Investigation of double beta decay of ^{116}Cd with the help of enriched $^{116}CdWO_4$ crystal scintillators

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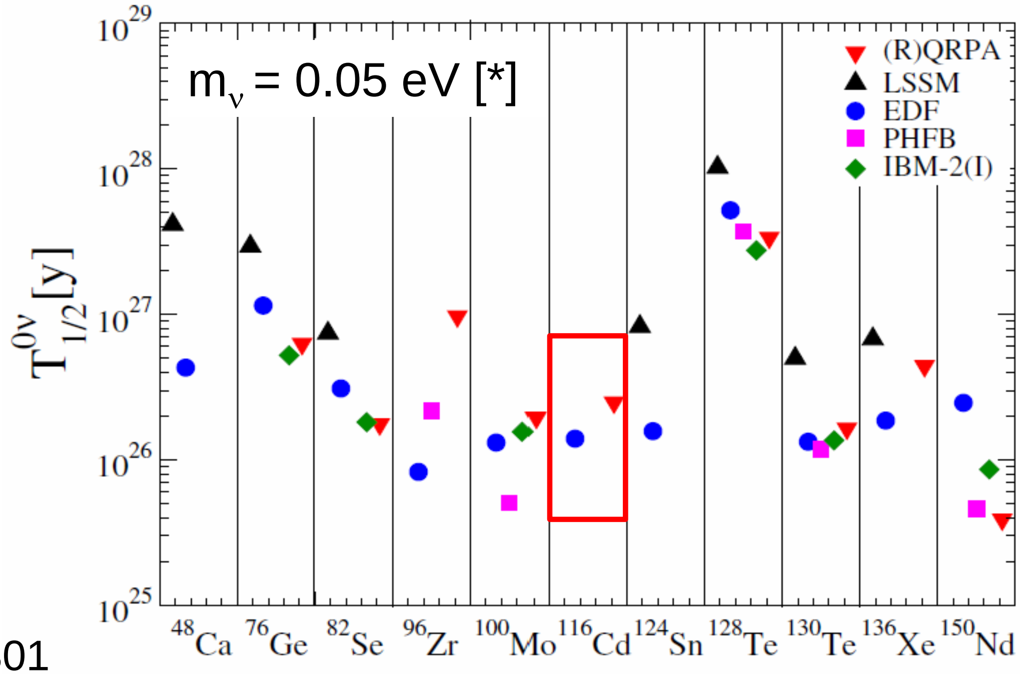
[+] deceased

^{116}Cd

One of the most promising isotopes to search for 0ν2β decay

- $Q_{2\beta}$ = 2813.44(13) keV, δ = 7.5%
- promising theoretical calculation
- possible isotopic enrichment in large amount



[*] J.D. Vergados et al., RPP 75(2012)106301

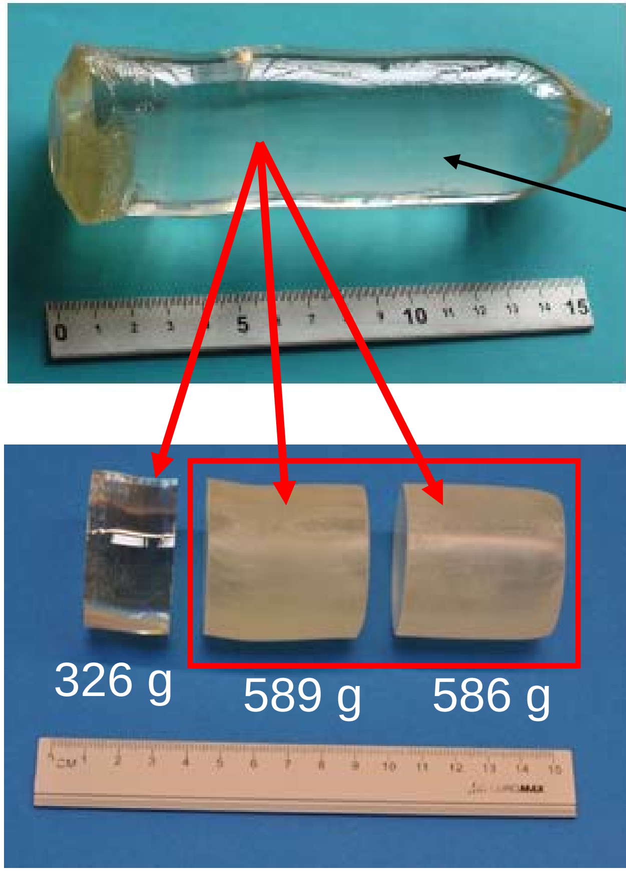
$CdWO_4$ crystals

- good scintillation properties
- source = detector approach
- low levels of internal contamination
- particle discrimination ability (↓ background)

$CdWO_4$ were successfully used in low-background experiments on search for 2β decay of Cd and W [1], as well as for the study of rare α [2] and β [3] decays

[1] ZPA 355(1996)433, PRC 68(2003)035501, EPJA 36(2008)167;
[2] PRC 67(2003)014310;
[3] PAN 59(1996)1, PRC 76(2007)064603

$^{116}CdWO_4$ crystal scintillator

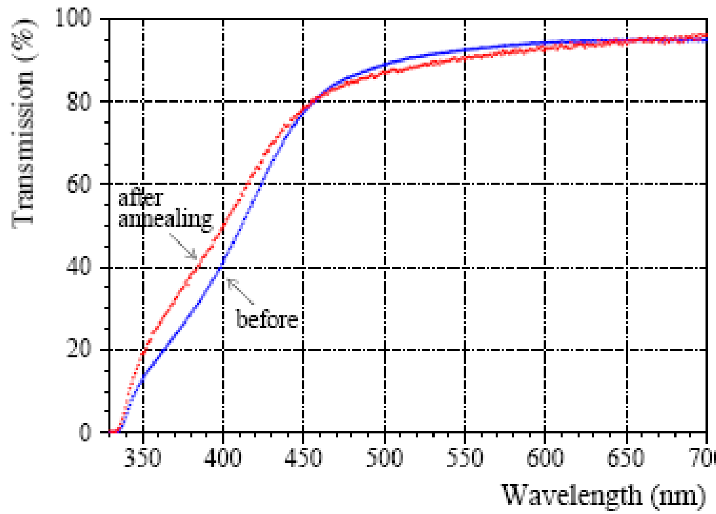


Good optical and scintillation properties of the crystal were obtained thanks to the deep purification of ^{116}Cd and W, and the advantage of the low-thermal-gradient Czochralski technique to grow the crystal [1]

Boule of enriched $^{116}CdWO_4$ crystal (82% of ^{116}Cd). The conic part of the boule is the beginning of the crystal growth.

Yield of the crystal boule is 87% of the initial powder

Losses (the total production cycle) < 3%



The optical transmission curve of $^{116}CdWO_4$ before and after annealing

Attenuation length is 31 cm at 480 nm

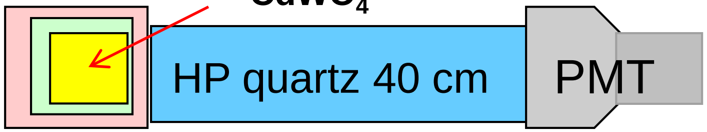
[1] JINST 6(2011)P08011

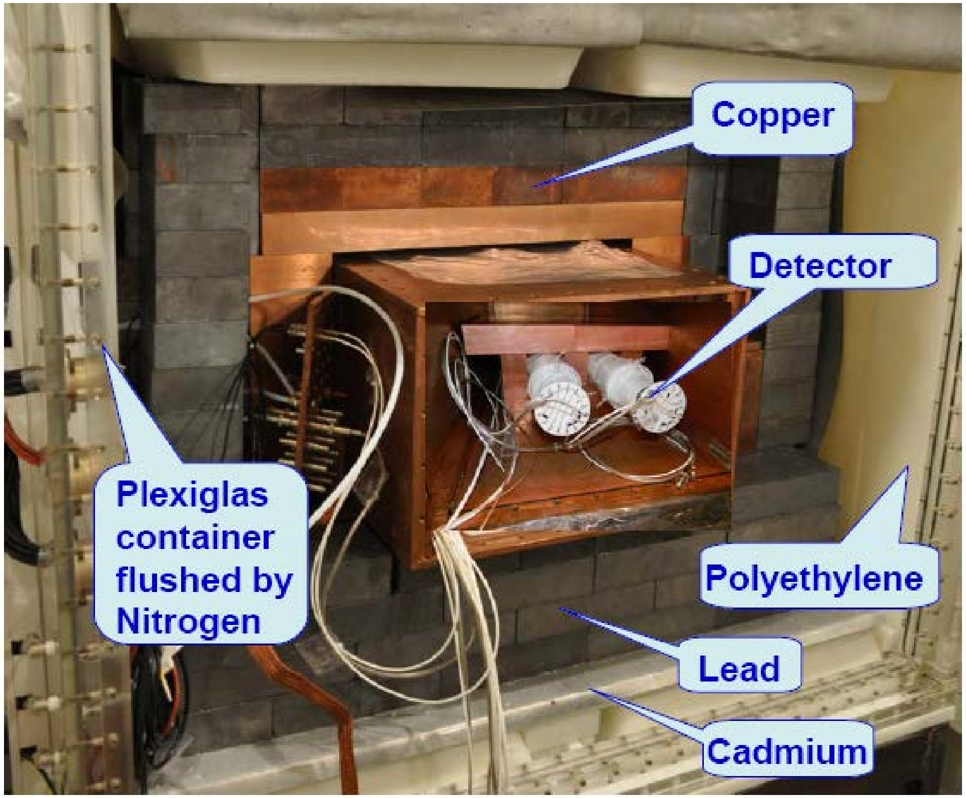
Experiment

2 crystals of $^{116}CdWO_4$, 1.162 kg in DAMA/R&D

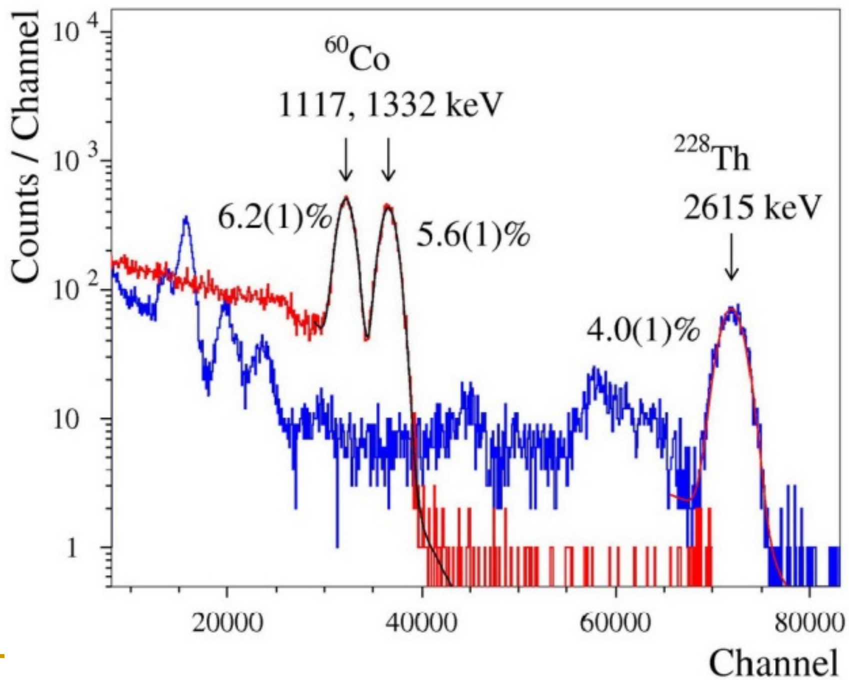
Experiment started in 2011

Upgrade - March 2014. Bg ↓ to ≈ 0.1 counts/(yr×kg×keV) at 2.7−2.9 MeV

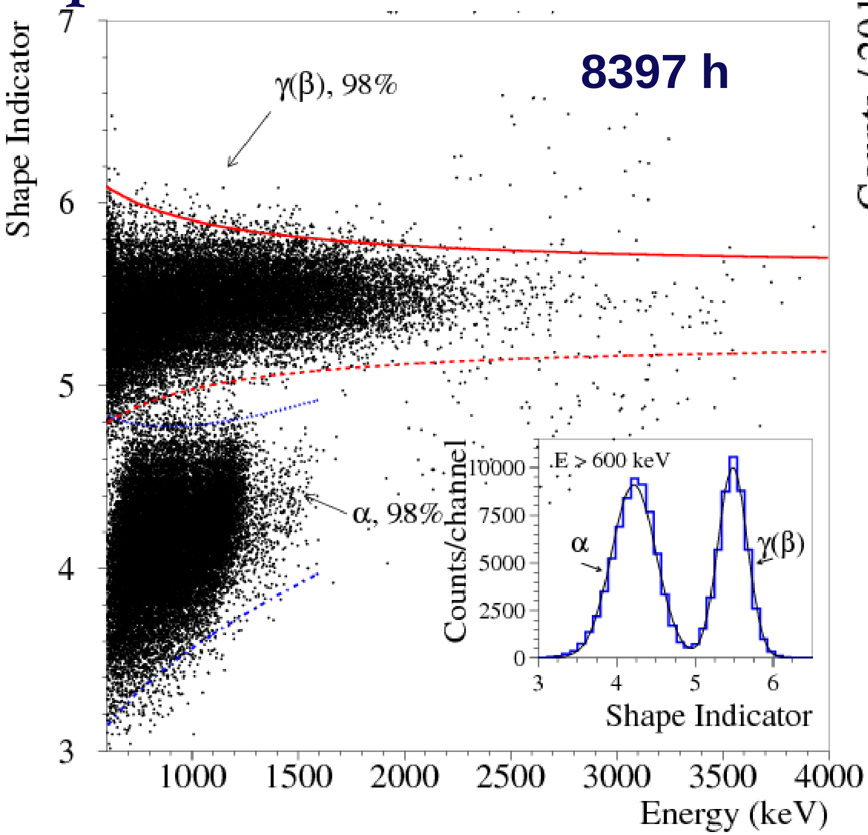




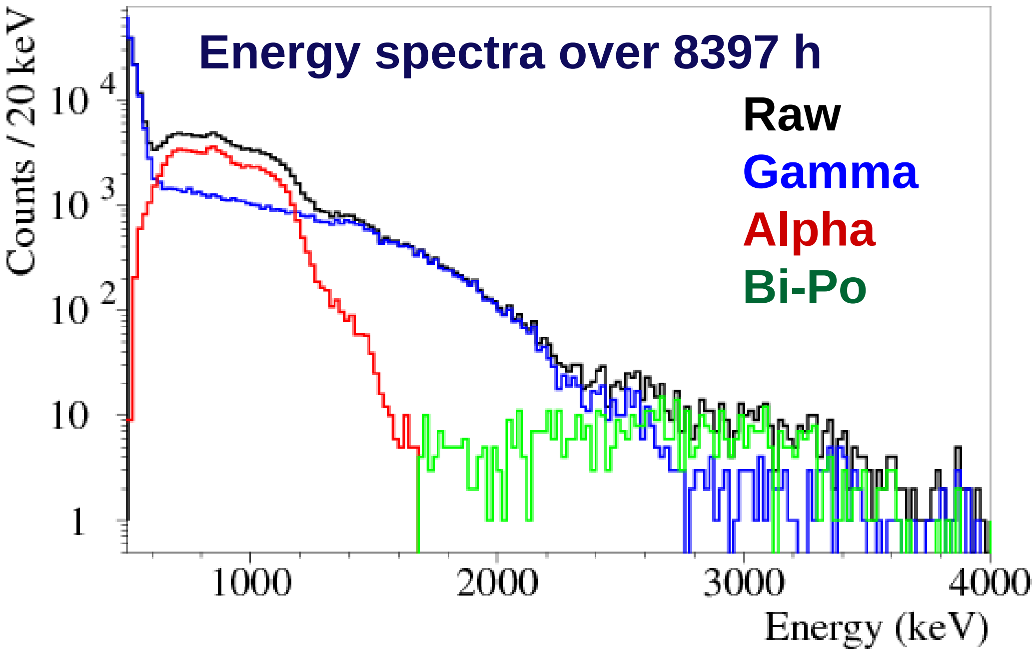
Energy resolution

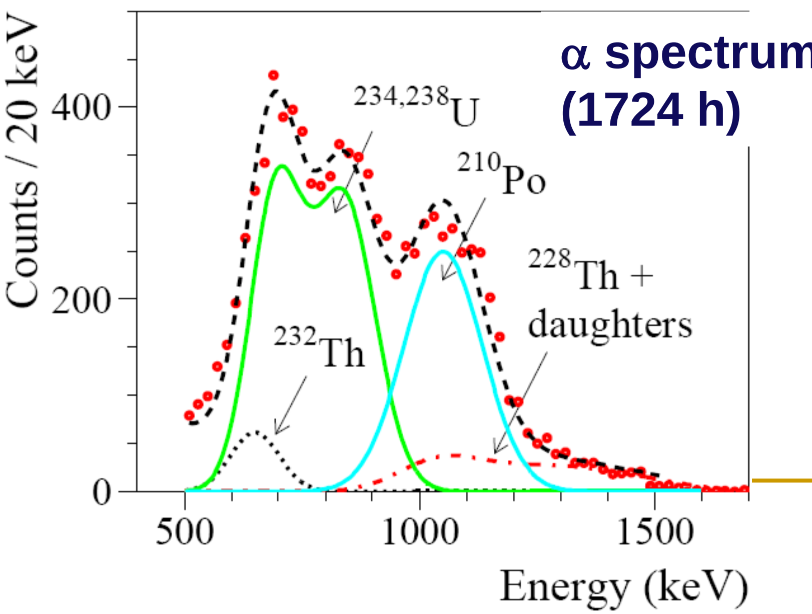


Pulse shape discrimination (PSD) between β(γ) and α particles

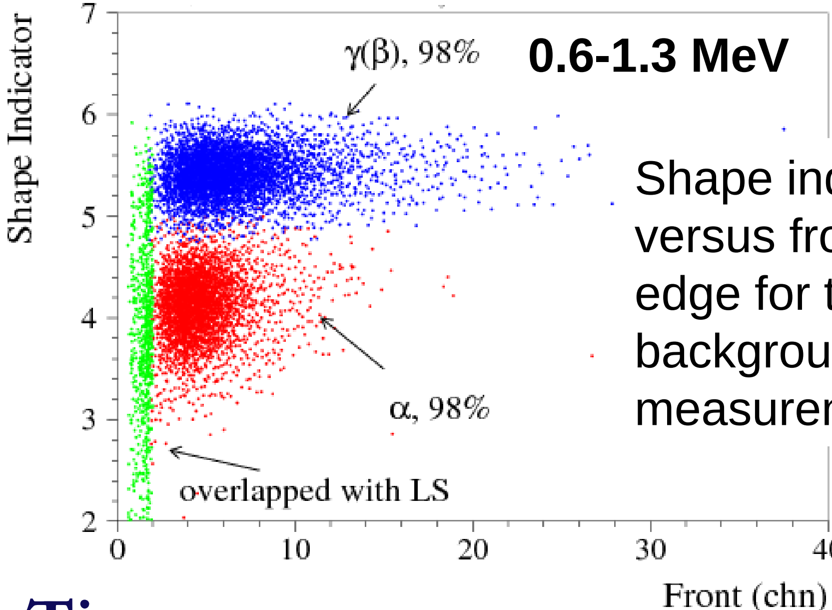


Shape indicator (SI) versus energy for the background exposure (8397 h × 1.162 kg)

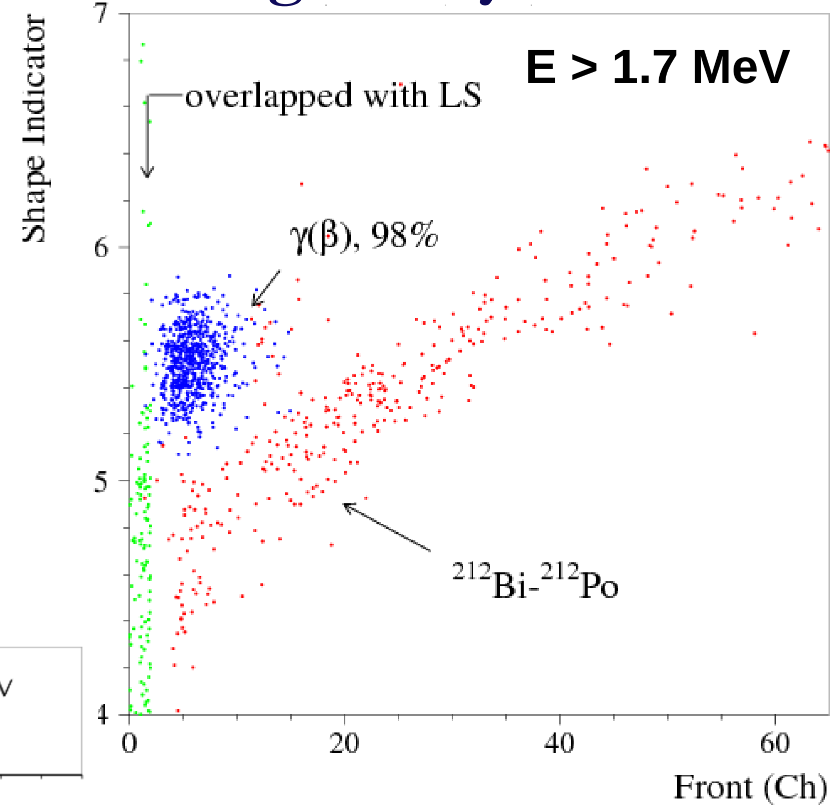




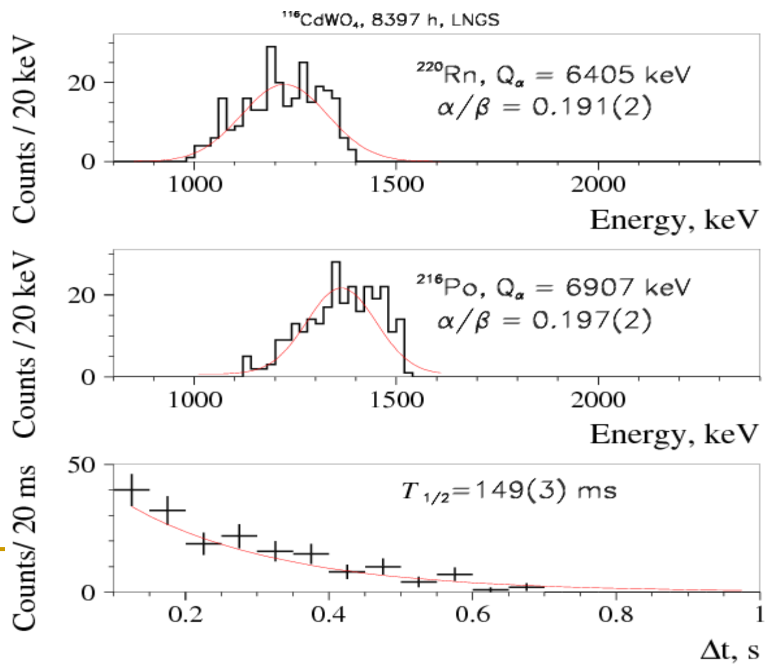
Selection of ^{212}Bi-^{212}Po events by front-edge analysis



Shape indicator versus front edge for the background measurements



Time-amplitude analysis (TAA)



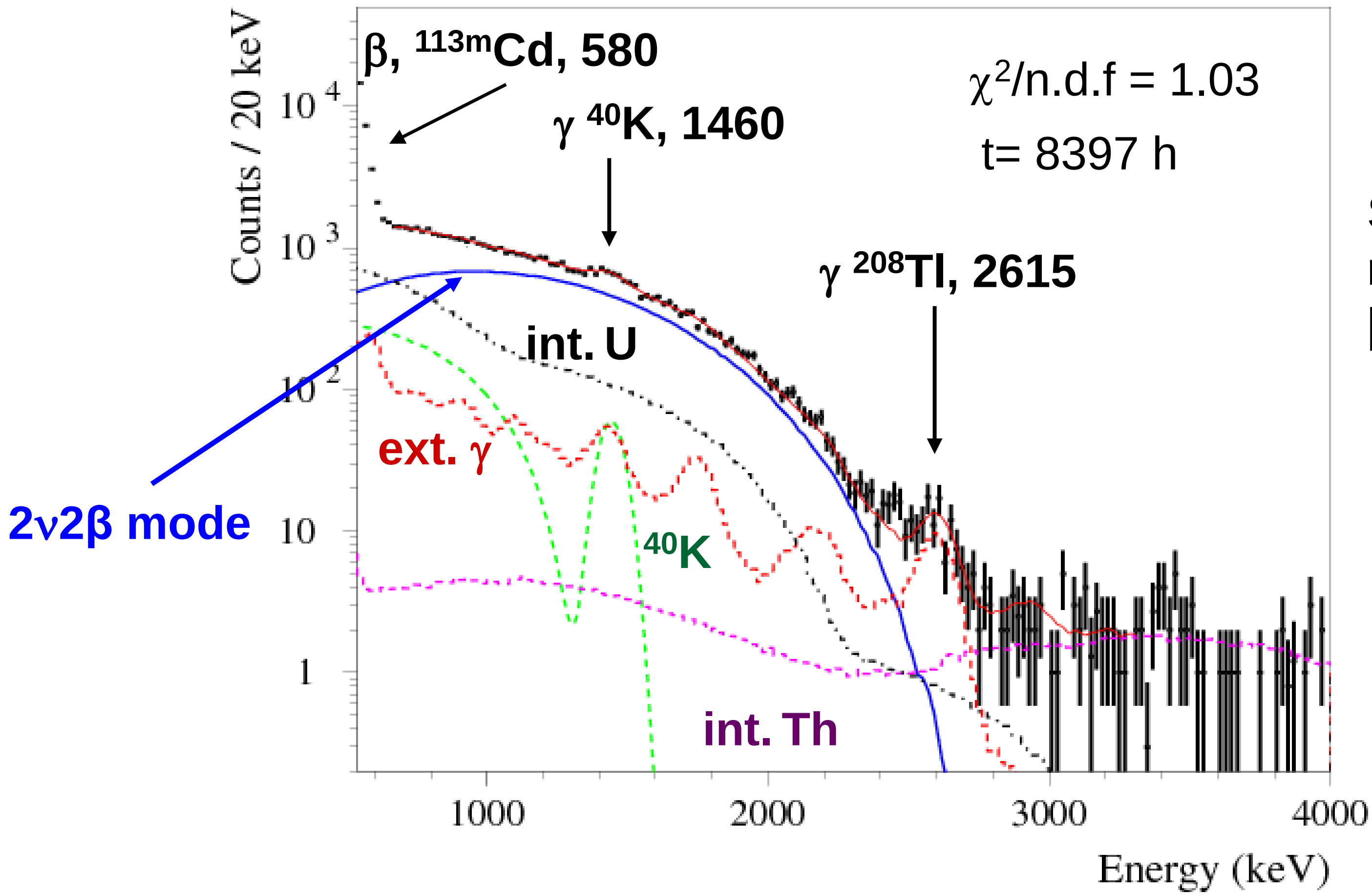
Activity ^{228}Th, μBq/kg

	TAA	FEA
Crystal 1	21(3)	20(2)
Crystal 2	32(4)	34(3)

Radioactive contaminations of $^{116}CdWO_4$ crystal scintillators

Chain	Nuclide	Activity, mBq/kg
^{232}Th	^{232}Th	≤ 0.07
	^{228}Th	0.026(2)
^{238}U	^{238}U-^{234}Th	0.4(2)
	^{226}Ra	≤ 0.009
	^{210}Pb	0.5(2)
	^{40}K	≤ 0.2
	^{110m}Ag	≤ 0.02

Two neutrino double beta decay of ^{116}Cd



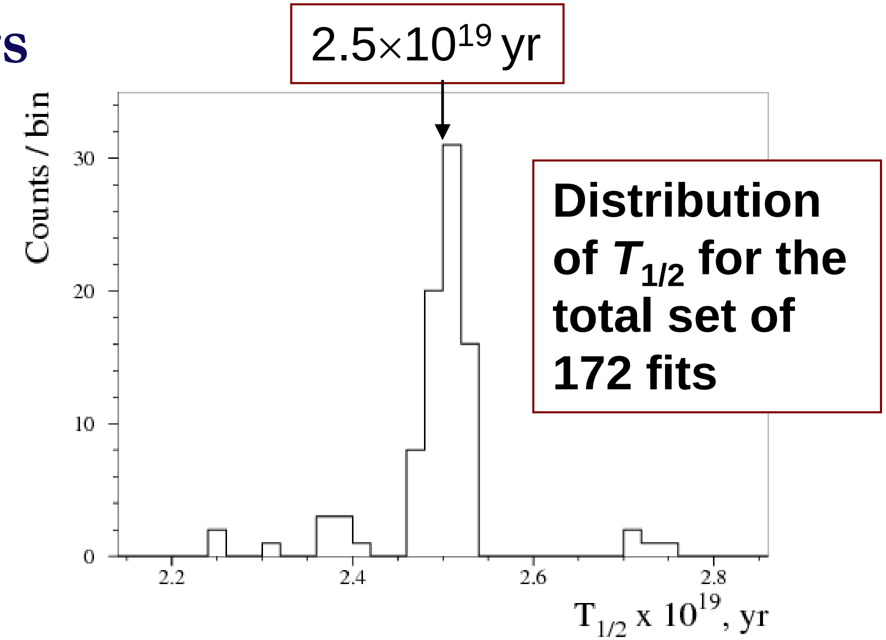
Signal to bg ratio = 2.6 in [1.1–2.8] MeV

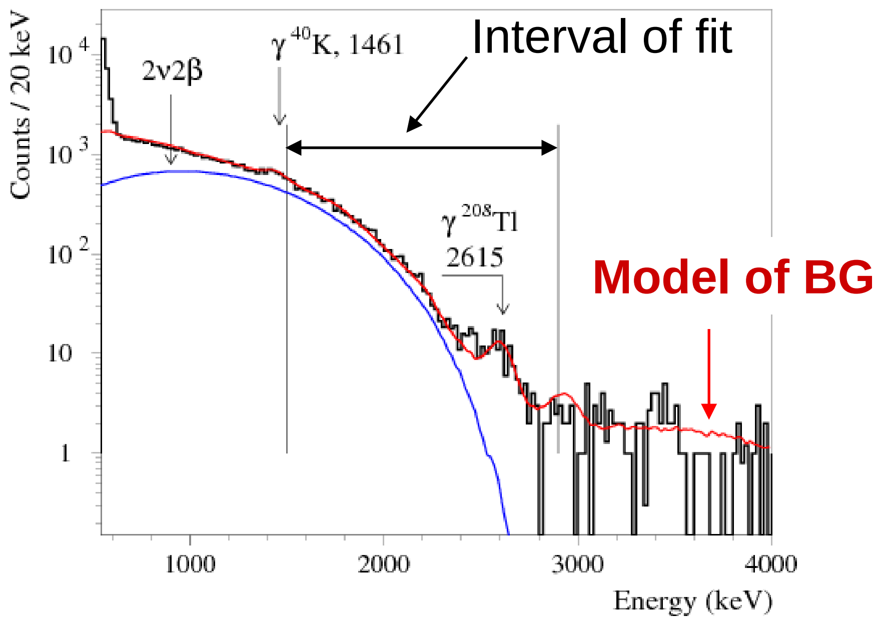
$T_{1/2}$ = [2.51 ± 0.14(syst.) ± 0.02(stat.)] × 10^{19} yr

Estimation of systematic errors

Conditions of the Fit:

- Variation of bounds for rad. contaminations
- Model of background
- Interval of fit
- Quenching for β (non proportional light response) [1,2]





Systematic errors

Source	Contribution,%
Number of nucleus	0.1
Live time	<0.1
Efficiency PSD	0.5
Fit	5
Simulation	?

[1] PRC 76(2007)064603 [2] NIMA 696(2012)144

Summary of the $T_{1/2}(2\nu 2\beta)$ results ^{116}Cd

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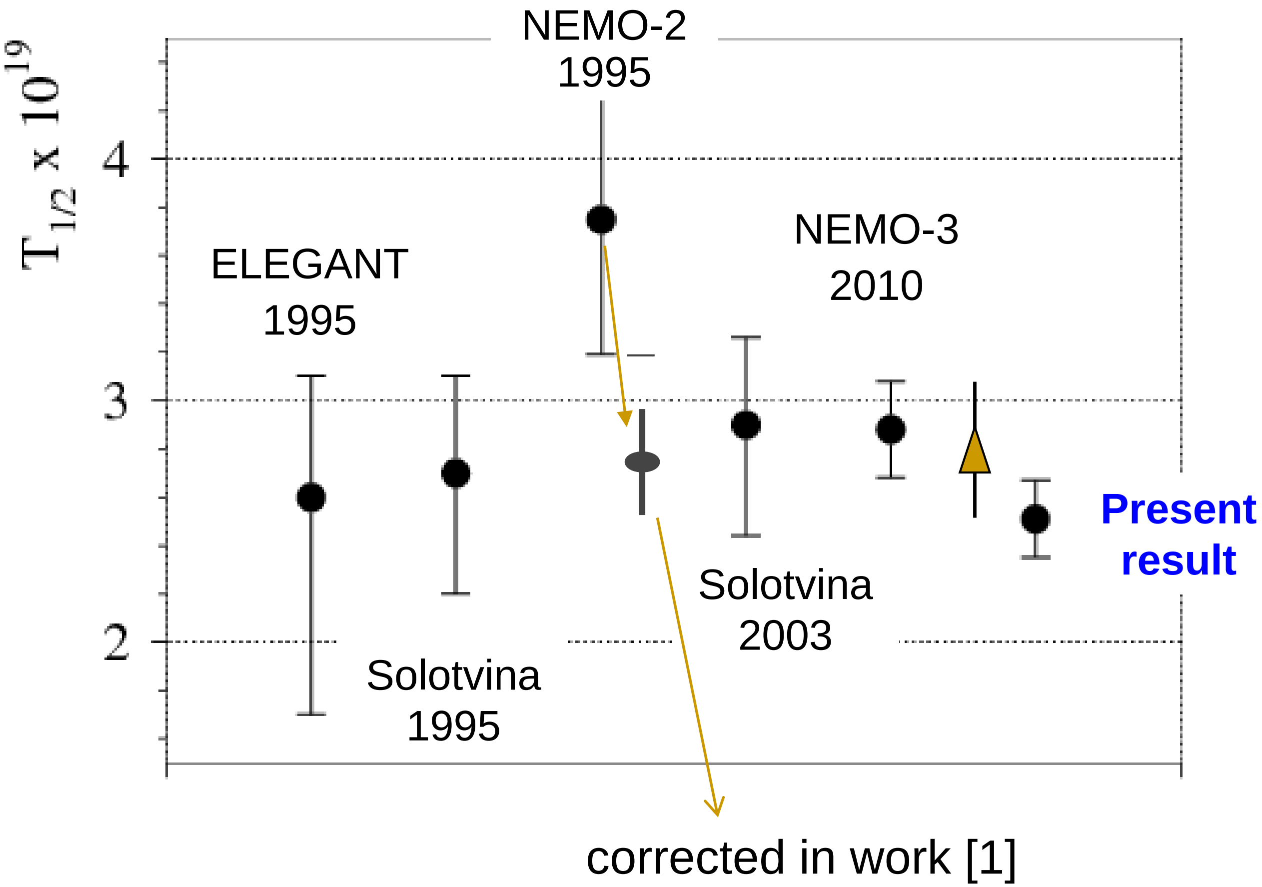
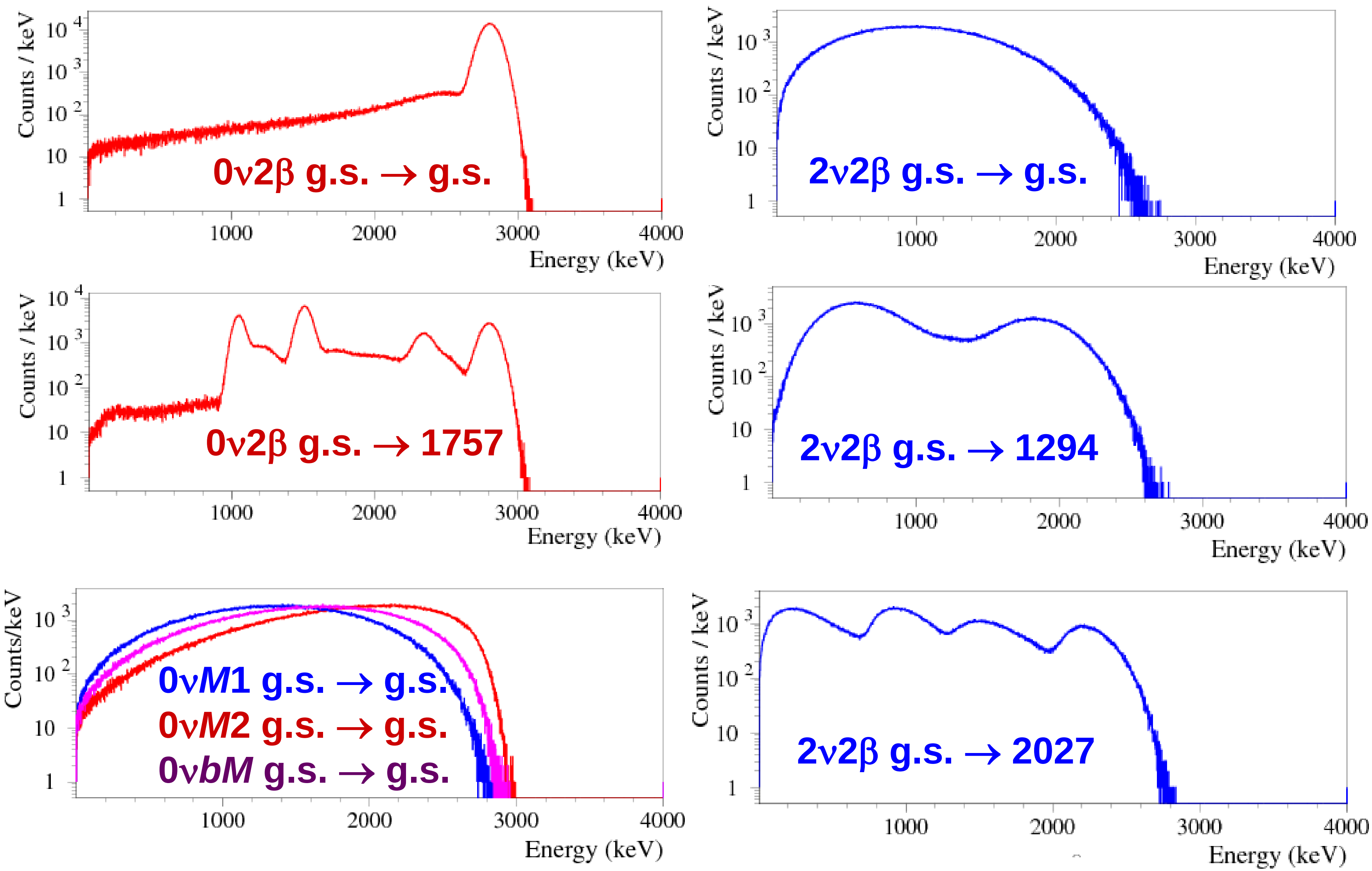
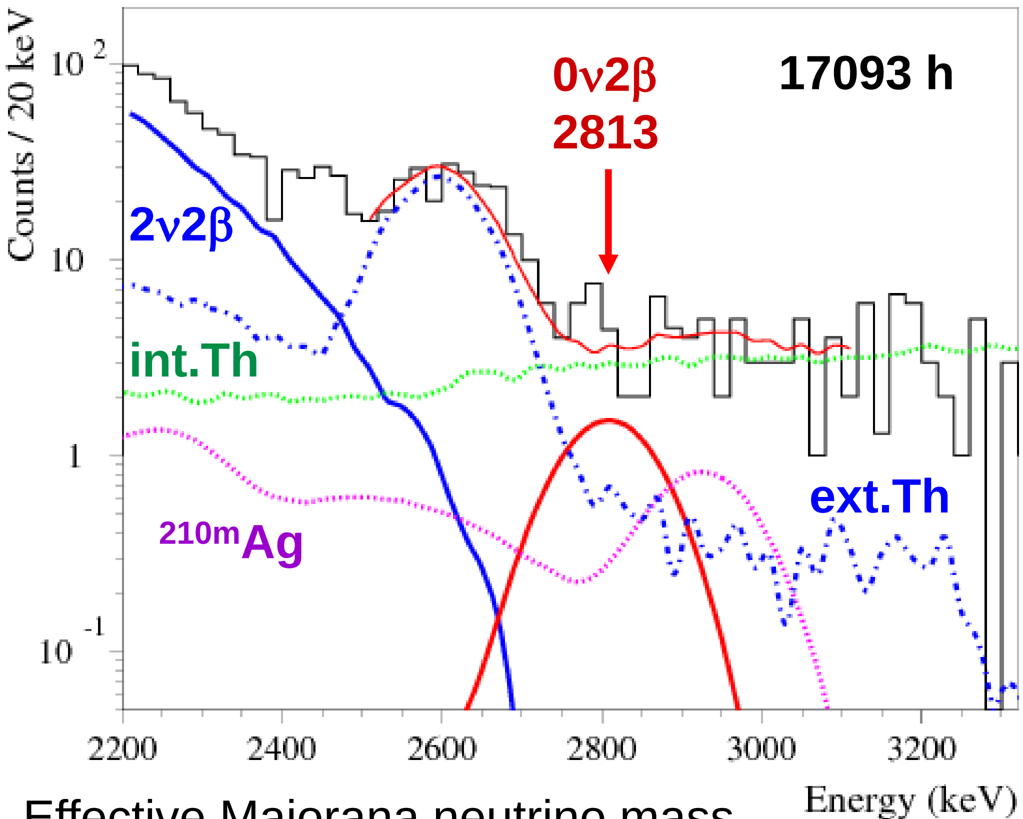


[1] PRC 81(2010)035501

Response of the $^{116}CdWO_4$ detector to 2β processes in ^{116}Cd simulated by EGS4



Limit on 0ν2β decay of ^{116}Cd to g.s. of ^{116}Sn



Fit in 2.5–3.1 MeV with χ^2/n.d.f. = 1.13

S = 2.1 ± 6.8 counts

lim$S$ = 13.3 counts @ 90% C.L. by [1]

$T_{1/2} > 1.6 \times 10^{23}$ yr

Estimation by square root of counts

Background in 2740-2920 keV = 47 counts

lim$S$ = 11.3 counts

79% of the 0ν2β peak

$T_{1/2} \geq 1.5 \times 10^{23}$ yr @ 90% C.L

Effective Majorana neutrino mass

$\langle m_\nu \rangle$ ~ 1.7 eV [2]

$\langle m_\nu \rangle$ ~ 1.4 – 1.8 eV [3]

[1] G.J. Feldman and R. D. Cousins, Phys. Rev. D 57(1998)3873
[2] J. Barea, J. Kotila, and F. Iachello Phys. Rev. Lett. 109(2012)042501
[3] J.D. Vergados, H.Ejiri and F.Simkovic Rep. Prog. Phys. 75(2012)106301

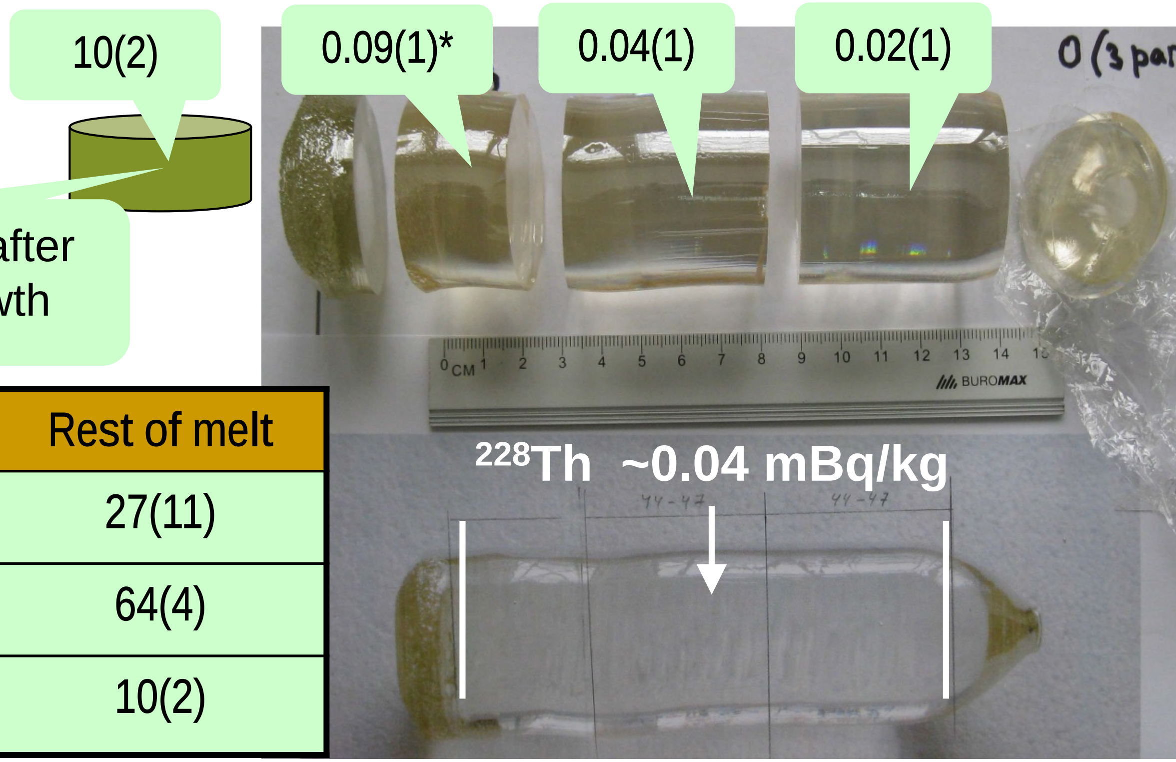
Results

Decay mode	Transition	$T_{1/2}$, yr , present results	$T_{1/2}$, yr at 90% C.L.
0ν	g.s.- g.s.	$\geq 1.6 \times 10^{23}$	$\geq 1.7 \times 10^{23}$ [1]
0ν	g.s.- 2^+(1294 keV)	$\geq 5.8 \times 10^{22}$	$\geq 2.9 \times 10^{22}$ [1]
0ν	g.s.- 0_1^+(1757 keV)	$\geq 7.8 \times 10^{22}$	$\geq 1.4 \times 10^{22}$ [1]
0ν	g.s.- 0_2^+(2027 keV)	$\geq 4.5 \times 10^{22}$	$\geq 0.6 \times 10^{22}$ [1]
0ν	g.s.- 2^+ (2112 keV)	$\geq 2.9 \times 10^{22}$	
0ν	g.s.- 2^+ (2225 keV)	$\geq 4.0 \times 10^{22}$	
0ν*M*1	g.s.- g.s.	$\geq 0.2 \times 10^{22}$	$\geq 0.8 \times 10^{22}$ [1]
0ν*M*2	g.s.- g.s.	$\geq 0.9 \times 10^{21}$	$\geq 0.8 \times 10^{21}$ [1]
0ν*bM*	g.s.- g.s.	$\geq 0.8 \times 10^{21}$	$\geq 1.7 \times 10^{21}$ [1]
2ν	g.s.- g.s.	$[2.51 \pm 0.02(stat.) \pm 0.14(syst.)] \times 10^{19}$	see slide 10
2ν	g.s.- 2^+(1294 keV)	$\geq 0.5 \times 10^{21}$	$\geq 2.3 \times 10^{21}$ [2]
2ν	g.s.- 0_1^+(1757 keV)	$\geq 1.1 \times 10^{21}$	$\geq 2.0 \times 10^{21}$ [2]
2ν	g.s.- 0_2^+(2027 keV)	$\geq 0.9 \times 10^{21}$	$\geq 2.0 \times 10^{21}$ [2]
2ν	g.s.- 2^+ (2112 keV)	$\geq 1.7 \times 10^{21}$	$\geq 1.7 \times 10^{20}$ * [3]
2ν	g.s.- 2^+ (2225 keV)	$\geq 1.6 \times 10^{21}$	$\geq 1.0 \times 10^{20}$ * [3]

[1] PRC 68(2003)035501 **[2]** NPA 577(1994)493 **[3]** Phys.Lett.B 249(1990)186 *68% C.L.

Possibility to improve the radiopurity of $^{116}CdWO_4$ by re-crystallization

Activity of ^{228}Th



Nuclide	Crystal	Rest of melt
^{40}K	<1	27(11)
^{226}Ra	<0.005	64(4)
^{228}Th	0.02 – 0.09	10(2)

^{228}Th in the initial $^{116}CdWO_4$ powder ~1.4 mBq/kg

Thorium expected to be reduced by a factor ~35 → 1 μBq/kg

Reduction of K, Th, U and Ra contamination by re-crystallization ⇒ reduction of the background by a factor 4 ⇒ advancement the sensitivity to 0ν2β ⇒ lim$T_{1/2}$~ 5×10^{23} yr

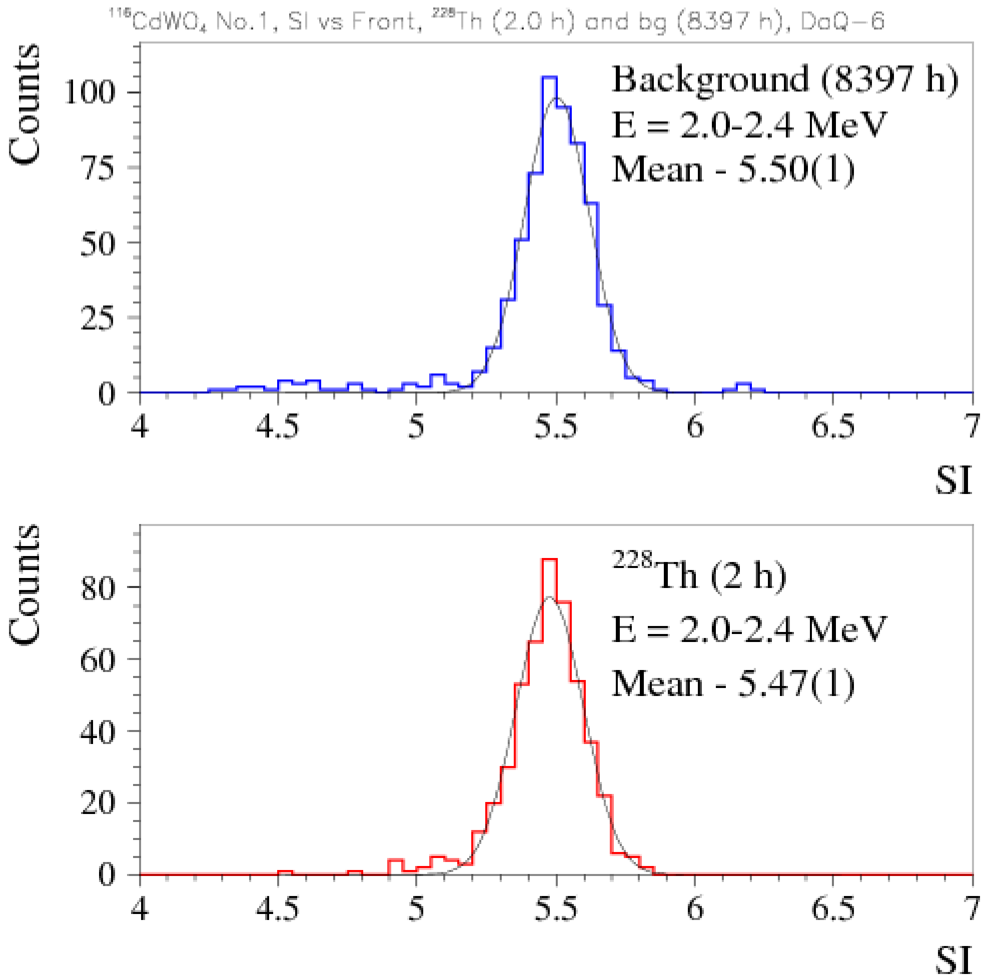
Conclusions

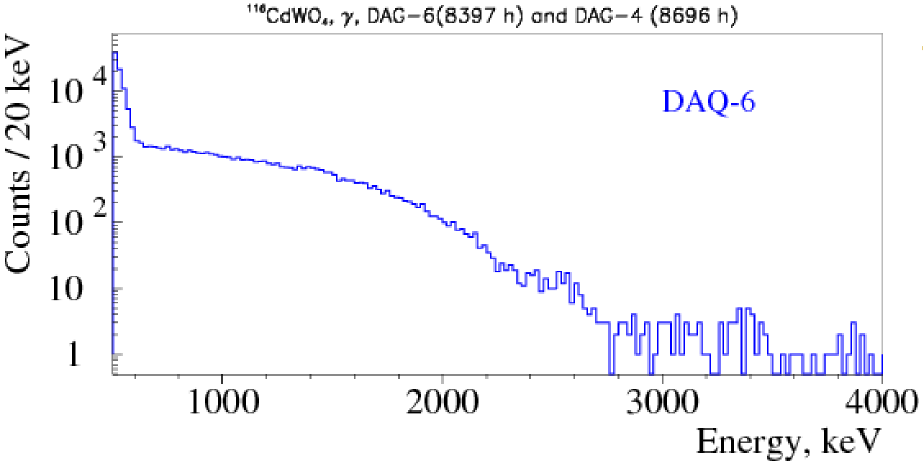
- Experiment to search for double beta decay processes in ^{116}Cd with the help of enriched in ^{116}Cd (to 82%) low background $^{116}CdWO_4$ scintillation detectors (1.16 kg) is in progress at the Gran Sasso underground laboratory of INFN (Italy).
- The 2ν2β half-life is $T_{1/2}$ (2ν2β) = [2.51± 0.02(stat.) ± 0.14(syst.)]×10^{19} yr
- $T_{1/2}(0\nu2\beta) \geq 1.6 \times 10^{23}$ yr $\rightarrow \langle m_\nu \rangle < (1.4 – 1.8)$ eV
- New improved limits are obtained for 0ν2β decay of ^{116}Cd to exited levels of ^{116}Sn: lim$T_{1/2}$ ~ (2.9–7.8) × 10^{22} yr

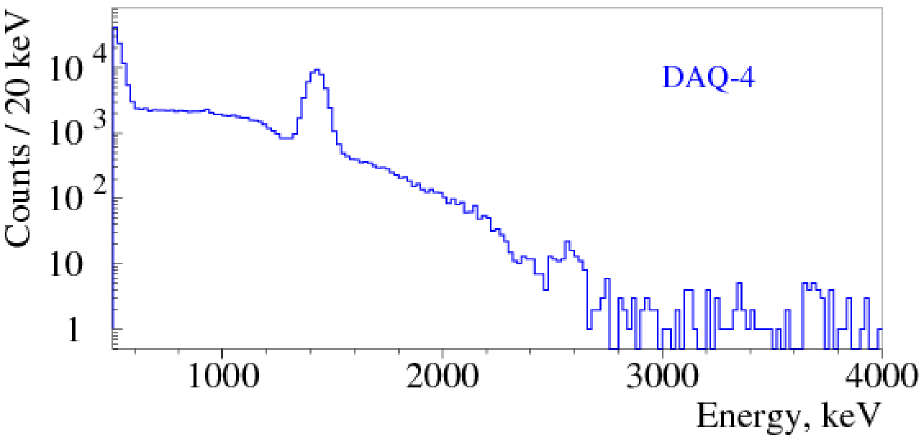
The main background component, internal ^{228}Th, can be reduced by a factor 35 by re-crystallization → sensitivity of the experiment $T_{1/2} \geq 5 \times 10^{23}$ yr

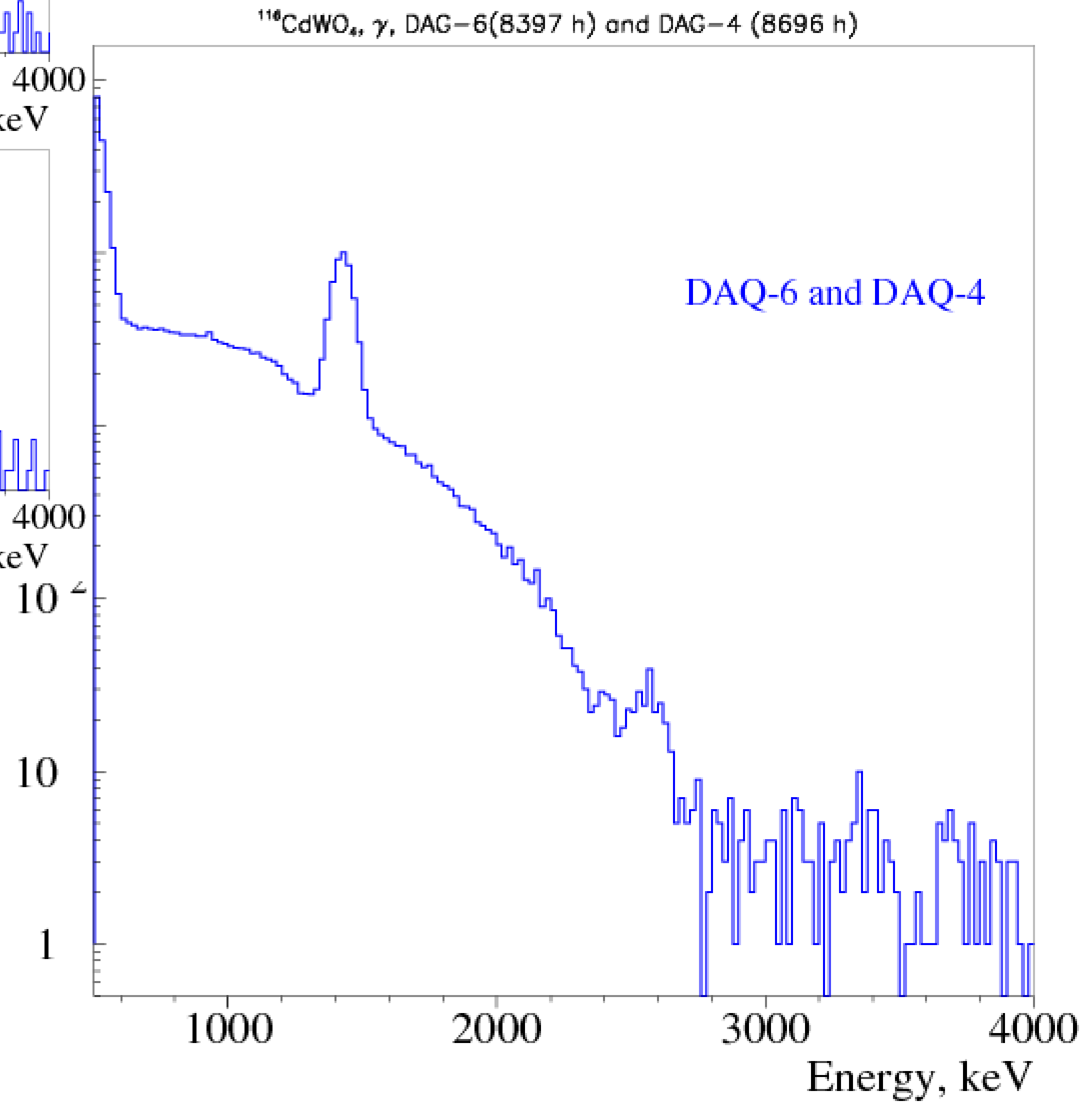
Thank you for attention!

Back-up slides

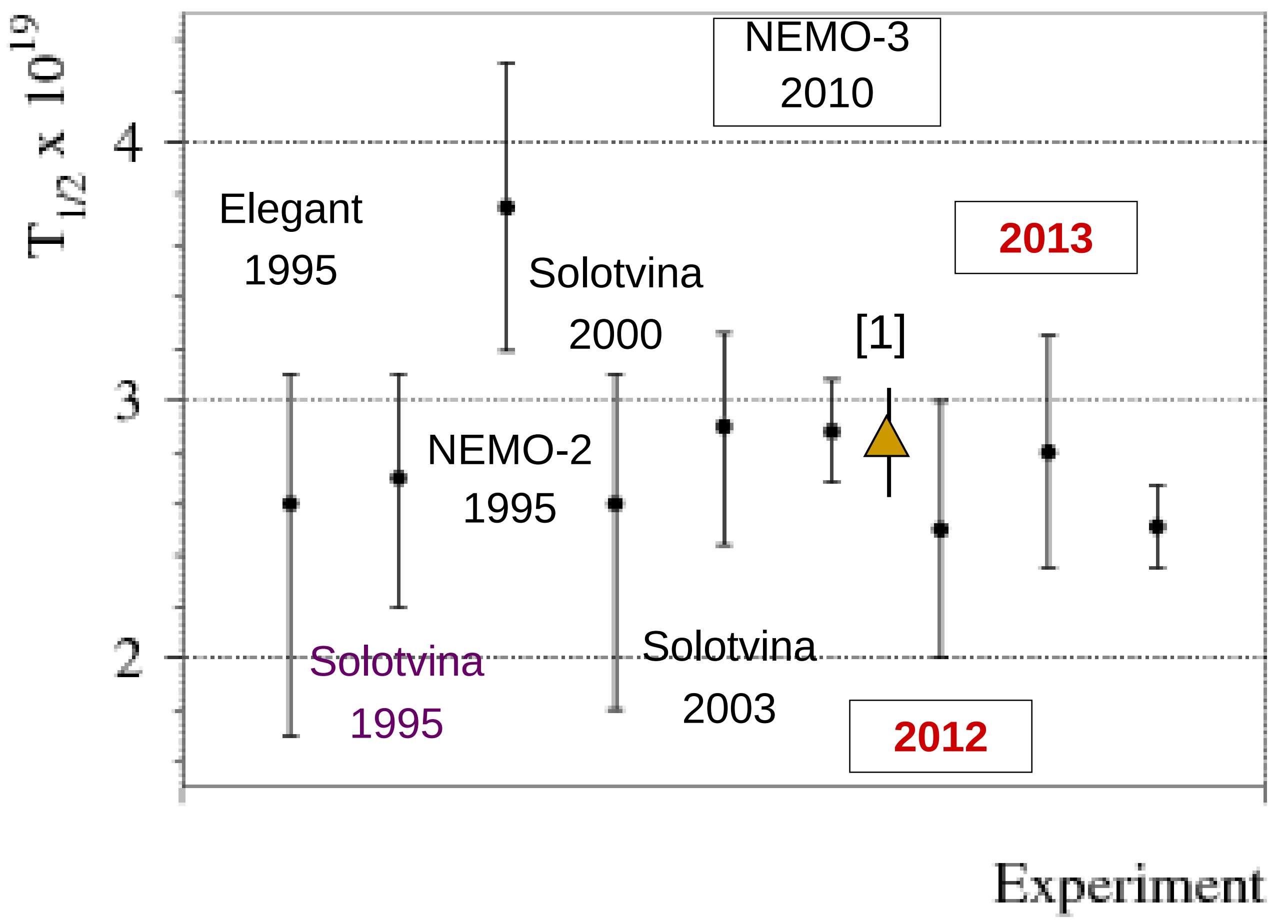



116CdWO4, γ, DAG−6(8397 h) and DAG−4 (8696 h)
DAQ-6
Counts / 20 keV
10 4
10 3
10 2
10
1
1000
2000
3000
4000
Energy, keV


DAQ-4
Counts / 20 keV
10 4
10 3
10 2
10
1
1000
2000
3000
4000
Energy, keV


116CdWO4, γ, DAG−6(8397 h) and DAG−4 (8696 h)
DAQ-6 and DAQ-4
10
1
1000
2000
3000
4000
Energy, keV

	Isotop	Activity, mBq/kg
PMT	^{226}Ra	548
	^{228}Ra	49
	^{228}Th	119
	^{40}K	218
Copper	U	0.06
	Th	0.02
	^{40}K	0.06
Light quides	U	0.51
	Th	0.17
	^{40}K	0.93



$T_{1/2} \times 10^{19}$
4
3
2
NEMO-3
2010
Elegant
1995
Solotvina
2000
2013
[1]
NEMO-2
1995
Solotvina
1995
Solotvina
2003
2012
Experiment