Final results of the CUPID-0 Phase I experiment

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for the CUPID-0 collaboration

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CUPID-0 for CUPID (Cuore Upgrade with Particle ID)

CUPID is a proposed bolometric $0\nu DBD$ experiment which aims at a sensitivity to the $m_{\beta\beta}$ on the order of 10 meV

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Technical challenges:

- **Detector mass in the range of several hundred kg of the isotope**
- **Background close to zero at the ton · year exposure scale**
- **Region Of Interest (RoI) of a few keV** around $0\nu DBD$ transition energy

Five steps to satisfy these technical challenges :

- **Isotopic enrichment** →
- **Active alpha rejection** →
- **Improved material selection**
- **Reduced cosmo-activation**
- **Better energy resolution**

CUPID-0 is the first demonstrator, of a series, of the new technologies that will be implemented in CUPID and, at the same time, it is also a competitive $0\nu DBD$ search in its own right.

Scintillating bolometers

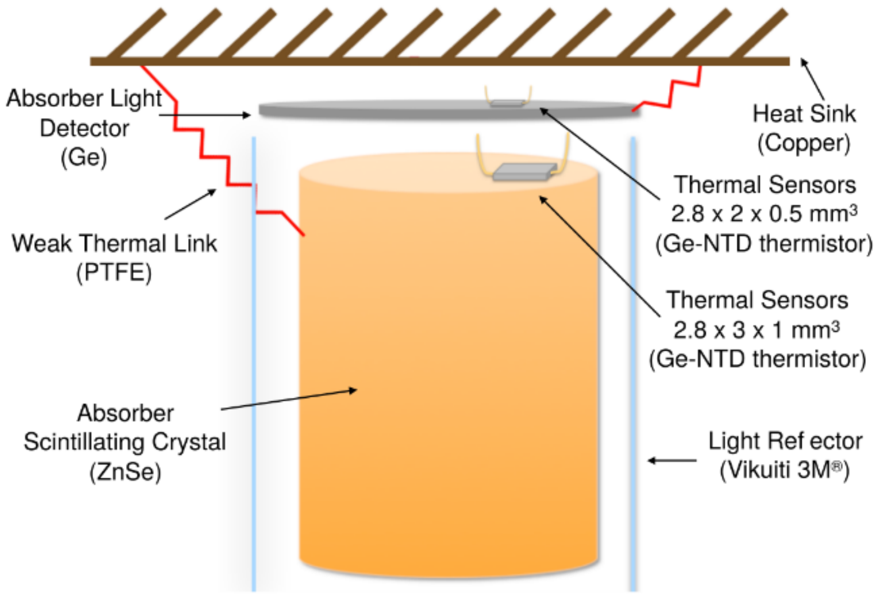
A bolometer is a highly sensitive calorimeter operated at cryogenic temperature (~10 mK)

Energy deposits are measured as temperature variations of the absorber

If the absorber is also an efficient scintillator the energy is converted into heat + light

Scintillating bolometer features:

- high energy resolution O(1/1000)
- high detection efficiency (source = detector)
- **particle IDentification**



A **close-to-zero background** experiment is feasible:

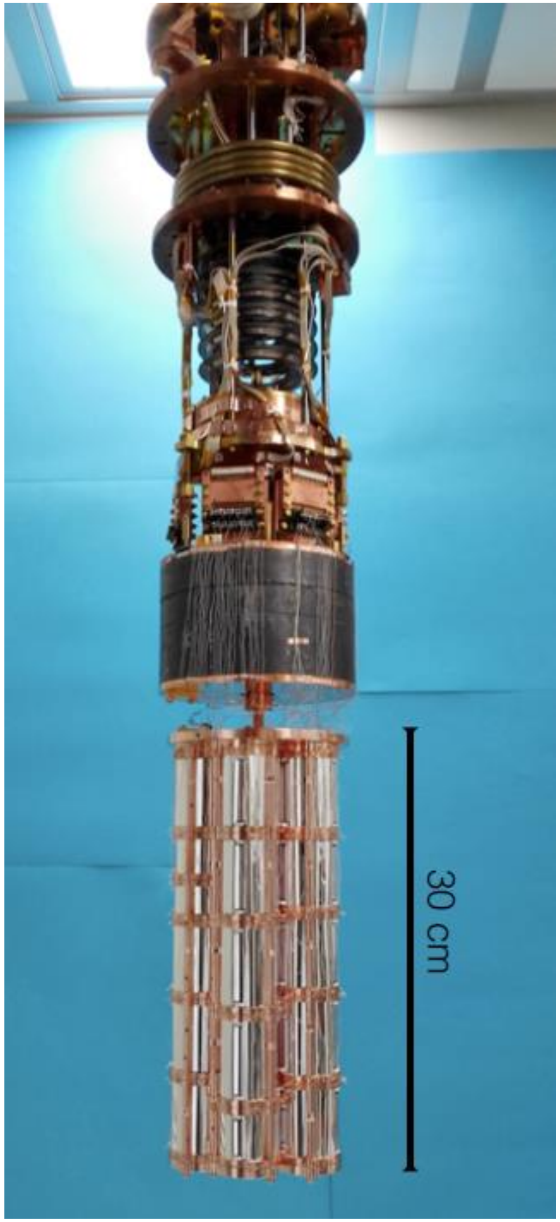
α background: identification and rejection

γ/β background: ββ isotope with large Q-value

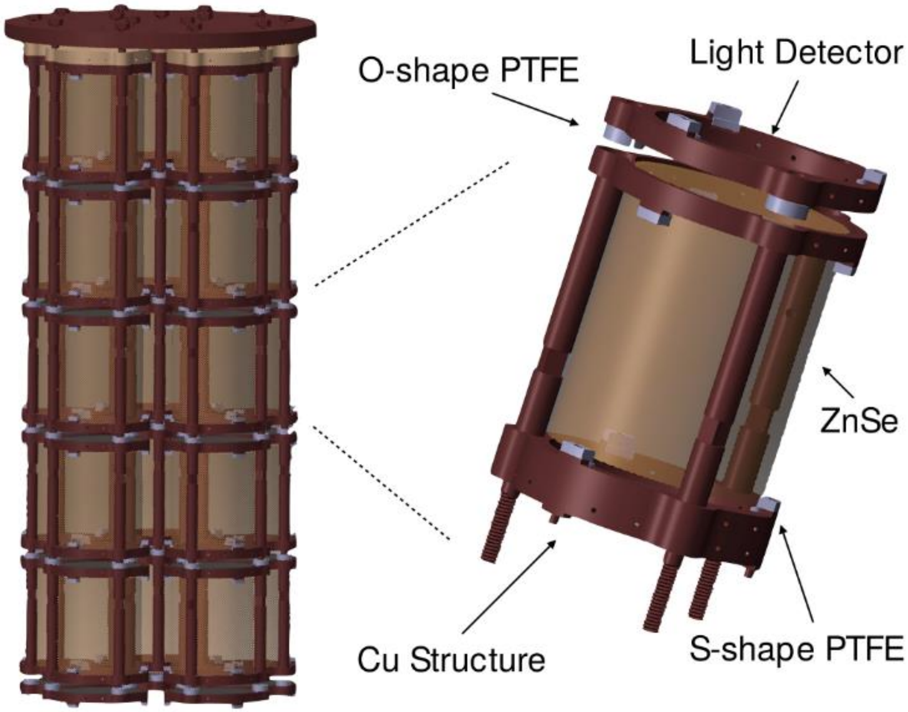
CUPID-0 - The detector

CUPID-0 is an array of scintillating bolometers for the investigation of ^{82}Se 0vDBD

- Q-value 2997.9 ± 0.3 keV
- 95% enriched Zn^{82}Se bolometers
- Installed in the underground laboratories at Gran Sasso
    - Hosted in the 'old' Cuoricino/CUORE-0 cryostat
- 10.5 kg of ZnSe, 5.17 kg of ^{82}Se ($3.8 \cdot 10^{25}$ $\beta\beta$ nuclei)
- Background goal ~10^{-3} c/keV/kg/y also thanks to discrimination capabilities (light yield and pulse shape)



CUPID-0 - The detector



26 ZnSe (24 enriched + 2 nat)

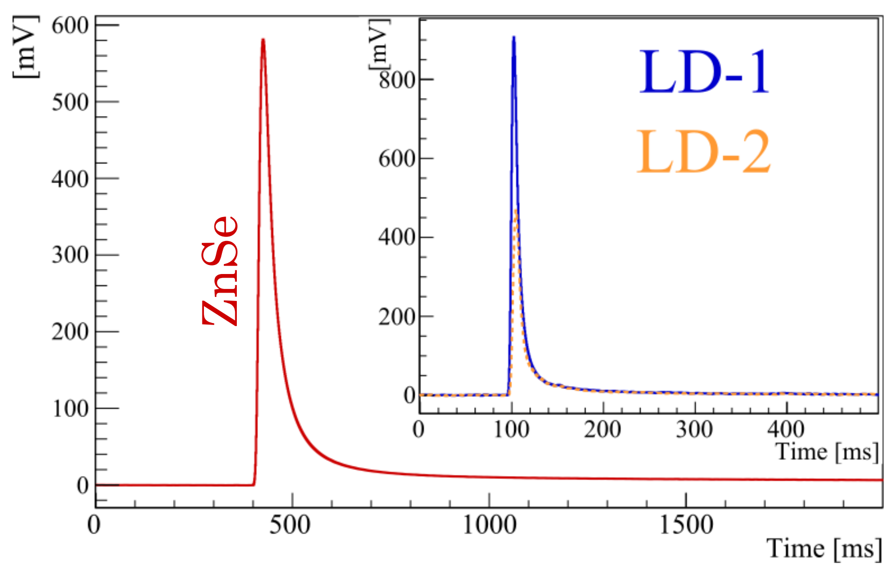
+

31 Ge Light Detectors (LD)

arranged in 5 towers

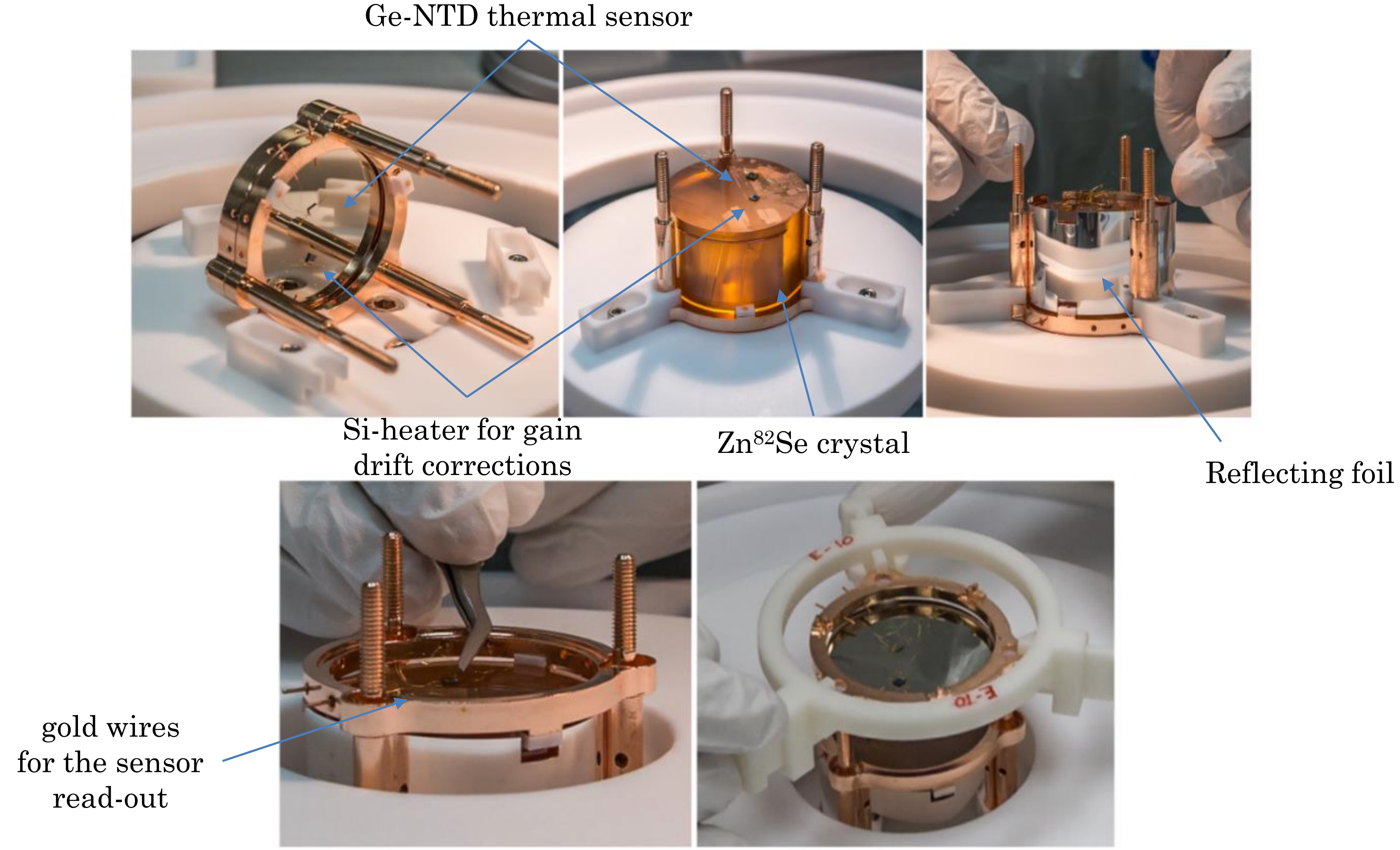
Simplest modular detector:

- Copper structure
- PTFE holders
- Reflecting foil (VIKUITI 3M)



CUPID-0 - The assembly

- All activities for the construction were carried out in an underground Rn-suppressed clean room
- Assembly started on October, 2016
- Complex assembly: crystals have all different shapes and heights

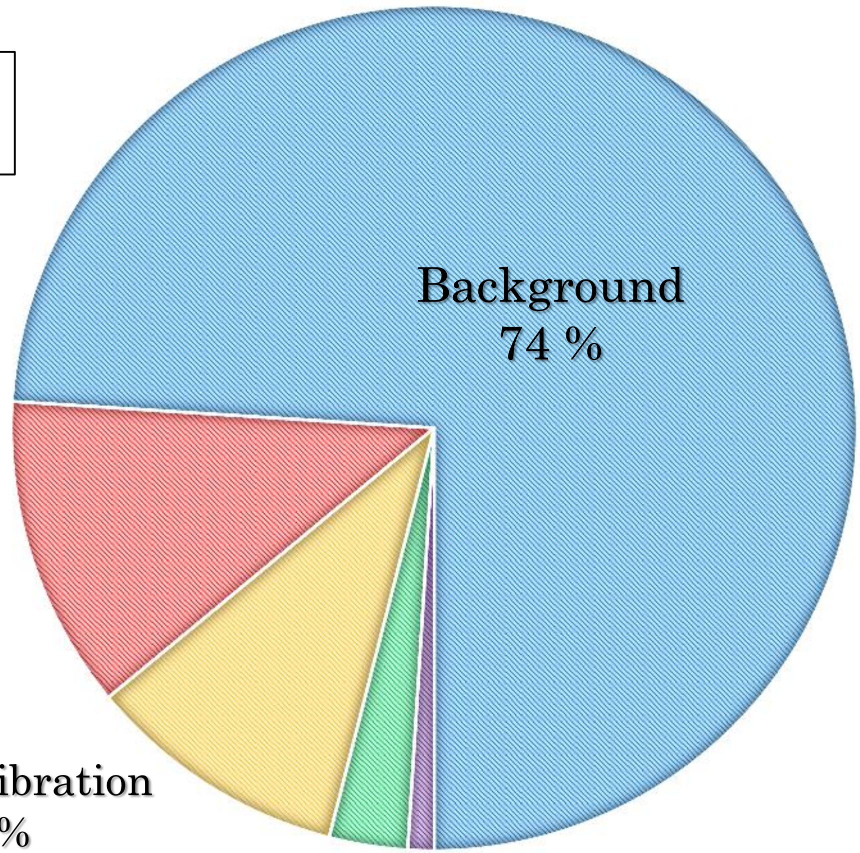


Data Taking - CUPID-0 Phase I

- Data taking started on March 17th, 2017
- Data presented here were collected between June 2017 and December 2018

Maintenance
cryogenic system

0vDBD
Physics



ZnSe exposure
9.95 kg·y

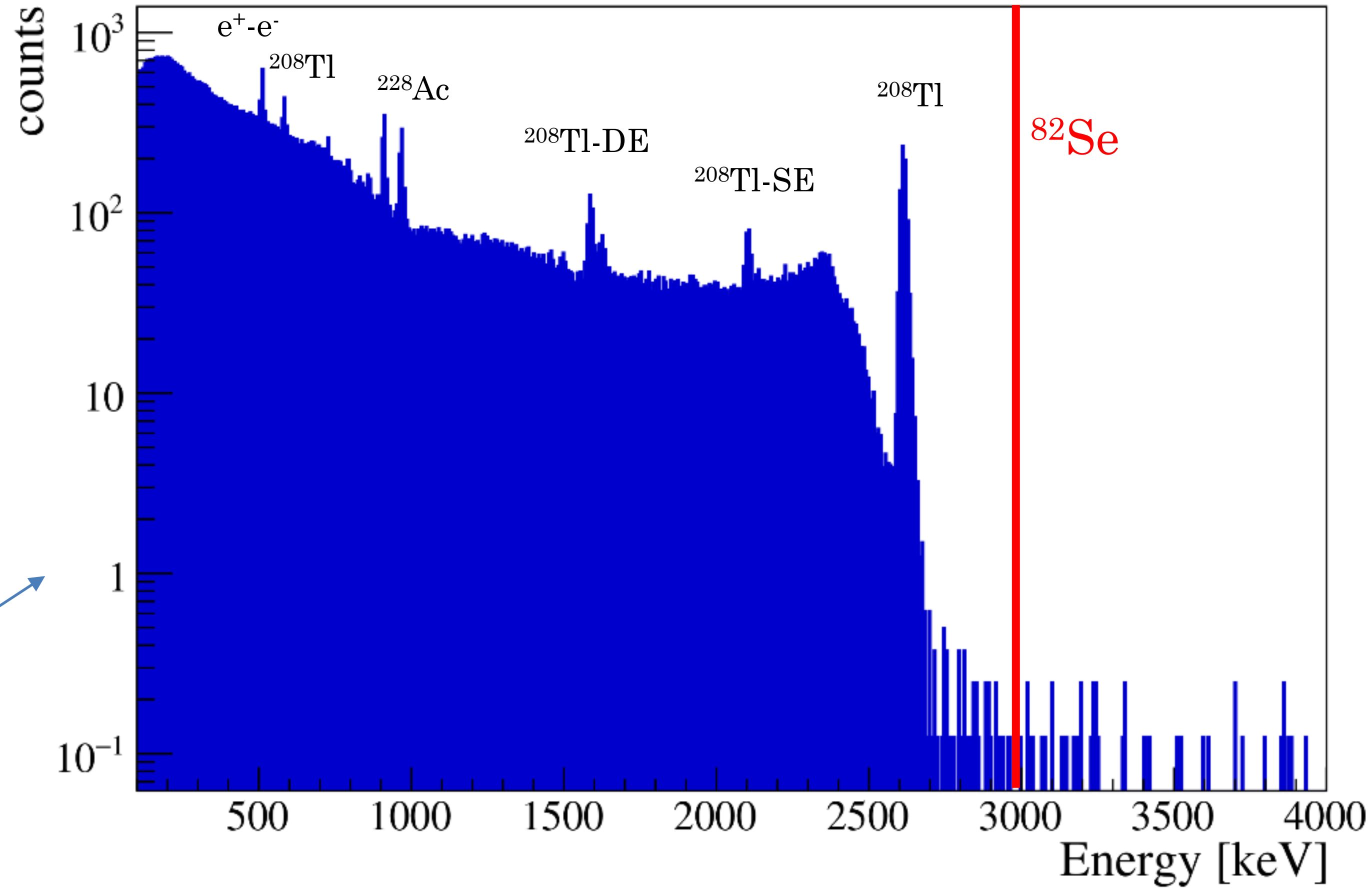
^{82}Se exposure
5.29 kg·yr

Energy calibration
Detector performance

Characterization of
β/γ shape parameters
at RoI

Detector performance - ^{232}Th calibrations

The detector performance were investigated using ^{232}Th sources placed outside the cryostat



Energy spectrum obtained summing all the ZnSe channels in a calibration run

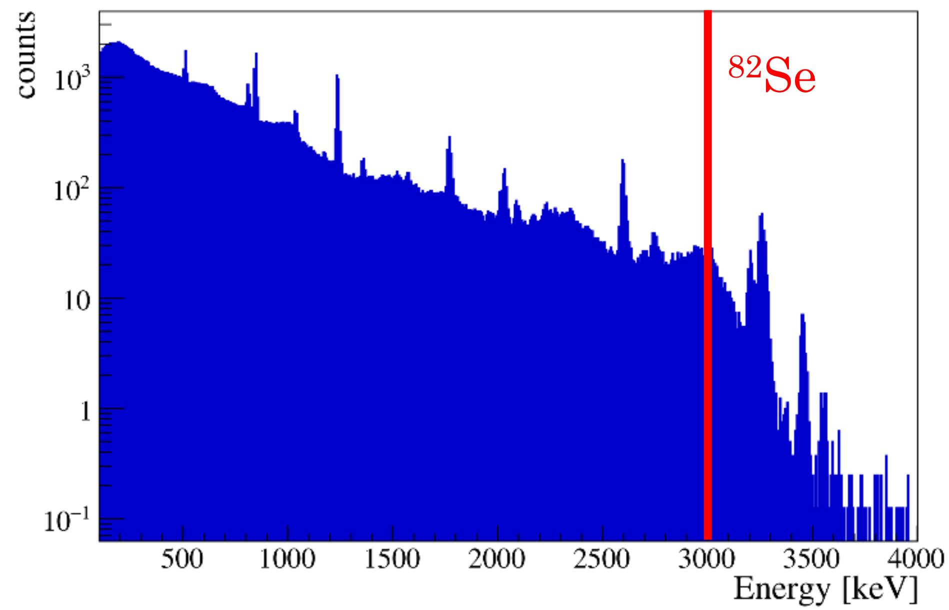
- Major contribution to the energy resolution is the crystal quality

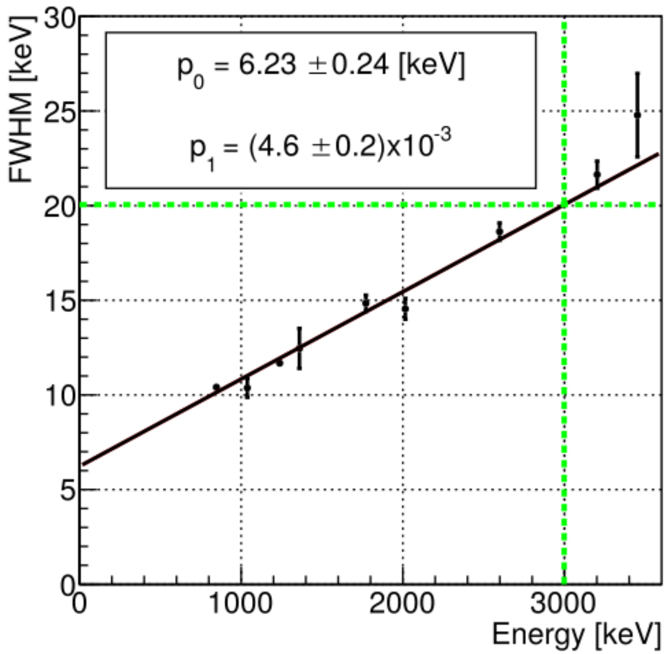
  - average baseline FWHM 3.5 keV

Detector performance - ^{56}Co calibration

We performed a calibration run also with a ^{56}Co source to:

- check the goodness of the energy reconstruction
- evaluate the FWHM energy resolution at the ^{82}Se Q-value



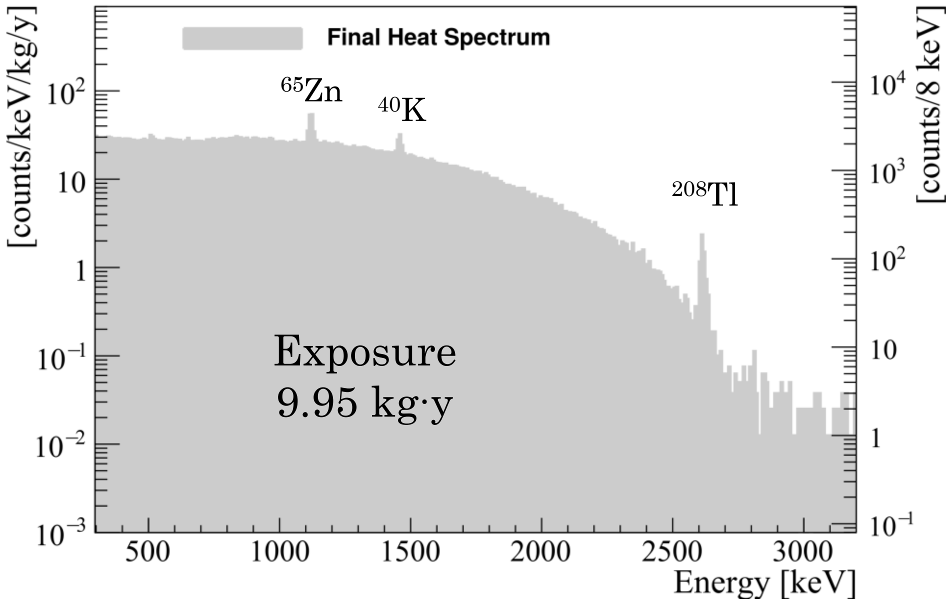


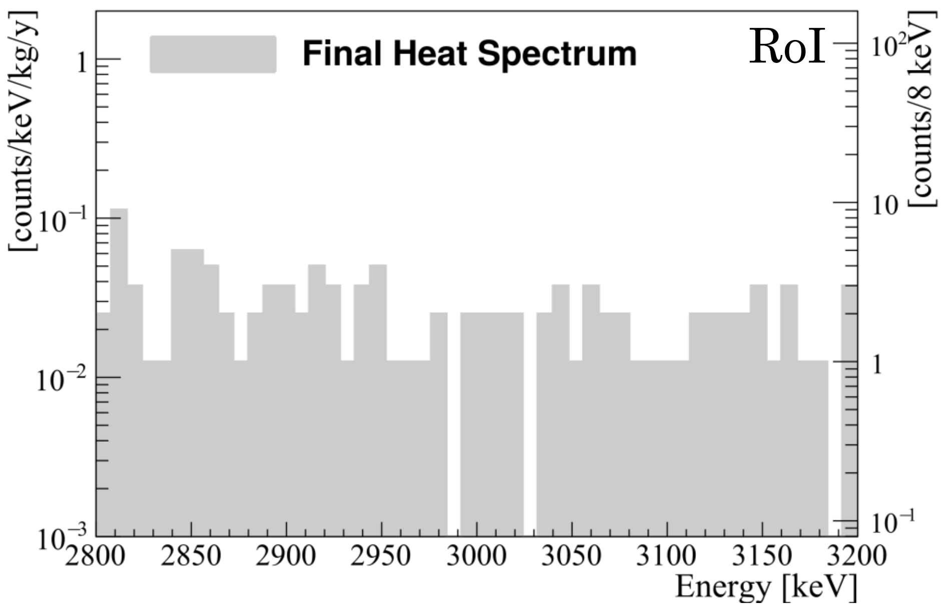
→ value corresponding to the ^{82}Se Q-value

The exposure-weighted harmonic mean FWHM energy resolution **at the $Q_{\beta\beta}$** results to be (**after de-correlation of heat and light signals**)

$$(\mathbf{20.05 \pm 0.34})\ \boldsymbol{keV}$$

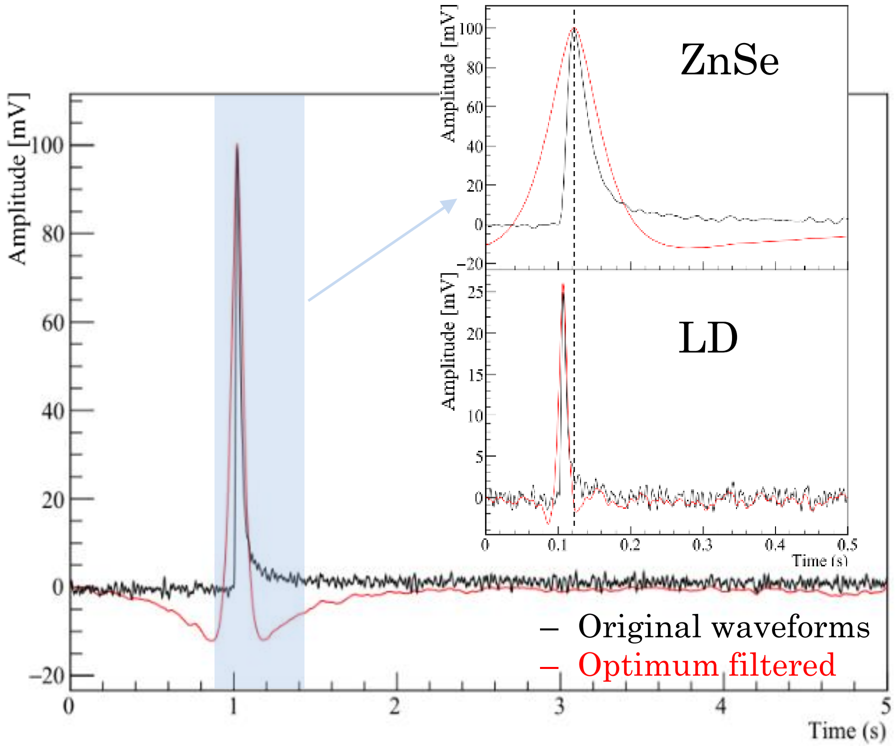
Background - Total energy spectrum





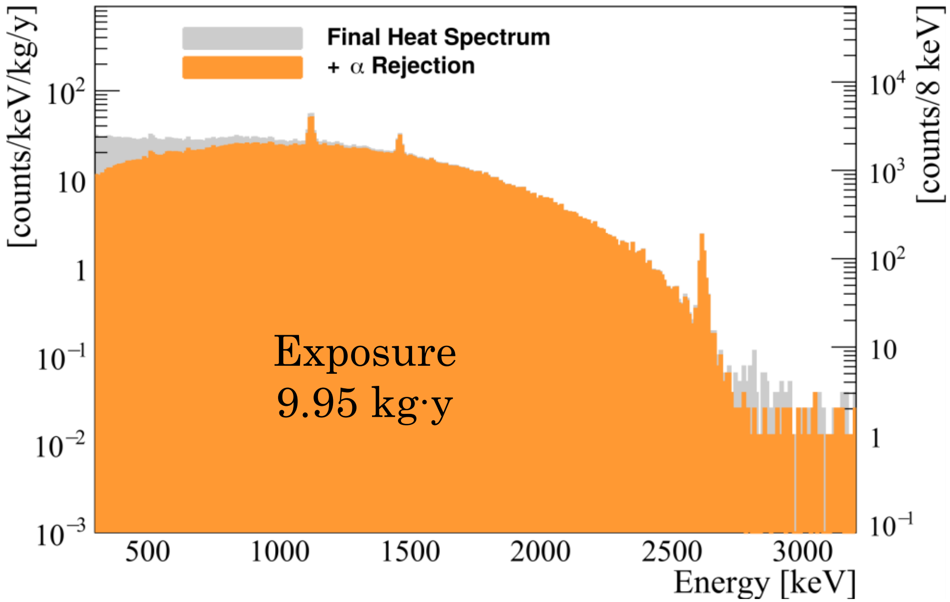
First level data analysis:

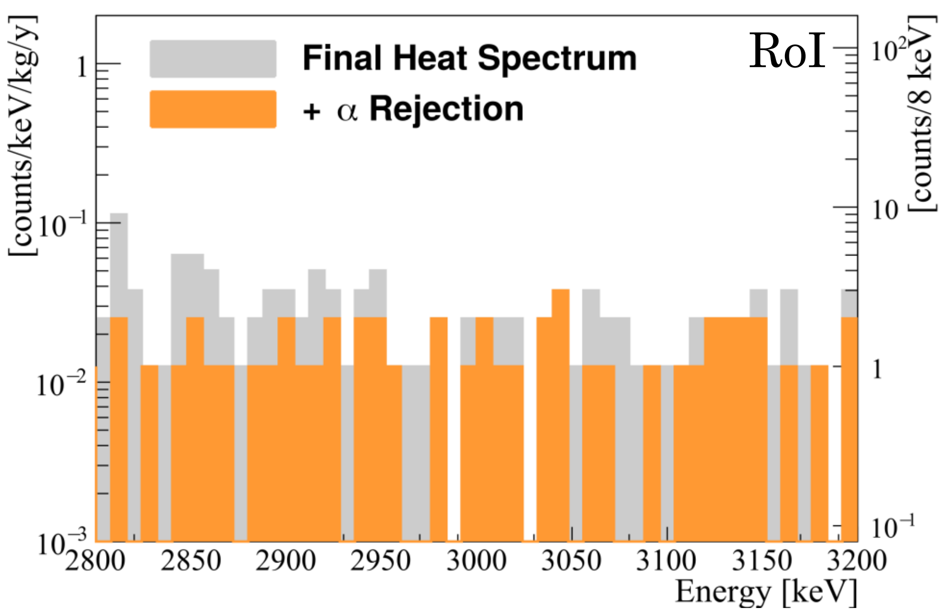
- Optimum filtering
- Gain stability corrections
- Synchronization Heat-Light



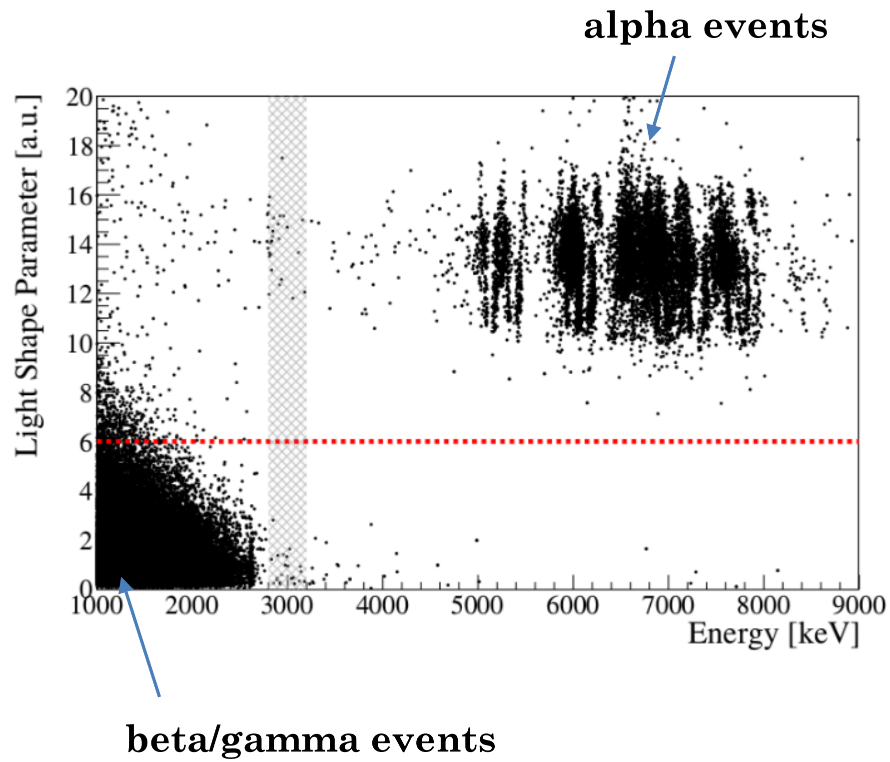
- Rejection of "non-particle-like" events through pulse shape on thermal pulses
- Anti-coincidence between crystals ($\Delta T = 20ms$)

Background – Data selection

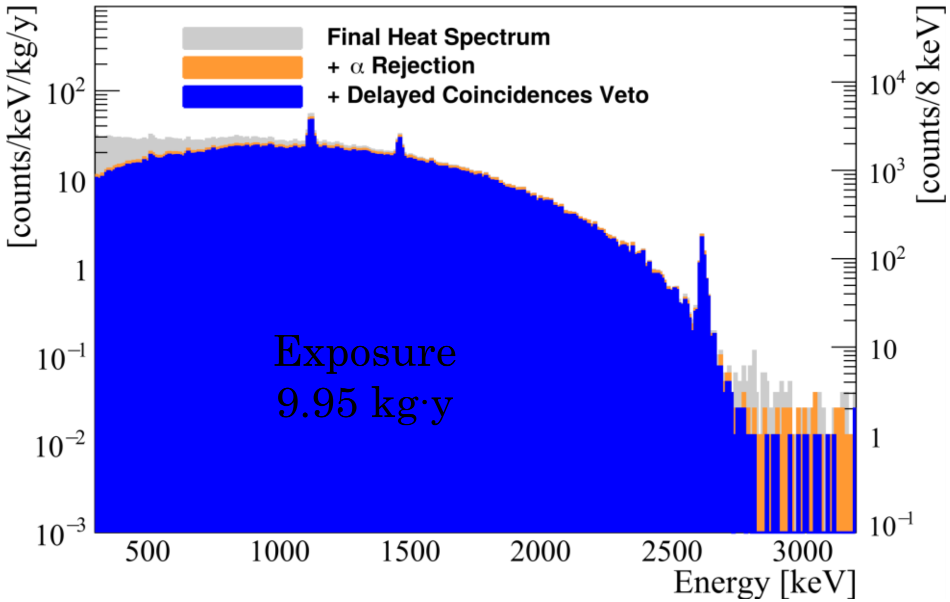


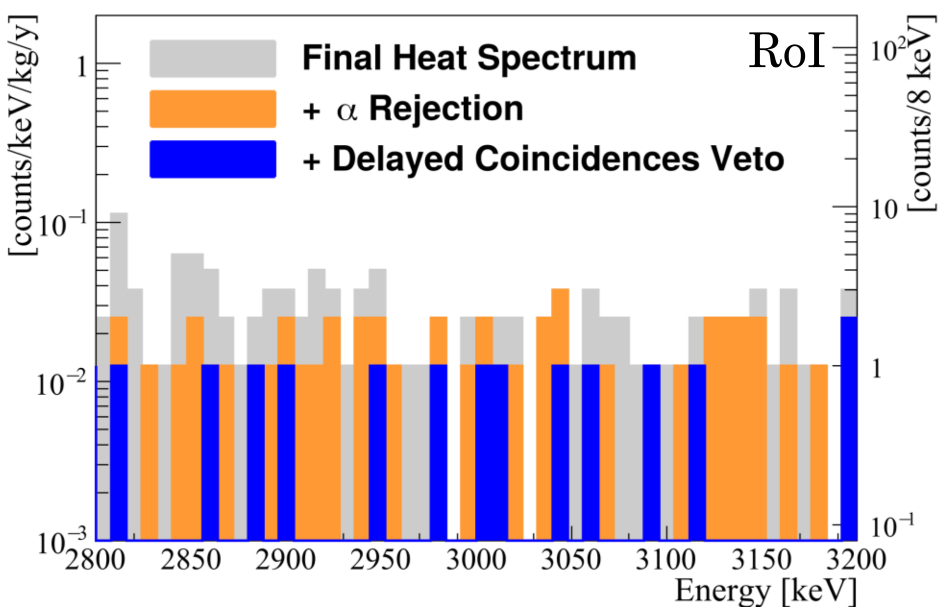


Alpha rejection with light-shape variable

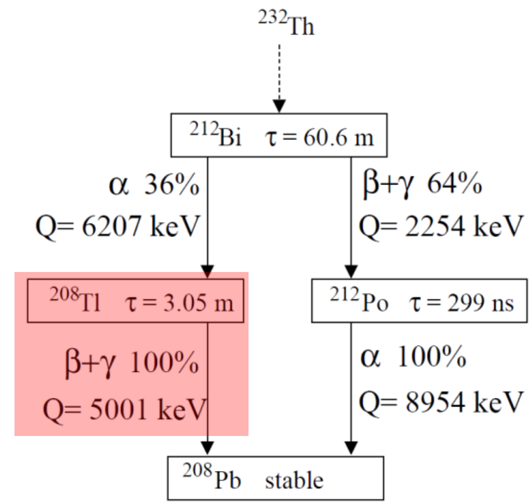


Background – Data selection





Delayed alpha coincidence
^{212}Bi-^{208}Tl rejection



We veto any event succeeding a primary ^{212}Bi α event in a window corresponding to 7 times the half-life.

If the contamination is close to the surface and the α escapes the crystal, only part of the energy of the decay is collected

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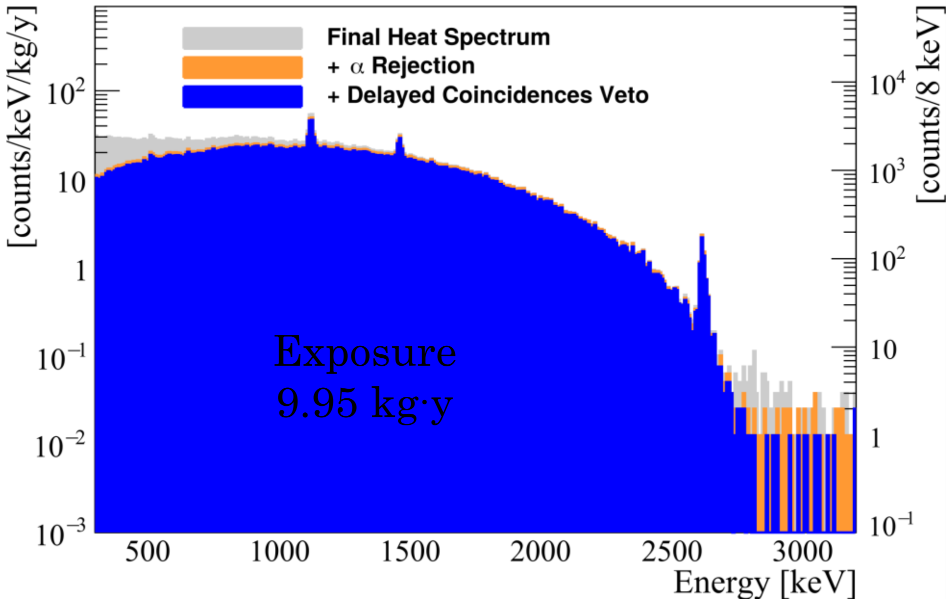
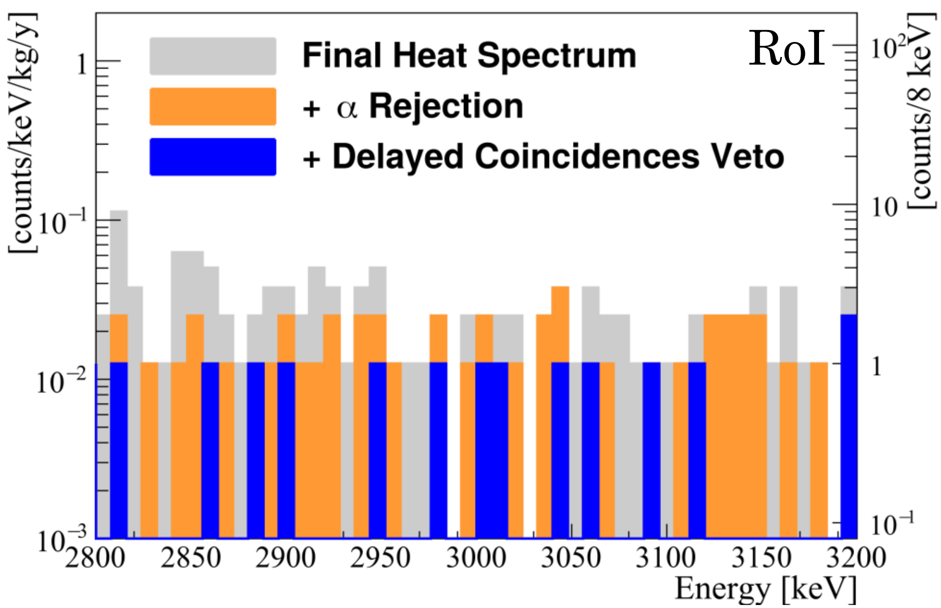
α pulse shape of the primary event and energy in the range (2.0-6.5) MeV

CUPID-0 Phase I: Results



probability 0vDBD event confined inside a single crystal	81.0±0.2 %
trigger efficiency + energy properly reconstructed	99.5 %
heat pulses selection efficiency + delayed coincidences	88 %
beta/gamma selection efficiency	98 %
Total signal efficiency	**70±1 %**

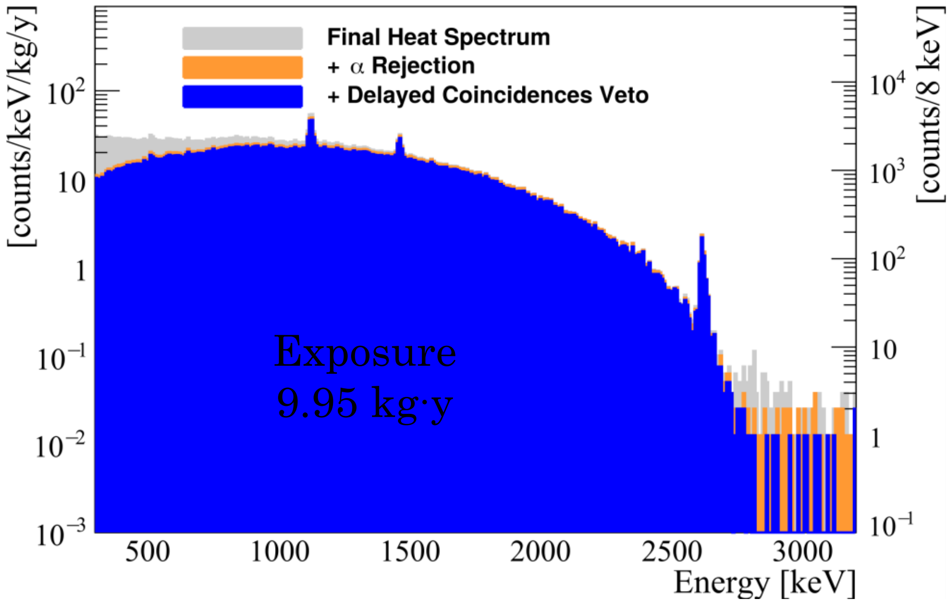


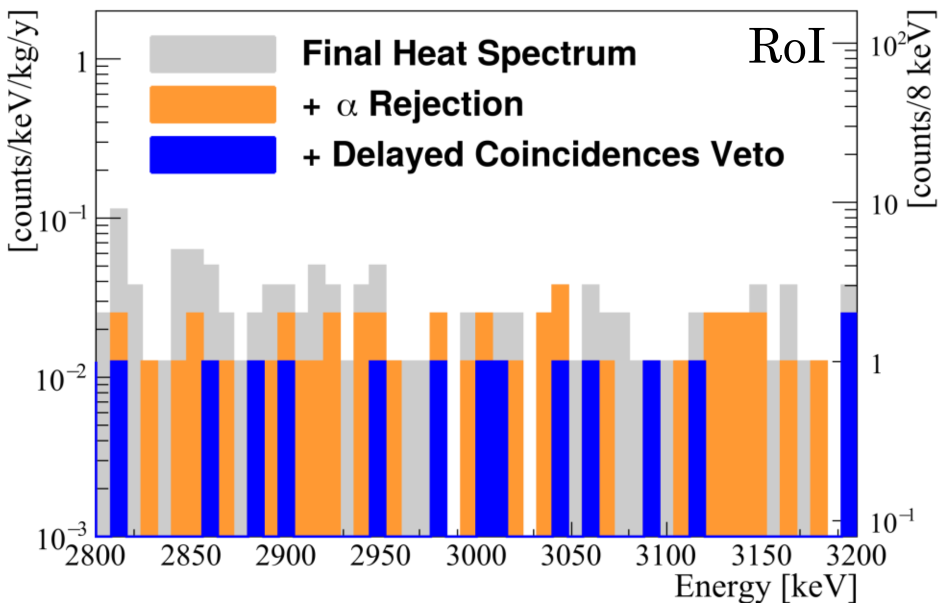
Background index in the RoI

$$\left(3.5^{+1.0}_{-0.9}\right) \cdot 10^{-3}\ \mathbf{cts/(keV \cdot kg \cdot yr)}$$

Thanks to the simultaneous heat-light readout we reached **the lowest background achieved with bolometric experiments**.

CUPID-0 Phase I: Results





No evidence of 0vDBD signal

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Best half-life limit on ^{82}Se 0vDBD

$$T^{0\nu}_{1/2} > 3.5 \cdot 10^{24}\ \text{yr (90\% C.I.)}$$

↓

$$m_{\beta\beta} < 311 - 638\ meV$$

range due to the nuclear matrix element calculations

Background model

Experimental data

divided according to multiplicity
and particle type

Background sources

identified the background sources
exploiting their distinctive signatures

evaluated the extremely low activities of
the (33) background sources

Monte Carlo Simulations

Radioactive decays generated in several
volume/surface of the CUPID-0 detector,
cryostat and shielding

The energy deposited in ZnSe crystals is
recorded in the Monte Carlo output

Reproduction of measured activity

Comprehension **Predictions**

Background model

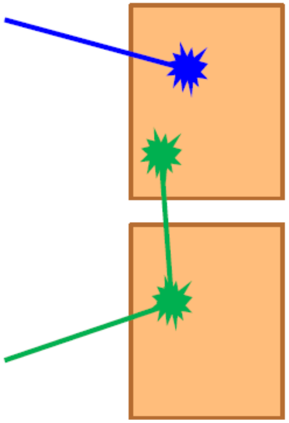
Experimental data

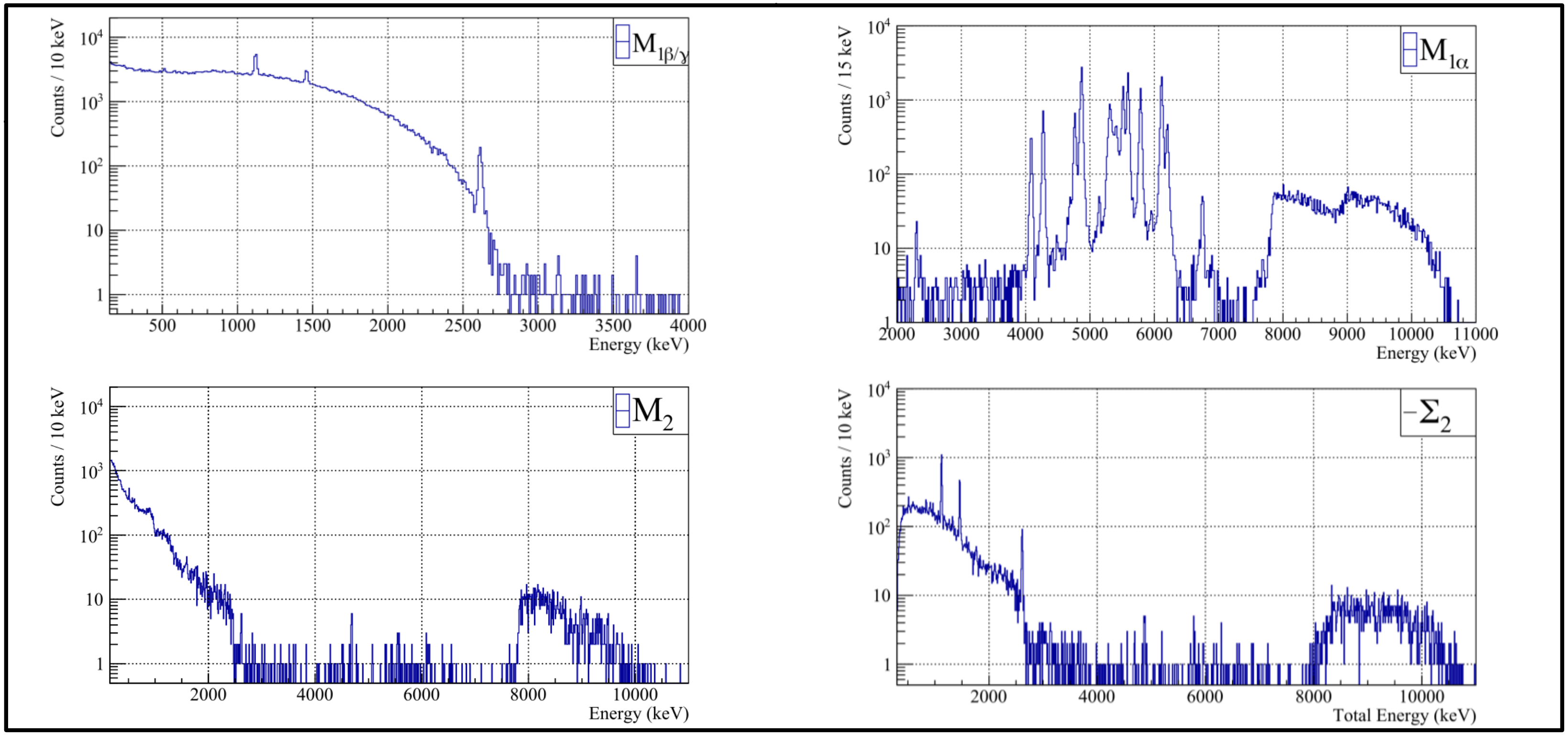
divided according to multiplicity
and particle type

Multiplicity

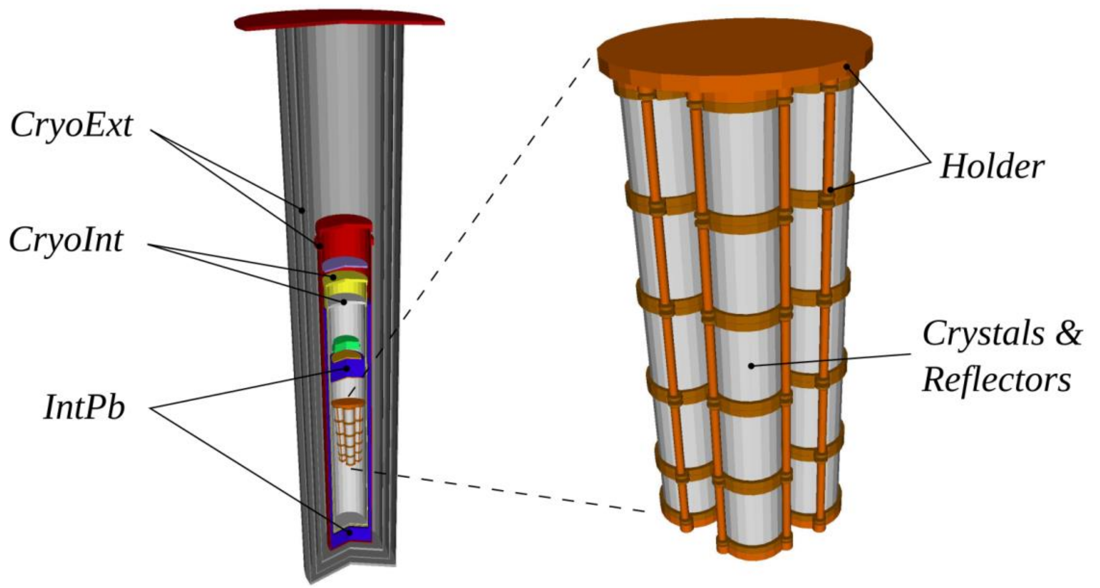
(crystals triggered in 20ms)

- M1 $\alpha\ -\beta/\gamma$
- M2 / M2 sum (Σ2)
- M>3 (to constrain μ)





Background model



Monte Carlo Simulations

Radioactive decays generated in several volume/surface of the CUPID-0 detector, cryostat and shielding

The energy deposited in ZnSe crystals is recorded in the Monte Carlo output

Radiation type

- **Natural chains**
  Father + secular equilibrium breaking points
- **Single isotopes**
  ^{40}K, ^{54}Mn, ^{65}Zn, ^{60}Co, …
- **Muons**

Background model

Sources positions

- ZnSe crystals
- Reflective foil
- Cryostat
  - Internal shields (holder + 600 mK + 50 mK)
  - Roman lead
  - External shields (IVC + OVC)
  - External lead
- Muons

Background sources

identified the background sources exploiting their distinctive signatures

evaluated the extremely low activities of the (33) background sources

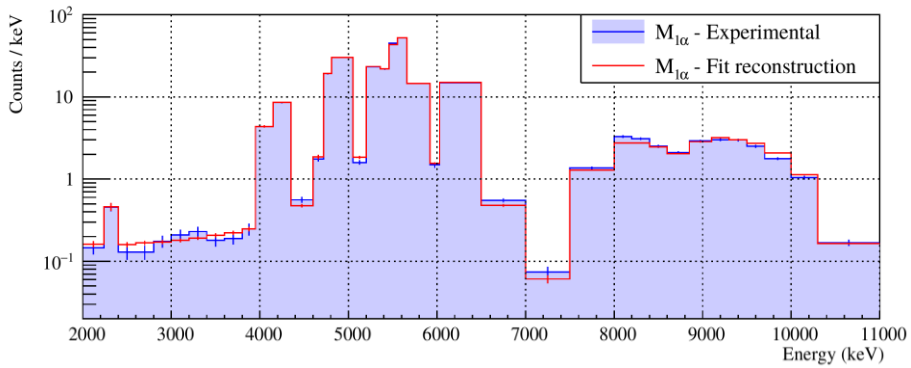
Depth of contaminations

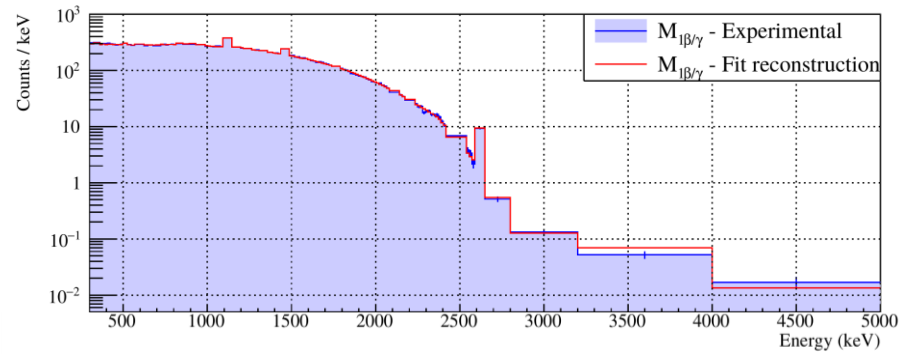
- Bulk
- Shallow surface ($\mu = 10\ nm$)
- Deep surface ($\mu = 10\ \mu m$)

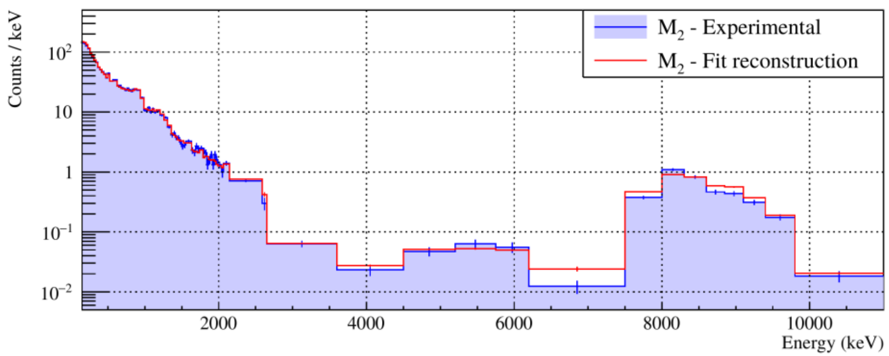
exponential profile

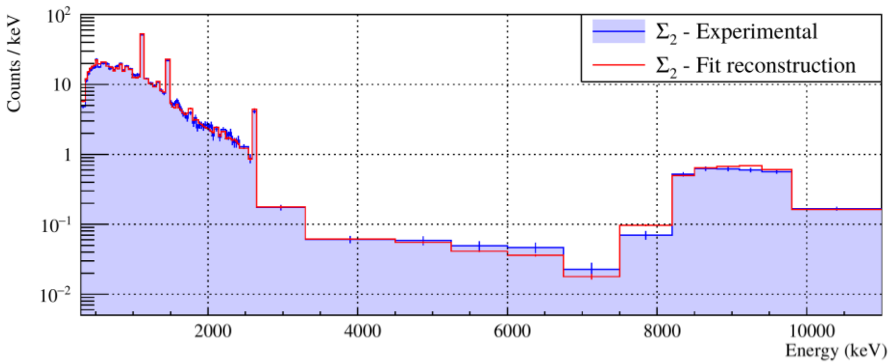
CUPID-0 Phase I: Results

Background model









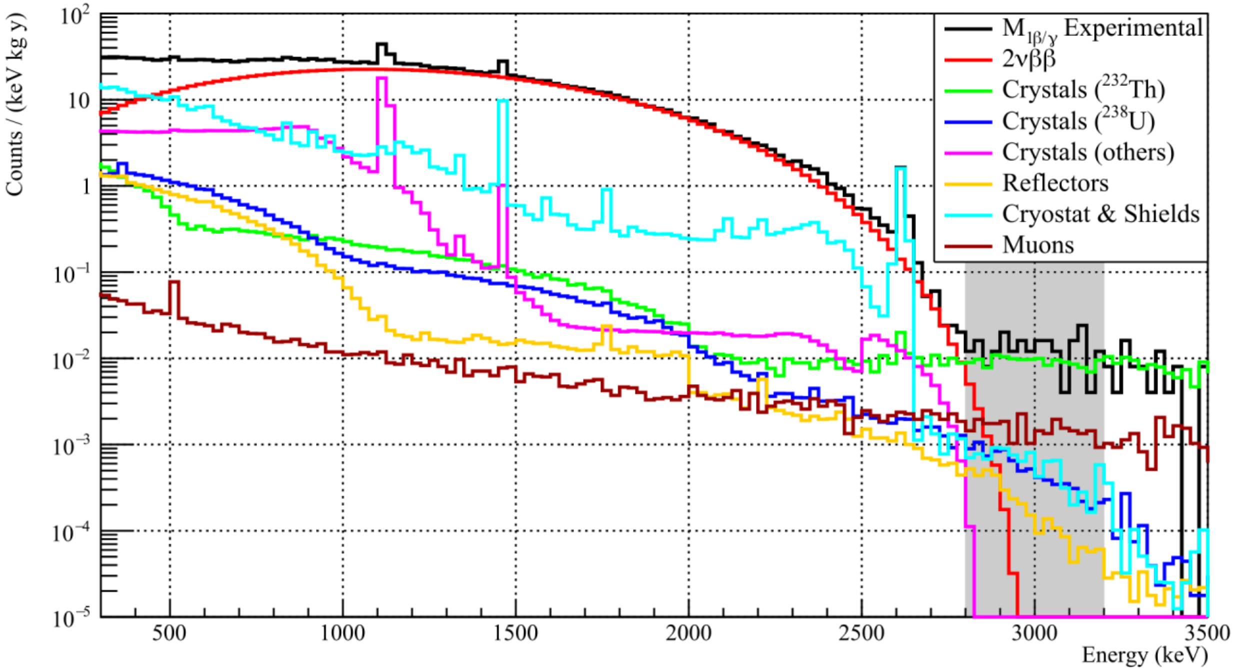
Reproduction of measured activity

Comprehension **Predictions**

CUPID-0 Phase I: Results

Background model

Background sources contributing to the M1β/γ reconstruction, grouped by source and component



2vDBD is a dominant contribution

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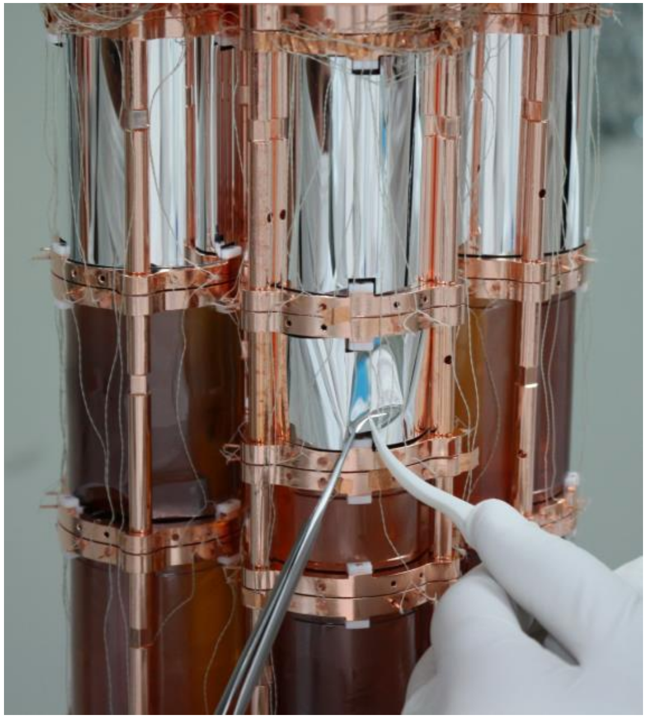
Detailed study on this decay

In the ROI:

- Time veto for the rejection of ^{208}Tl events not applied
- **Muons give 44% of residual background**
- **Reflectors** play a primary role:
  - contaminations
  - anti-coincidences

CUPID-0 Phase II: Upgrades

- The $\mu's$ are the main residual background → Installation of μ-veto
- No reflective foil → Sensitivity to M2 α events
- New cleaner Cu shield → Thermalization and additional shielding



Data taking started this week!!!!!

Conclusions

- CUPID-0 is the first large array of enriched scintillating bolometers
- CUPID-0 Phase I: June 2017 - December 2018

ZnSe exposure: **9.95 kg · y**

- Excellent background index in the region of interest

  - **lowest background** level achieved with bolometric experiments

$$(3.5^{+1.0}_{-0.9}) \cdot 10^{-3}\ \text{cts/(keV} \cdot \text{kg} \cdot \text{yr)}$$

- Acquired data allowed to establish the **best half-life limit** on ^{82}Se 0vDBD

$$T^{0\nu}_{1/2} > 3.5 \cdot 10^{24}\ yr\ (90\%\ \text{C.I.})$$

- Background model (information on background sources) and the best half-life measurement on the ^{82}Se 2vDBD
- CUPID-0 Phase II:
  - Goal: better understanding of background sources

Thank you for the attention!!!

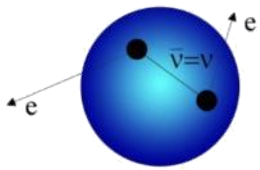
BACKUP

SLIDES

Neutrinoless Double Beta Decay (0νDBD)

0νDBD

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$



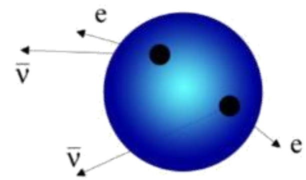
- Not allowed in Standard Model (ΔL=2)
- The decay occurs only if neutrinos are Majorana particles
- Requires neutrino is a massive particle
- The decay rate $T_{1/2}^{0\nu}$ depends on the "effective Majorana mass" $m_{\beta\beta}$

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}|M_{0\nu}|^2 m_{\beta\beta}^2$$

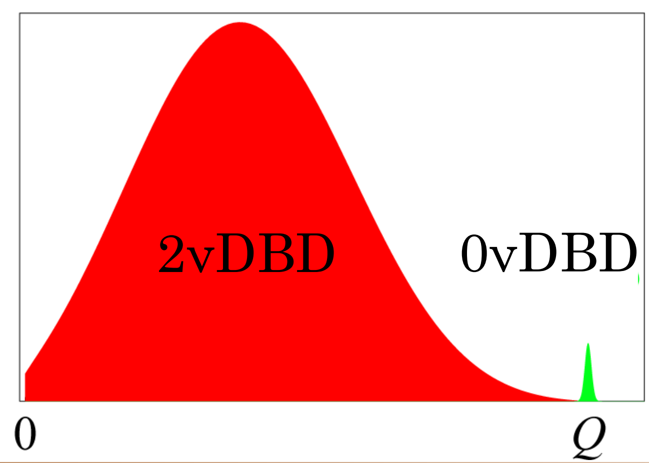
$G_{0\nu}$ - phase space factor
$M_{0\nu}$ - nuclear matrix element

2νDBD

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}$$



- Allowed in Standard Model
- Already observed for several nuclei (half-lives of the order $10^{18} - 10^{21}$ y)



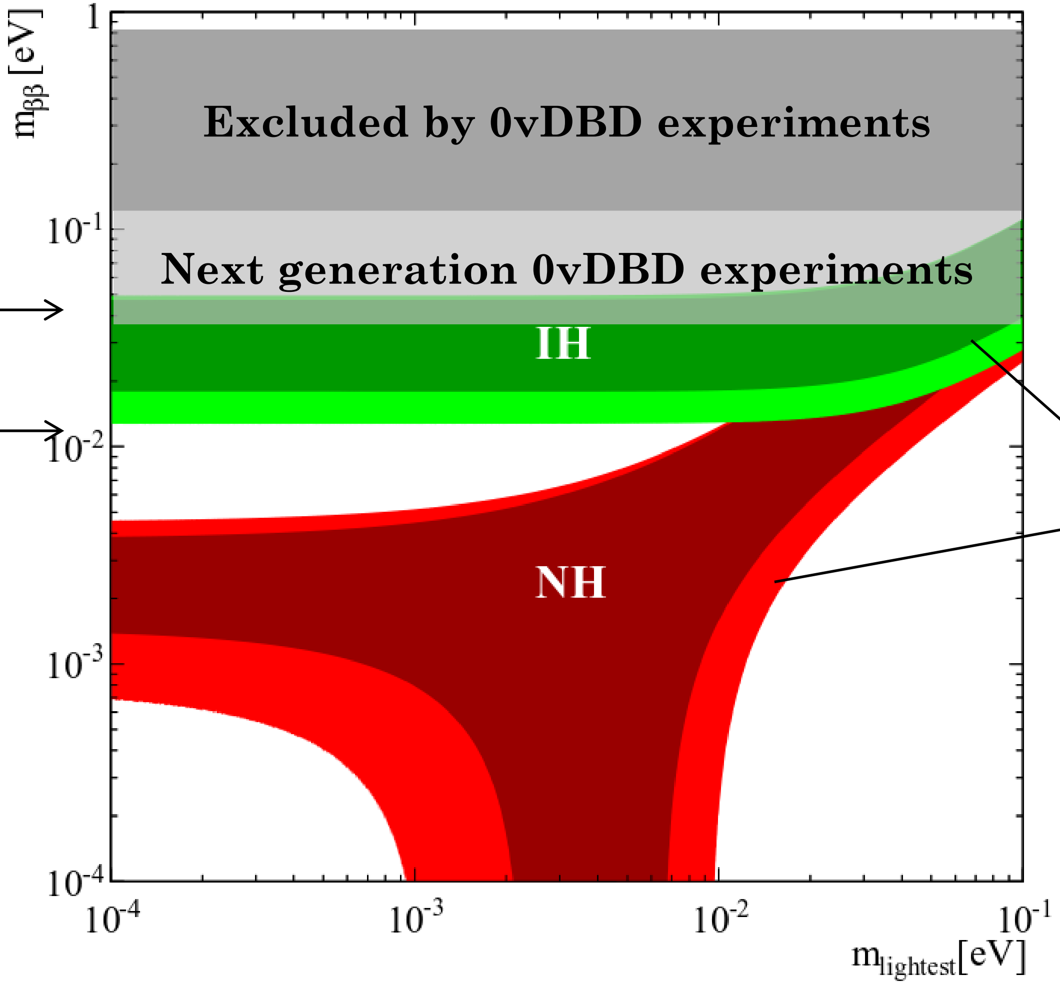
Neutrinoless Double Beta Decay (0vDBD)

- Possible for ~35 nuclei, only ~10 really interesting
- Extremely rare process ($T^{0v}_{1/2} > 10^{24}$ -10^{25} y)

$T^{0v} \sim 10^{26}$-10^{27}y

$T^{0v} \sim 10^{27}$-10^{28}y

Experiments able of measuring such low rate are a technological challenge!!!

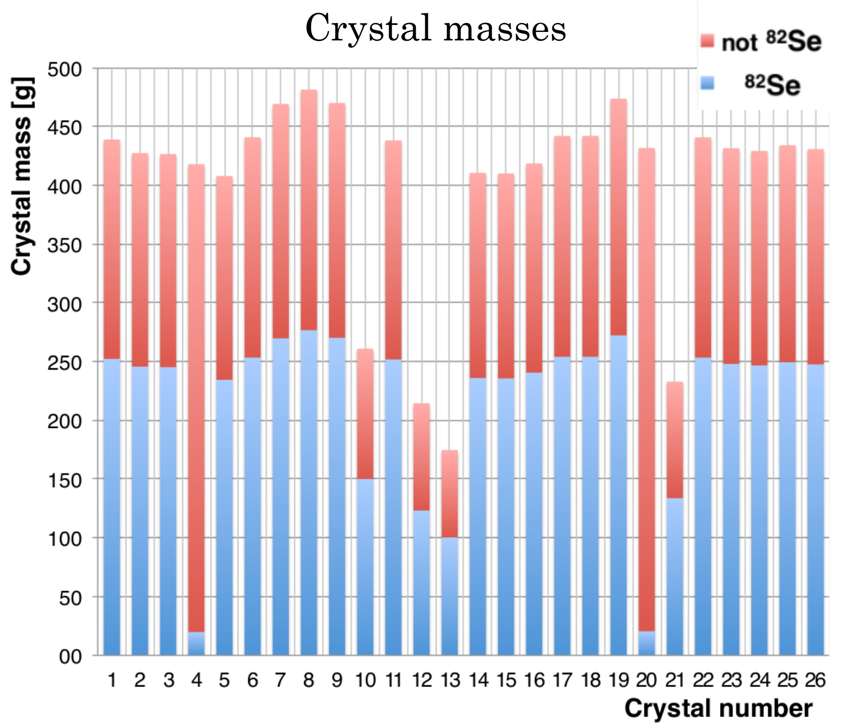


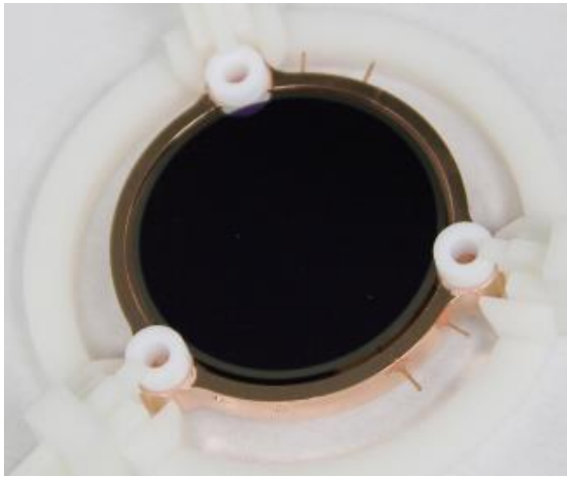
Neutrino oscillations constrains

CUPID-0 - The detector

$Zn^{82}Se$ crystals

- The enriched $Zn^{82}Se$ crystals were produced starting from highly pure raw materials
- The crystal is grown using the Bridgman technique.
- The final crystal is then shaped and optical polished





Ge light detectors

- Well established technology for bolometric LDs
  - Ge disk (44.5 x 0.17 mm) with NTD thermal sensor
  - SiO antireflecting coating on one side
- LD performance are crucial for background suppression
  - Light vs Heat: possible α leakage in β/γ ROI
  - PSA of Light: highly efficient particle-ID

Detector sensitivity for 0νDBD searches

Sensitivity: the process half-life corresponding to the maximum signal that could be observed at a given statistical C.L..

n = confidence level	T = live time [y]
$N_{\beta\beta}^{eff} = N_{\beta\beta} \cdot \varepsilon$	M = detector mass [kg]
$N_{\beta\beta}$ = isotope number	B = background [c/keV/kg/y]
ε = detector efficiency	Δ = energy resolution [keV]
$N_{\beta\beta} = \frac{N_A \cdot M \cdot x \cdot \eta}{A}$	A = atomic mass
	x = isotopic ab.
	$\eta = N_{\beta\beta}$ per molecule

$$\boldsymbol{S = ln2 \cdot N_{\beta\beta}^{eff} \cdot \frac{T}{N}}$$

'Zero' background experiments

$$M \cdot T \cdot B \cdot \Delta \approx 0$$

$$\downarrow$$

$$n = 2.8 \ (68\% \ \text{C.L.})$$

$$\boxed{S_{0B} = \ln 2 \cdot N_{\beta\beta}^{eff} \cdot \frac{T}{2.8} \propto M \cdot T}$$

Experiments with background

$$M \cdot T \cdot B \cdot \Delta >> 0$$

$$\downarrow$$

$$n = \sqrt{M \cdot T \cdot B \cdot \Delta} \ (68\% \ \text{C.L.})$$

Assumption: B∝M

$$\boxed{S_B = \ln 2 \cdot N_{\beta\beta}^{eff} \cdot \sqrt{\frac{T}{M \cdot B \cdot \Delta}} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta}}}$$

Critical experimental parameters: M, T, B, Δ

Neutrino mass

$$T_{1/2}^{0\nu} > 3.5 \cdot 10^{24} \text{ yr (90\% C.I.)}$$

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}|M_{0\nu}|^2 m_{\beta\beta}^2$$

$$m_{\beta\beta} < 311 - 678\, meV$$

$G_{0\nu}$ - Phase space factor

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012).
S. Stoica and M. Mirea, Phys. Rev. C 88, 037303 (2013).

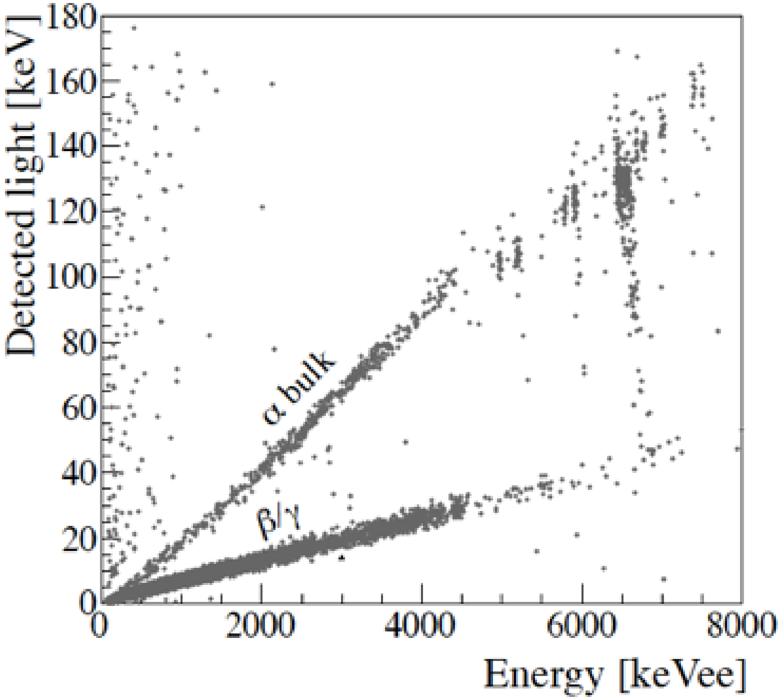
$M_{0\nu}$ - Nuclear matrix element

J. Engel and J. Menendez, Rept. Prog. Phys. 80, 046301 (2017)
J. M. Yao, L. S. Song, K. Hagino, P. Ring, and J. Meng, Phys. Rev. C 91, 024316 (2015)
J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A 818, 139 (2009)
F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C 87, 045501 (2013)
T. R. Rodriguez and G. Martinez-Pinedo, Phys. Rev. Lett. 105, 252503 (2010)
A. Meroni, S. T. Petcov, and F. Simkovic, JHEP 02, 025 (2013)

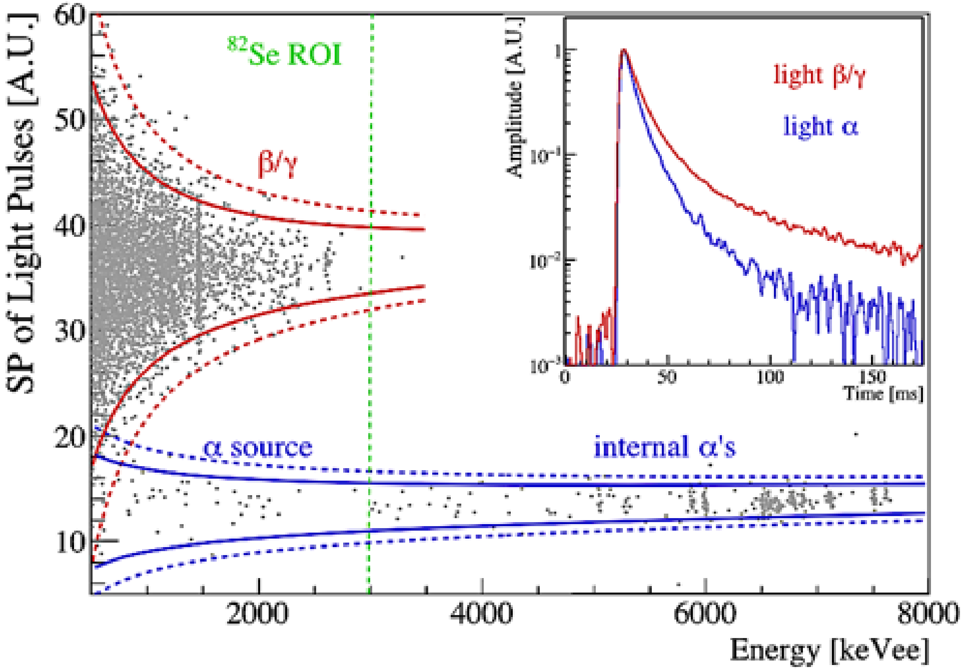
$g_a = 1.269$ – Axial coupling constant

Particle Identification

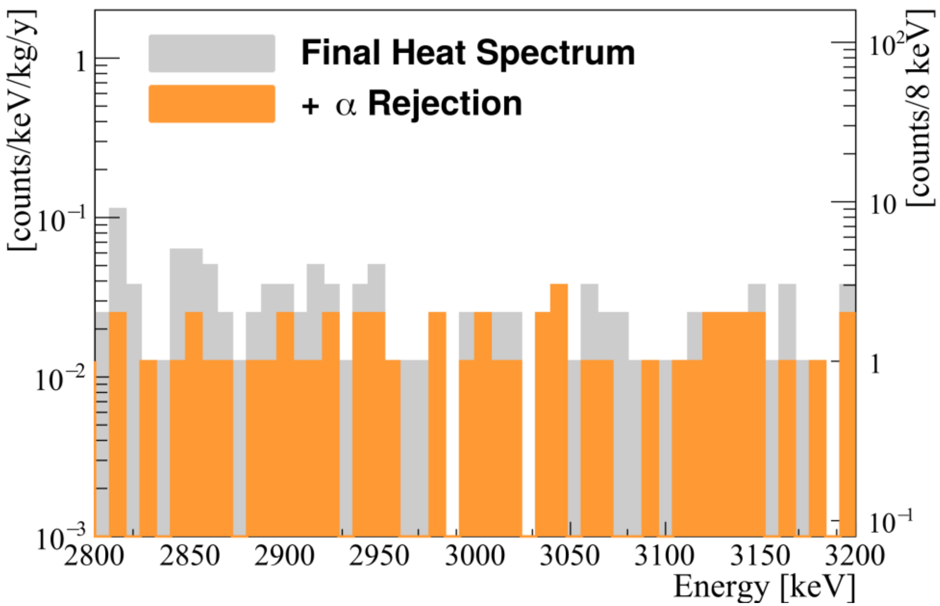
ZnSe Light Yield



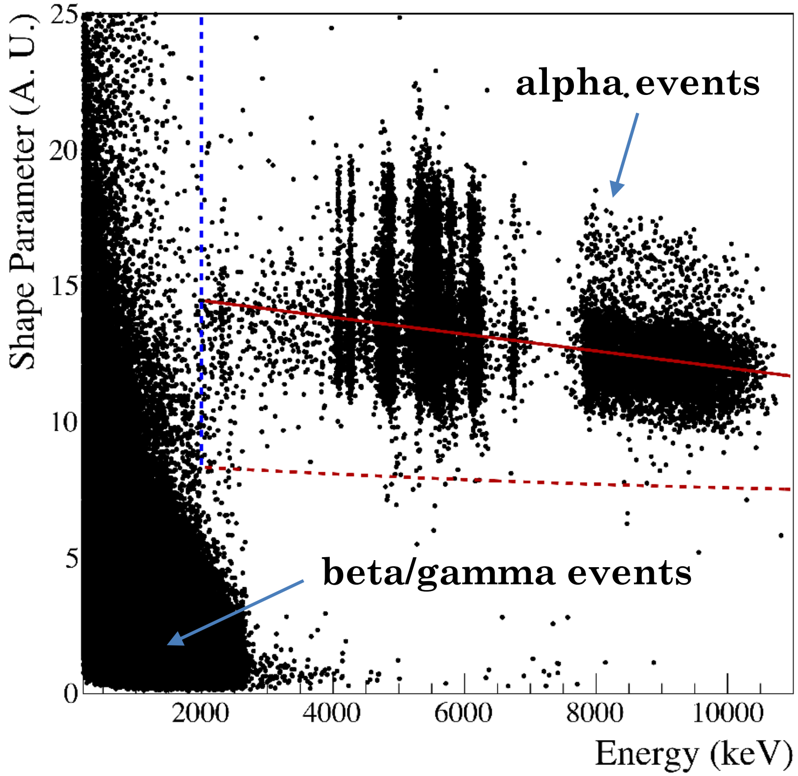
Pulse shape



Particle Identification

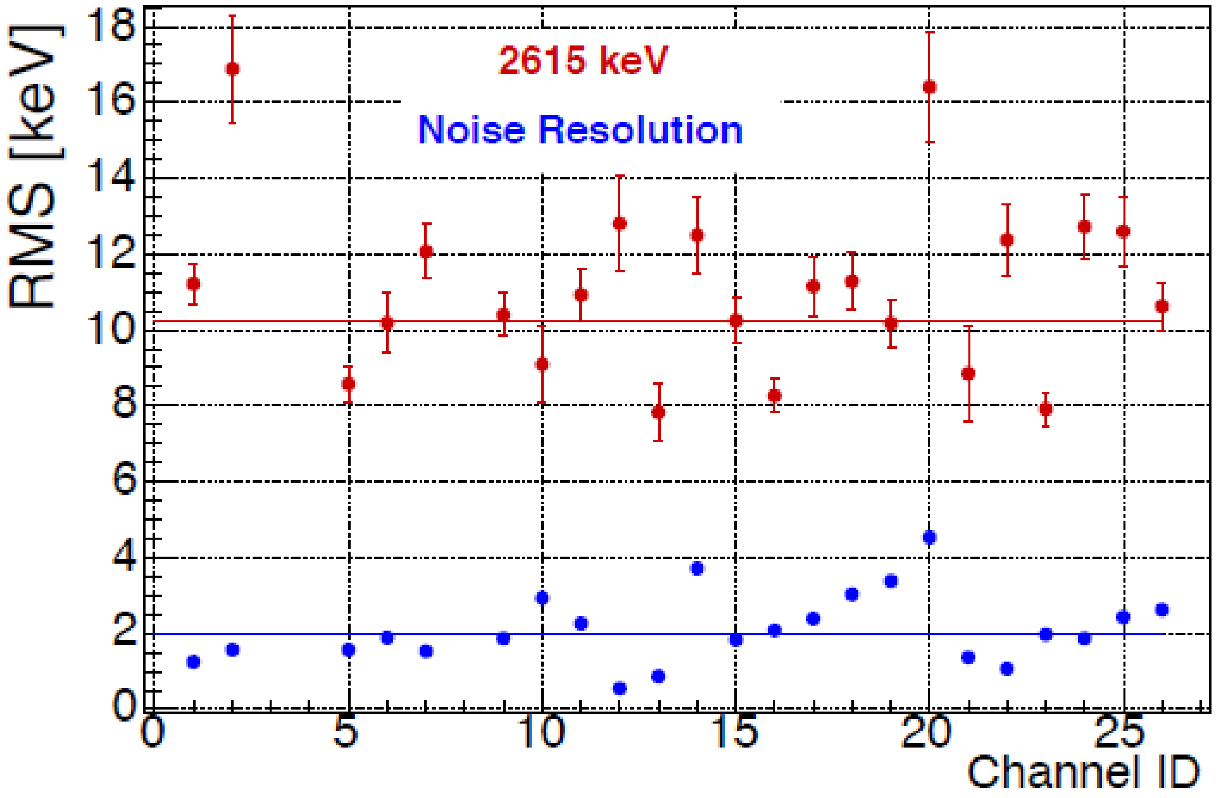


Alpha rejection with light-shape variable

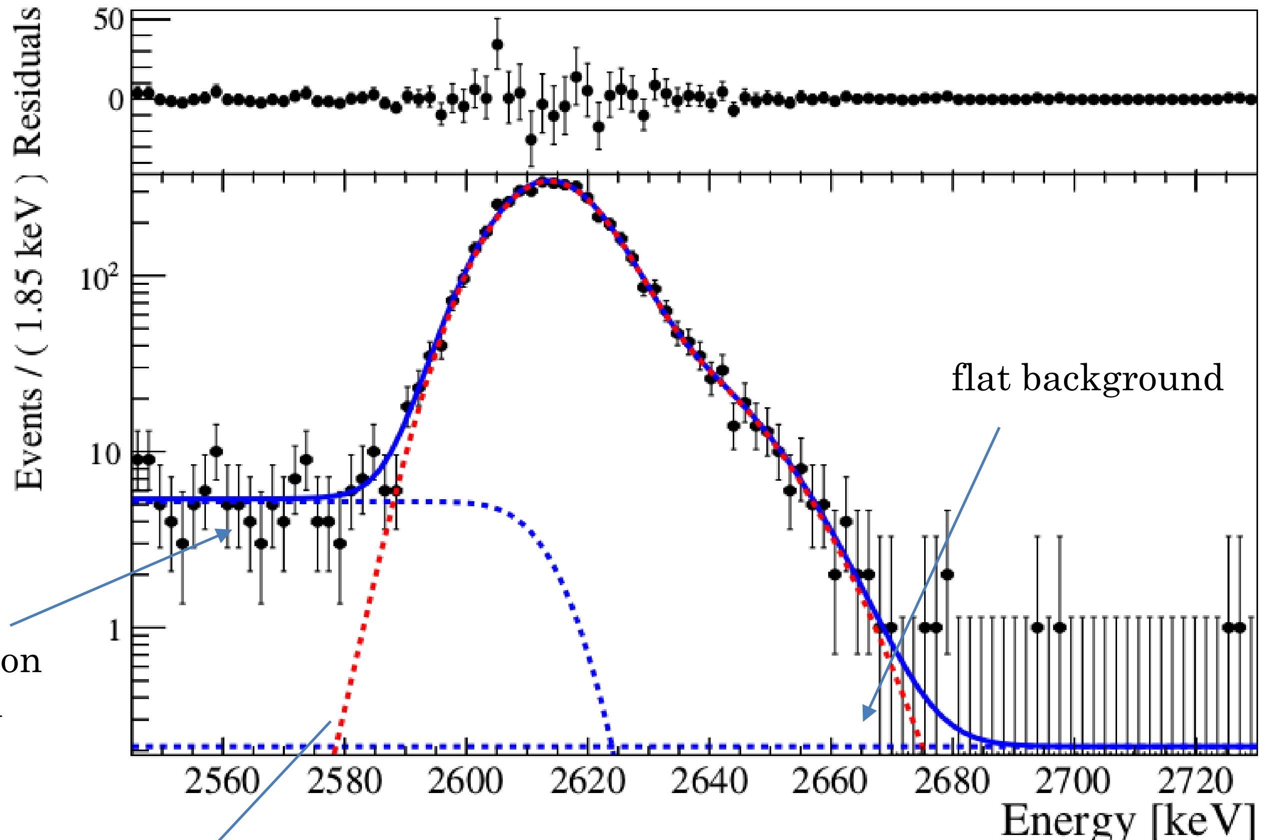


- mean value of α particle SP ($\mu_\alpha(E)$)
- acceptance threshold = $\mu_\alpha(E) - 3 \cdot \sigma_\alpha(E)$
- energy below which the PID is not applied

Detector performances



Detector response function - Energy resolution



Double gaussian

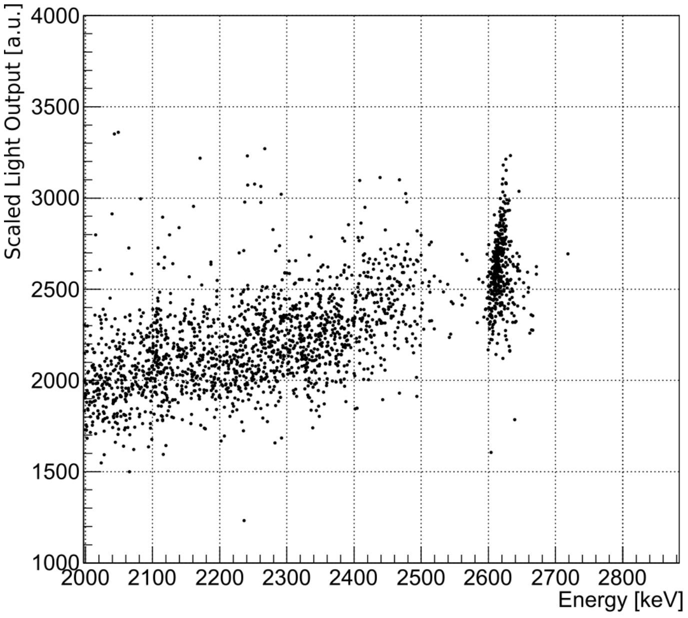
- The simplest model which well reproduces the detector response function over the entire spectrum
- Deviations from the single gaussian model already observed in other bolometric experiments

FWHM at 2615 keV

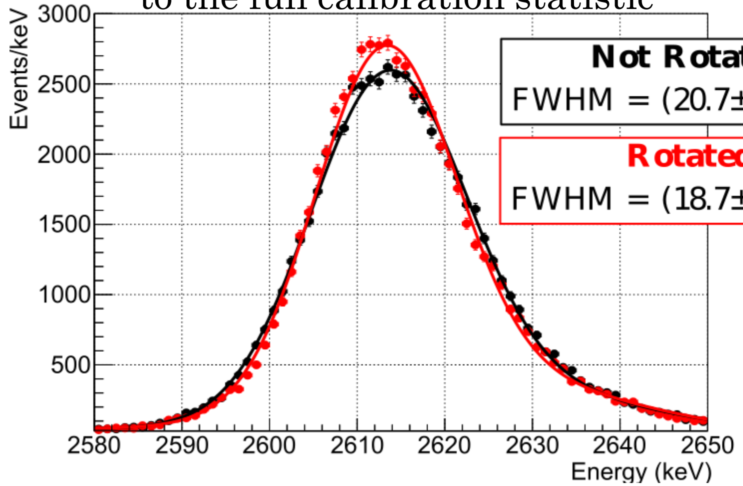
$\mathbf{(20.7 \pm 0.5)}\ \boldsymbol{keV}$

Detector response function - Energy resolution

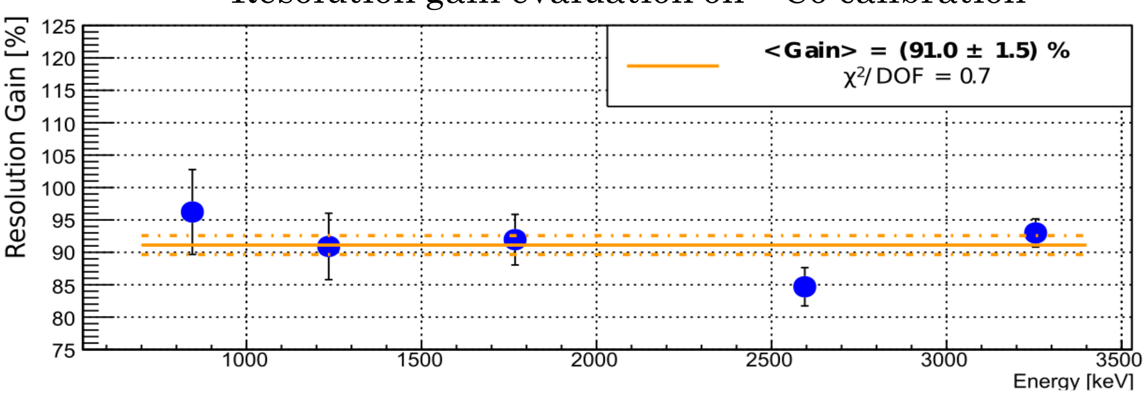
The heat-light **correlation** has been exploited to improve the energy resolution



Application of the rotation method to the full calibration statistic

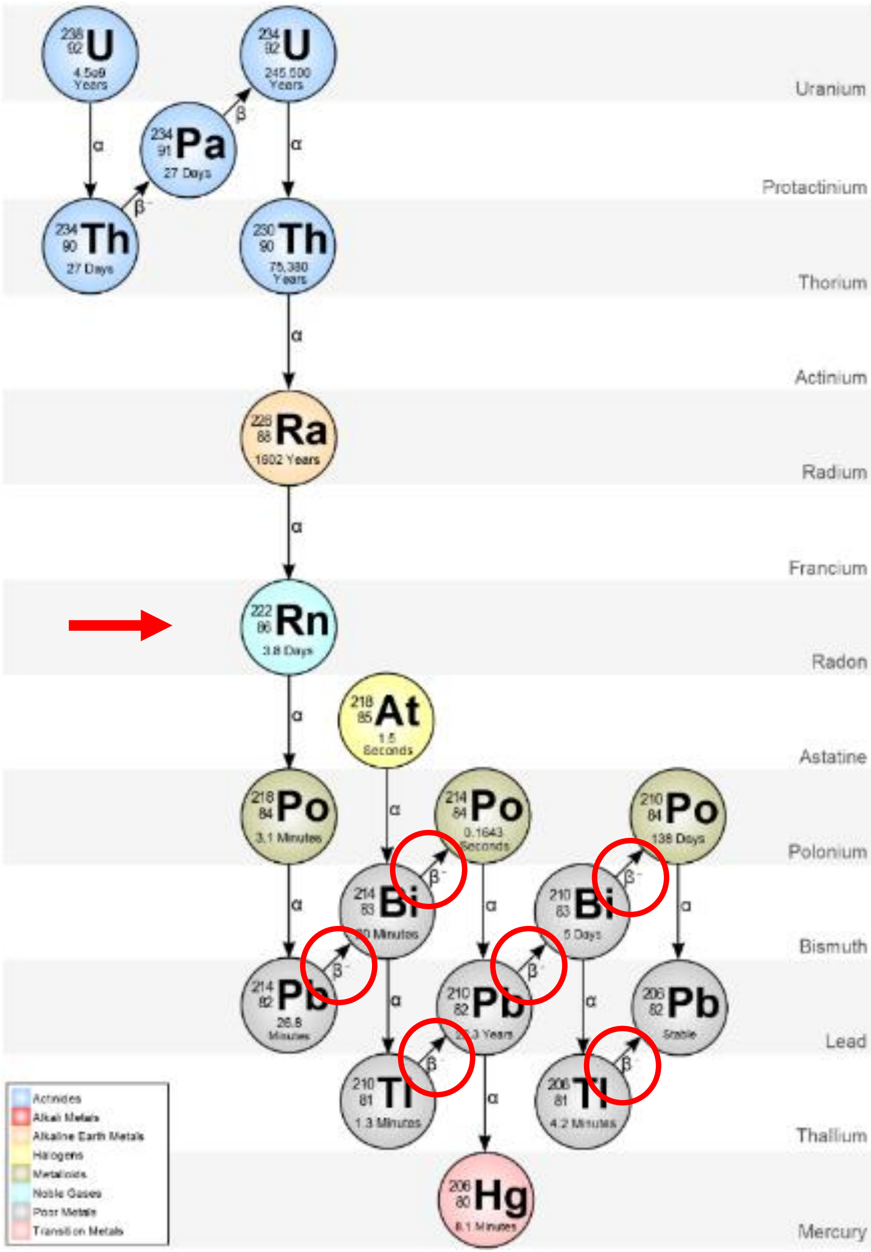


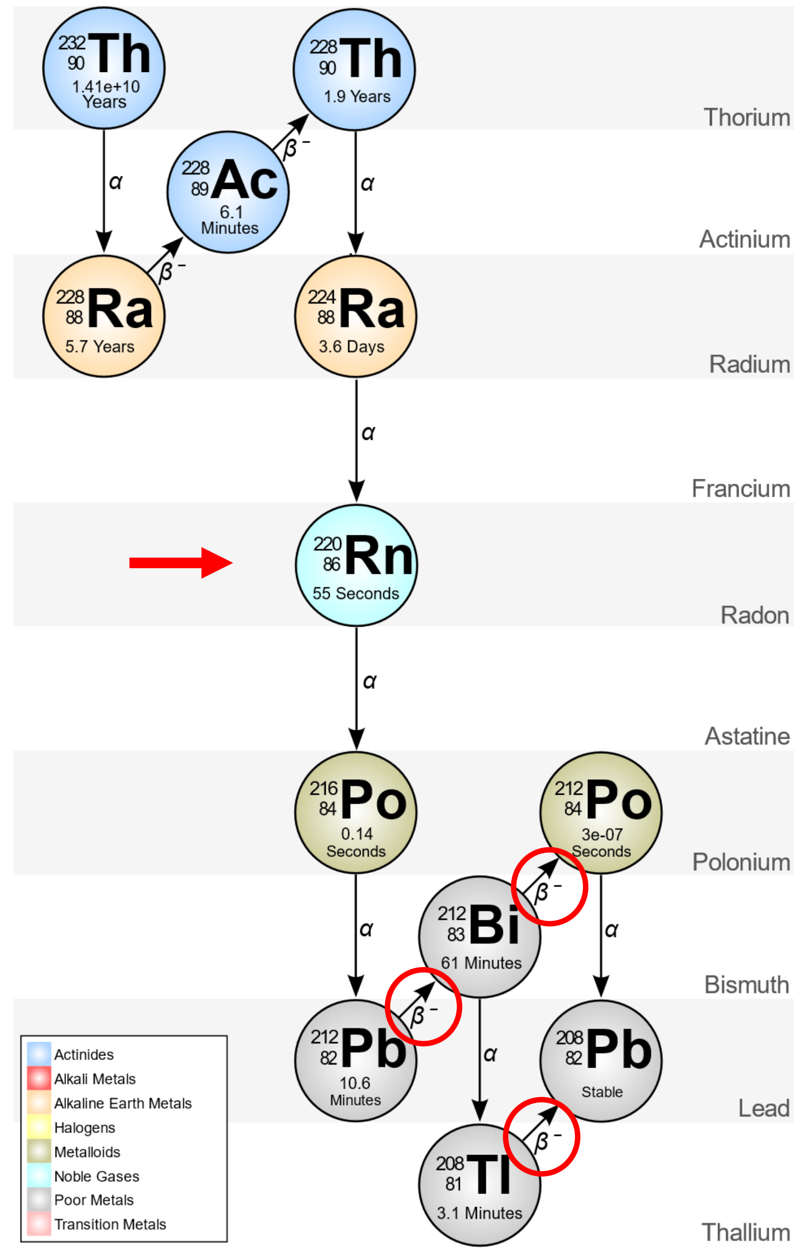
Resolution gain evaluation on ^{56}Co calibration



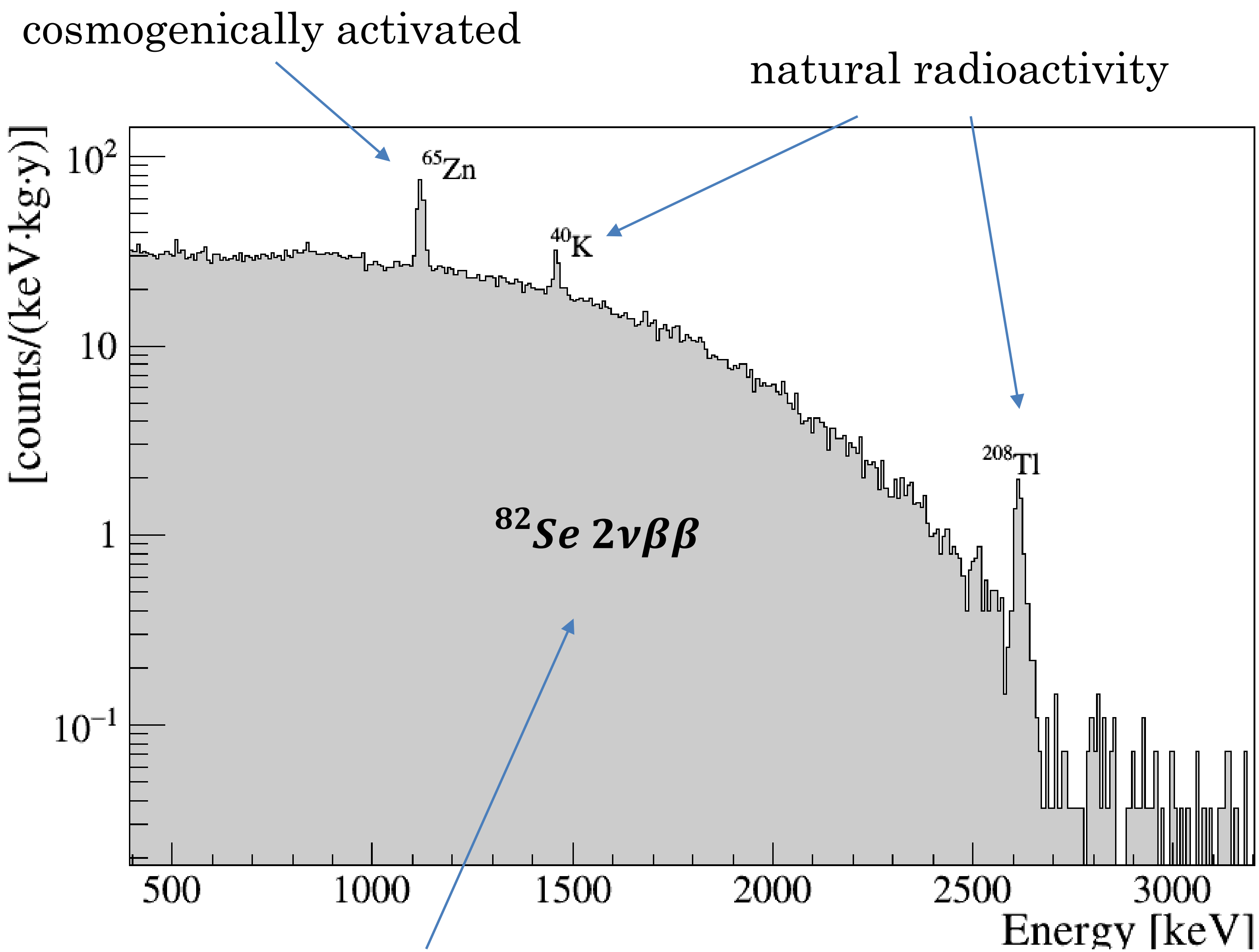
$$\frac{FWHM(\theta_{min})}{FWHM(\theta=0)} \cdot 100$$

Rn contaminations





Background energy spectrum components



continuous spectrum generated by the 2vDBD decay of ^{82}Se

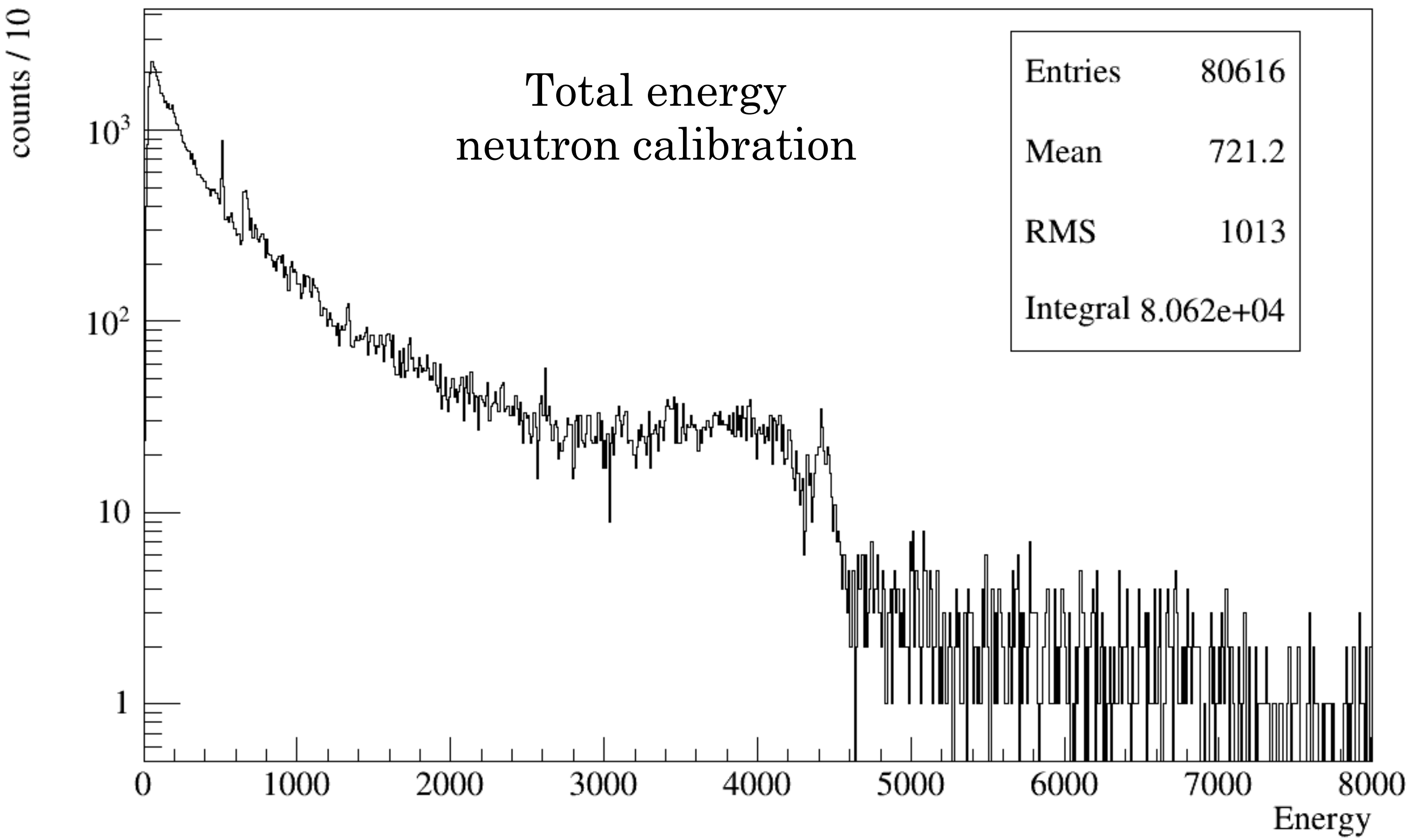
$$T_{1/2}^{2\nu} = (9.2 \pm 0.7) \cdot 10^{19}\ \text{yr}$$

Background sources

Component	Mass (kg)	Source	Index	Activity (Bq/kg)
Crystals	10.5	$2\nu\beta\beta$	1	$(9.96 \pm 0.03) \times 10^{-4}$
		^{65}Zn	2	$(3.52 \pm 0.06) \times 10^{-4}$
		^{40}K	3	$(8.5 \pm 0.4) \times 10^{-5}$
		^{60}Co	4	$(1.4 \pm 0.3) \times 10^{-5}$
		^{147}Sm	5	$(1.6 \pm 0.3) \times 10^{-7}$
		^{238}U–^{226}Ra	6	$(5.51 \pm 0.10) \times 10^{-6}$
		^{226}Ra–^{210}Pb	7	$(1.54 \pm 0.02) \times 10^{-5}$
		^{210}Pb–^{206}Pb	8	$(7.05 \pm 0.16) \times 10^{-6}$
		^{232}Th–^{228}Ra	9	$(2.74 \pm 0.10) \times 10^{-6}$
		^{228}Ra–^{208}Pb	10	$(1.20 \pm 0.03) \times 10^{-5}$
		^{235}U–^{231}Pa	11	$(5.3 \pm 0.7) \times 10^{-7}$
		^{231}Pa–^{207}Pb	12	$(7.8 \pm 0.4) \times 10^{-7}$
Holder	3.10	^{54}Mn	13	$(2.2 \pm 0.3) \times 10^{-4}$
CryoInt (^{a})	36.9	^{232}Th	14	$< 4.5 \times 10^{-5}$
		^{238}U	15	$(7 \pm 3) \times 10^{-5}$
		^{40}K	16	$(3.0 \pm 0.6) \times 10^{-3}$
		^{60}Co	17	$(6.8 \pm 1.3) \times 10^{-5}$
IntPb	202	^{232}Th	18	$< 6.3 \times 10^{-5}$
		^{238}U	19	$< 7.3 \times 10^{-5}$
CryoExt	832	^{60}Co	20	$(2.6 \pm 0.9) \times 10^{-5}$
ExtPb (^{b})	24694	^{232}Th	21	$(4.3 \pm 0.6) \times 10^{-4}$
		^{238}U	22	$(2.5 \pm 1.2) \times 10^{-4}$
		^{40}K	23	$(2.8 \pm 0.8) \times 10^{-3}$
		^{210}Pb	24	7.8 ± 0.3
Component	Surface (cm^2)	Source	Index	Activity (Bq/cm^2)
Crystals	2574	^{226}Ra–^{210}Pb–0.01μm	25	$(2.63 \pm 0.15) \times 10^{-8}$
		^{228}Ra–^{208}Pb–0.01μm	26	$(6.5 \pm 1.1) \times 10^{-9}$
		^{226}Ra–^{210}Pb–10μm	27	$< 2.3 \times 10^{-9}$
		^{228}Ra–^{208}Pb–10μm	28	$(4.2 \pm 1.6) \times 10^{-9}$
Reflectors (^{c})	2100	^{232}Th–10μm	29	$< 7.3 \times 10^{-10}$
		^{226}Ra–^{210}Pb–10μm	30	$(8.7 \pm 1.3) \times 10^{-9}$
		^{210}Pb–^{206}Pb–10μm	31	$(1.0 \pm 0.5) \times 10^{-8}$
		^{210}Pb–^{206}Pb–0.01μm	32	$(1.43 \pm 0.02) \times 10^{-7}$
Muons	Flux in units of $\mu/(\text{cm}^2\text{s})$		33	$(3.7 \pm 0.2) \times 10^{-8}$

Neutrons calibration

We used neutrons in order to have gamma events also in the 3-4 MeV energy region



Crystals radiopuruty

Table 1: Internal radioactive contamination for 2.5 kg of 96.3% enriched ^{82}Se metal beads and for 2.5 kg of ^{nat}Zn. Limits are computed at 90% C.L.. The measurements were carried out on October 2014.

Chain	Nuclide	^{82}Se Activity [μBq/kg]	^{nat}Zn Activity [μBq/kg]
^{232}Th			
	^{228}Ra	< 61	< 95
	^{228}Th	< 110	< 36
^{238}U			
	^{226}Ra	< 110	< 66
	^{234}Th	< 6200	< 6200
	^{234m}Pa	< 3400	< 4700
^{235}U	^{235}U	< 74	< 91
	^{40}K	< 990	< 380
	^{60}Co	< 65	< 36
	^{56}Co	–	80 ± 20
	^{65}Zn	–	5200 ± 600