nu$ captures to excited level of ^{106}Pd (2718 keV – $2K0\nu$, 2741 keV – $KL_10\nu$, 2748 keV – $KL_30\nu$)
5) Theoretical $T_{1/2}$ favorable for some modes (10^{20} – 10^{22} yr) [1] (g.s. to g.s.)



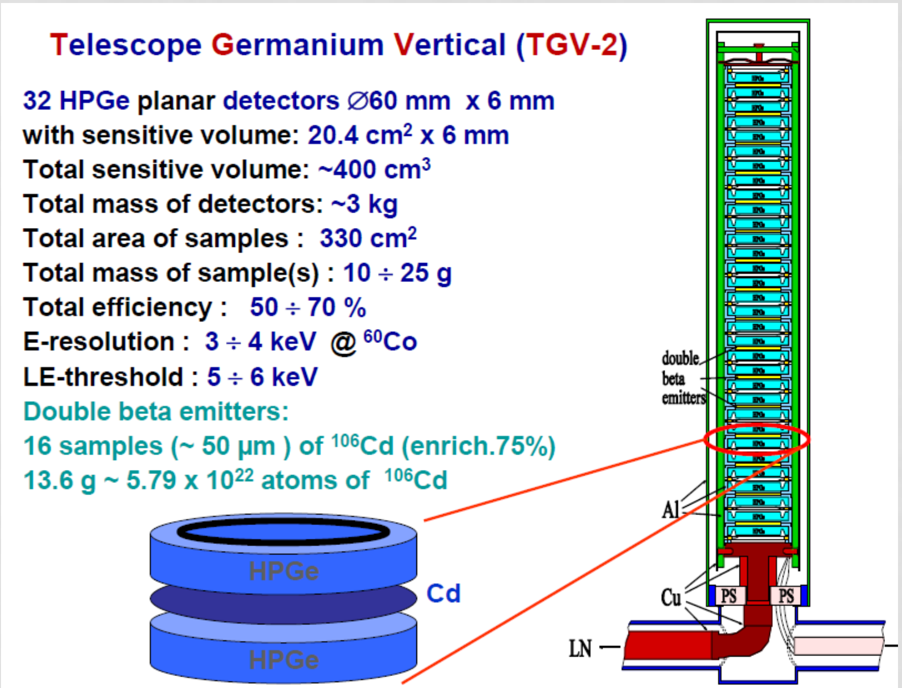
Decay scheme

[1] EPJA 17(2003)529, PRC 86(2012)024301

Current activity on 2β decay of ^{106}Cd

TGV-2 Experiment:

32 planar HPGe + 16 foils of ^{106}Cd (δ=75%, 13,6 g), LSM (France)



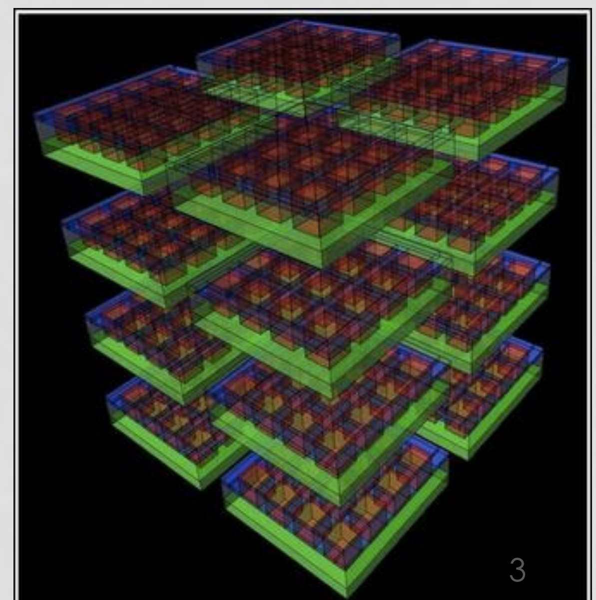
Current sensitivity:

$T_{1/2} \approx 10^{20}$ yr

N.I. Rukhadze et al., NPA 852 (2011) 197, BRASP 75 (2011) 879

COBRA:

32 semiconductors CdZnTe (1 cm³ each), LNGS (Italy)



Current sensitivity: $T_{1/2} \approx 10^{18}$ yr

K. Zuber, Prog. Part. Nucl. Phys. 64 (2010) 267

$CdWO_4$ as a 2β detector

$CdWO_4$ crystal scintillator:

- ✓ Good scintillation properties
- ✓ Low levels of internal contamination in U, Th and K
- ✓ α/β discrimination capability

Properties	Value
Density [g/cm^3]	7.9
Melting point [K]	1598
Hygroscopic	No
Wavelength of max emission [nm]	475
Refractive index @ max em.	2.2-2.3
Primary decay time [μs]	14
Photoelectron yield [% of NaI(Tl)]	30-50

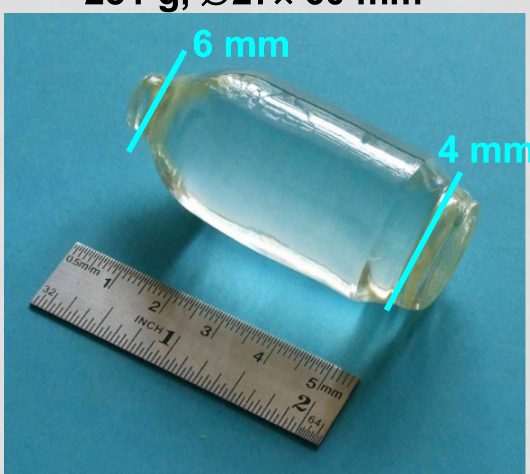
PRC 68 (2003) 035501; P. Belli et al., *PRC 85 (2012) 044610;* F.A. Danevich et al., NIMA 741(2014)41

$^{106}CdWO_4$ crystal scintillator

NIMA615(2010)301

- DAMA and INR-Kiev Collaboration
- Samples of cadmium were purified by vacuum distillation (Institute of Physics and Technology, Kharkiv) and the Cadmium tungstate compounds were synthesized from solutions
- Crystal boule was grown by the low-thermal-gradient Czochralski technique (NIIC Novosibirsk) (initial powder 265 g)
- Crystal scintillator (**216 g**), **66.4%** enrichment in ^{106}Cd measured by thermal ionisation mass-spectrometry (**2.66×10^{23}** nuclei of ^{106}Cd)
- 2nd enriched $CdWO_4$ crystal ever produced
- Measured in DAMA/R&D set-up and in LNGS Stella facility

231 g, ∅27× 60 mm



216 g, ∅27× 50 mm

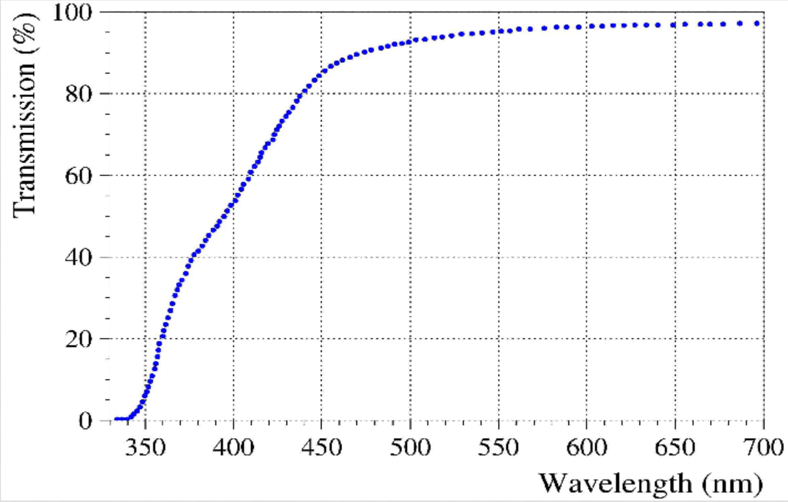
crystal surface has been diffused to improve light collection

$^{106}CdWO_4$ crystal scintillator

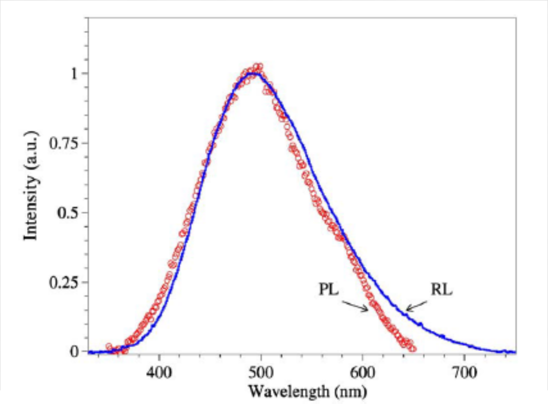
NIMA615(2010)301

Excellent optical and luminescence properties were reached thanks to a special R&D (deep purification of raw materials and low-gradient crystal growth by the Czochralski method). High light output.

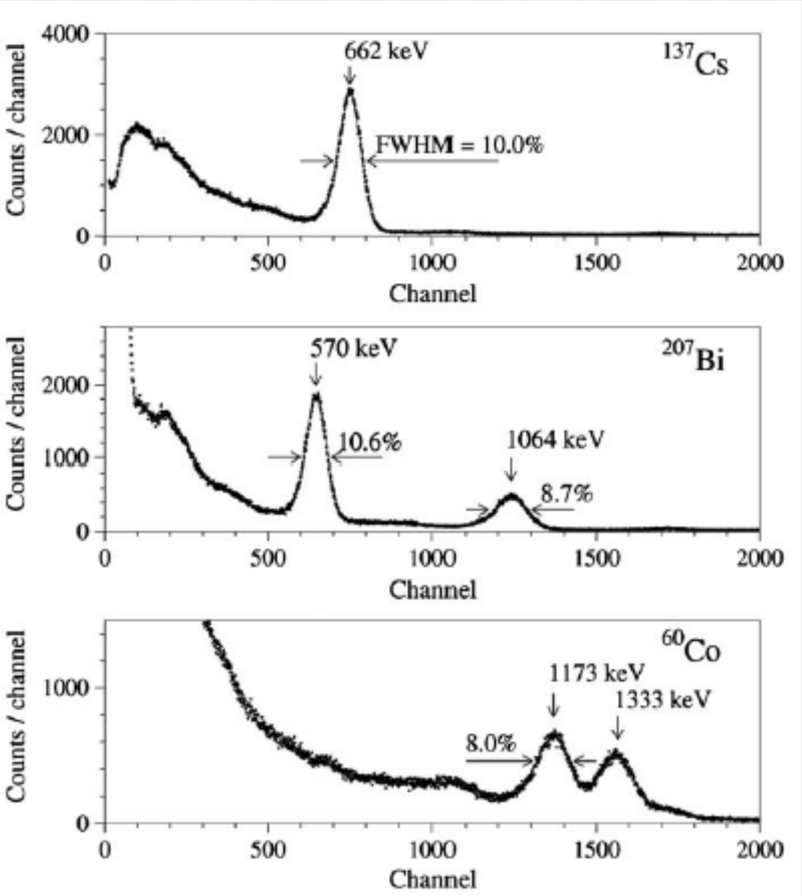
Optical transmission curve



Emission spectra of ^{106}CdWO4 crystal under ultraviolet (PL) and X-ray (RL) excitation



Response of the detector to γ sources



FWHM = 10% @ 662 keV

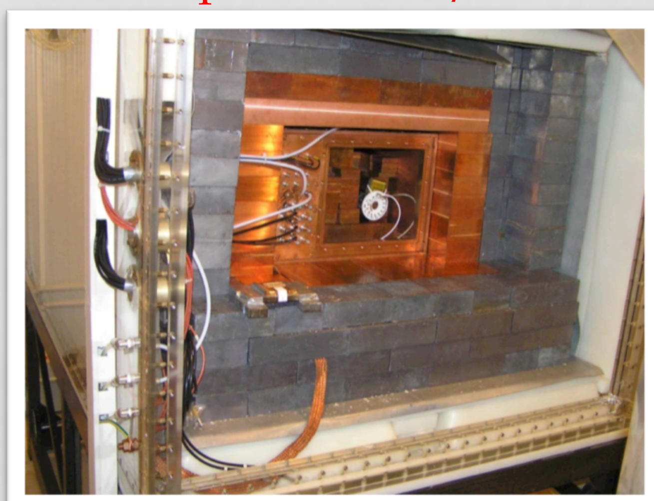
Searching for 2β decay by using $^{106}CdWO_4$ at LNGS

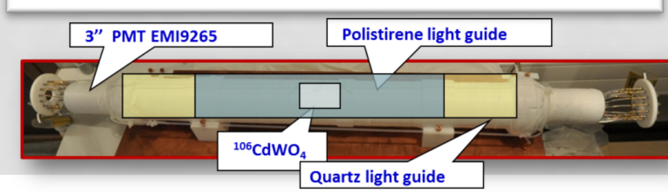
PRC85(2012)044610

Experiment with ^{106}CdWO4 performed at LNGS in the framework of the DAMA and INR-Kiev Collaboration:

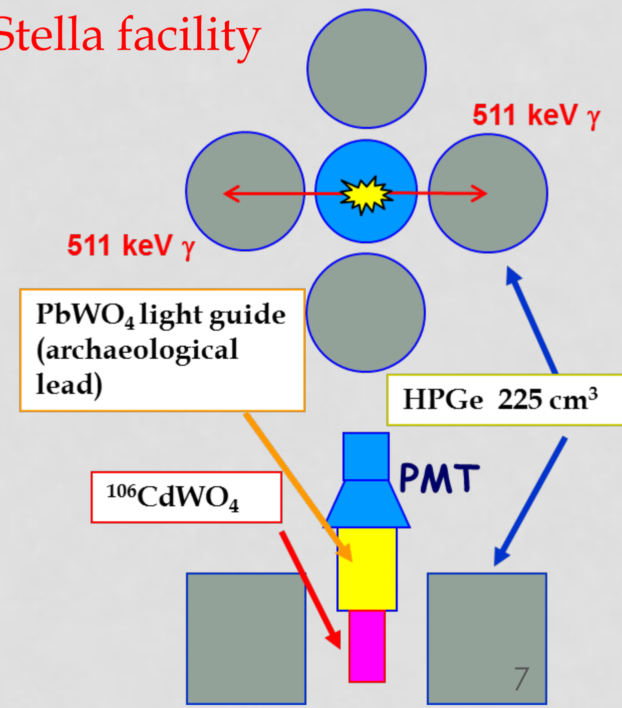
- single crystal in DAMA/R&D
- in coincidence with 4 HP-Ge in the Stella facility

1st exp in DAMA/R&D





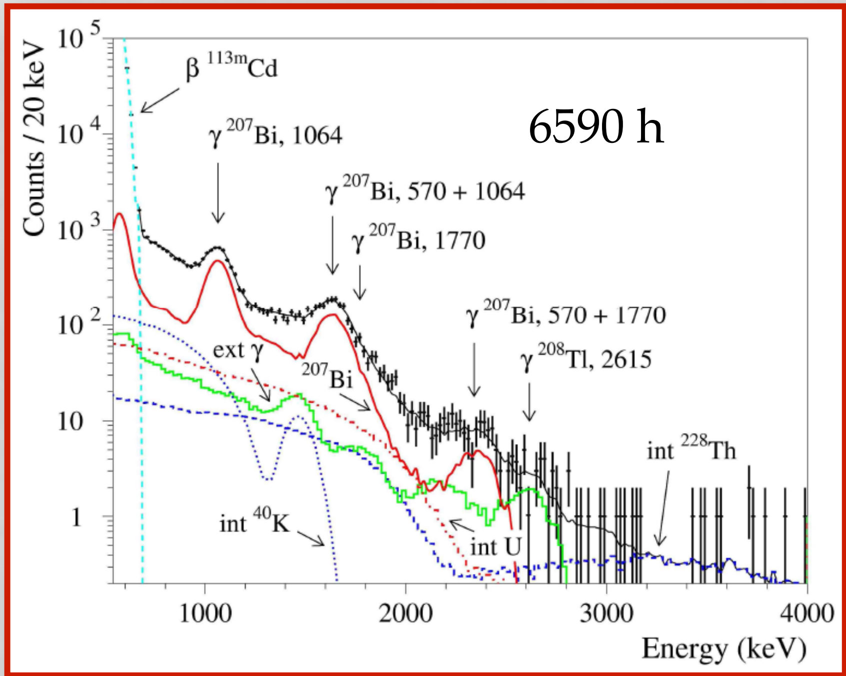
2nd exp in HP-Ge Stella facility



Search for 2β decay in ^{106}Cd in DAMA/R&D

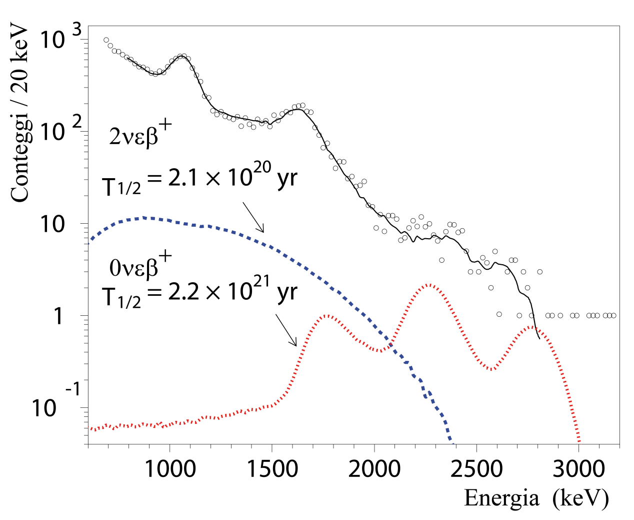
Energy distribution of the γ/β events (by PSD)

Phys. Rev. C 85 (2012) 044610



Contamination level in $^{106}CdWO_4$ (mBq/Kg)

^{207}Bi	<0.7
^{113m}Cd	116 ·10^{3}
^{232}Th	< 0.07
^{228}Th	0.042(4)
^{238}U	<0.6
^{226}Ra	0.012(3)
^{40}K	<1.4
^{207}Bi surface	0.06 mBq/cm^{3}



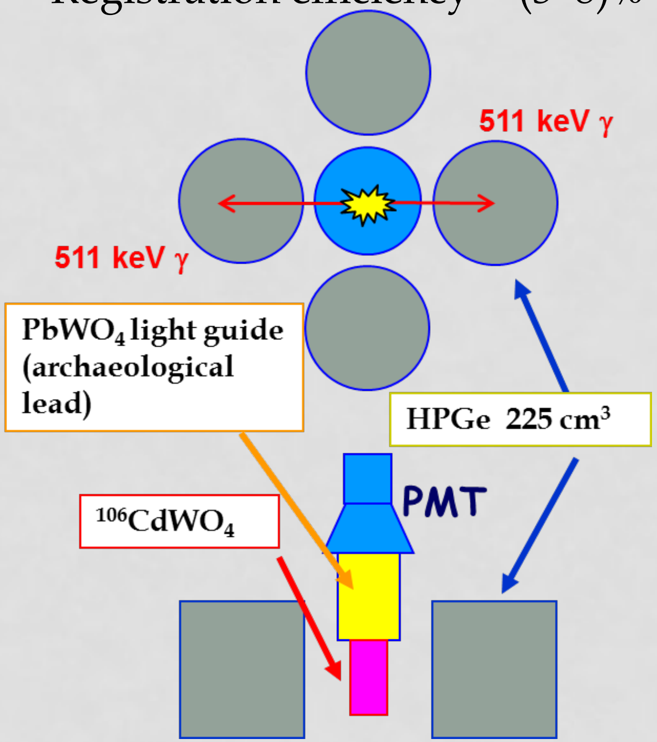
Result:

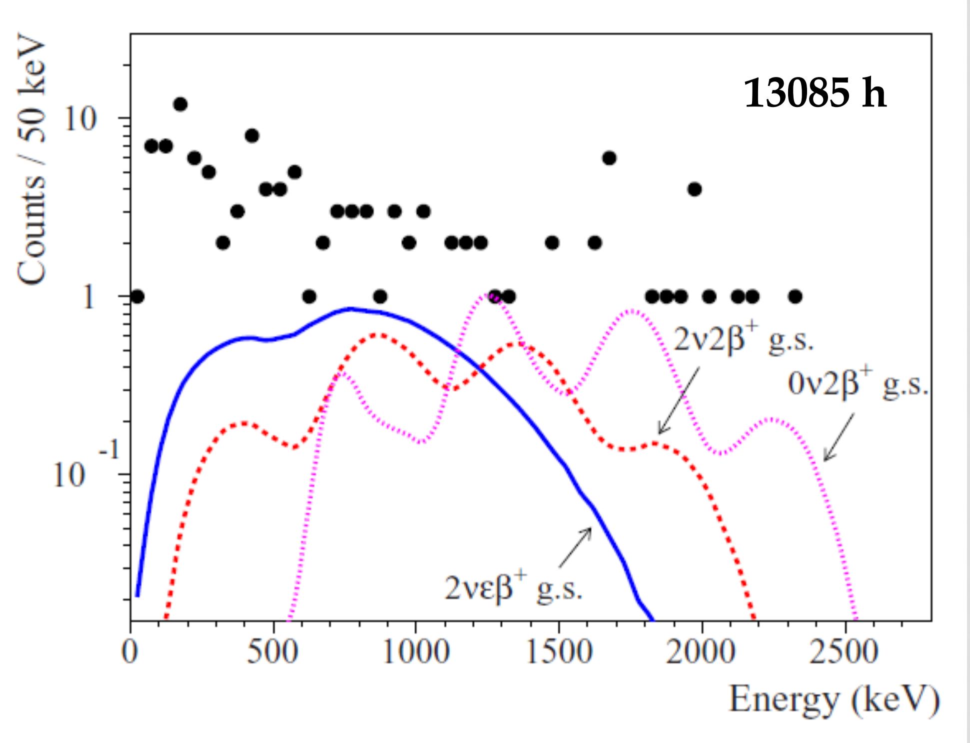
$T_{1/2}$ (2β, ^{106}Cd→ ^{106}Pd) ≥ 10^{19-21} yr

27 new results for 2β ^{106}Cd
9 of them – for the first time

$^{106}CdWO_4$ in GeMulti

- $^{106}CdWO_4$ in coincidence / anticoincidence with 4-crystals HPGe detector (GeMulti)
- Crystal Surface cleaned
- Registration efficiency ~ (3–8)%



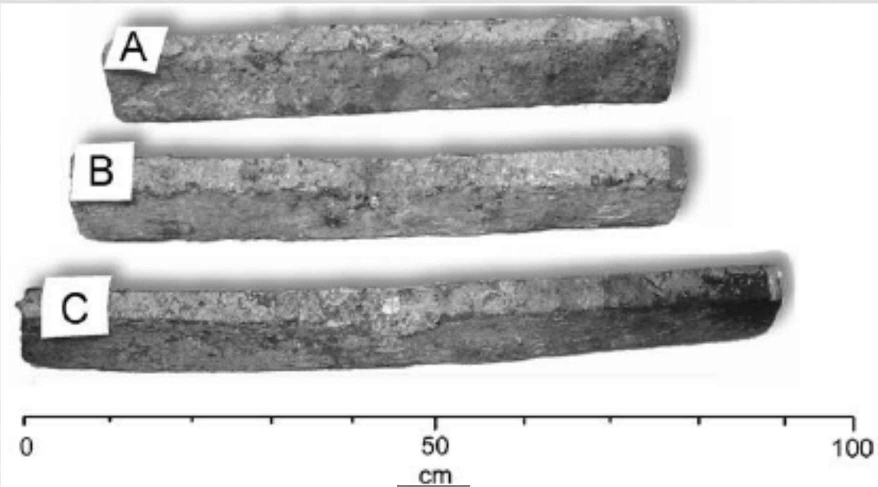


Energy spectrum of $^{106}CdWO_4$ detector in coincidence with 511 keV in HPGe (circles). Monte Carlo simulated distributions of 2β decay of ^{106}Cd excluded at 90% CL.

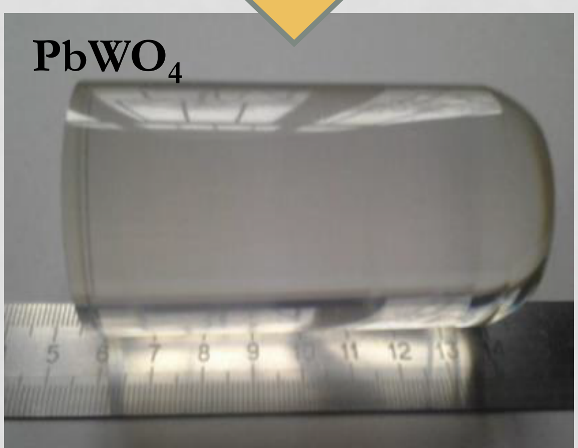
- **New limits on 2ε, εβ$^+$, 2β$^+$ processes on the level of $T_{1/2} > 10^{20}$ -10^{21} yr**
- **The half-life limit on the 2νεβ$^+$ decay, $T_{1/2} > 1.1\times10^{21}$ yr, reached the region of theoretical predictions**
- **For 0νε2 resonant captures: $T_{1/2} > (8.5 \times 10^{20} - 1.4 \times 10^{21})$ yr**

$^{arch}PbWO_4$ light guide

- $PbWO_4$ light-guide realized in order to suppress the radioactive components from the photomultiplier
- Archaeological lead: A (^{210}Pb) <0.3 mBq/kg [3]



- Purification Pb: Institute of Physics and Technology (Kharkiv)
- Crystal growth: Institute of Scintillation Materials (Kharkiv)

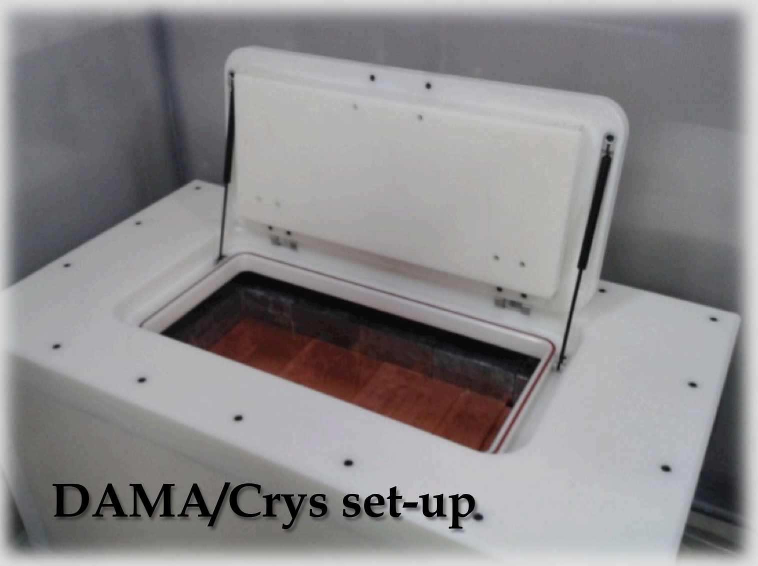


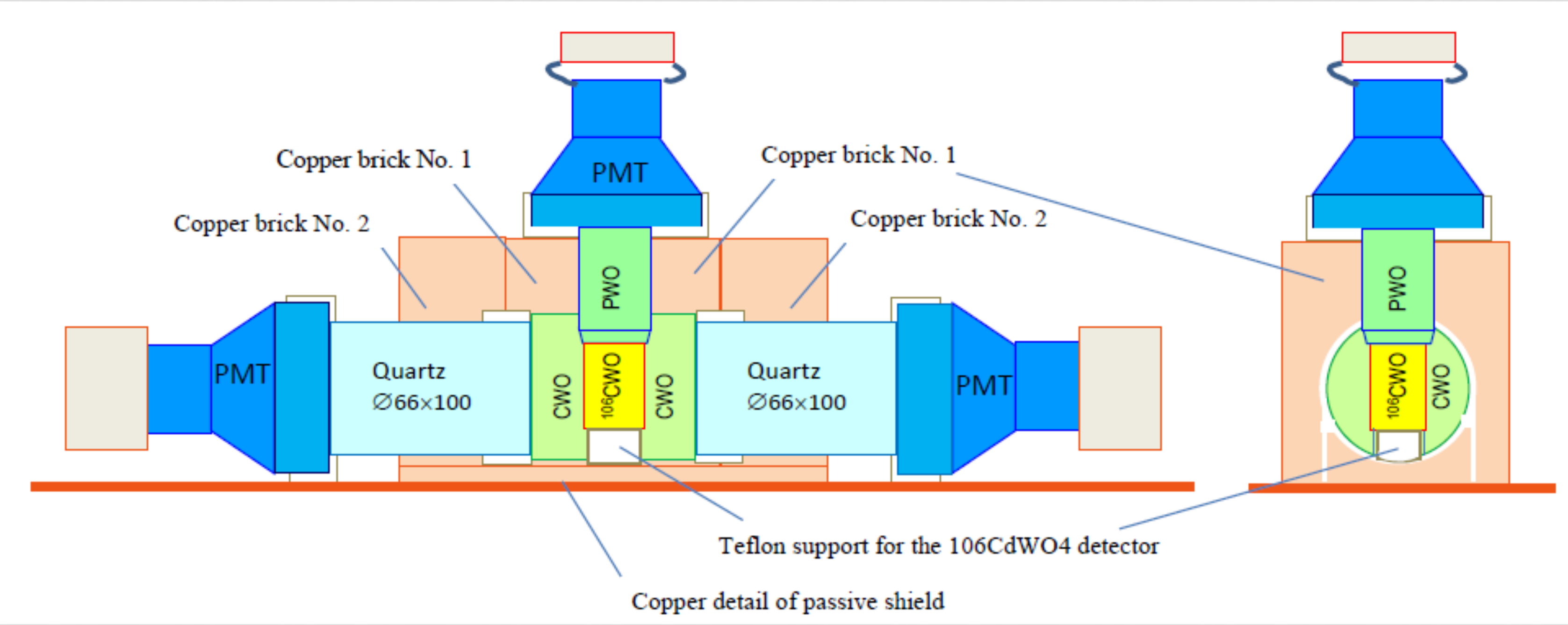
Firstly used in the ^{106}Cd experiment in GeMulti

[1] P. Belli et al., *PRC 85 (2012) 044610*
[2] F.A. Danevich et al., NIMA 741(2014)41
[3] NIMA 603 (2009) 328; Inorganic Mater. 47 (2011) 645.

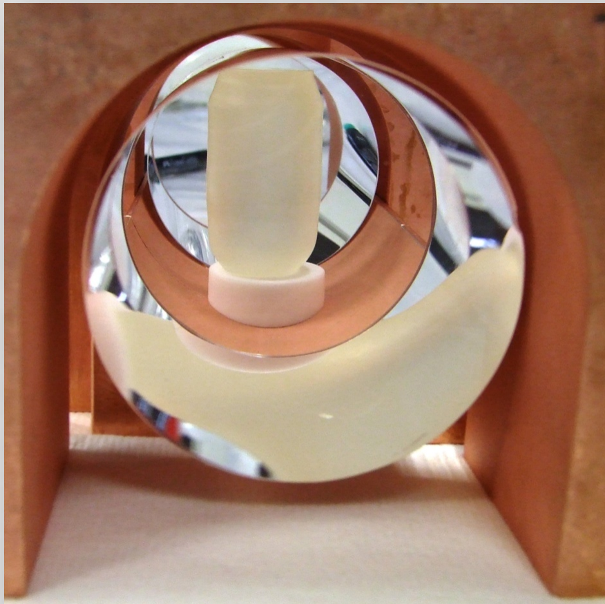
New $^{106}CdWO_4$ experiment in DAMA/Crys set-up

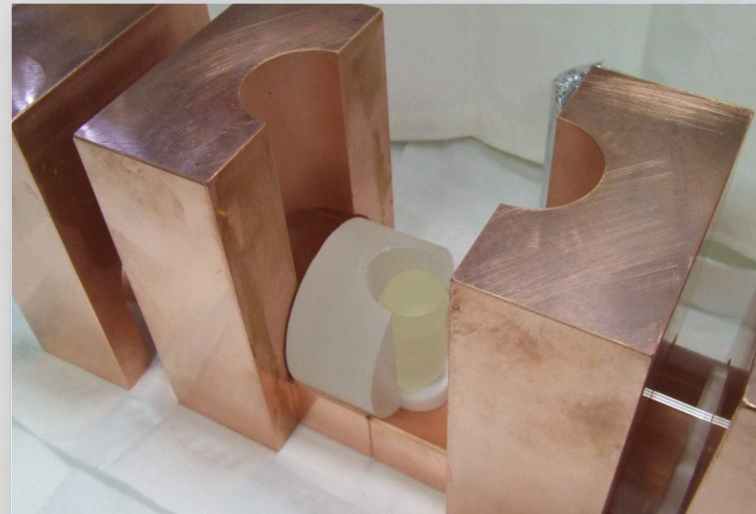
1) New experiment with $^{106}CdWO_4$ in (anti)coincidence with two large $CdWO_4$ scintillators mounted in DAMA/Crys set-up at LNGS
2) High efficiency
3) Experiment in data taking since May 2016

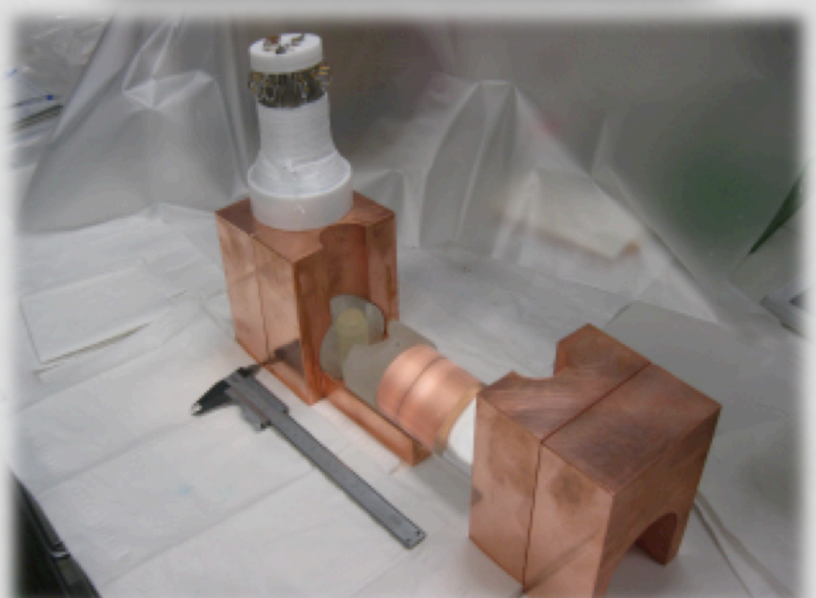


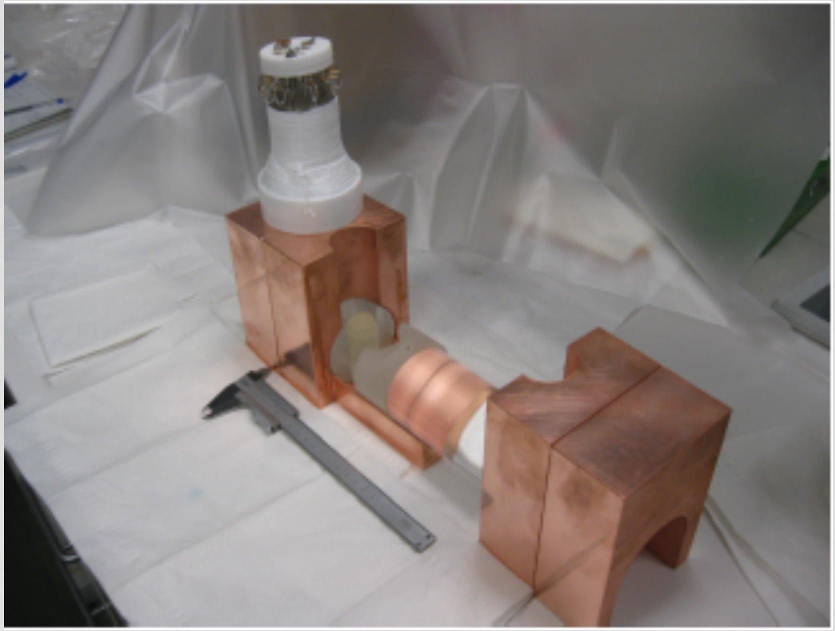


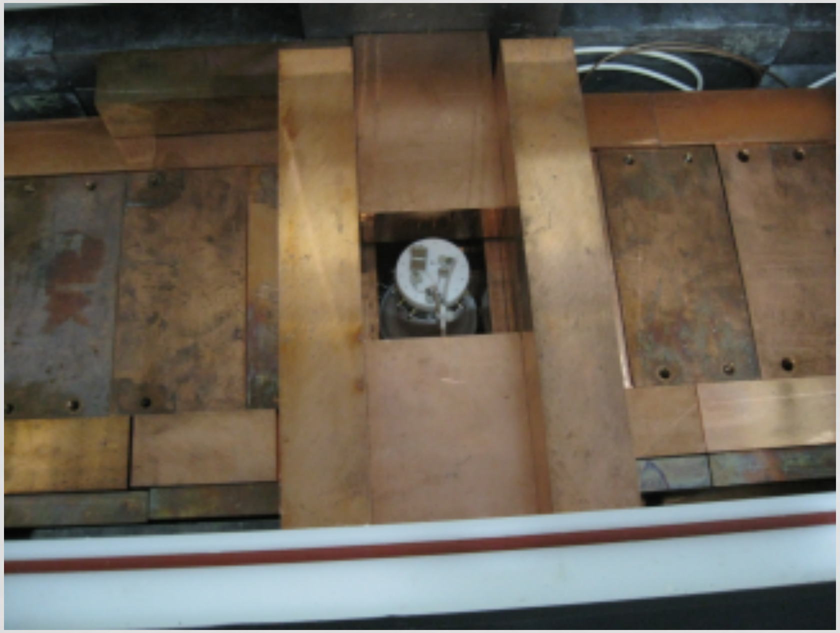
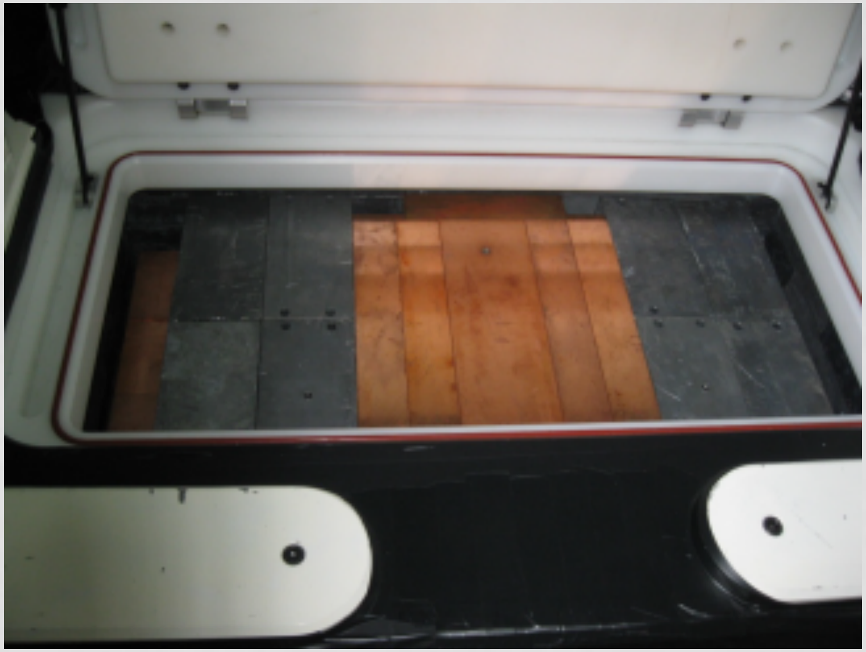
New $^{106}CdWO_4$ experiment in DAMA/Crys set-up



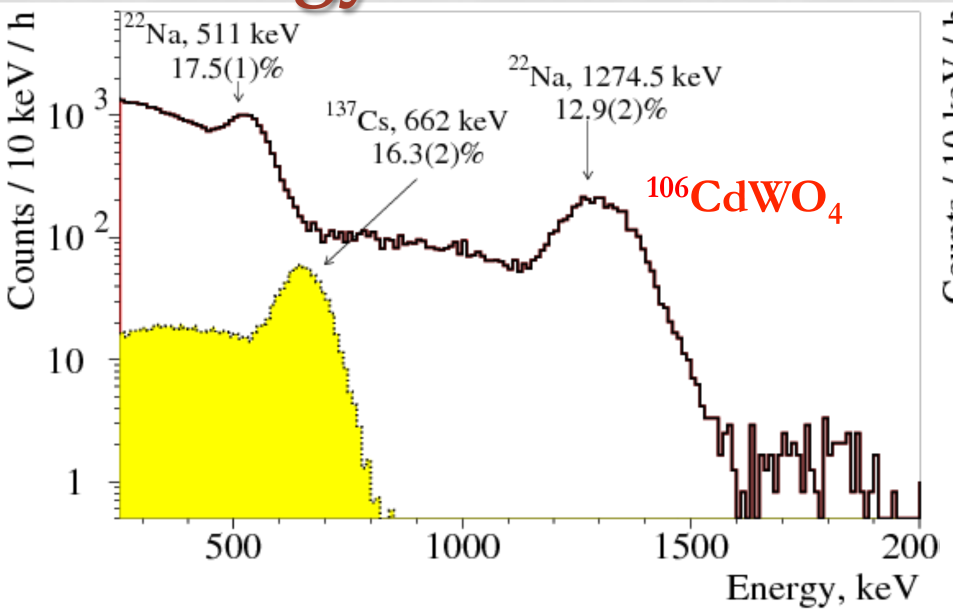


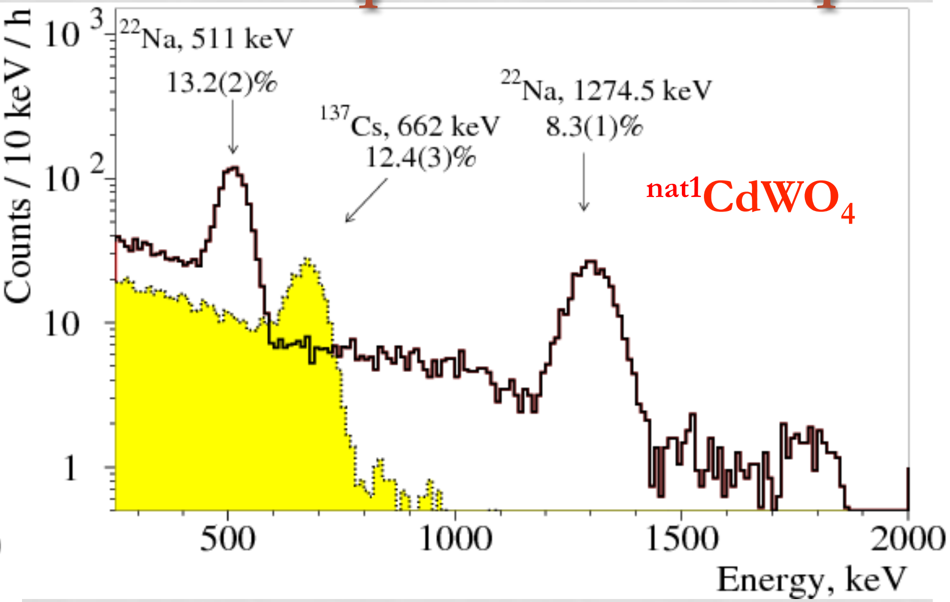


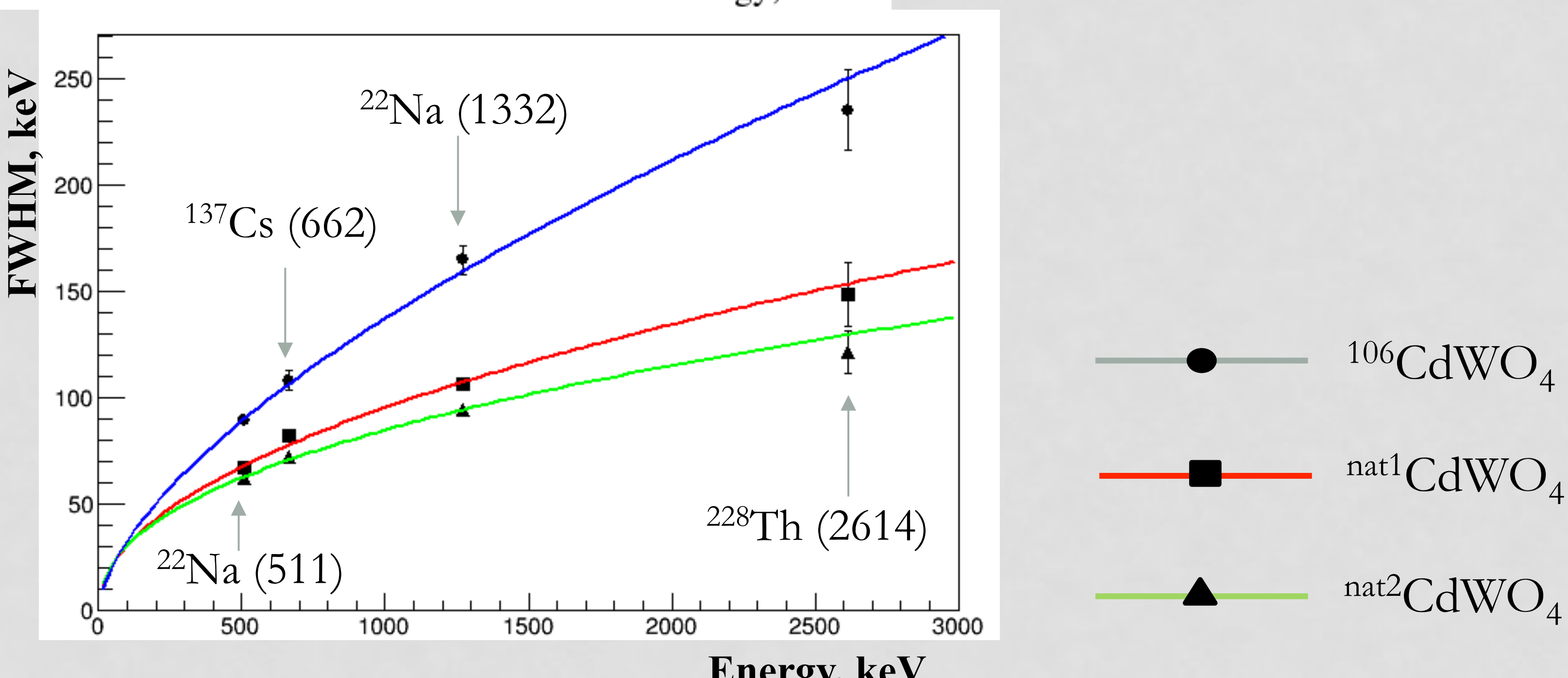


Energy resolutions for $^{106}CdWO_4$ and $CdWO_4$

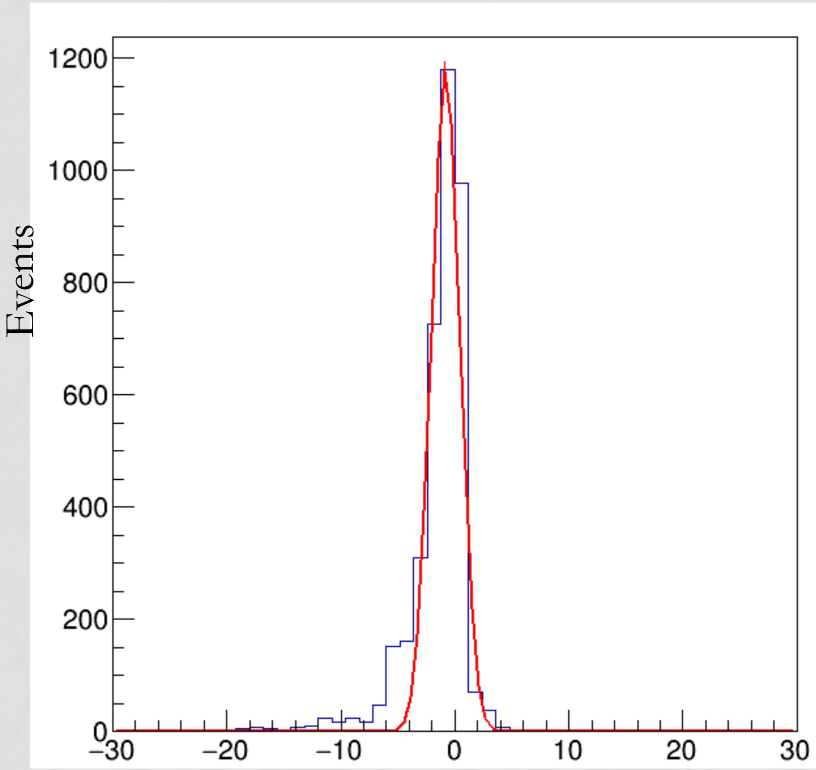


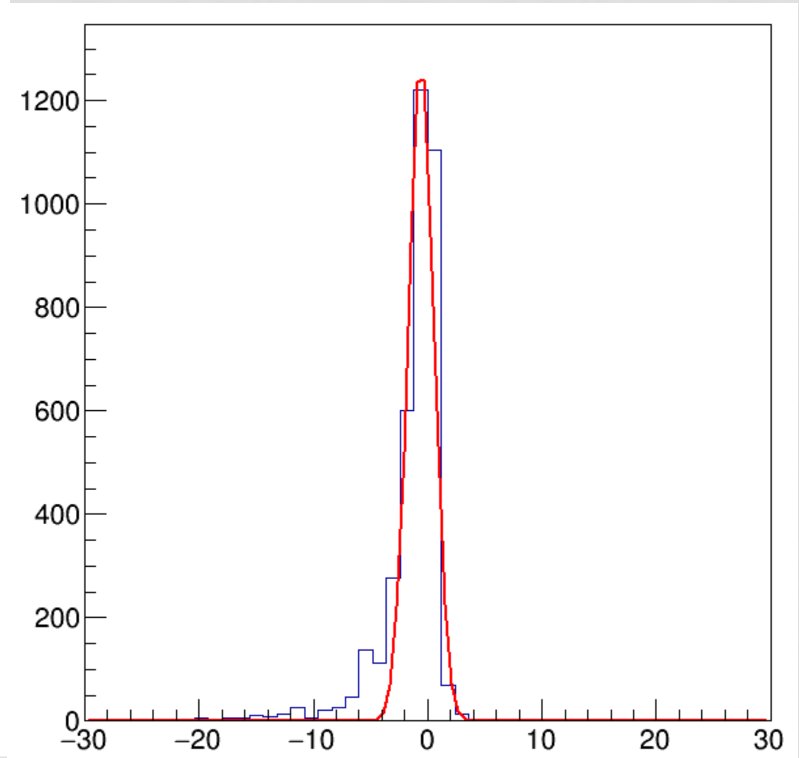




Detector Performances

$^{106}CdWO_4$ detector pulses start positions relatively to the $^{nat}CdWO_4$ signals





ΔT, μs

ΔT, μs

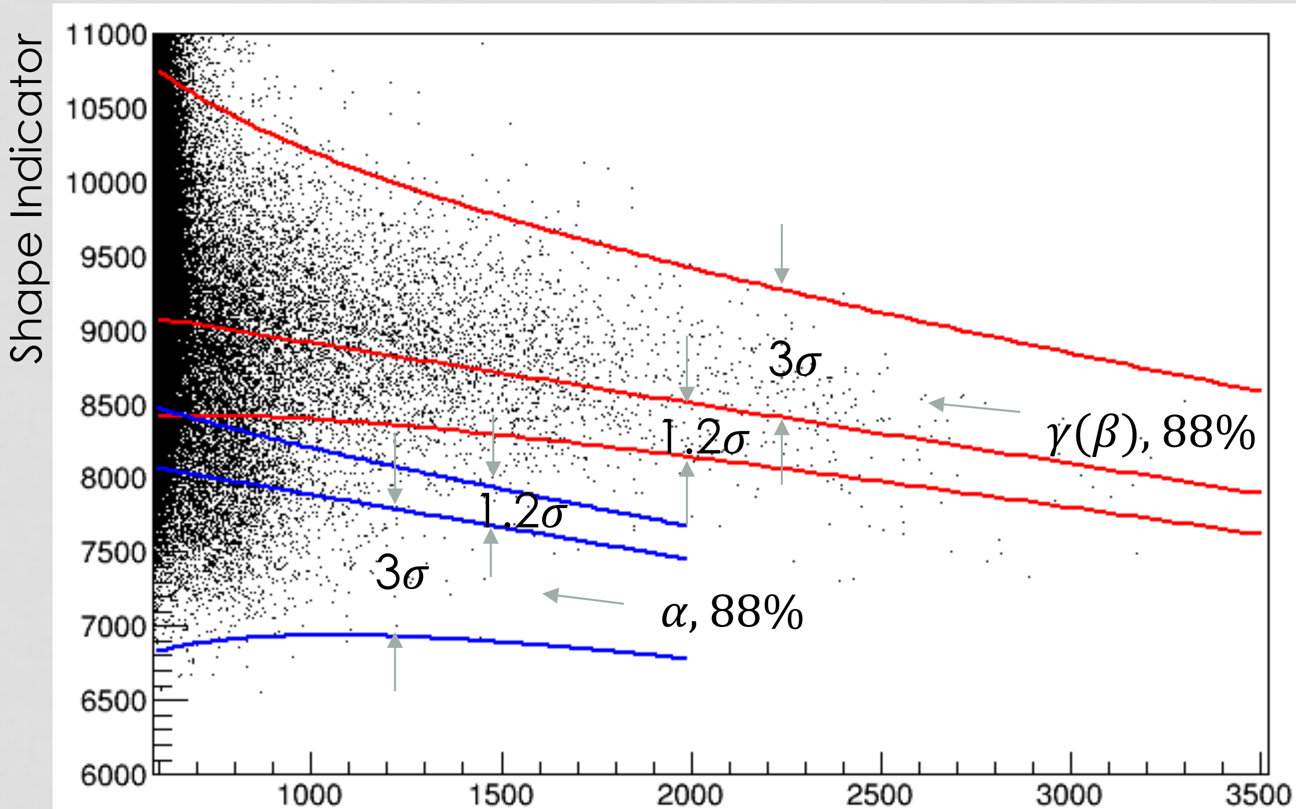
$\boldsymbol{\Delta T} = T_{nat,i} - T_{106}$

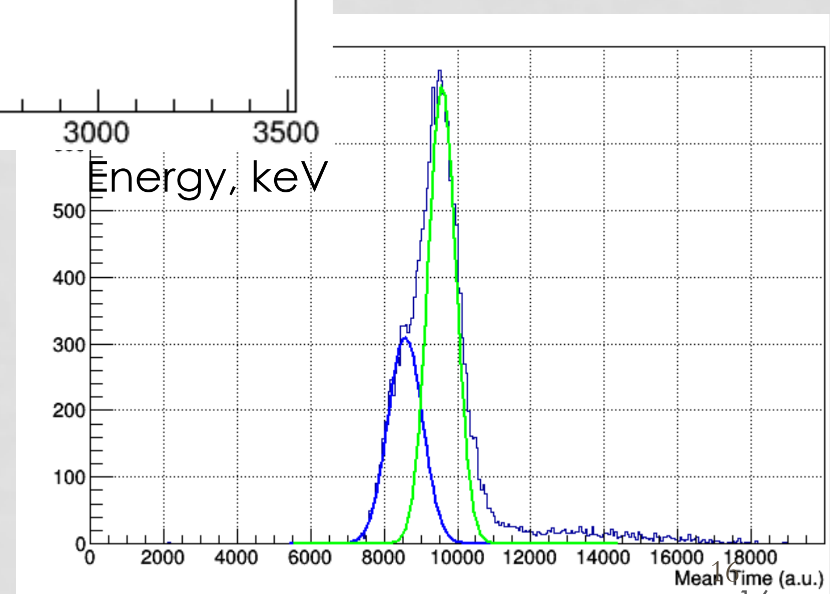
$T_{nat,i}$: start of the signal in the *i-th* $CdWO_4$ detector

T_{106} : start of the signal in $^{106}CdWO_4$ detector

- Events collected irradiating the detectors with a ^{22}Na source.
- Event with energy 1273 keV in $^{106}CdWO_4$ and with 511 keV (within 3σ) in the first (left) and second (right) $CdWO_4$.

Pulse shape discrimination (PSD)





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

$$P(t) = [f_\alpha(t) - f_\gamma(t)] / [f_\alpha(t) + f_\gamma(t)]$$

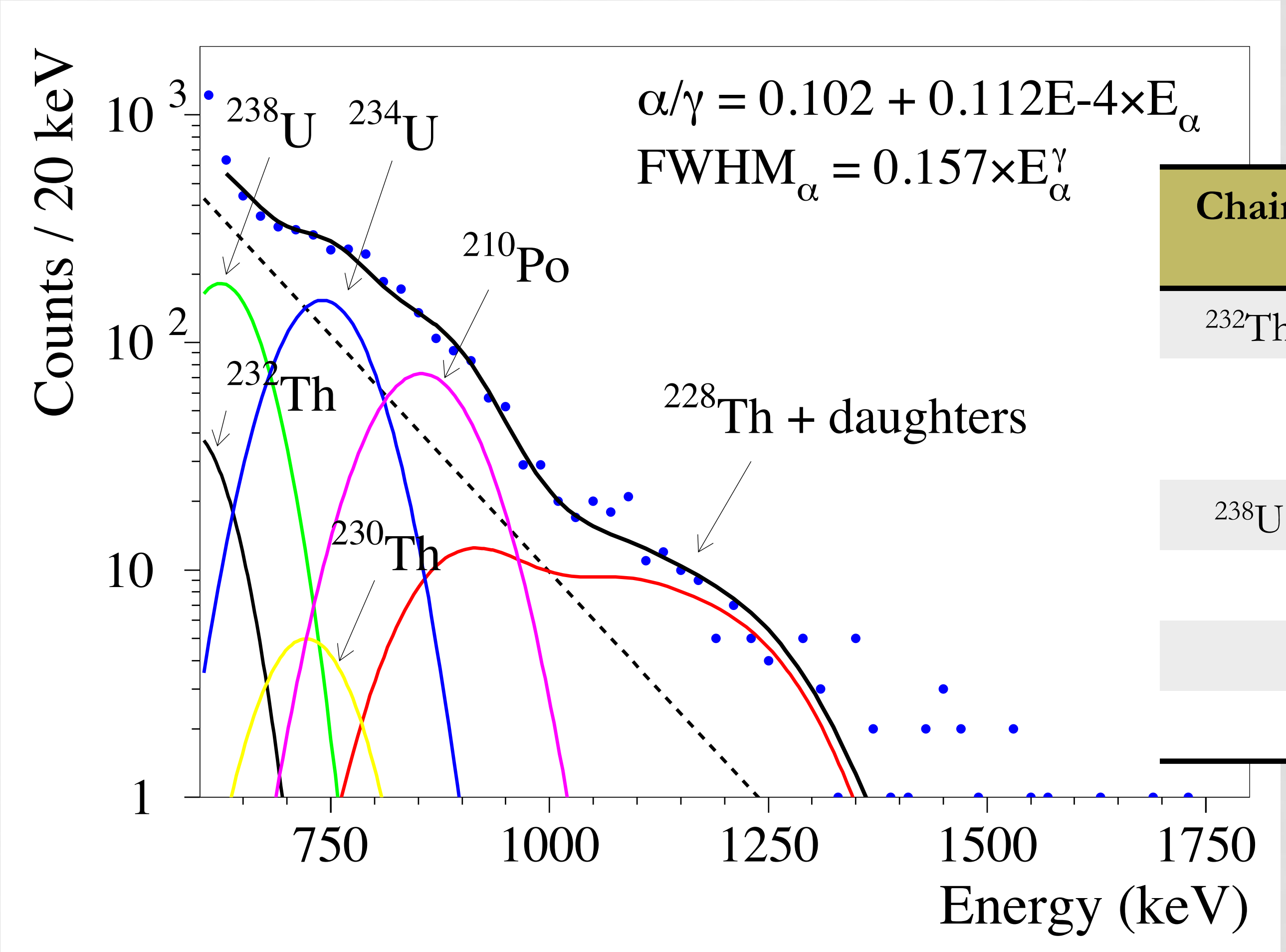
$f(t_k)$: amplitude at t_k

$P(t_k)$: weight function

$f_{\alpha,\beta}(t_k)$: reference pulse

The α spectrum

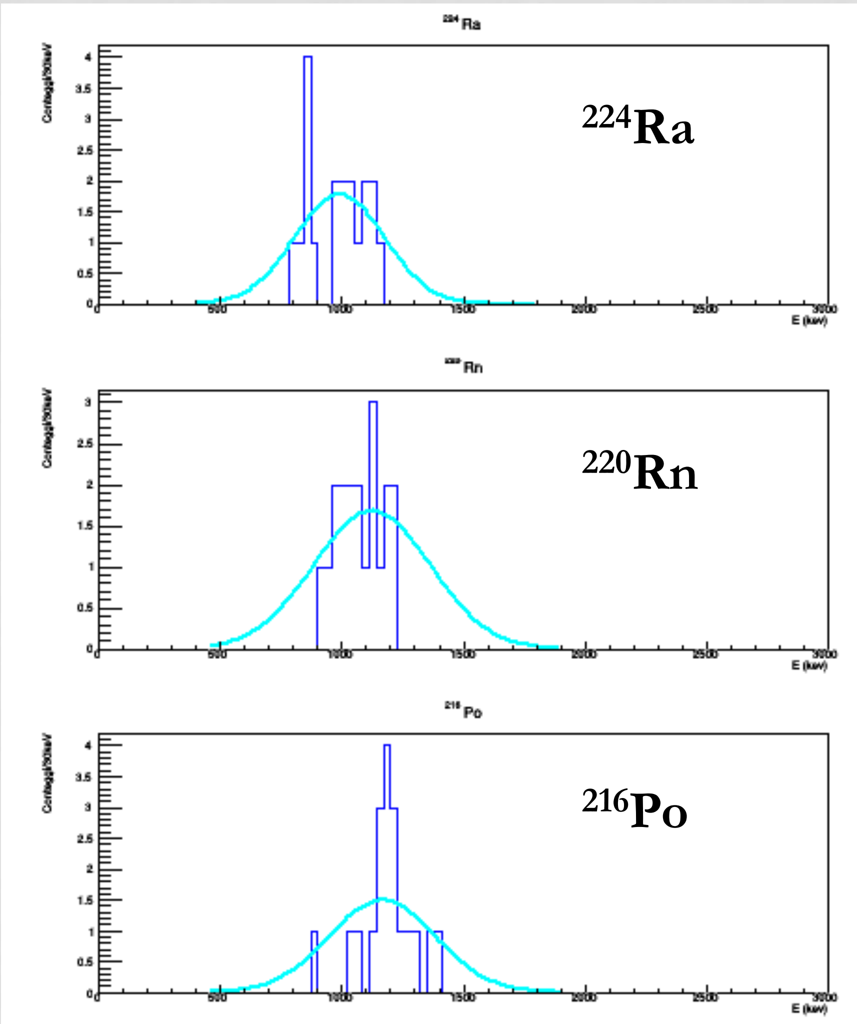
Spectrum of α particles obtained by PSD over 3300 h with fit of radioactive contamination



Chain	Nuclide	Activity, mBq/kg
^{232}Th	^{232}Th	<0.07
	^{228}Th+ daughters	<0.02
^{238}U	^{238}U	<0.6
	^{234}Th	<0.6
	^{230}Th	<0.4
	^{210}Po	<0.2

Time-Amplitude Analysis

T = 6935 h



Activity of ^{228}Th:

- The arrival time, the energy and the pulse shape of each event were used to select the fast decay chain in the ^{228}Th sub-chain of the ^{232}Th family:

^{224}Ra (Q = 5.789 MeV, $T_{1/2}$ = 3.66 d)

↓

^{220}Rn (Q = 6.405 MeV, $T_{1/2}$ = 55.6 s)

↓

^{216}Po (Q = 6.906 MeV, $T_{1/2}$ = 0.145 s)

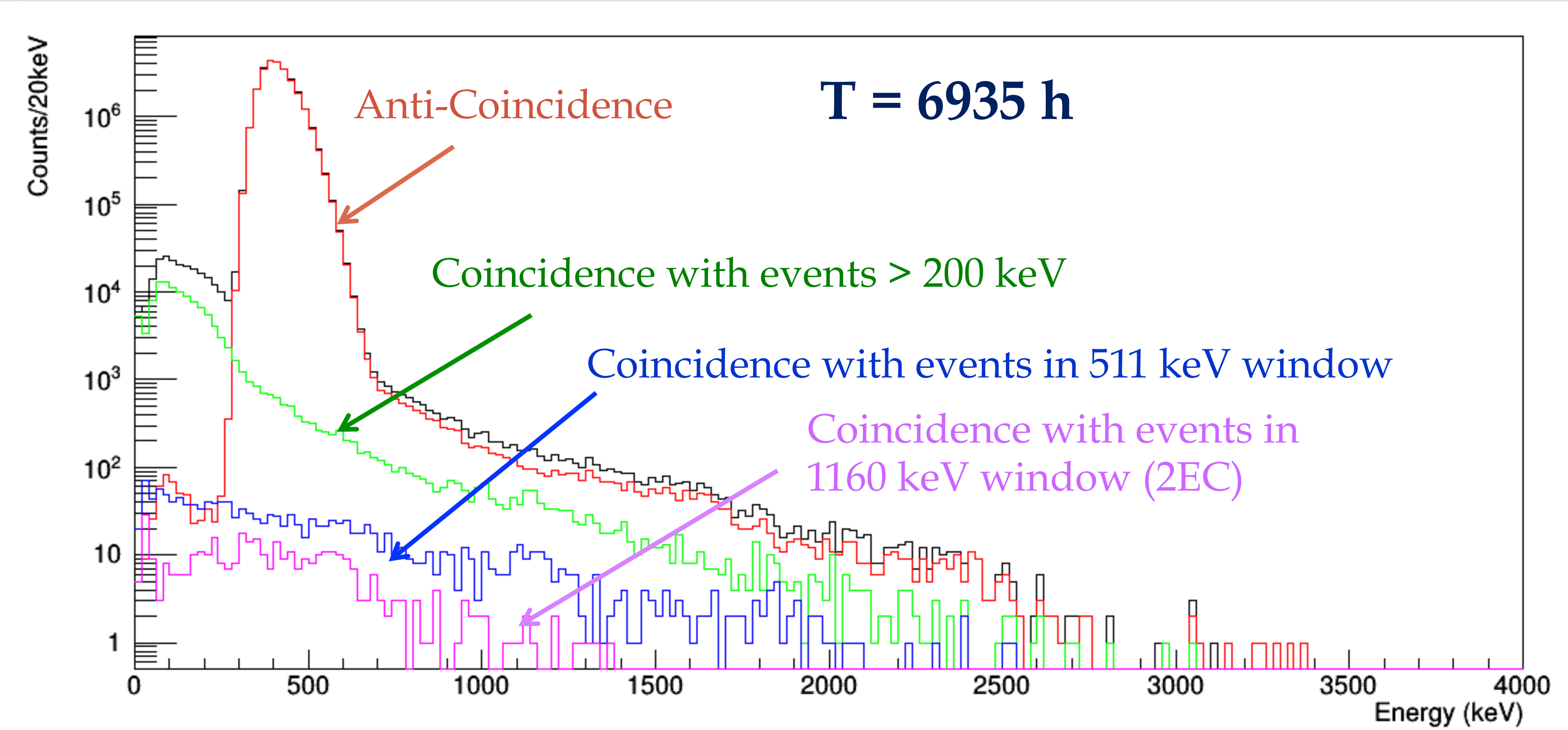
↓

^{212}Pb

Activity of ^{228}Th in $^{106}CdWO_4$ crystal was estimated as: **5(1) μBq/kg**

Also was estimated α/γ ratio and energy resolution for alpha-particles.

Energy spectra of ^{106}Cd

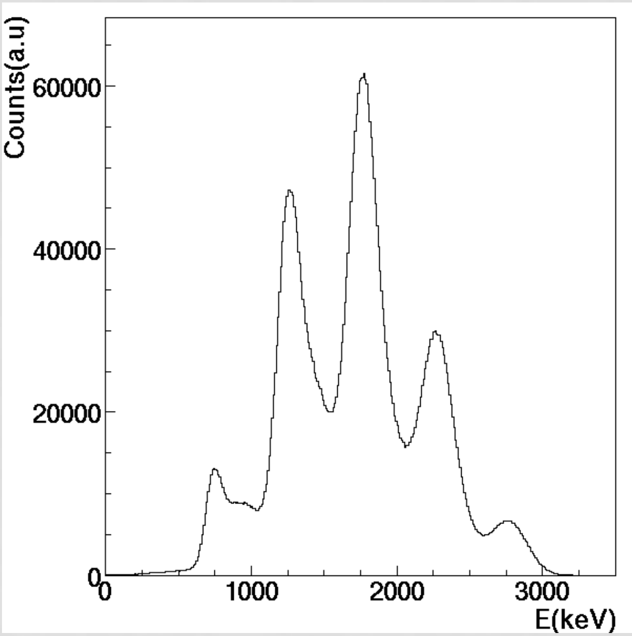


The energy spectra accumulated over **6935 h** by the $^{106}CdWO_4$ detector in anticoincidence with the ^{nat}CdWO4 detectors, in coincidence with event(s) and when at least one of the ^{nat}CdWO4 detectors with energy E > 200 keV, E = 511 keV, and E = 1160 keV

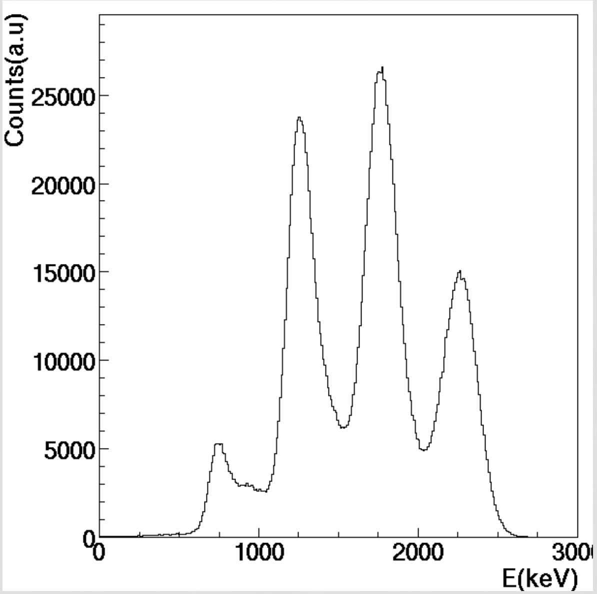
Sensitivity estimation

Expected signal for ^{106}Cd 0ν2β($0^+ \rightarrow 0^+$):

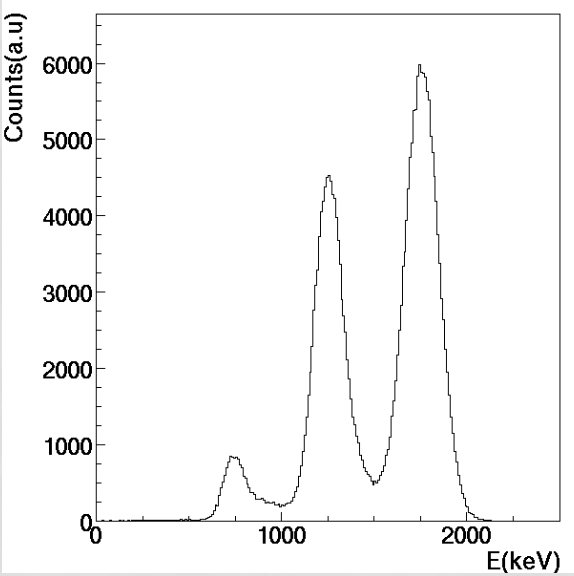
Spectrum in $^{106}CdWO_4$ detector



Spectrum in $^{106}CdWO_4$ detector when one of the two $CdWO_4$ detectors detects γ of 511 keV (±2σ)



Spectrum in $^{106}CdWO_4$ detector when both the $CdWO_4$ detectors detect γ of 511 keV (±2σ)



Sensitivity estimation after 1yr:

In the hypothesis of about 29 background counts in [0.-3.] MeV

0νεβ⁺ (g.s.): $T_{1/2} \approx$ **5. × 10^{21} yr**
2ν2β⁺ (g.s.): $T_{1/2} \approx$ **2. × 10^{21} yr**

Conclusion

- $^{106}CdWO_4$ successfully cleaned from the surface contamination (^{207}Bi).
- The detector is running in coincidence with two $^{nat}CdWO_4$ to search for 2β processes in ^{106}Cd.
- Deeply purified lead tungstate ($PbWO_4$) crystal light-guide from low-radioactive archaeological lead (that is free from ^{210}Pb) used as light-guide to supress γ's from PMT.
- Selection the events of $^{106}CdWO_4$ detector in coincidence with $^{nat}CdWO_4$ reduces background to search for $2\beta^+$ processes ^{106}Cd.
- Improvement in sensitivity expected for different of $2\beta^+$ decay modes for ^{106}Cd (10^{20}-10^{21} years).
- Data taking and analysis of the experiment are in progress.
- Future production of $^{106}CdWO4$ depleted in ^{113}Cd foreseen