First results of the experiment to search for double beta decay of ^{106}Cd with $^{106}CdWO_4$ crystal scintillator in coincidence with four crystals HPGe detector

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2. **R&D for $^{106}CdWO_4$**
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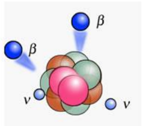
Double beta decay: $(A,Z) \rightarrow (A,Z\pm2)$

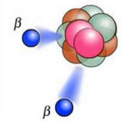
Allowed in SM:

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ – two-neutrino $2\beta^-$ decay



Forbidden in SM, $\Delta L=2$:

$(A,Z) \rightarrow (A,Z+2) + 2e^-$ – neutrinoless $2\beta^-$ decay



$(A,Z) \rightarrow (A,Z+2) + 2e^- + M$ – $2\beta^-0\nu$ decay with Majoron emission

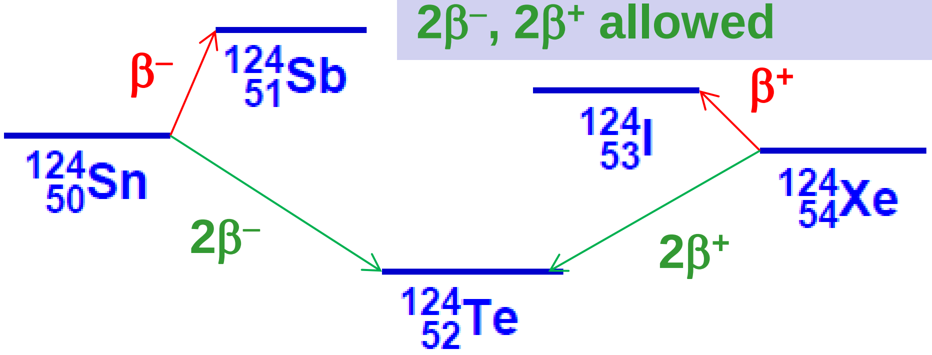
$2\beta^+/\ \varepsilon\beta^+/2\varepsilon$ processes, decays to excited states, different Majorons …

$2\beta0\nu$ requires: $\nu_e = -\nu_e$ (Majorana particle)

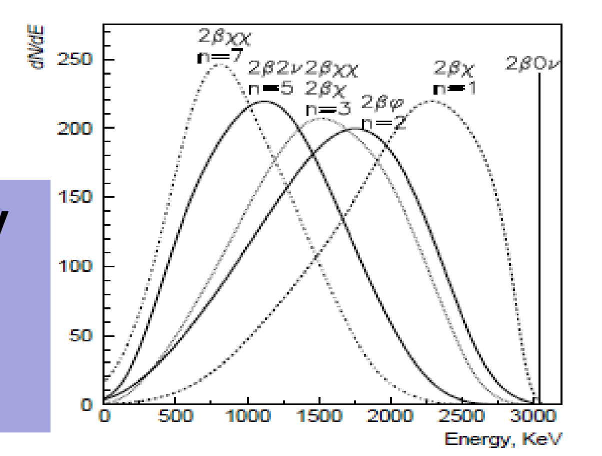
$m(\nu_e) \neq 0$ (or right-handed admixtures)

Many extensions of the SM predict $m(\nu_e) \neq 0$ and, as a result, $2\beta0\nu$ processes. Experimental observation of this exotic phenomenon would be an unambiguous signal of new physics which lies beyond the SM.

β^-, β^+ energetically forbidden
$2\beta^-$, $2\beta^+$ allowed



e_1+e_2 energy spectra in different 2β modes



Status of experimental investigations of 2β decay

$2\beta^-$	$2\beta^+/\varepsilon\beta^+/2\varepsilon$
35 candidates	34 candidates
Nat. abundances $\delta \sim$ (5-10-100)%	Typical $\delta < 1\%$ with few exclusions
$Q_{2\beta}$ up to 4.3 MeV	$Q_{2\beta} > 2$ MeV only for 6 nuclides
$2\beta2\nu$ is registered for 11 nuclei (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U) with $T_{1/2} = 10^{18} - 10^{24}$ yr	$2\varepsilon2\nu$ - ^{130}Ba ? ($T_{1/2} \sim 10^{21}$ yr) - ^{78}Kr ? ($T_{1/2} \sim 10^{22}$ yr)
Sensitivity to $2\beta0\nu$ up to 10^{25} yr	Sensitivity to 0ν up to 10^{21} yr

One positive claim on observation of $2\beta^-0\nu$ in ^{76}Ge by part of HM ($T_{1/2} = 2.2\times10^{25}$ yr), on the edge of current sensitivity of GERDA (2.1×10^{25} yr)

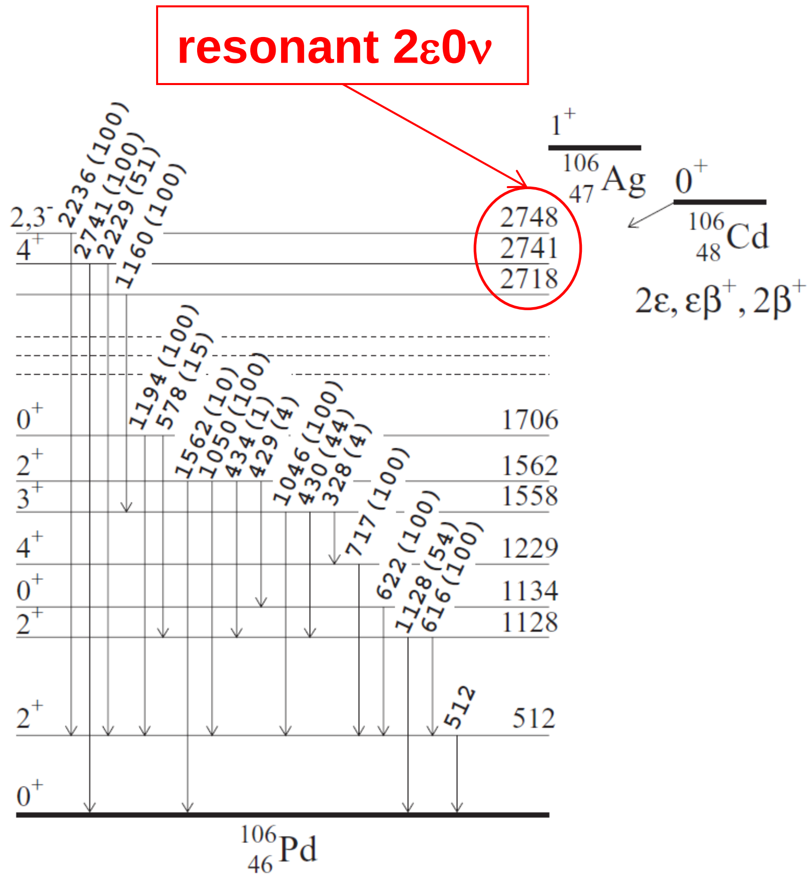
$2\beta^+/\varepsilon\beta^+/2\varepsilon$ studies are less popular but nevertheless:

Information from $2\beta^+/\varepsilon\beta^+/2\varepsilon$ is supplementary to $2\beta^-$ (possible contributions of right-handed currents to 0ν, M. Hirsch et al., ZPA 347 (1994) 151)

^{106}Cd is attractive because of:

(1) $Q_{2\beta}$ = 2775.39±0.10 keV – one of only six $2\beta^+$ nuclides
(2) Quite high natural abundance δ = 1.25%
(3) Possibility of resonant 2ε0ν captures to excited levels of daughter ^{106}Pd (2718 keV – 2K0ν, 2741 keV – $KL_1$0ν, 2748 keV – $KL_3$0ν)
(4) Theoretical $T_{1/2}$ are quite optimistic for some modes (g.s.→g.s.):
2ε2ν - (2.0-2.6)×10^{20} yr [1],
- 4.8×10^{21} yr [2],
$\varepsilon\beta^+2\nu$ - (1.4-1.6)×10^{21} yr [1],
- 2.9×10^{22} yr [2]

[1] S. Stoica et al., EPJA 17 (2003) 529
[2] J. Suhonen, PRC 86 (2012) 024301



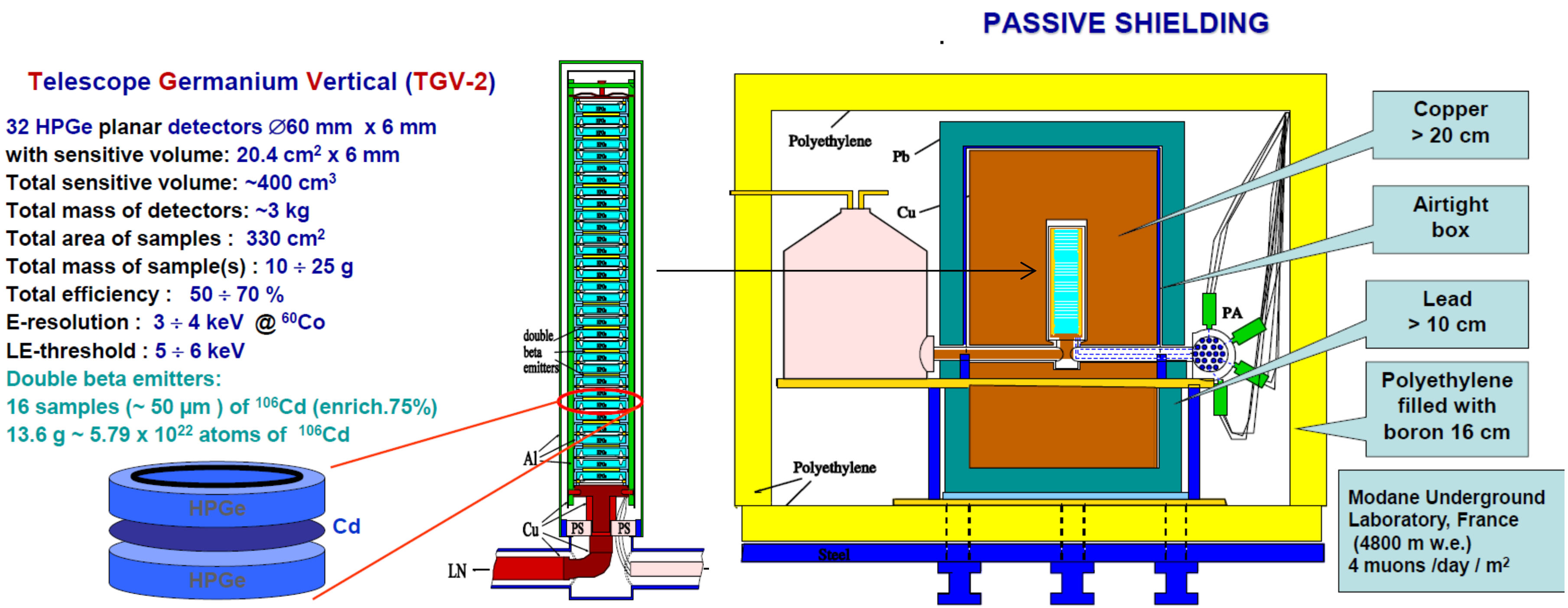
Decay scheme of ^{106}Cd

Current experiments to search for 2β processes in ^{106}Cd

(1) TGV-2: 32 planar HPGe + 16 foils of ^{106}Cd (δ=75%), LSM (France)

$T_{1/2}$ limits for different modes: ~ 10^{20} yr

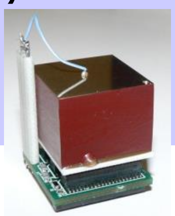
N.I. Rukhadze et al., NPA 852 (2011) 197, BRASP 75 (2011) 879



(2) COBRA: 32 semiconductors CdZnTe 1 cm³ each, LNGS (Italy)

$T_{1/2}$ limits for different modes: ~ 10^{18} yr

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



(3) Our previous measurements with $^{106}CdWO_4$ crystal scintillator, LNGS (Italy)

$T_{1/2}$ limits for different modes: ~ 10^{20}–10^{21} yr (mostly the best limits)

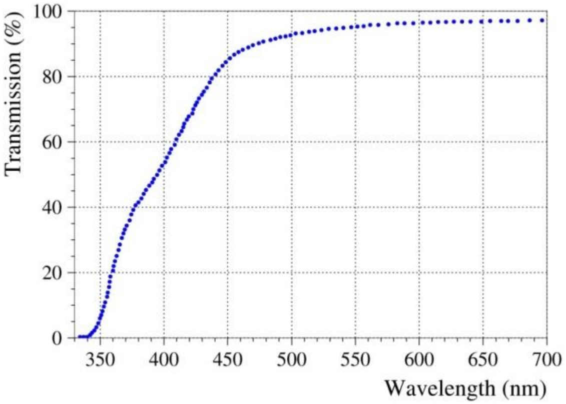
P. Belli et al., PRC 85 (2012) 044610

R&D: **Purification of enriched ^{nat}Cd & ^{106}Cd by vacuum distillation (~ 0.1 ppm; Kharkiv Phys. Techn. Institute, Kharkiv, Ukraine);**
Synthesis of $CdWO_4$ & $^{106}CdWO_4$ powders;
Growth of $^{nat}CdWO_4$ of improved quality (Czochralski method).
R. Bernabey et al., Metallofiz. Nov. Tekhn. 30 (2008) 477

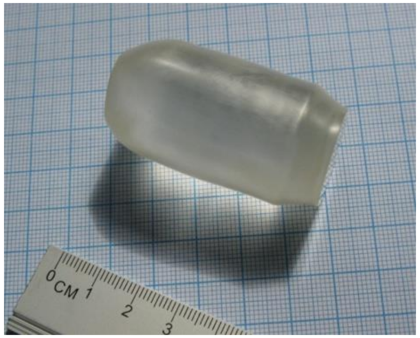
Growth of $^{106}CdWO_4$ crystals by Low-Thermal-Gradient Czochralski technique (Nikolaev Institute of Inorg. Chem., Novosibirsk, Russia): output ~90%, loss of powder <0.3%, better quality and radiopurity
P. Belli et al., NIMA 615 (2010) 301

$^{106}CdWO_4$ crystal scintillators (^{106}Cd enrichment – 66%)

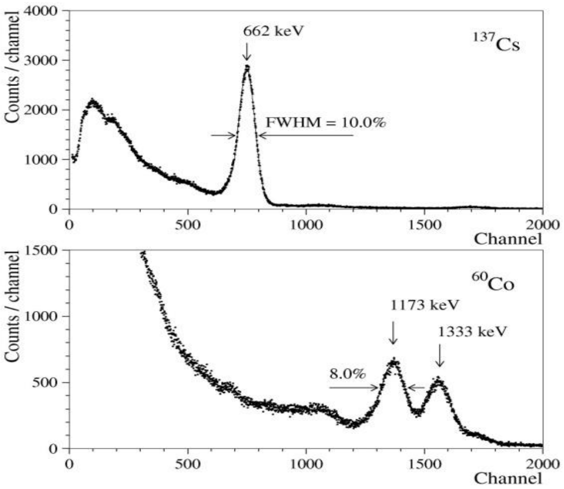
Attenuation length 60 cm
(the best reported for $CdWO_4$)



$^{106}CdWO_4$ boule 231 g (87.2%)
Total losses of ^{106}Cd = 2.3%



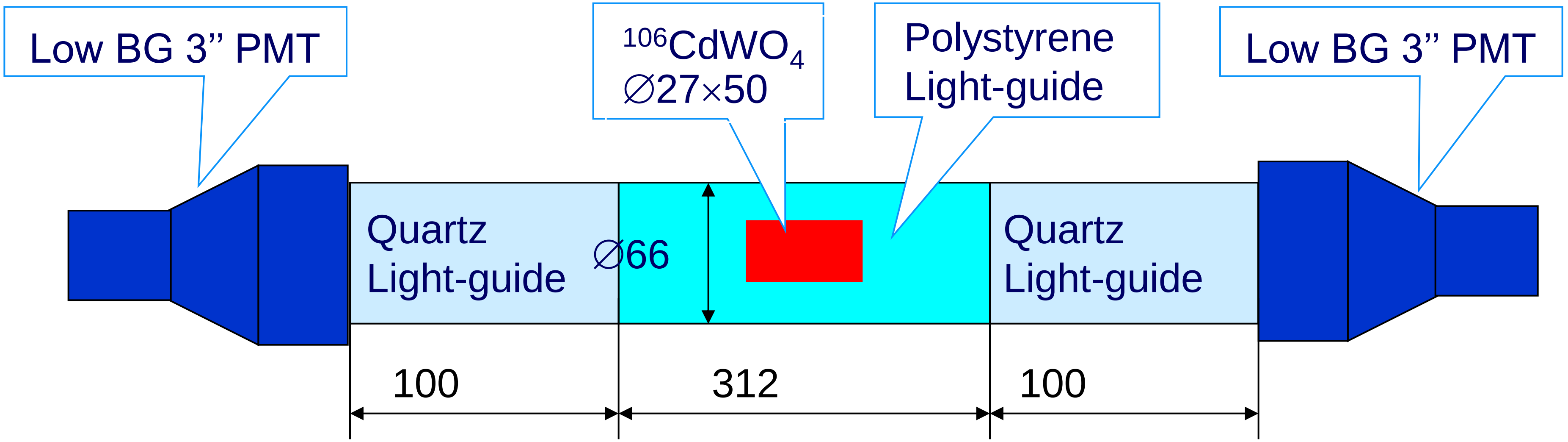
FWHM=10% at 662 keV

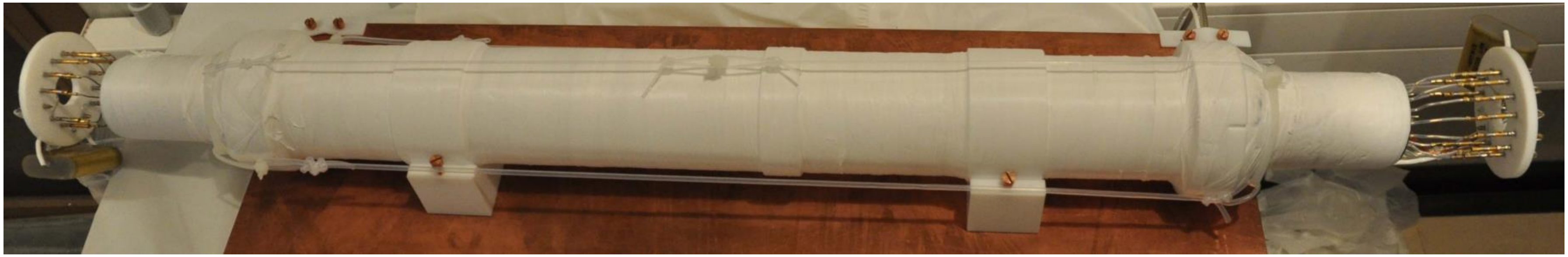


$^{106}CdWO_4$ scintillator 215 g

Excellent optical and scintillation properties thanks to special R&D to purify raw materials and Low-Thermal-Gradient Czochralski technique to grow the crystal [P. Belli et al., NIMA 615 (2010) 301]

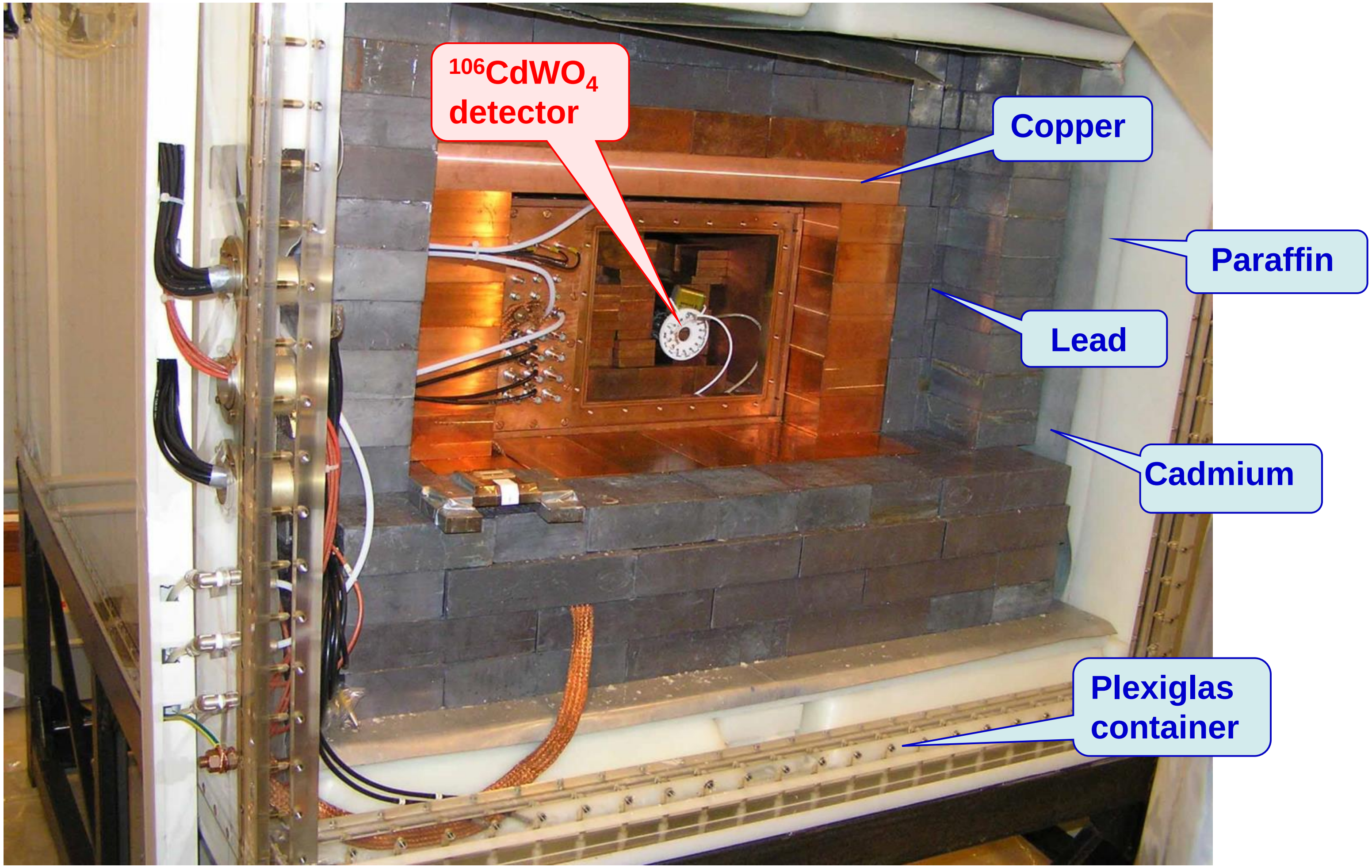
Low background scintillation detector with $^{106}CdWO_4$ crystal scintillator





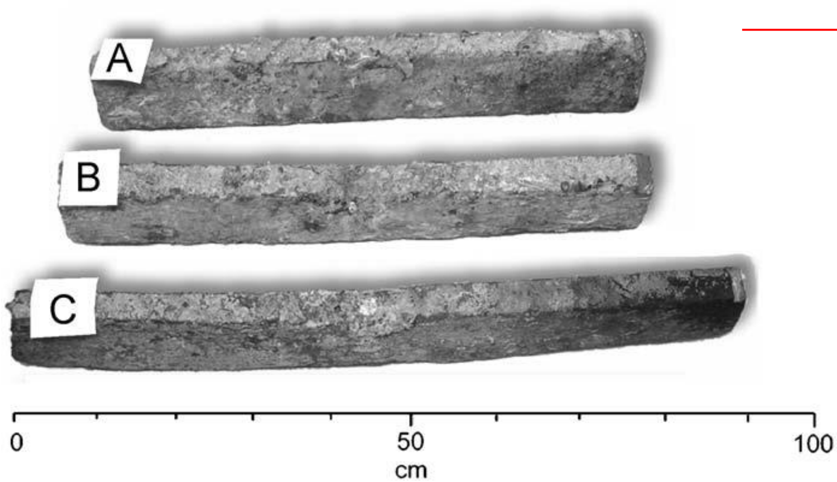
Low background scintillation set-up DAMA/R&D

LNGS (Italy), 3600 m w.e.



Next step: $^{106}CdWO_4$ scintillator in coincidence/anticoincidence with four HPGe detectors

To suppress radioactivity from PMT, $PbWO_4$ light-guide is used.
It is grown from archeological lead: A(^{210}Pb) < 0.3 mBq/kg
[F.A. Danevich et al., NIMA 603 (2009) 328]

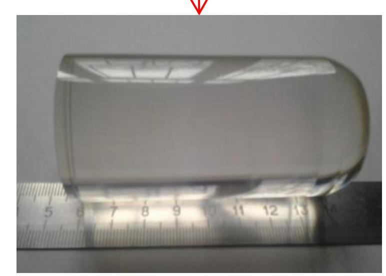


Samples of archeological lead (1st cent. BC, Black Sea, Ukraine)

Pb was purified by vacuum distillation [R.S. Boiko et al., Inorganic Mater. 47 (2011) 645]

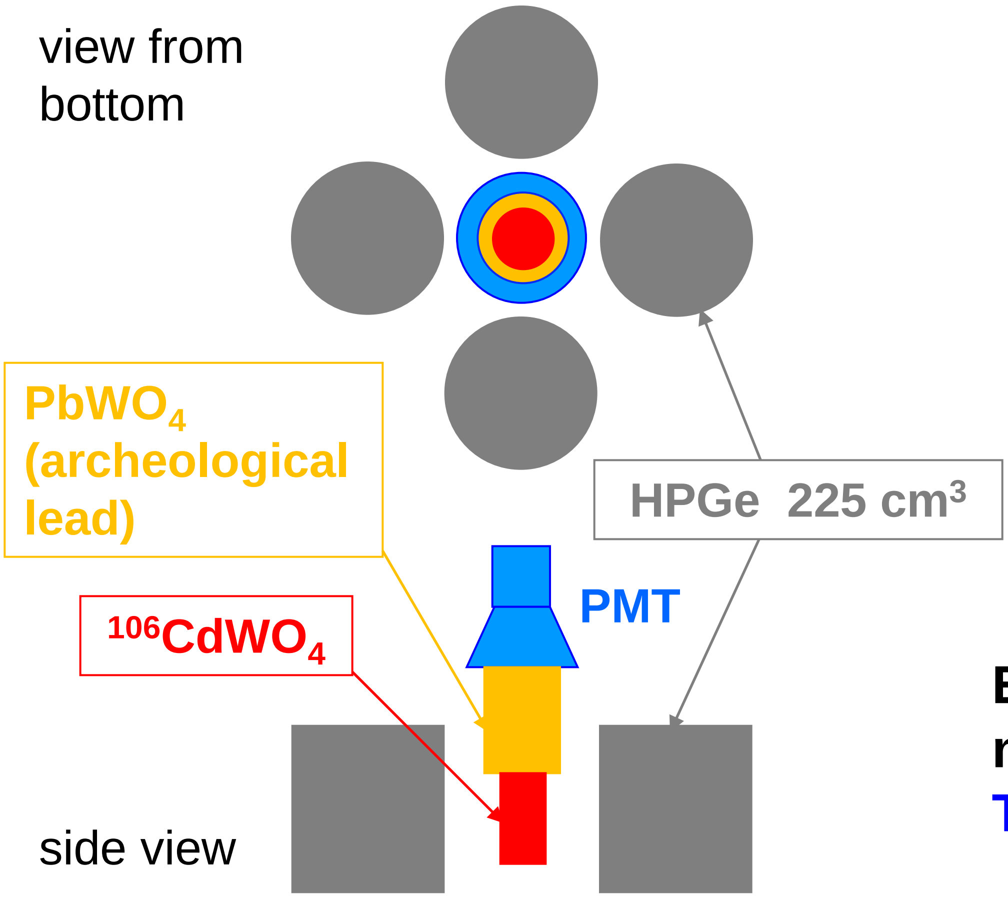
Initial $PbWO_4$

After mechanical treatment (daylight exposure?)



After annealing (24 h, 750° C) optical properties were restored

$^{106}CdWO_4$ in the GeMulti setup with 4 HPGe detectors (in one cryostat)



4 HPGe, ~ 225 cm^3 each, in one cryostat

$^{106}CdWO_4$ in coincidence / anticoincidence with HPGe

Detection efficiency ~ 5 – 7%

Background expected to be several events during year

Estimated sensitivity to two neutrino $\varepsilon\beta^+$ and $2\beta^+$ in ^{106}Cd:
$T_{1/2} \sim 10^{20} - 10^{21}$ yr

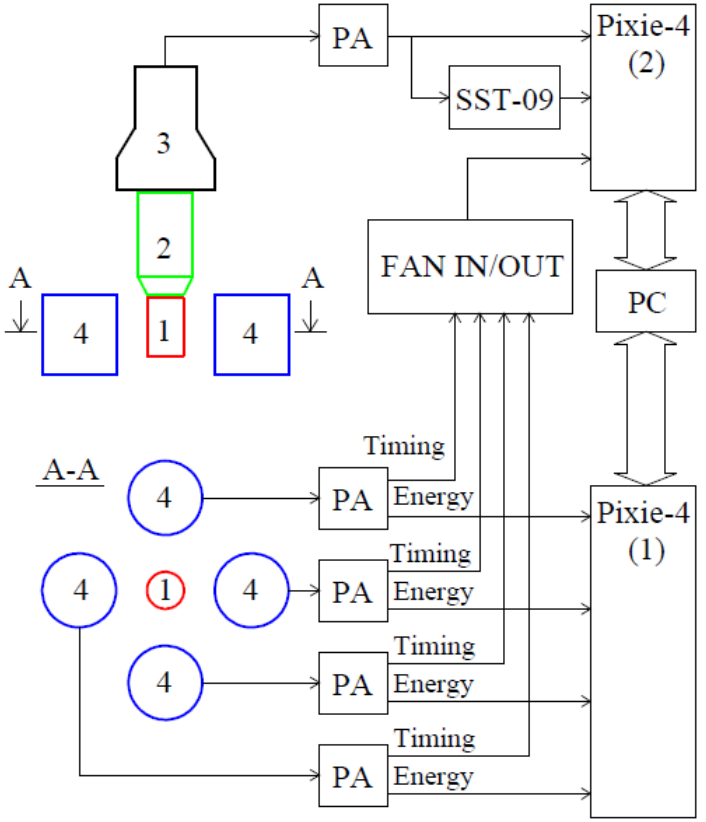
Theory: $2\nu 2K$ $10^{20} - 5\times10^{21}$ yr
$2\nu\varepsilon\beta^+$ $8\times10^{20} - 4\times10^{22}$ yr

DAQ:

time and energy for each HPGe;

shape of signal (in time) for $^{106}CdWO_4$ (>580 keV);

different triggers (c/ac)

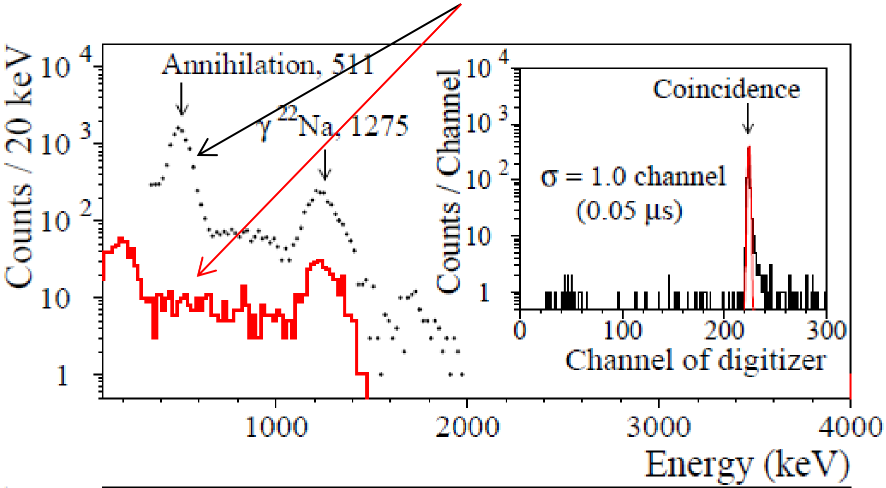


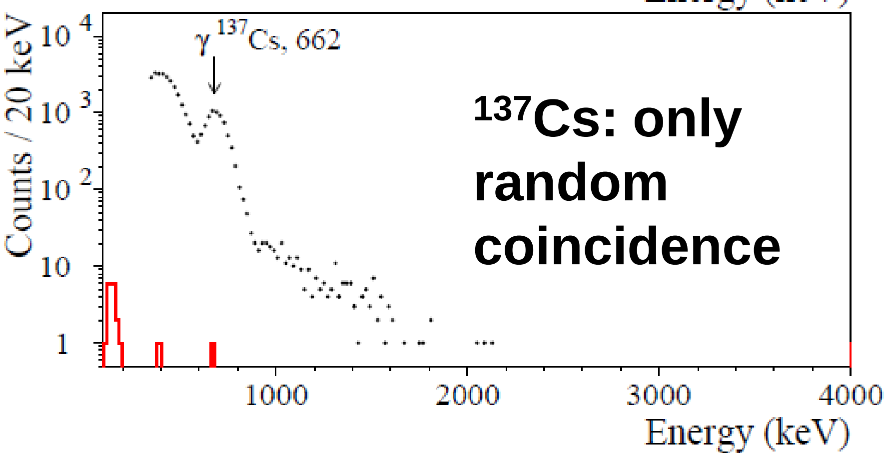
Calibration: ^{22}Na, ^{60}Co, ^{137}Cs, ^{228}Th

$^{106}CdWO_4$ – $FWHM_\gamma = (20.4 \times E_\gamma)^{1/2}$

^{22}Na:

no coincidence with HPGe and coincidence with 511 keV in HPGe

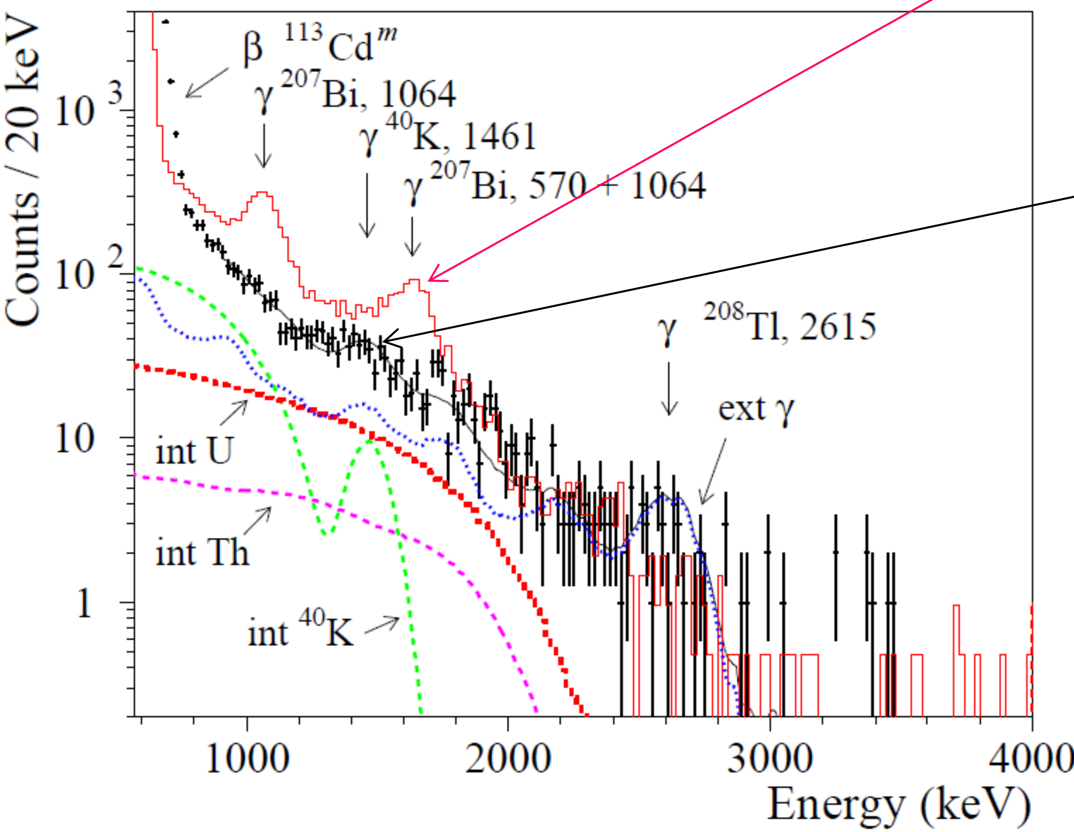




^{137}Cs: only random coincidence

Results

Previous measurements
PRC 85 (2012) 044610

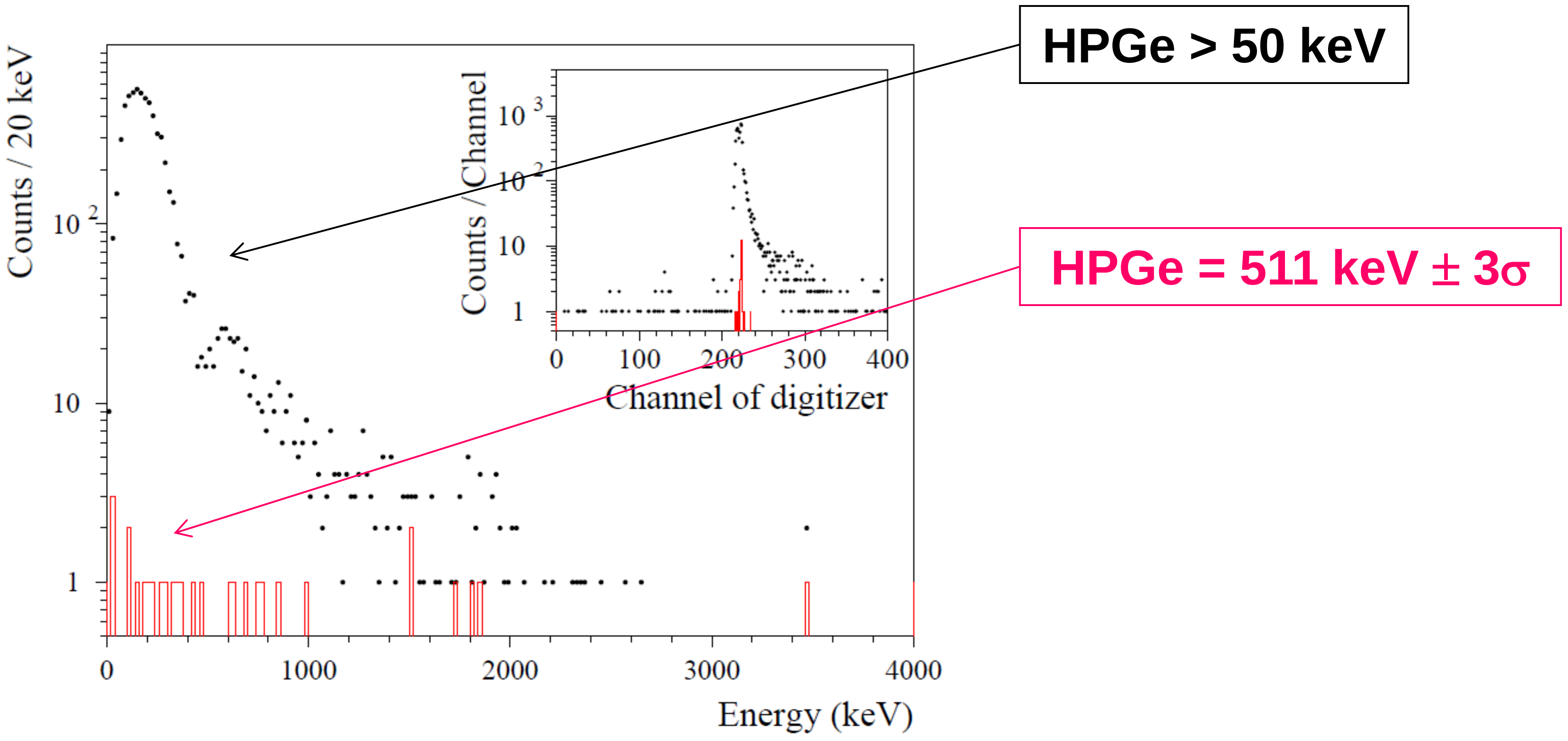


Current measurements (^{207}Bi disappeared thanks to cleaning of $^{106}CdWO_4$ by ultra-pure nitric acid + K-free detergent)

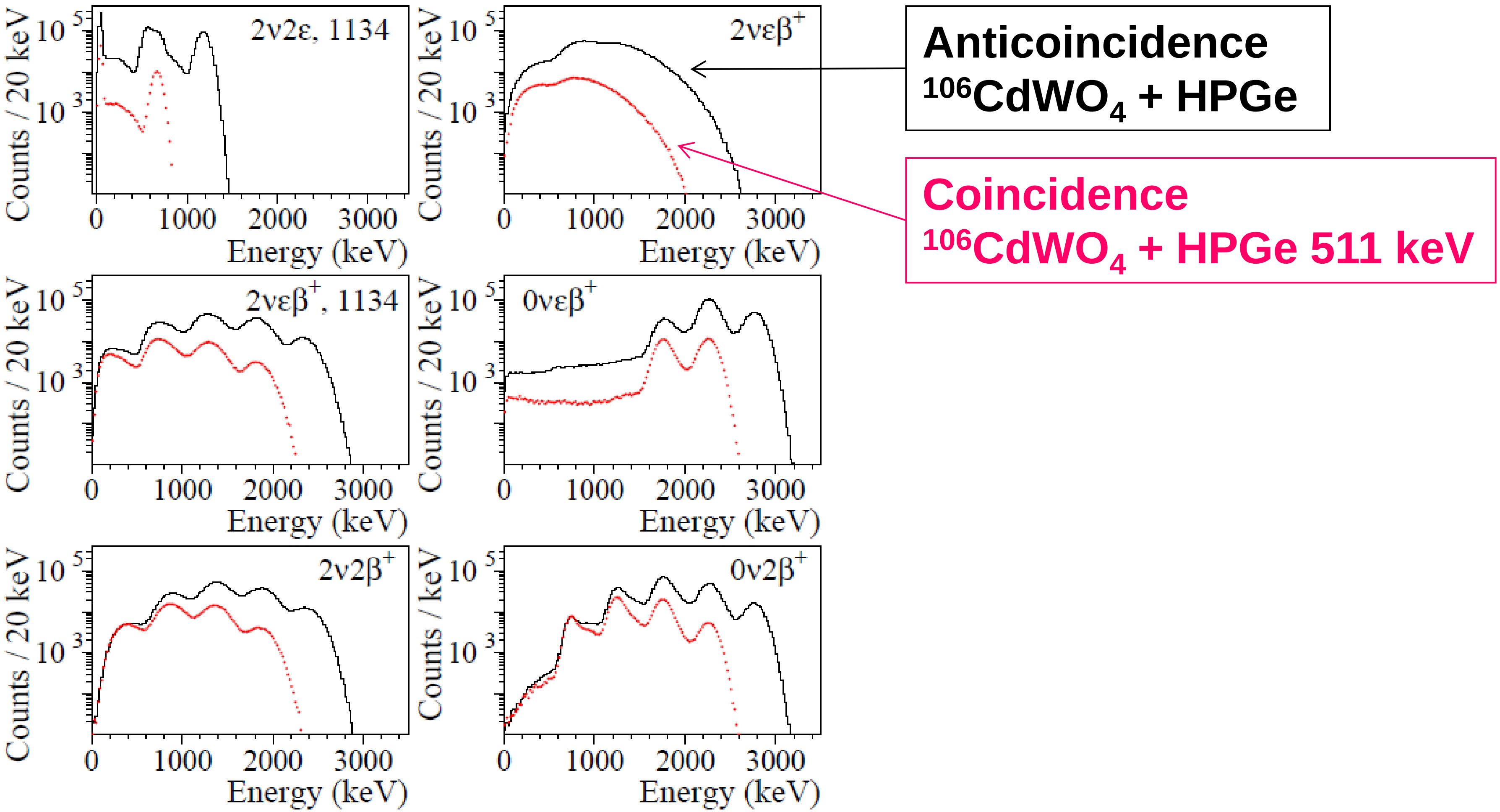
Spectrum of $^{106}CdWO_4$ (β/γ events) measured during 3189 h (anticoincidence with HPGe)

Simulations (EGS4):
$^{106}CdWO_4$ contaminations
PMT
$PbWO_4$
Cu shield
Al cryostat
…

Spectrum of $^{106}CdWO_4$ (3189 h) in coincidence with HPGe detectors:



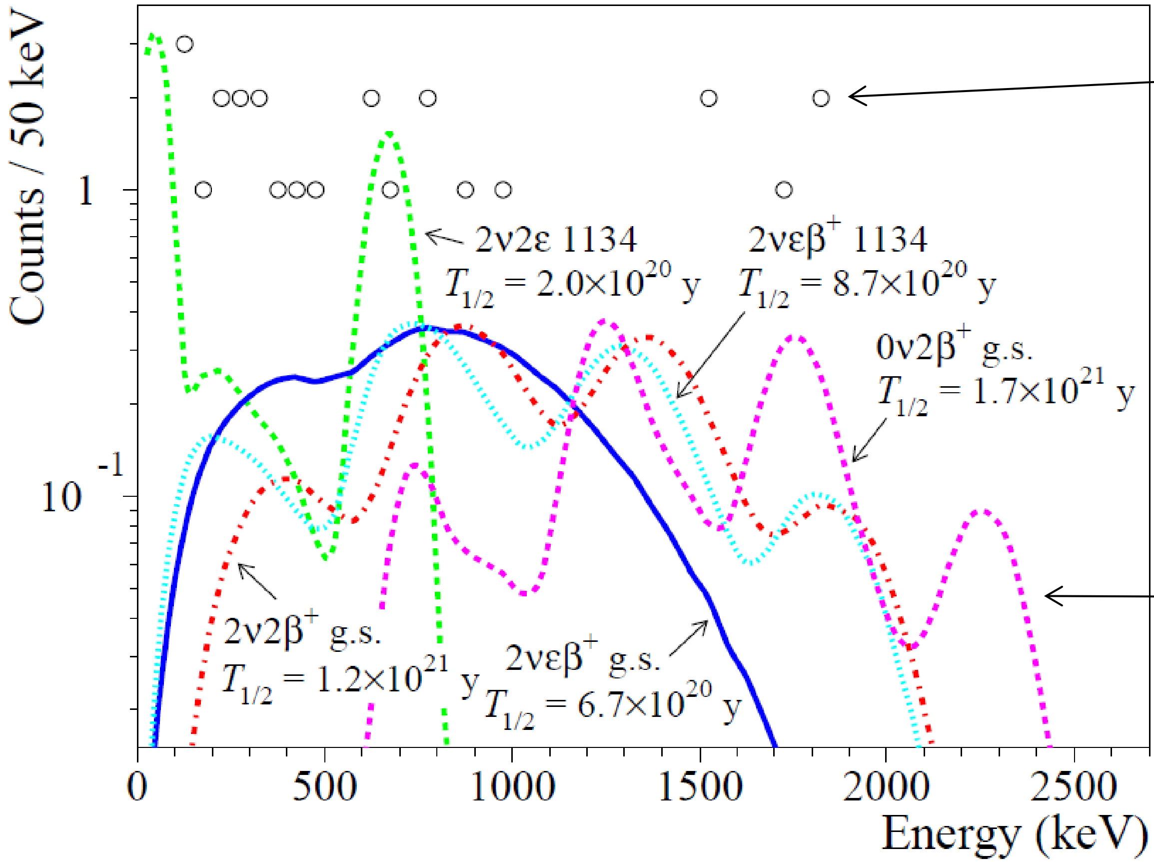
Simulation of 2β processes in ^{106}Cd: EGS4 + DECAY0 event generator



DECAY0: O.A. Ponkratenko et al., Phys. At. Nucl. 63 (2000) 1282

$T_{1/2}$ limits on 2β processes in ^{106}Cd

Comparison of number of events, expected from fit of $^{106}CdWO_4$, w/o coincidence with experimental number of events measured in coincidence of $^{106}CdWO_4$ + HPGe



Experimental spectrum $^{106}CdWO_4$ + HPGe

Excluded distributions of 2β processes at 90% C.L.

Very preliminary $T_{1/2}$ limits:

Decay channel	Decay mode	Level of ^{106}Pd (keV)	δE (keV)	η	$\lim S$	$T_{1/2}$ limit (yr) at 90% C.L.	
						Present work	Best previous limits
2ε	2ν	0_1^+ 1134	50 – 750	0.037	10.2	$\geq 2.2 \times 10^{20}$	$\geq 1.7 \times 10^{20}$ [7]
	0ν	g.s.	1550 – 2400	0.004	6.3	$\geq 3.6 \times 10^{19}$	$\geq 1.0 \times 10^{21}$ [7]
$\varepsilon\beta^+$	2ν	g.s.	550 – 1500	0.056	4.9	$\geq 6.8 \times 10^{20}$	$\geq 4.1 \times 10^{20}$ [25]
	2ν	0_1^+ 1134	550 – 1500	0.072	4.9	$\geq 8.8 \times 10^{20}$	$\geq 3.7 \times 10^{20}$ [7]
	0ν	g.s.	950 – 2500	0.069	4.7	$\geq 8.8 \times 10^{20}$	$\geq 2.2 \times 10^{21}$ [7]
$2\beta^+$	2ν	g.s.	550 – 1500	0.101	4.9	$\geq 1.2 \times 10^{21}$	$\geq 4.3 \times 10^{20}$ [7]
	0ν	g.s.	950 – 2500	0.119	4.7	$\geq 1.5 \times 10^{21}$	$\geq 1.2 \times 10^{21}$ [7]

References:

7. P. Belli et al., PRC 85 (2012) 044610

25. P. Belli et al., APP 10 (1999) 115

Conclusions

$^{106}CdWO_4$ crystal scintillator works now with four HPGe detectors ~225 cm^3 each, thus one can use coincidence/anticoincidence modes suppressing background

$^{106}CdWO_4$ was cleaned by ultra-pure nitric acid + K-free detergent that leads to removing of ^{207}Bi surface contamination

Radiopure $PbWO_4$ crystal – grown from archeological lead – and with good optical properties is used as the light-guide to further suppress background from PMT

After 3189 h of measurements underground in the LNGS, first (preliminary) $T_{1/2}$ limits on 2β processes in ^{106}Cd are achieved on the level of 10^{20} – 10^{21} yr. Some of them are better than those obtained on the previous stage of the experiment and close to theoretical expectations

Data collection is in progress

Thanks for your attention!