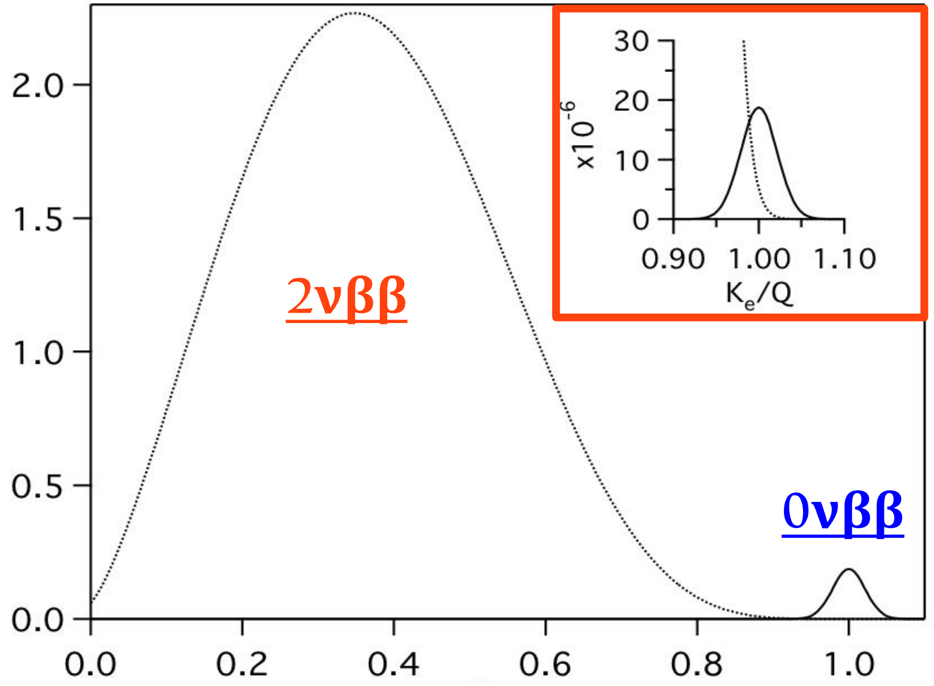
Final results of the CUPID-0 Phase I experiment

Mattia Beretta

On behalf of the CUPID-0 collaboration

The first enriched scintillating bolometer ββ experiment



Sum of two e⁻ energy

2νββ

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

0νββ:

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

^{82}Se

$Q_{\beta\beta}$ = (2997±0.3) keV

Performing resolution
At the Q value

Low Background
Few counts expected

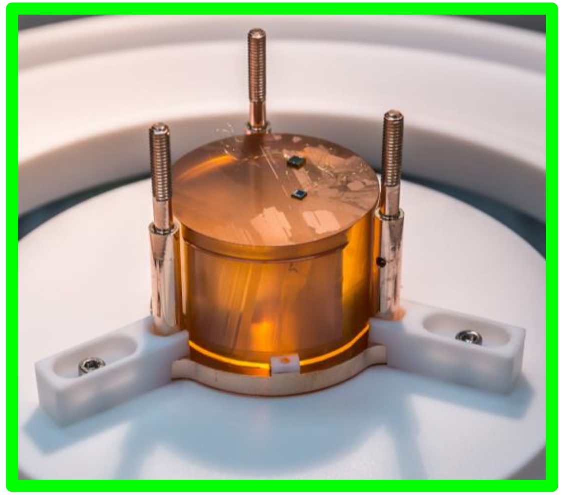
CUPID-0 Detector

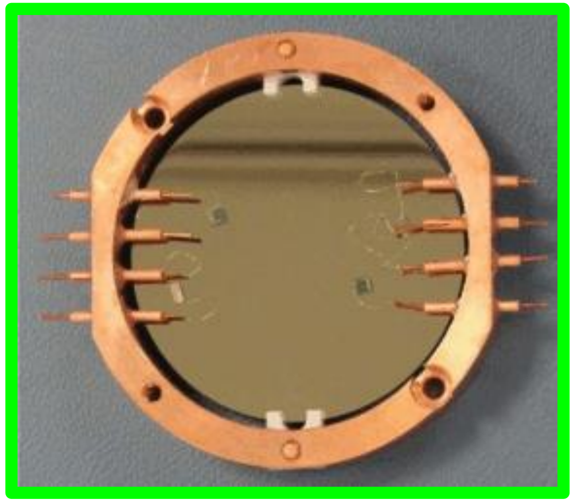
Scintillating $Zn^{82}Se$ crystals.

Bolometric Ge Light detectors

Heat signal:

bolometric high resolved output

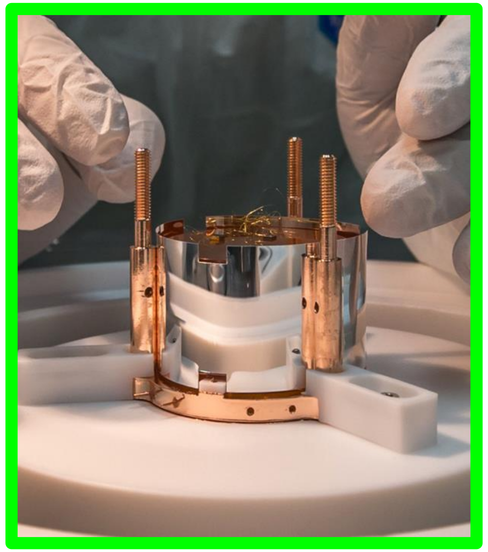




Light signal:

particle identification

- **26 ZnSe crystals**
  - 24 enriched in ^{82}Se (95%) + 2 naturals
- **Total mass= 10.5 kg**
  - ^{82}Se mass =5.17 kg ($3.8 \cdot 10^{25}$ ββ emitters)



Vikuiti Reflector

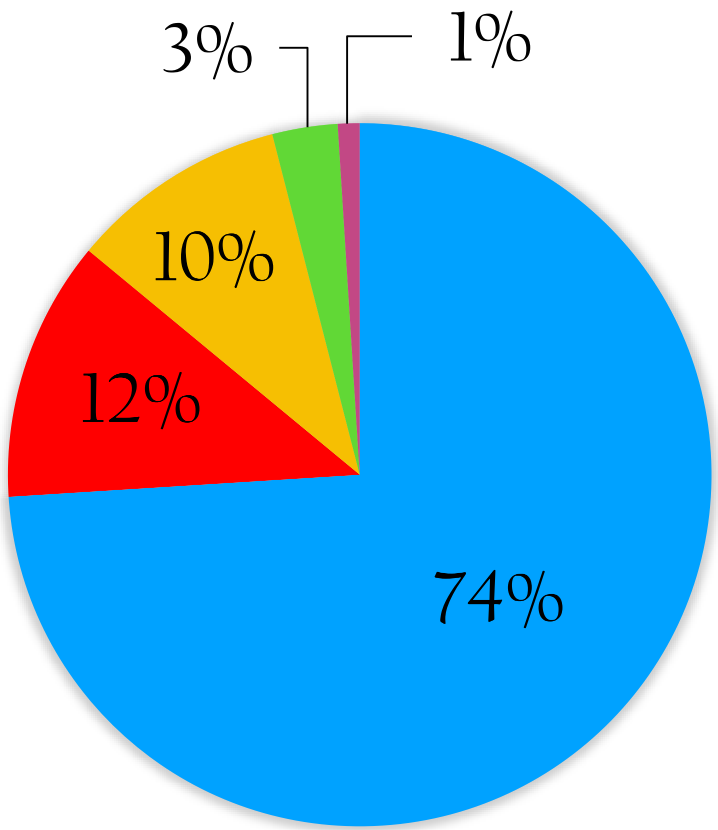
More collected light

NOSV Copper

Surface cleaned

CUPID-0 Time-line

2017	June 2017 – December 2018	2019
Commissioning	**Phase I** 560 d with 74% of livetime	Preparation of Phase II



^{56}Co Energy Calibration

^{232}Th Energy Calibration

System manteinance

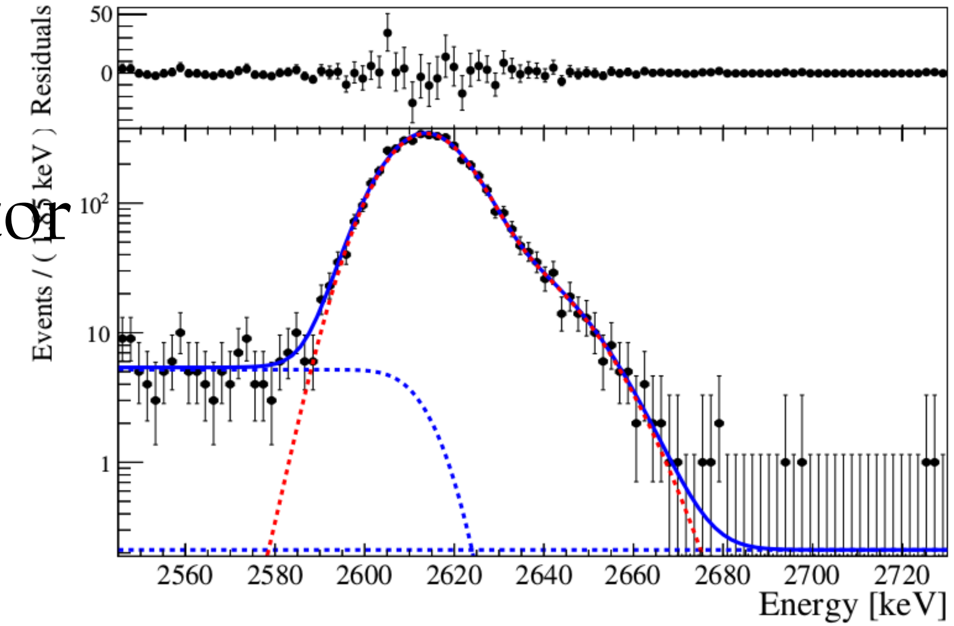
AmBe source
βγ Shape Characterization in the ROI

ββ physics
Exposure: 9.95 kg·y

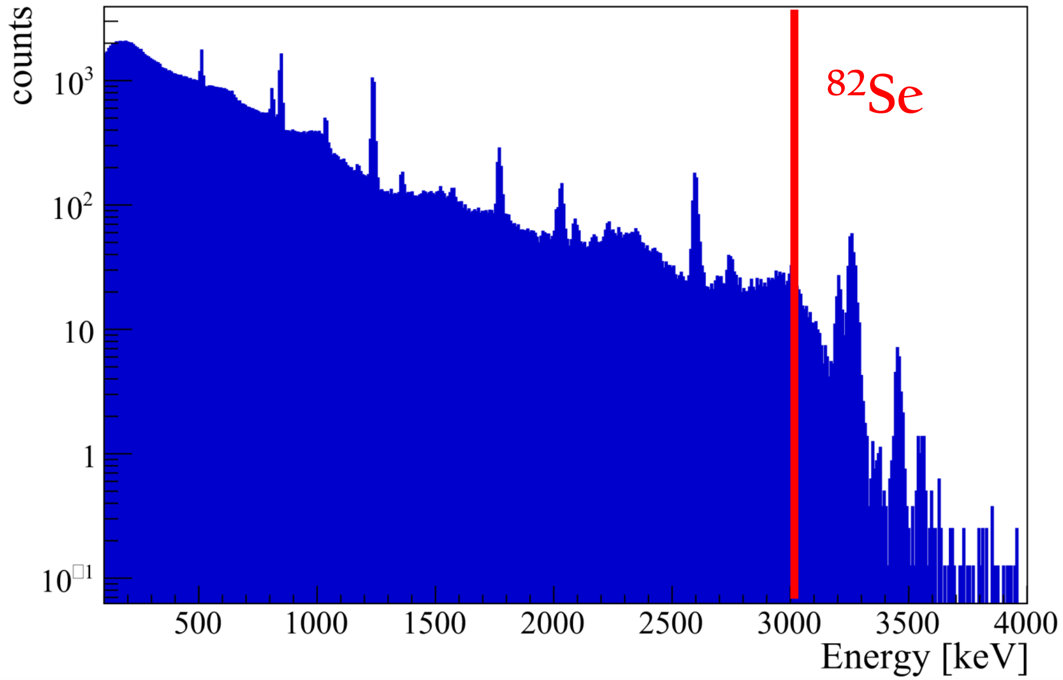
Calibrations

^{232}Th Energy Calibration

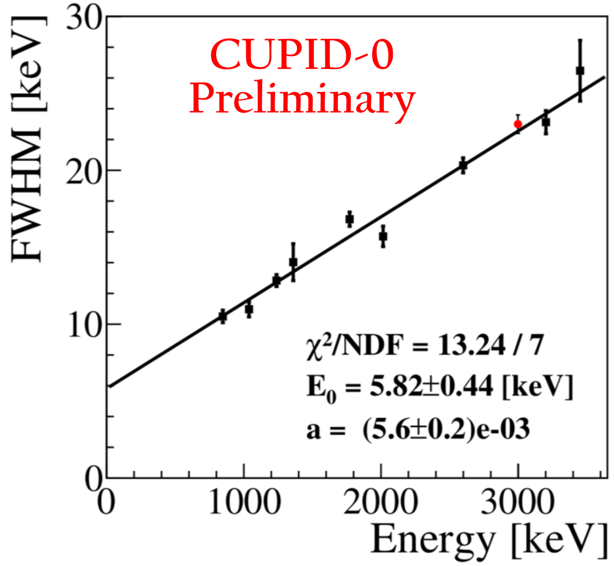
- Periodic Bolometer calibration and light detector intercalibration
- Response function: Double Gaussian
  - Also observed in other bolometers



^{56}Co Energy Calibration



- Check of the energy reconstruction
- Evaluation of FWHM energy resolution @ ^{82}Se Q

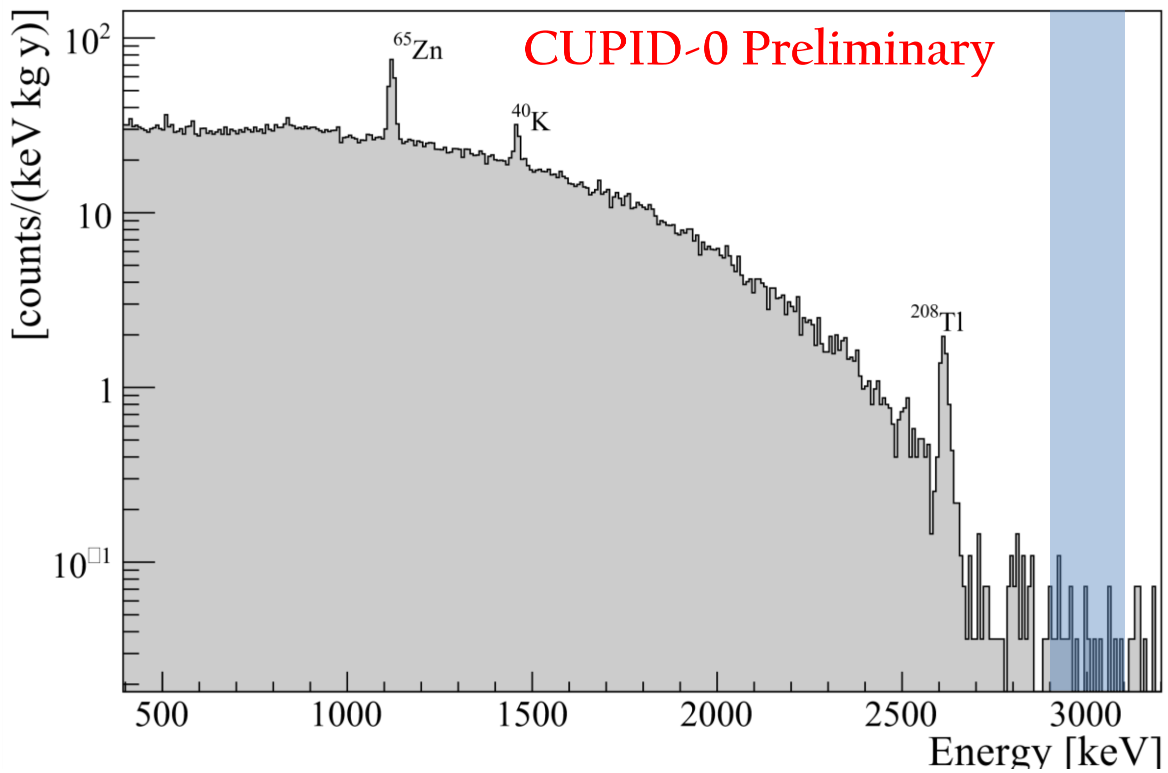


FWHM @ $Q_{\beta\beta}$

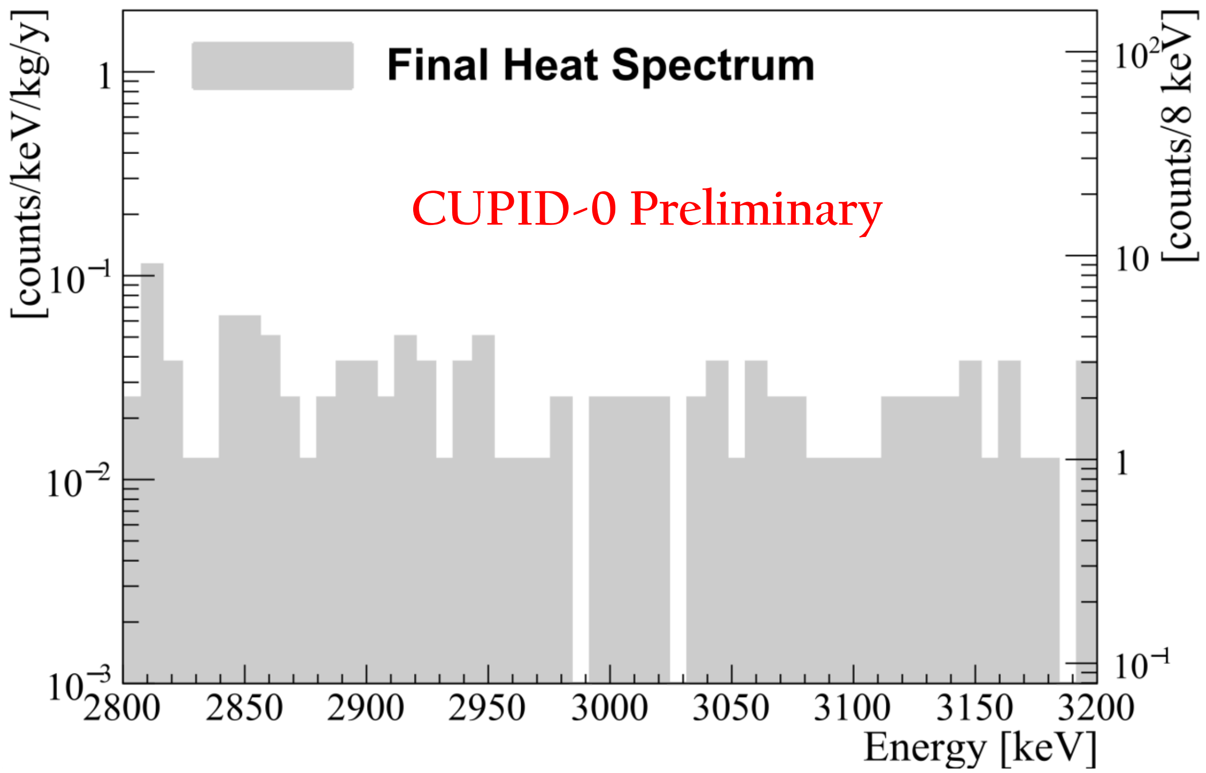
(20.0±0.6) keV

0νββ search

Total Background spectrum



0νββ ROI



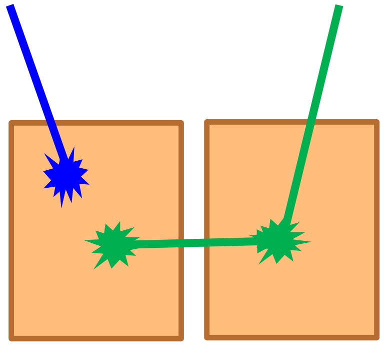
$$\mathrm{BKG} = (3.2 \pm 0.4) \cdot 10^{-2}\ \mathrm{cnts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{y})$$

Basic Selections

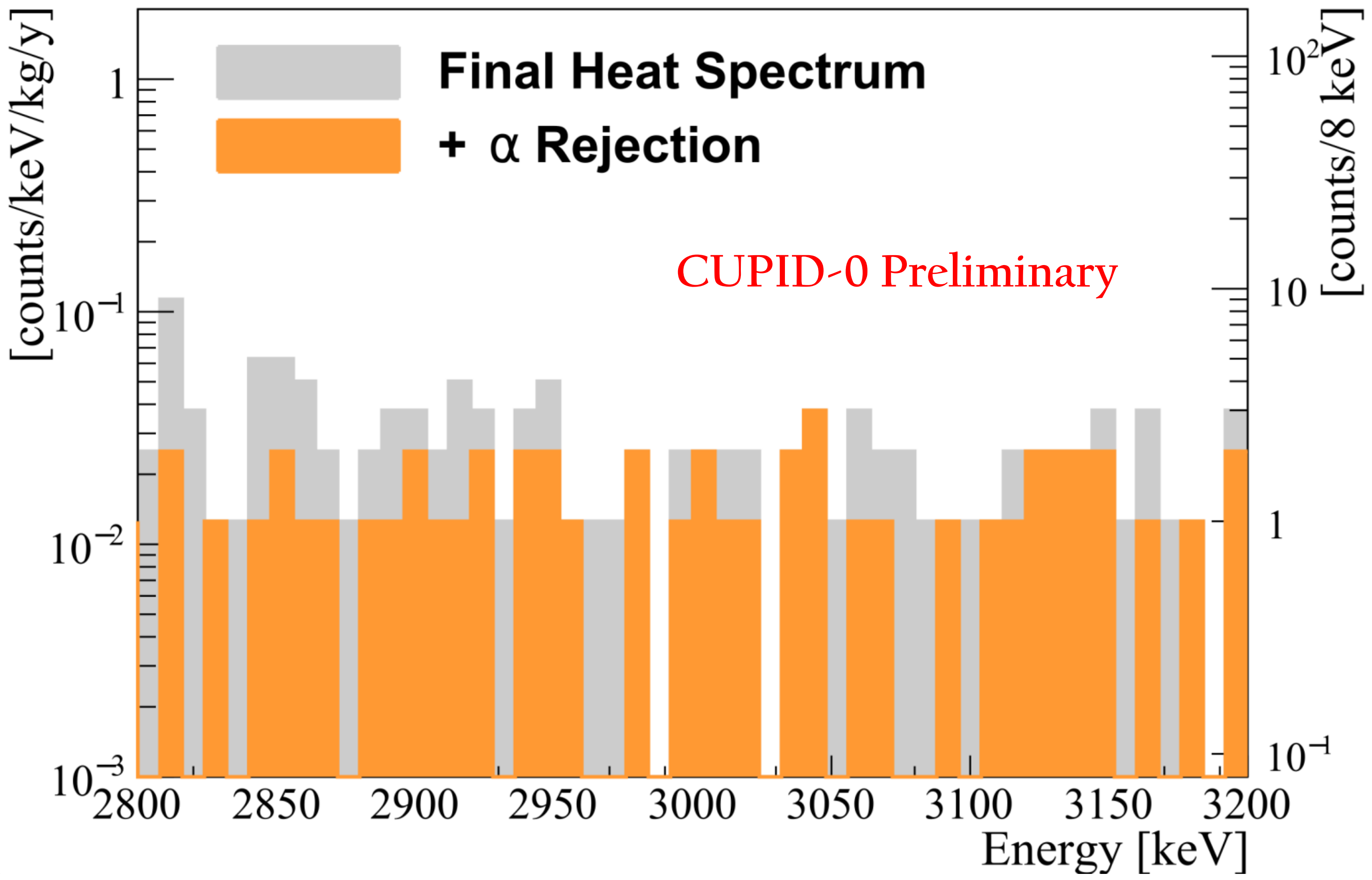
Rejection of “non-particle-like” events through pulse shape on thermal pulses

Multiplicity (M)

Anti-coincidence between crystals (ΔT=20ms)



Background – Alpha Rejection

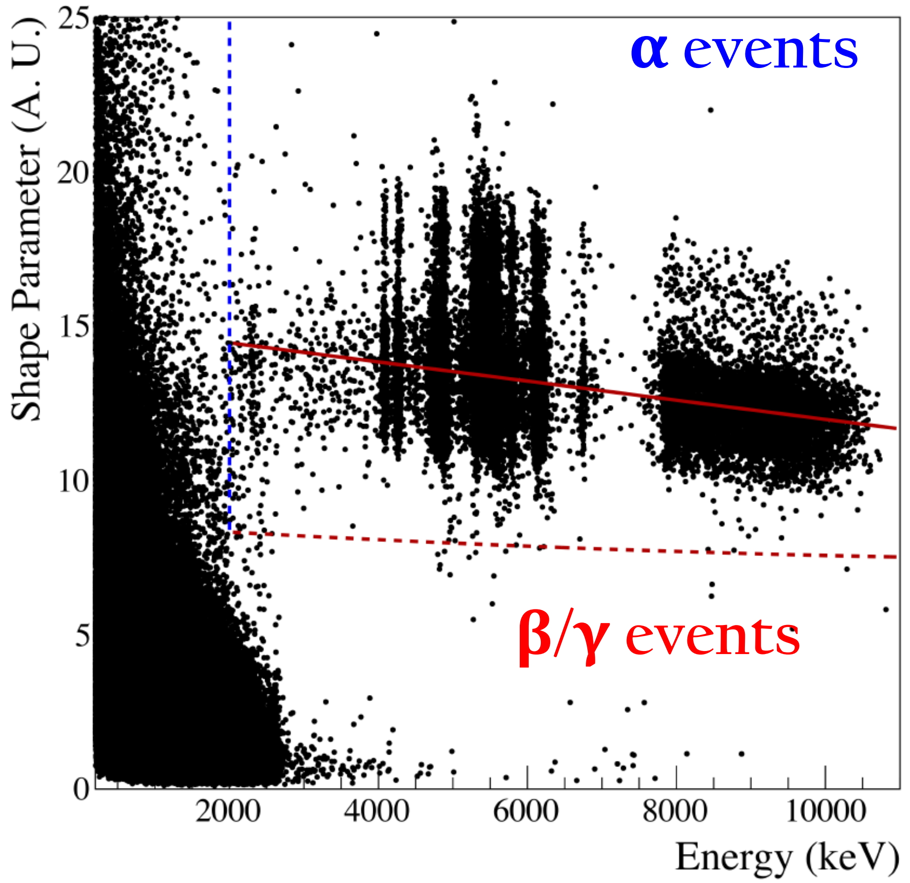


$$BKG = (3.2 \pm 0.4) \cdot 10^{-2}\ \text{cnts}/(\text{keV} \cdot \text{kg} \cdot \text{y})$$

$$BKG = (1.3 \pm 0.2) \cdot 10^{-2}\ \text{cnts}/(\text{keV} \cdot \text{kg} \cdot \text{y})$$

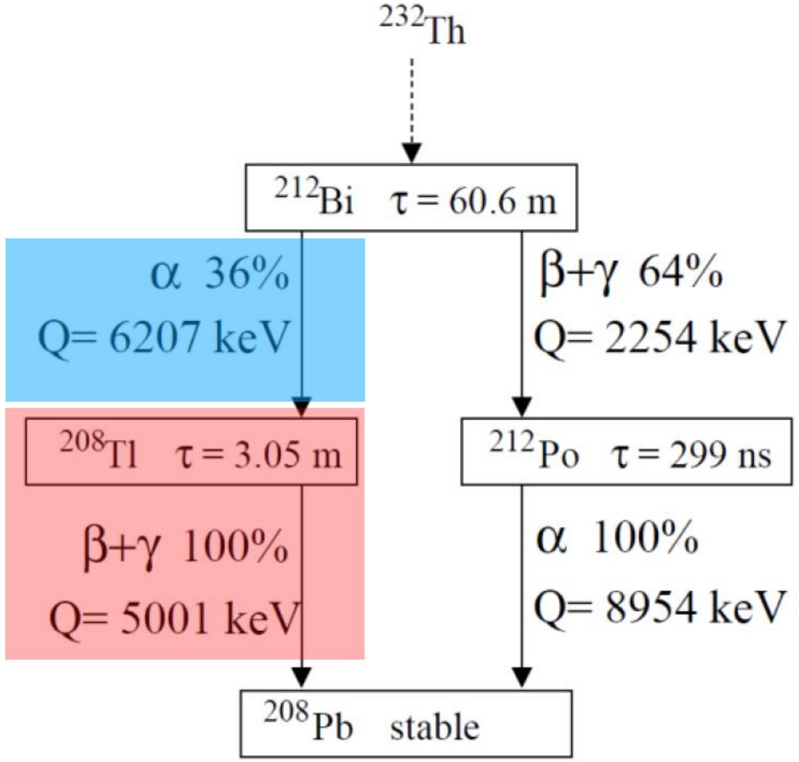
Light Signal depends on particle type

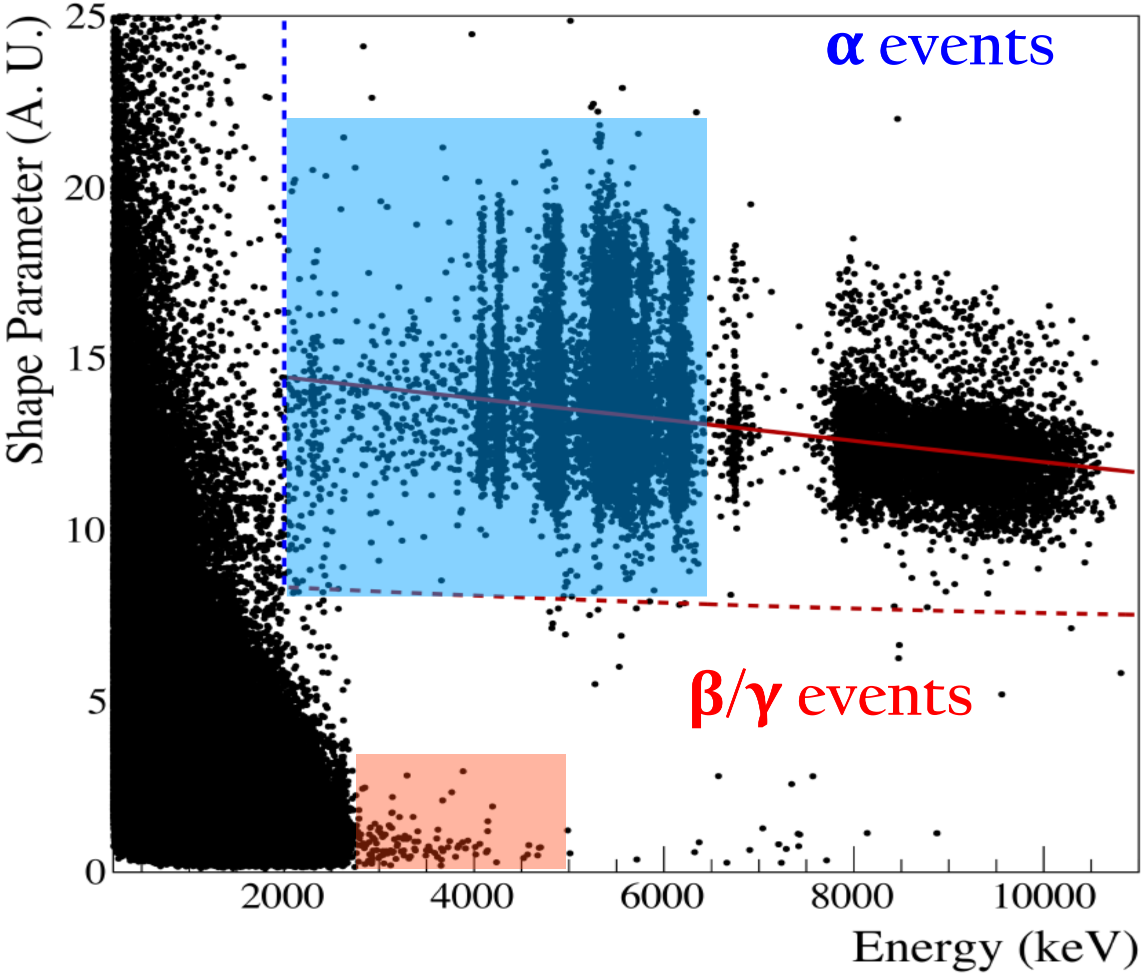
Selection based on light shape parameter



Background – Delayed coincidences rejection

Delayed ^{212}Bi-^{208}Tl (α/β) coincidences



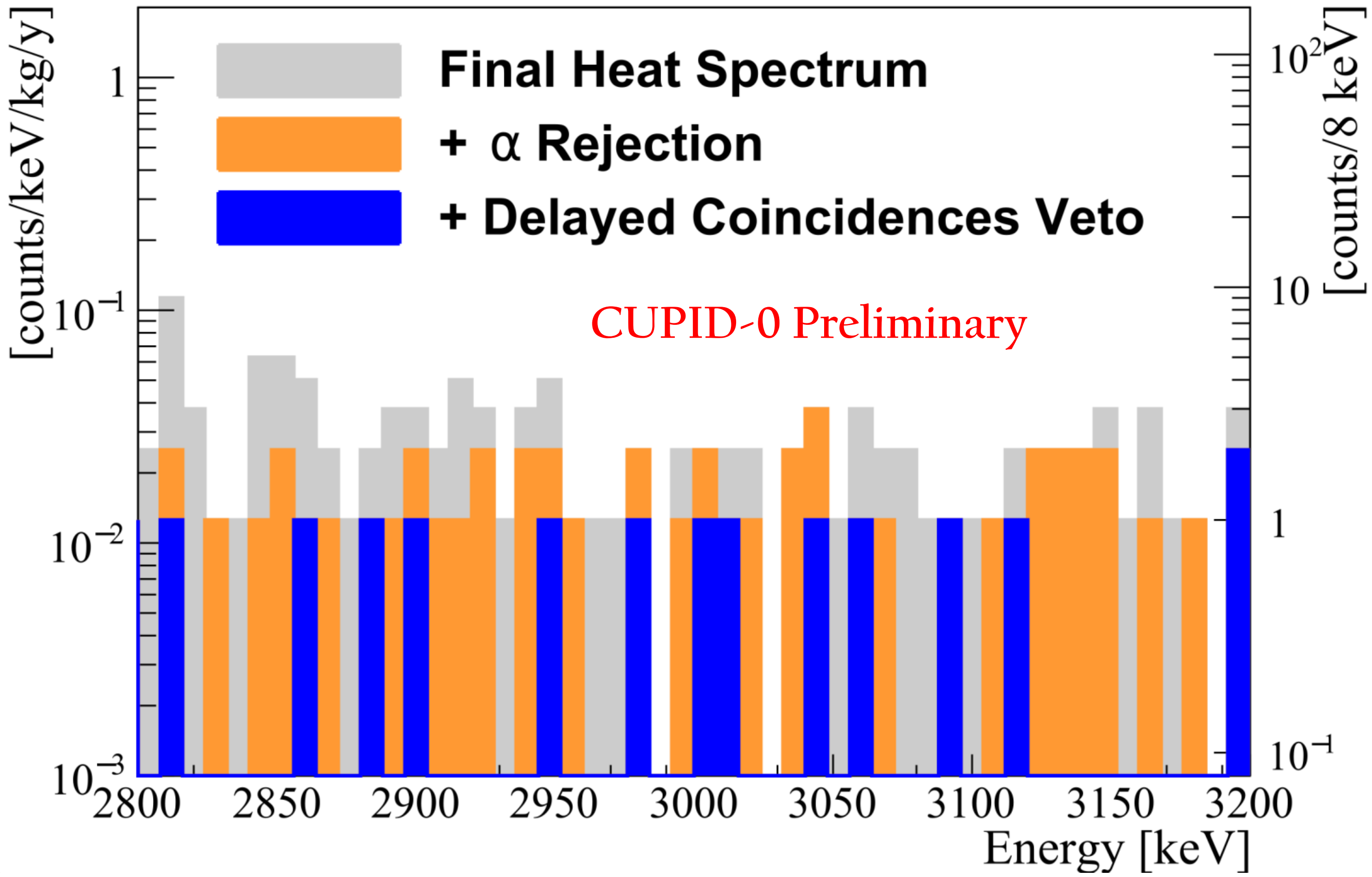


Selection of ^{212}Bi α events

- α pulse shape
- 2.0 MeV<Energy<6.5MeV
  - Degraded tag

⟶ Veto for 7 half-life

Background – Delayed coincidences rejection



$$(3.5^{+1}_{-0.9}) \cdot 10^{-3}\ \mathrm{cnts/(keV \cdot kg \cdot y)}$$

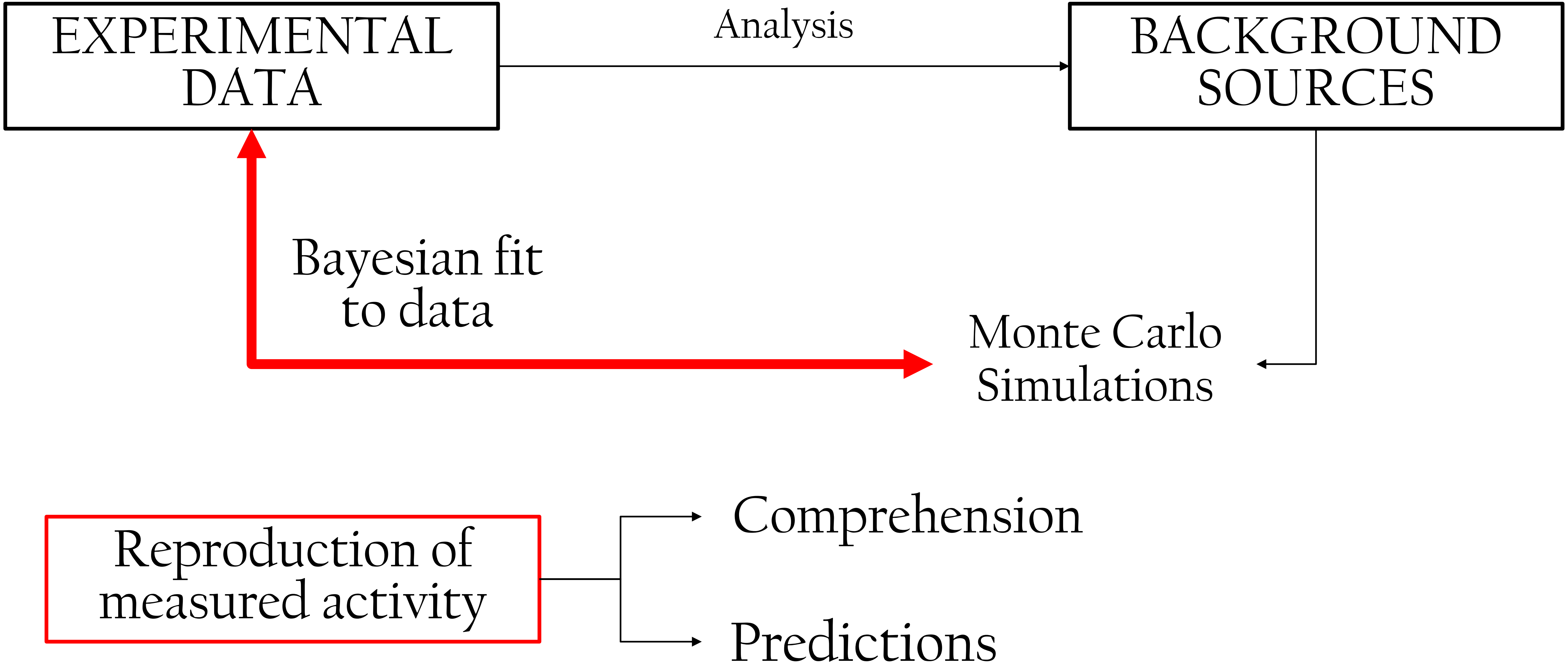
Lowest background ever measured with a calorimeter

Total cut efficiency:
(86±1)%

No evidence of 0νββ signal

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

A complete model of the background sources



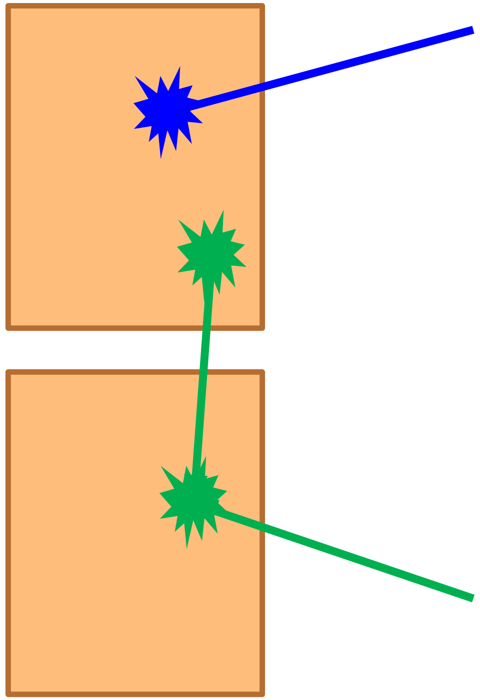
O. Azzolini et al. (CUPID), (2019), arXiv:1904.10397 [nucl-ex].

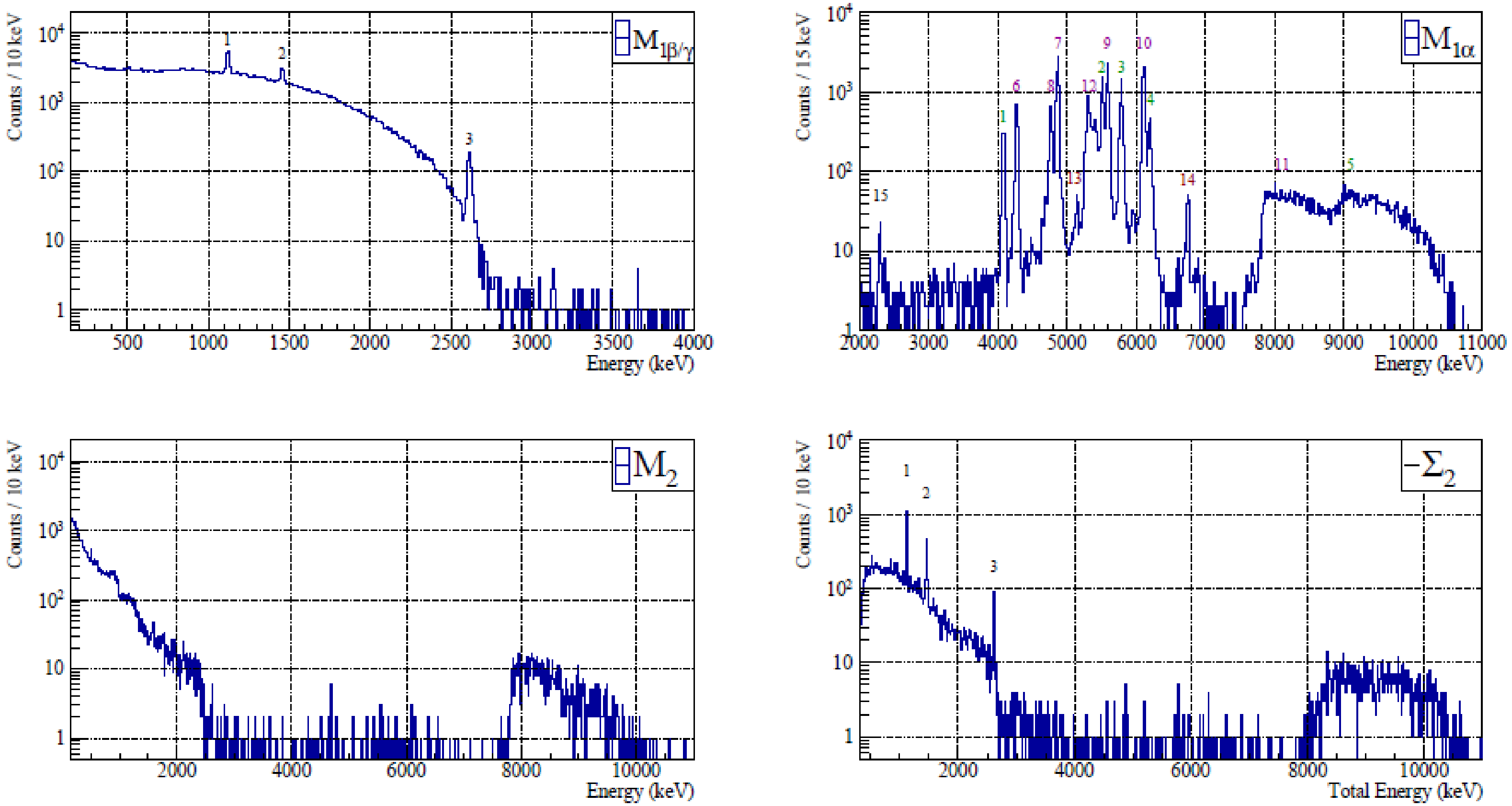
Experimental data for the model

Divided according to multiplicity and particle type →

- M1 α – β/γ
- M2 / M2 sum (Σ2)
- M›3 (to constraint Muons)

Multiplicity (M)
Crystals triggered in 20ms

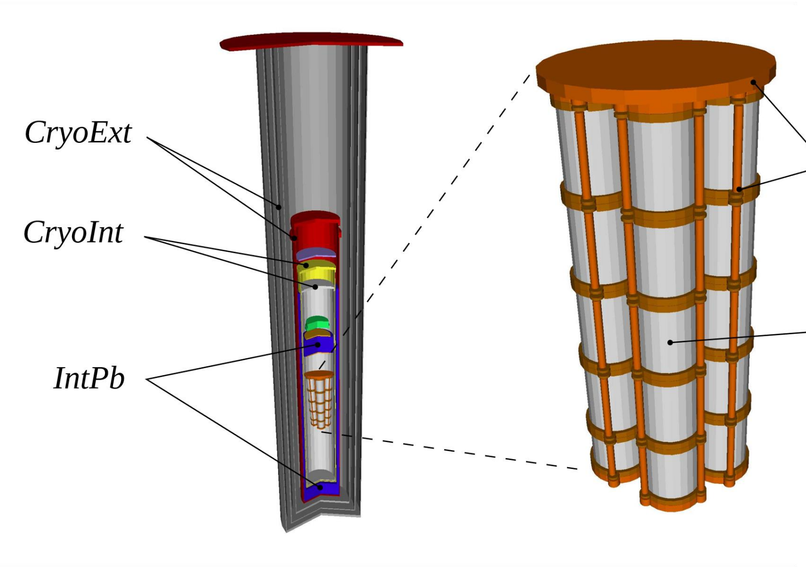




Background source identification

O. Azzolini et al. (CUPID), (2019), arXiv:1904.10397 [nucl-ex].

- Localization in the detector



- Depth of contamination

Surface

Exponential profile

- Radiation type

Natural Chains

- Fathers + saecular equilibrium breaking points

Single isotopes

- 40K, 54Mn, 65Zn, 60Co, …

Muons

Monte Carlo simulations

Generation

Detection

O. Azzolini et al. (CUPID), (2019), arXiv:1904.10397 [nucl-ex].

Additional informations

O. Azzolini et al. (CUPID), (2019), arXiv:1904.10397 [nucl-ex].

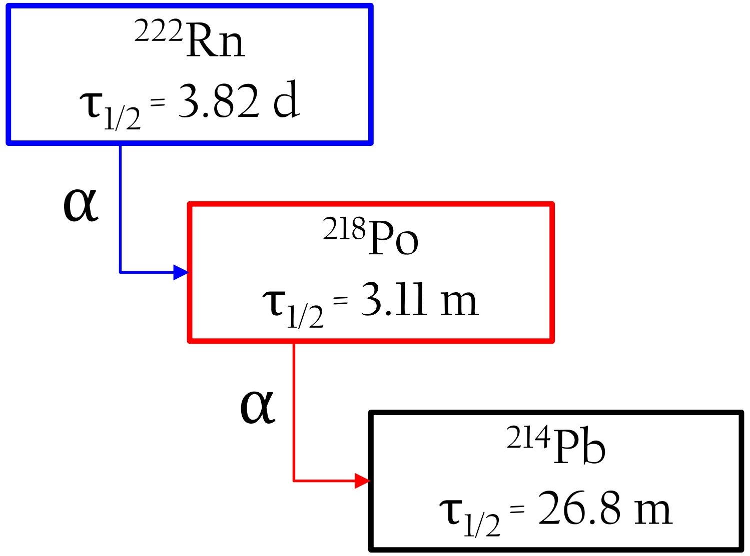
MODEL

- 33 background sources → Linear combination

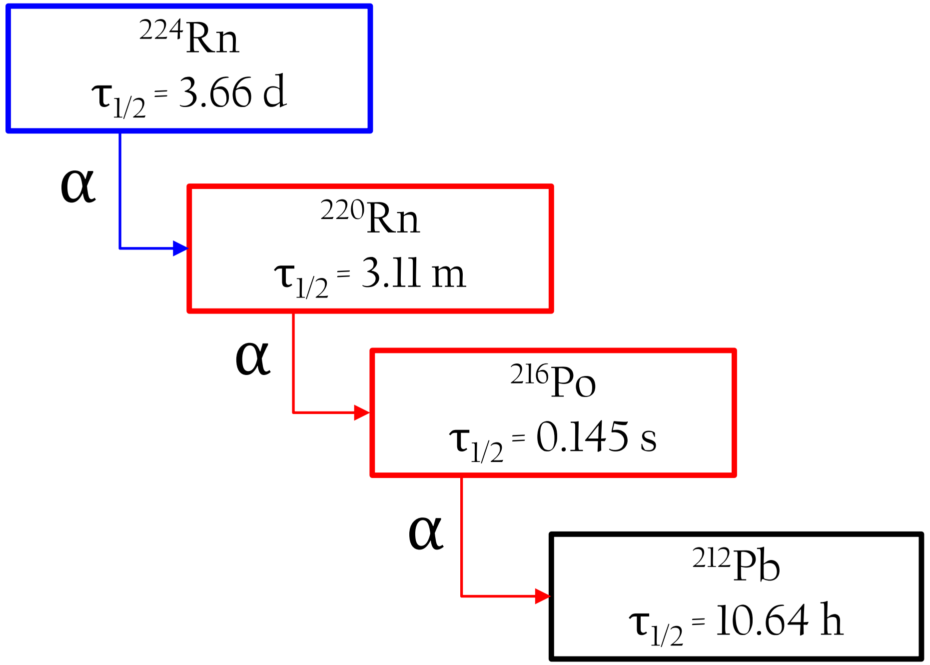
Coefficients = Activities

PRIORS

- Experimental signatures
  - α/α coincidences
- Previous contamination measurements
  - Reflective foil



^{238}U ($^{226}Ra \rightarrow {}^{210}Pb$)



^{232}Th ($^{224}Ra \rightarrow {}^{208}Pb$)

$$P(N|N)_{Q_{value}}$$

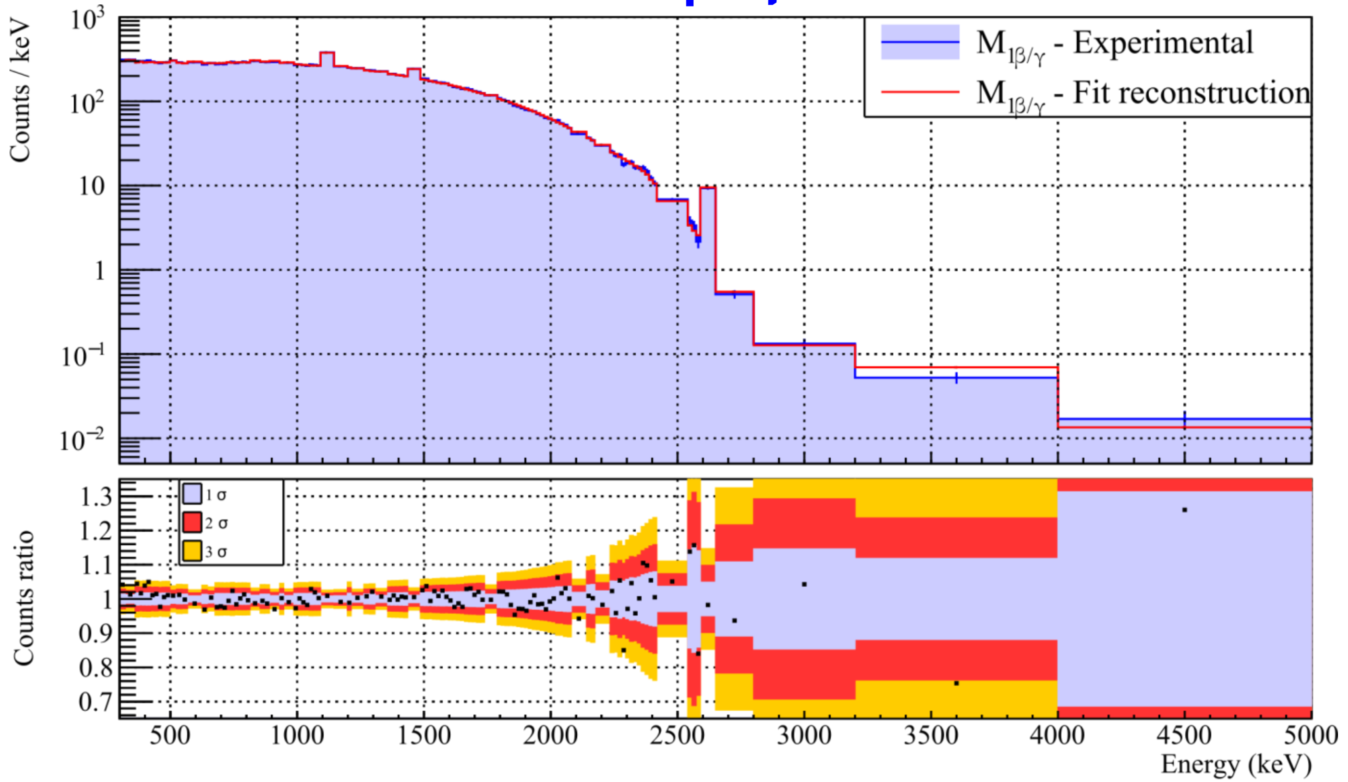
Depends on source localization

Daughter/parent gives a prior on surface vs bulk contaminations

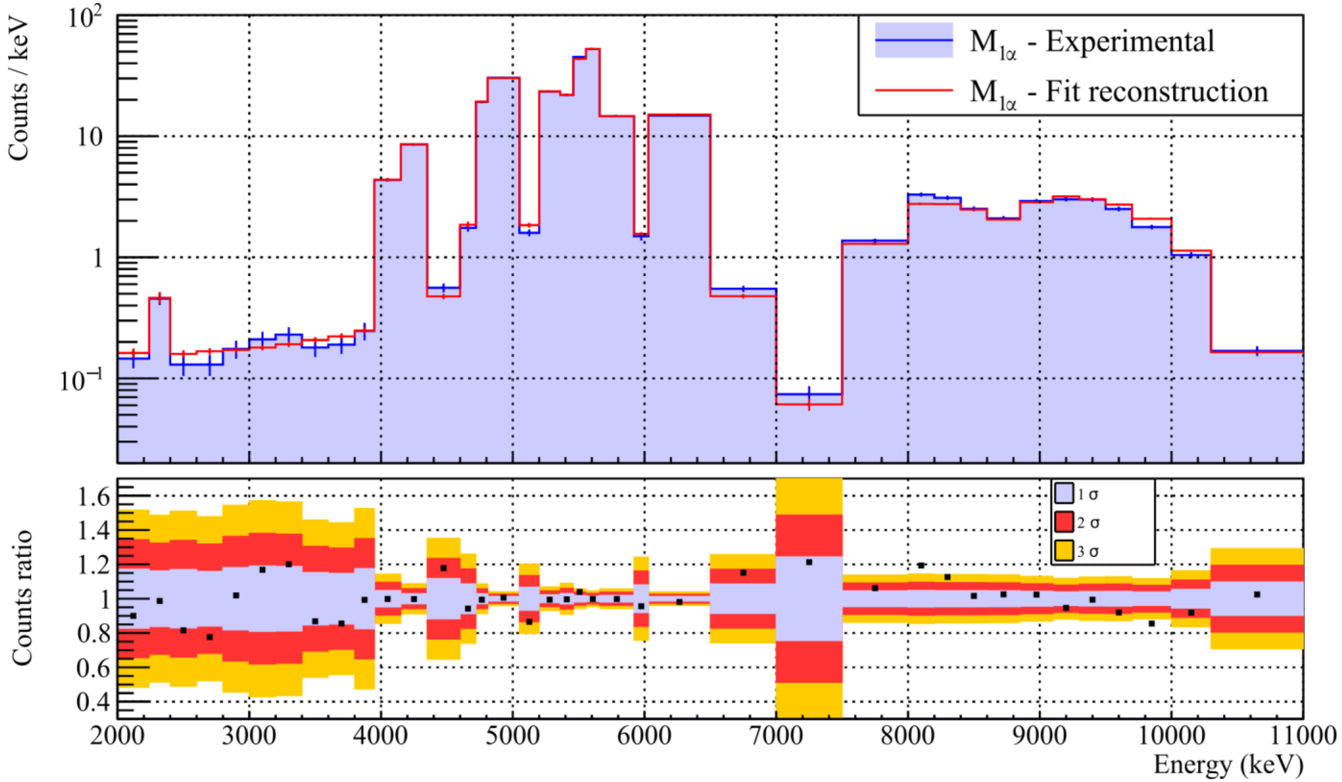
Reconstruction results: M1 Spectra

- Full spectrum reconstruction
- Peaks and continuum are well modelled

M1 β/γ



M1 α



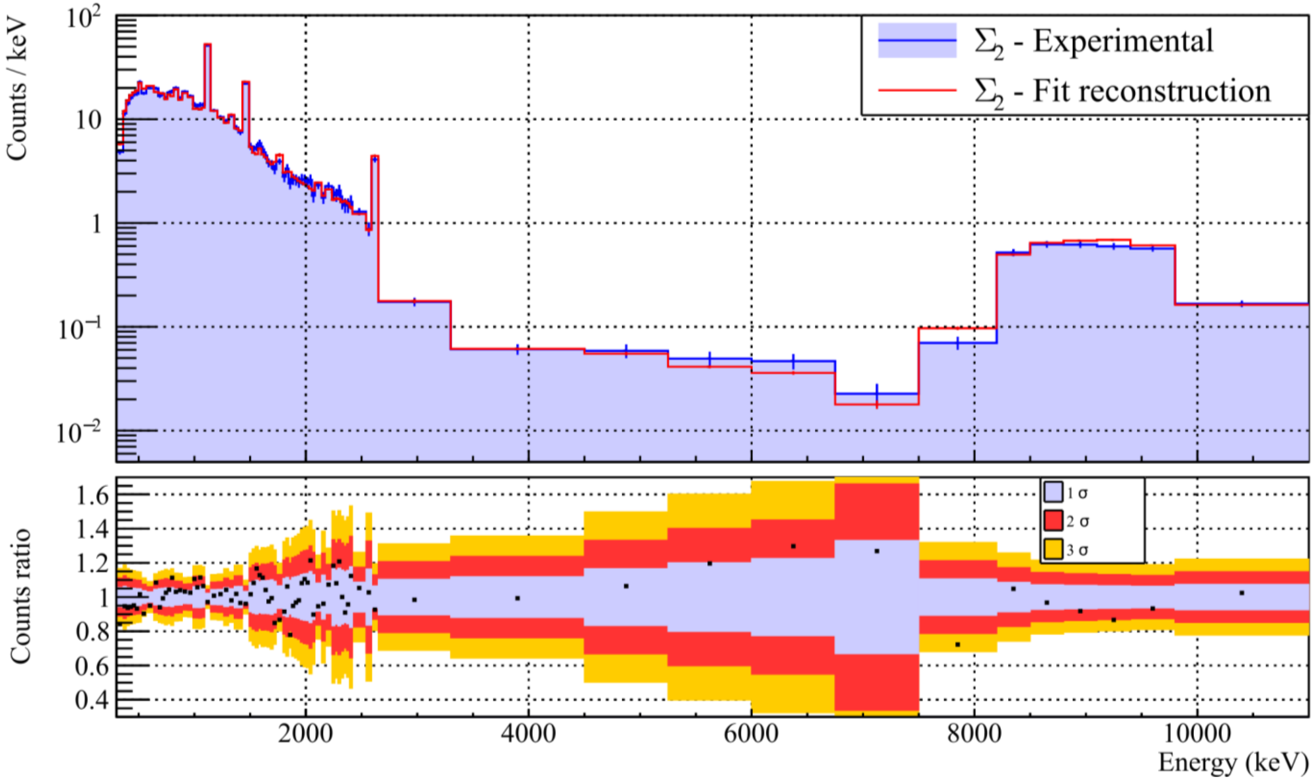
The α – β/γ separation allows to disentangle the different contributions

O. Azzolini et al. (CUPID), (2019), arXiv:1904.10397 [nucl-ex].

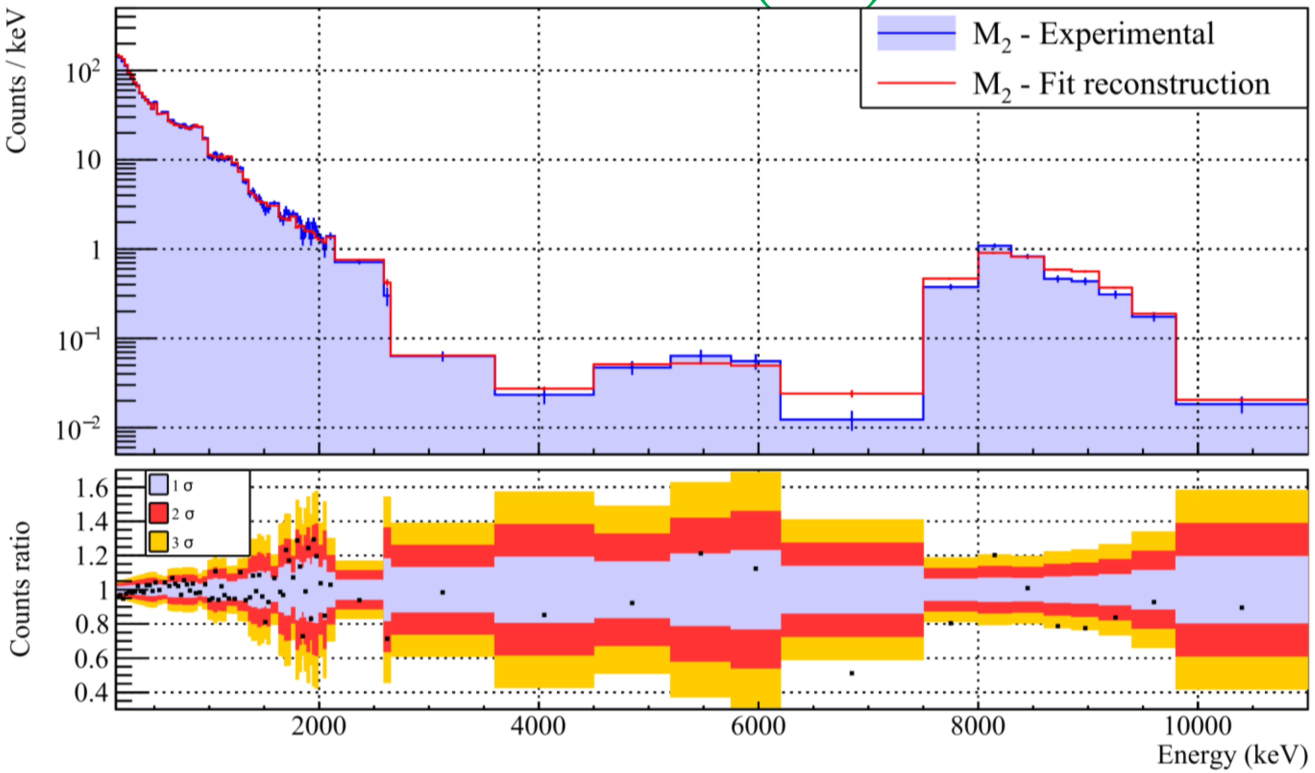
Reconstruction results: M2 spectra

- Both α and β/γ regions are well modelled in peaks and continuum
  - The surface/bulk prior is a key ingredient

M2



M2 sum (Σ2)



Some differences on the Bi-Po pileup

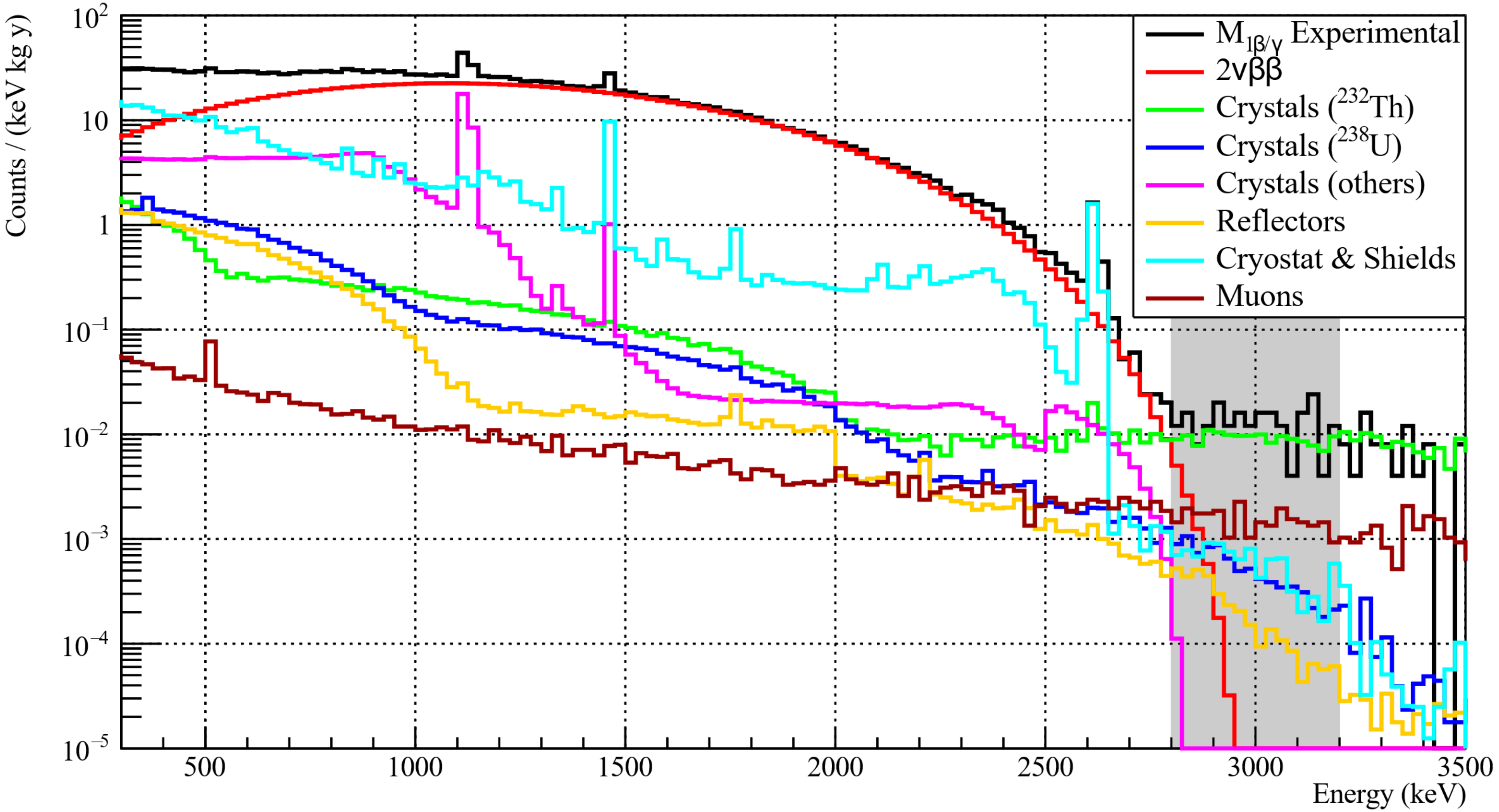
- Imperfect reconstruction of the deposited energy

$^{214}Bi \rightarrow {}^{218}Po$

$^{212}Bi \rightarrow {}^{212}Po$

O. Azzolini et al. (CUPID), (2019), arXiv:1904.10397 [nucl-ex].

Result: Beta/Gamma spectrum



In the ROI

^{232}Th is dominant, because no delayed cut is applied

Delayed coincidences

Muons give 44% of residual background

$2\nu\beta\beta$ is a dominant contribution

Possibility to perform detailed study on this decay

O. Azzolini et al. (CUPID), (2019), arXiv:1904.10397 [nucl-ex].

Phase II upgrade

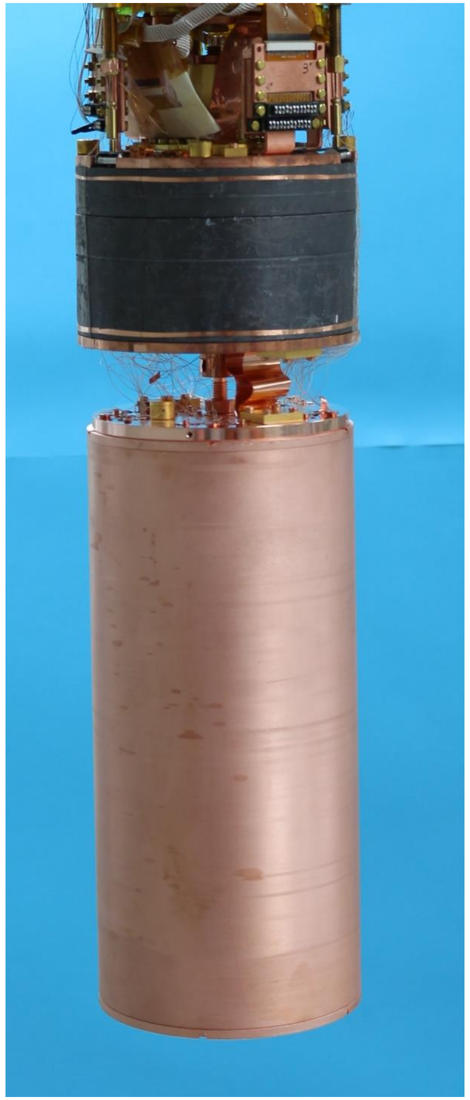
- μ are the main residual background
  - Installation of μ-veto

No reflective foil

- Sensitivity to M2 α events

New clear Cu Shield

- Thermalization
- Additional shielding



NOW COOLING

CUPID 0: current results and future perspectives

- CUPID-0 is the first large array of enriched scintillating bolometers

- We reached the lowest background level achieved with bolometric experiments:

$$(3.5^{+1}_{-0.9}) \cdot 10^{-3} \ \text{cnts}/(\text{keV} \cdot \text{kg} \cdot \text{y})$$

- A complete background model has been developed
  - Major ROI background (^{208}Tl β events) is reduced with delayed cut
  - Muons give 44% of residual counts

- Phase II upgrade focused on background improvement
  - Muon veto installed
  - No Reflective foil: M2 alpha events direct tagging
  - Additional shielding

BackUp Slides

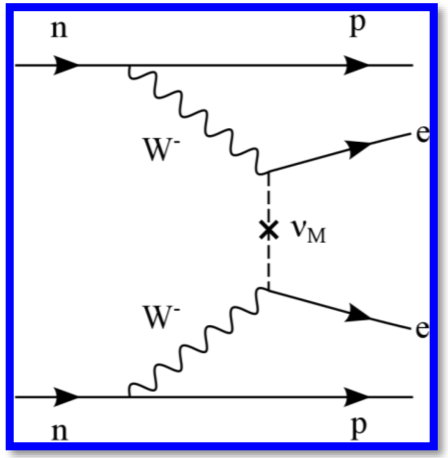
Double beta decay (ββ)

0νββ: (A,Z) → (A,Z+2) + 2e⁻

$$m_\nu \neq 0$$

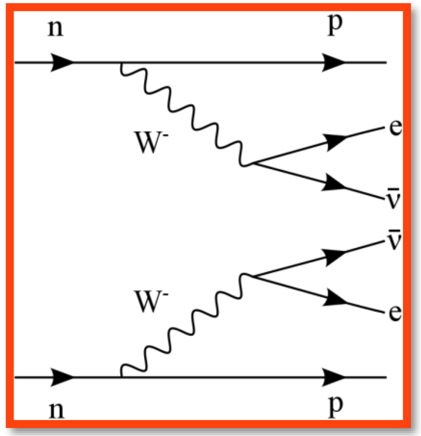
$$\nu \equiv \overline{\nu}$$

- Prohibited in the Standar Model (ΔL=2)
- Limits: $T^{0\nu}_{1/2}$ > 10^{24} - 10^{25} y

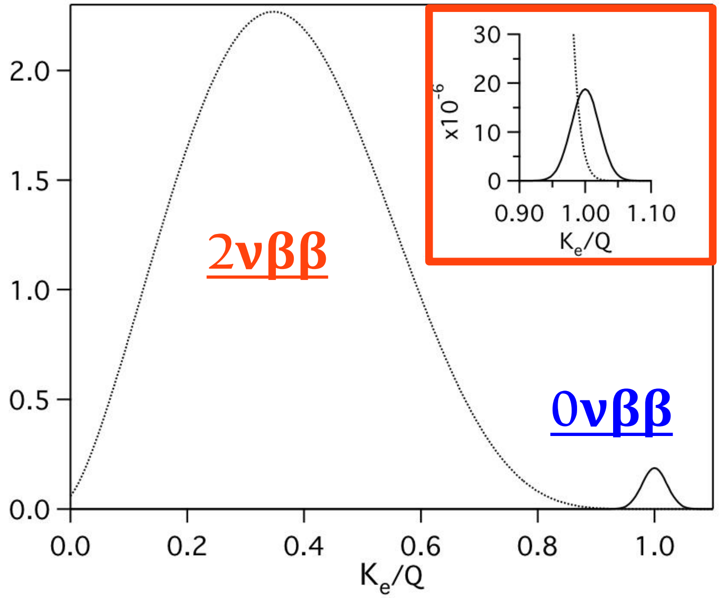


2νββ: (A,Z) → (A,Z+2) + 2e⁻+2ν

- Predicted and detected



Measuring the two electron energy



Performing resolution

- At 2-3 MeV (Q_{value} of different isotopes)

Low Background

- Observing few counts above background

Experimental search for **0νββ**

Experimental sensitivity
Maximum measurable half-life at a given C.L.

$$S_{0\nu} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta}}$$

Crytical experimental parameters:

- Isotope Mass (M) → **Mass scalability** at low cost and **high isotopic abundance**
- FWHM energy resolution (Δ) → **Δ of few % at** Q_{value} to avoid **the 2νββ** induced **background**
- Background (B) → **High purity materials** (< ppb radioactive contaminations) **Rejection techniques**

Ratio 0νββ signal/2νββ background

$$\frac{S^{0\nu}}{B^{2\nu}} = \frac{m_e}{7} \frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}} \frac{Q^5_{value}}{\Delta^6}$$

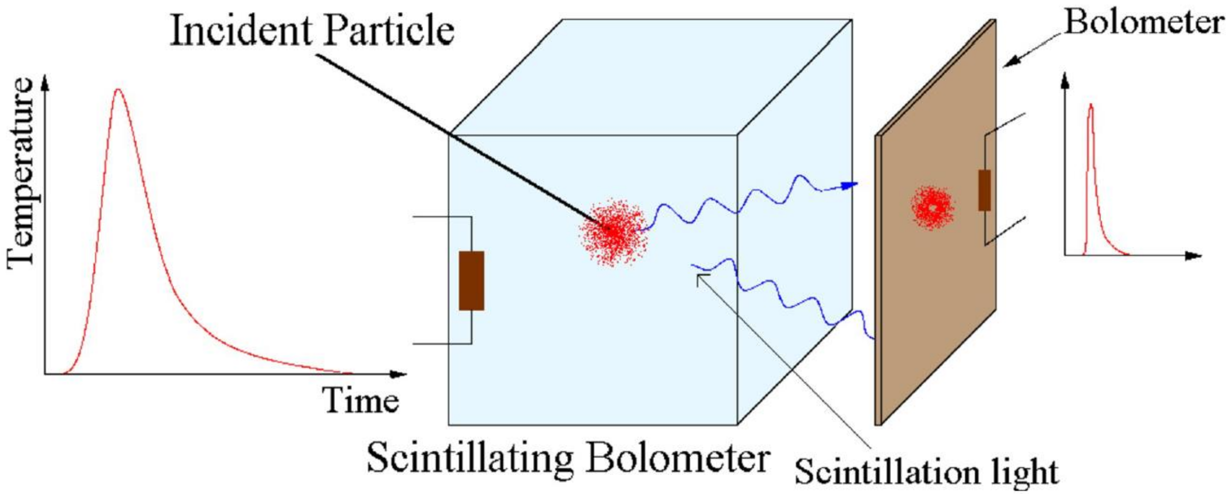
CUPID-0

The first enriched scintillating bolometer ββ experiment

Demonstrating achievable Background rejection

Precision measurements on ^{82}Se ββ

^{82}Se - $Q_{\beta\beta}$ = (2997±0.3) keV



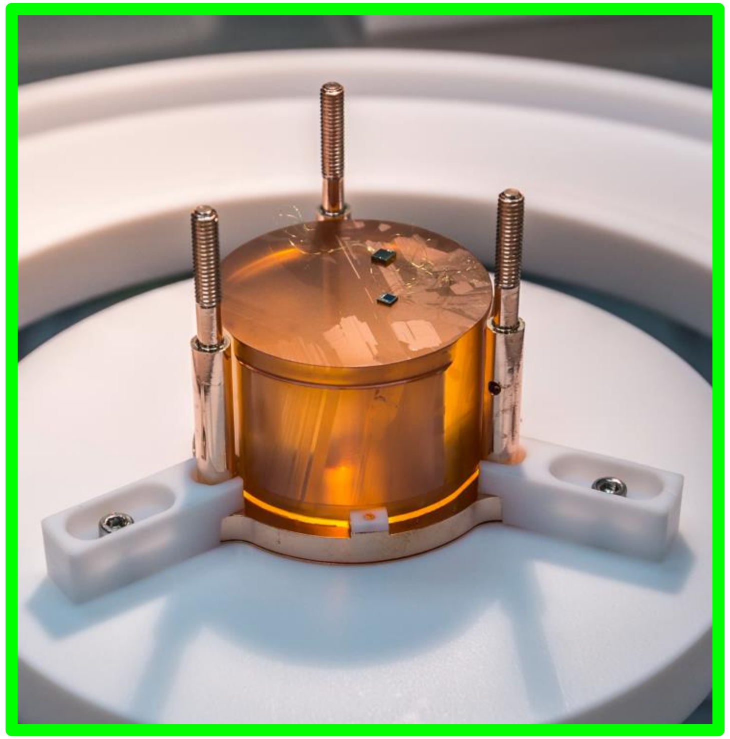
Heat:

bolometric high resolved output

Light:

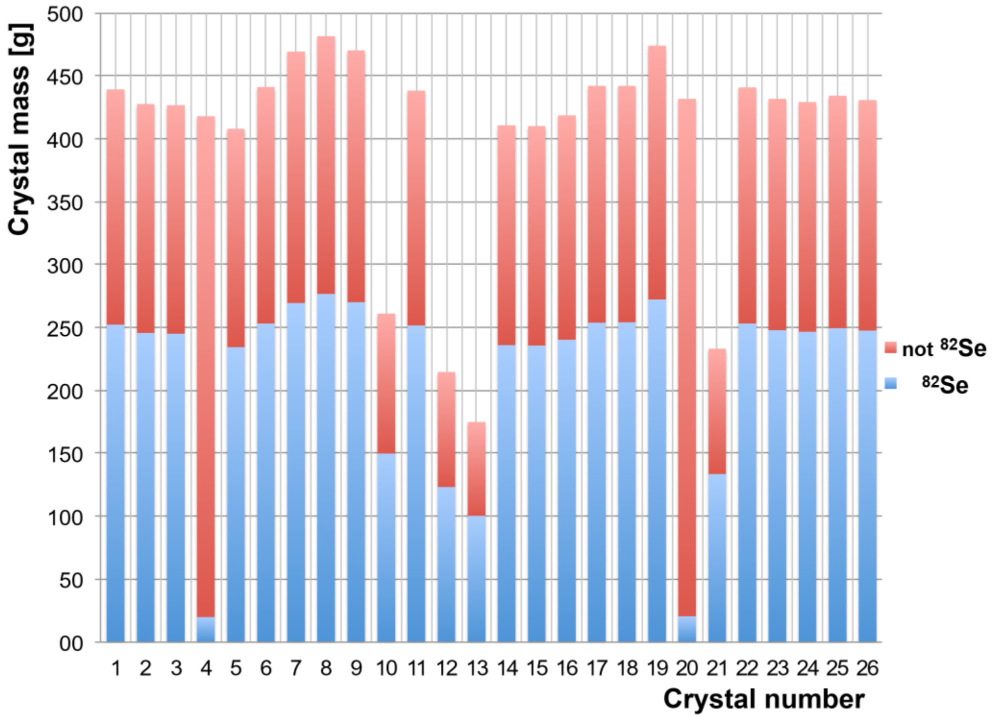
particle identification

$Zn^{82}Se$ crystals



Fist large mass $\mathbf{Zn^{82}Se}$ enriched crystals ever grown.

- **26 ZnSe crystals**
  - 24 enriched in ^{82}Se (95%) + 2 naturals
- **Total mass= 10.5 kg**
  - ^{82}Se mass =5.17 kg
  - $3.8 \cdot 10^{25}$ ββ emitters



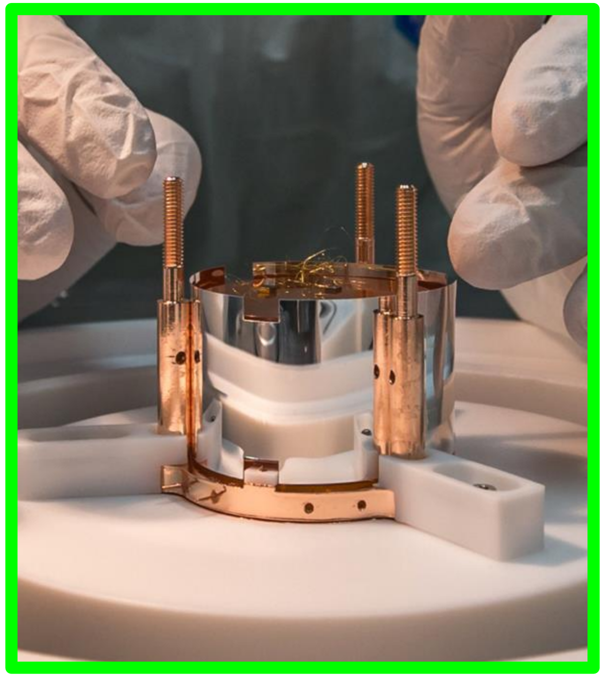
O. Azzolini et al. (CUPID), Eur. Phys. J. C 78, 428 (2018), arXiv:1802.06562

Material surrounding the crystal

Copper structure

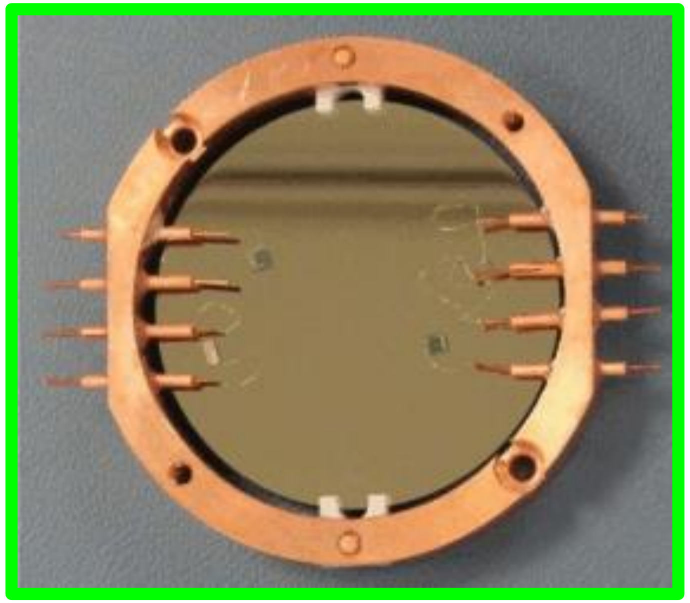
NOSV ultra–pure copper

- Cleaning procedure vs surface contaminations



Vikuiti Reflector

- Enhances the light output
- Low Th/U contaminations measured



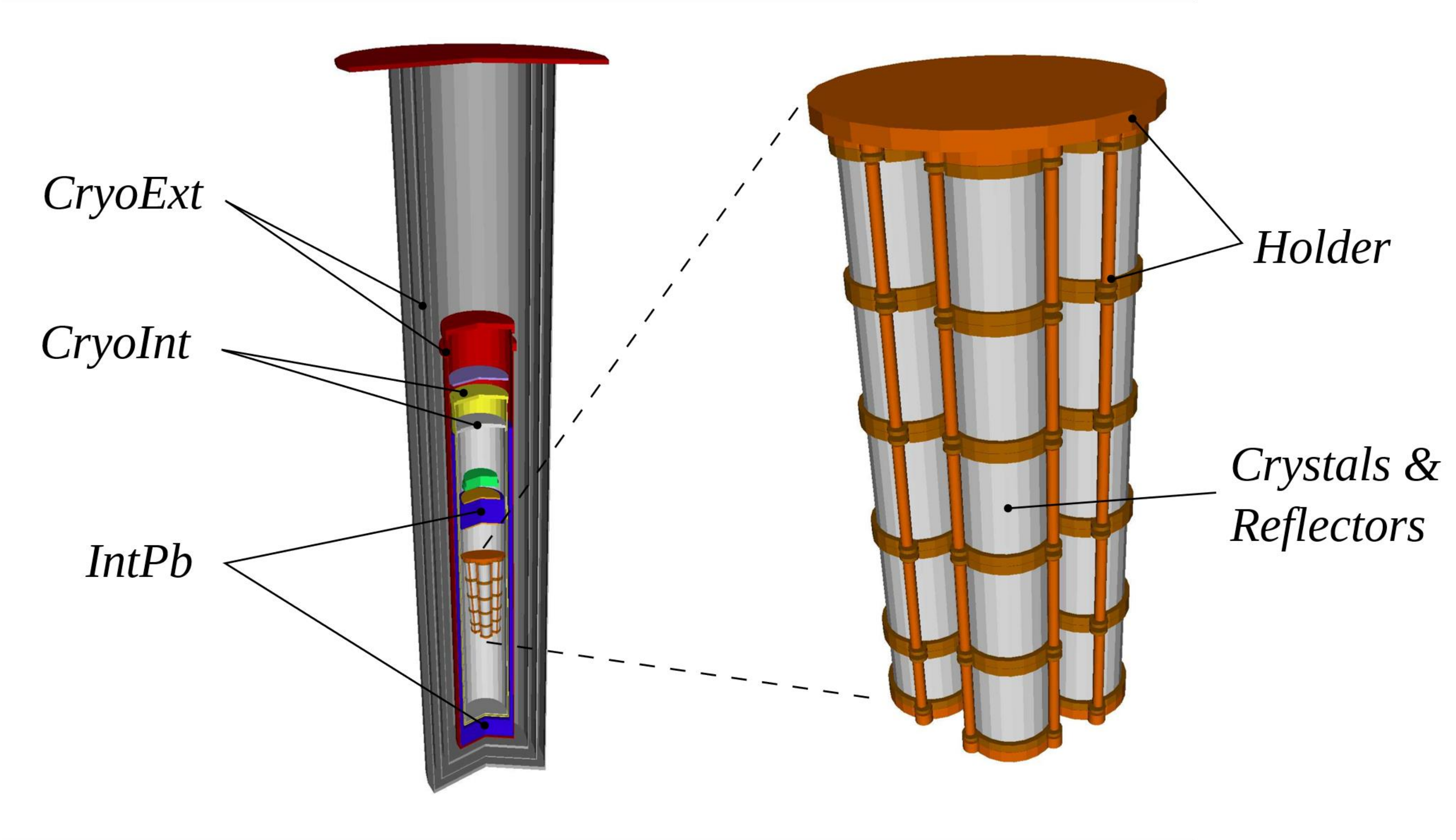
Ge Bolometric Light Detector

- SiO_2 anti-reflective coating
- Sensible to few keV energy deposition

O. Azzolini et al. (CUPID), Eur. Phys. J. C 78, 428 (2018), arXiv:1802.06562

The Cryostat

- Oxford 1000 $^3He/^4He$ diluition cryostat (CUORE-0)
- Radially divided by the Roman Lead shield:
  - CryoExt, RomanPb, CryoInt

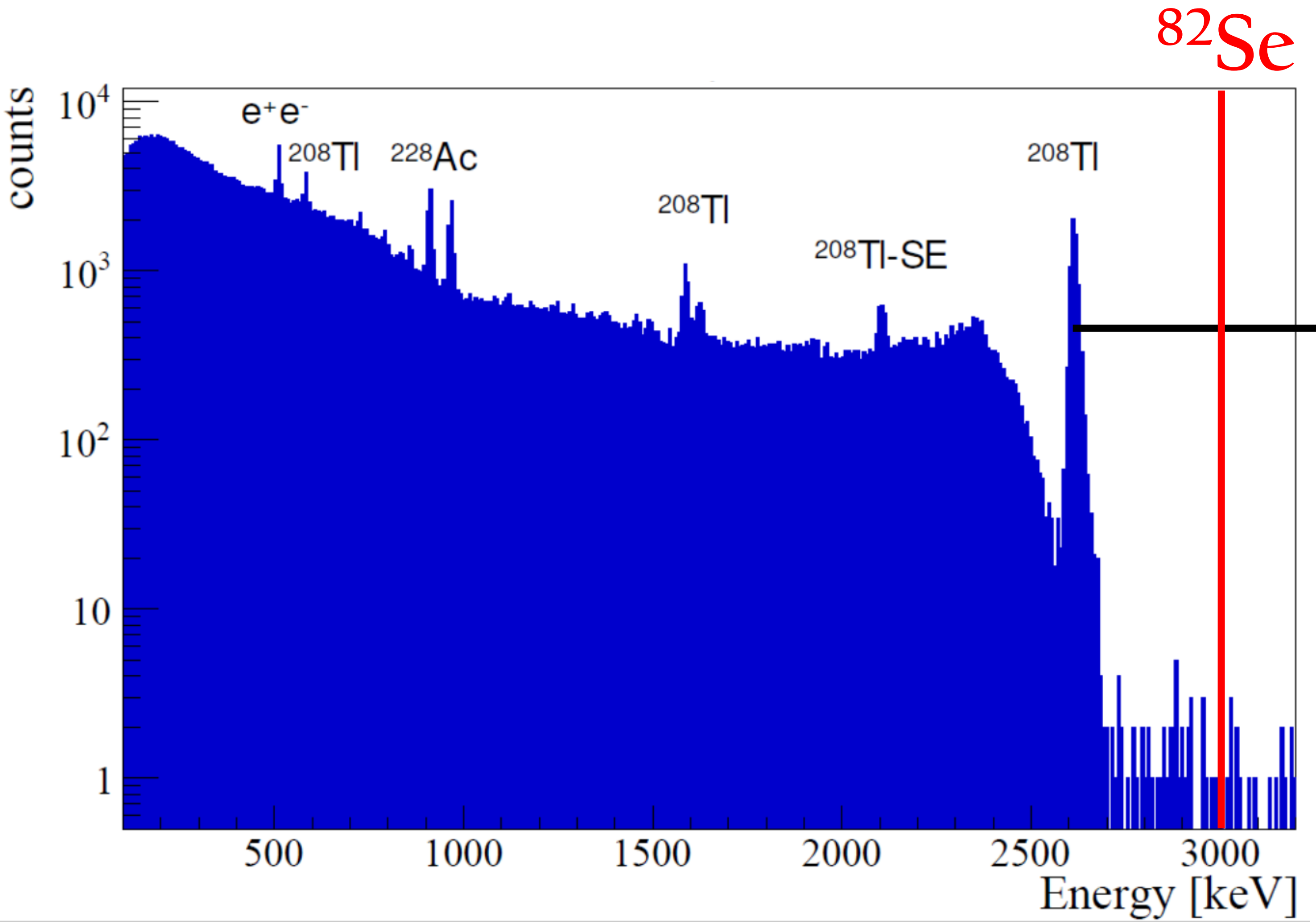


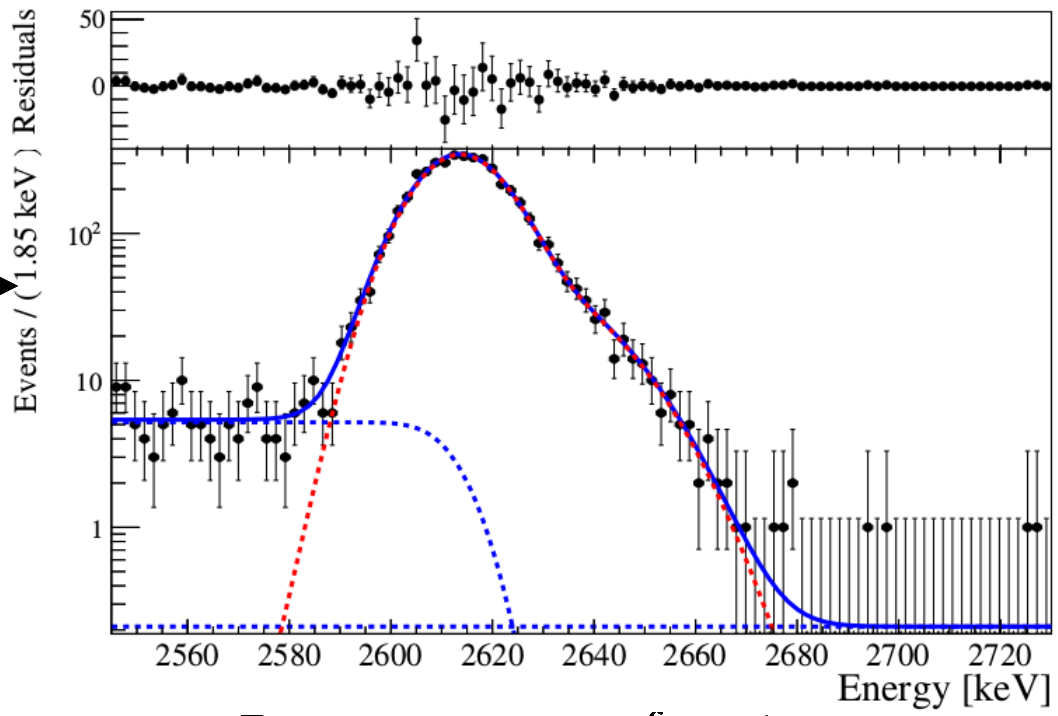
The cryostat contamination have been evaluated from experimental data

Detector Performances

^{232}Th Energy Calibration

- Bolometer calibration and light detector intercalibration
- Response function evaluation





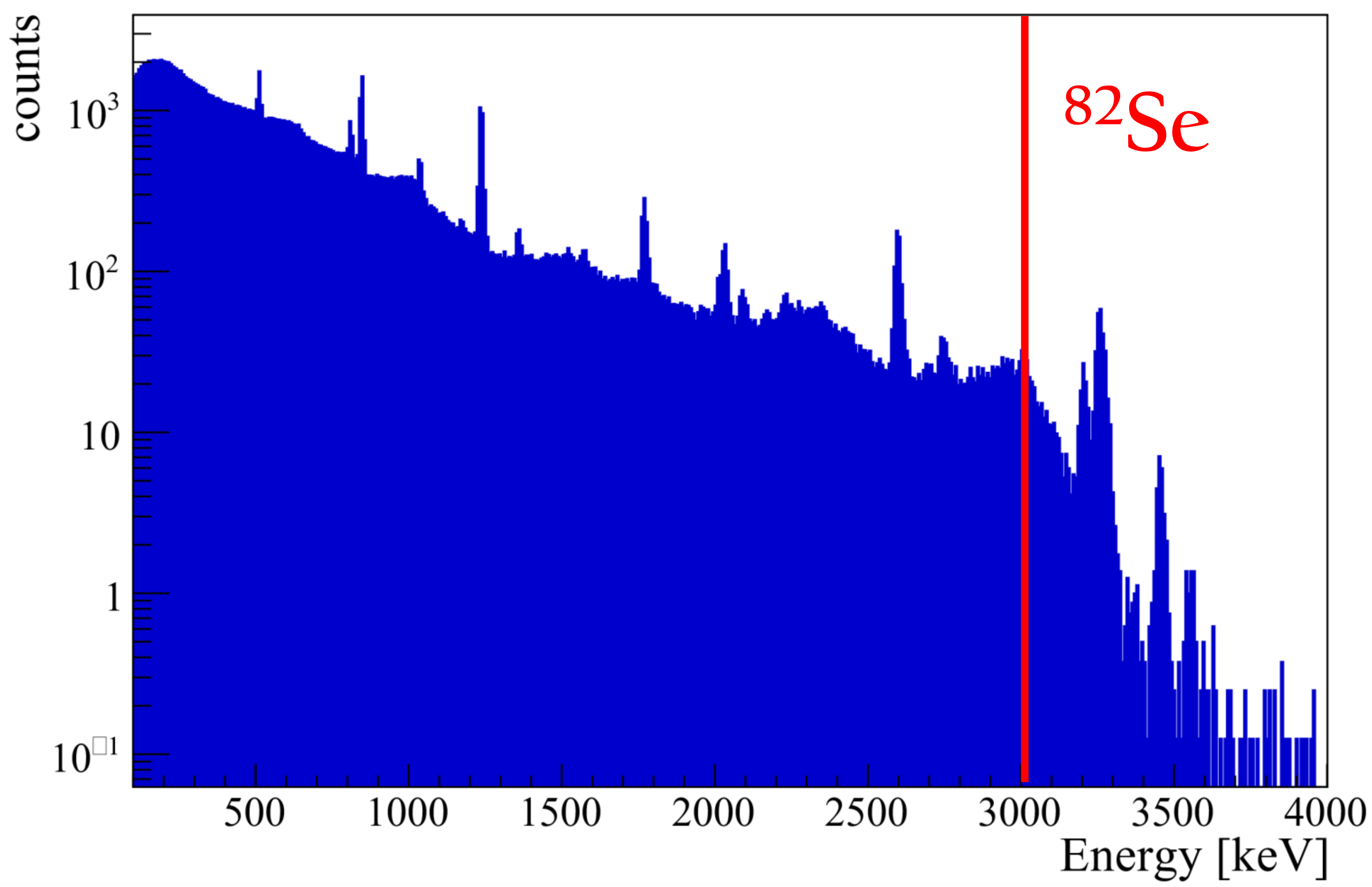
Detector response function

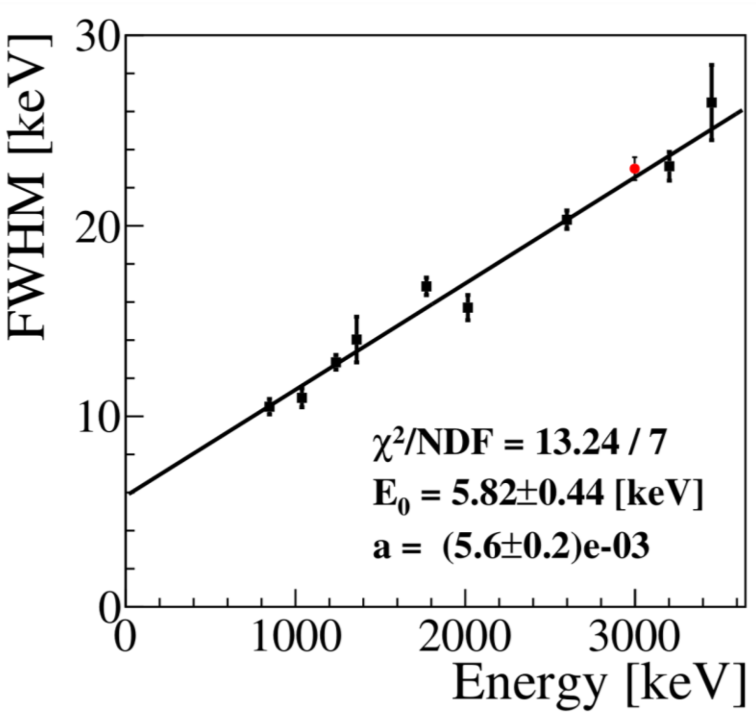
Double Gaussian
(deviation from simple gaussian observed in other bolometers)

Detector Performances

^{56}Co Energy Calibration

- Check of the energy reconstruction
- Evaluation of FWHM energy resolution @^{82}Se Q



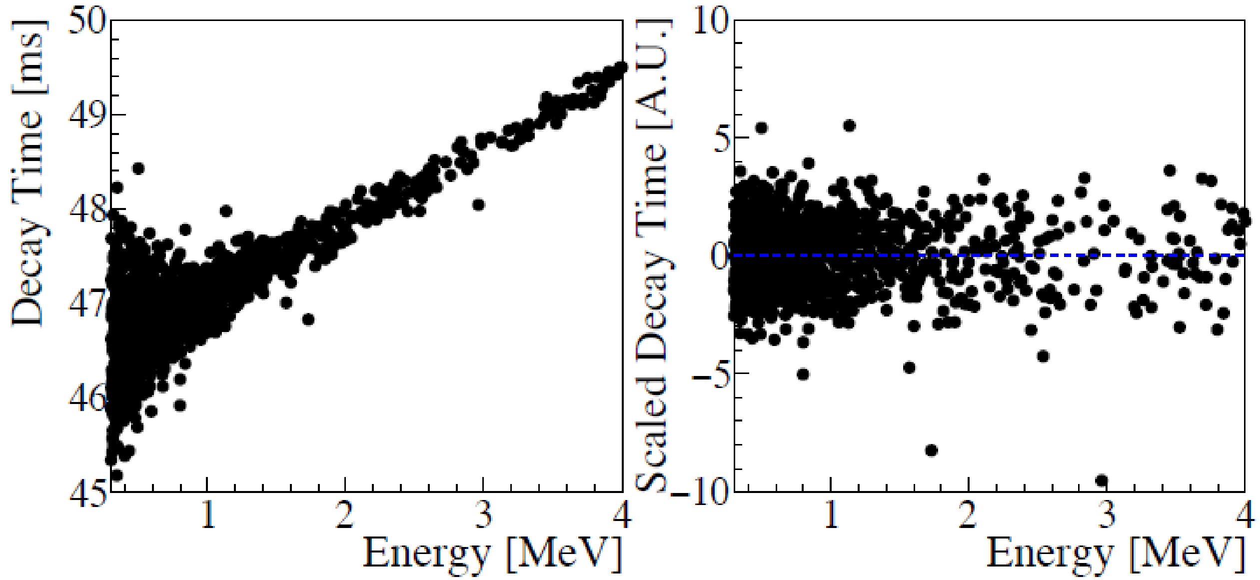


FWHM @ $Q_{\beta\beta}$

(20.0±0.6) keV

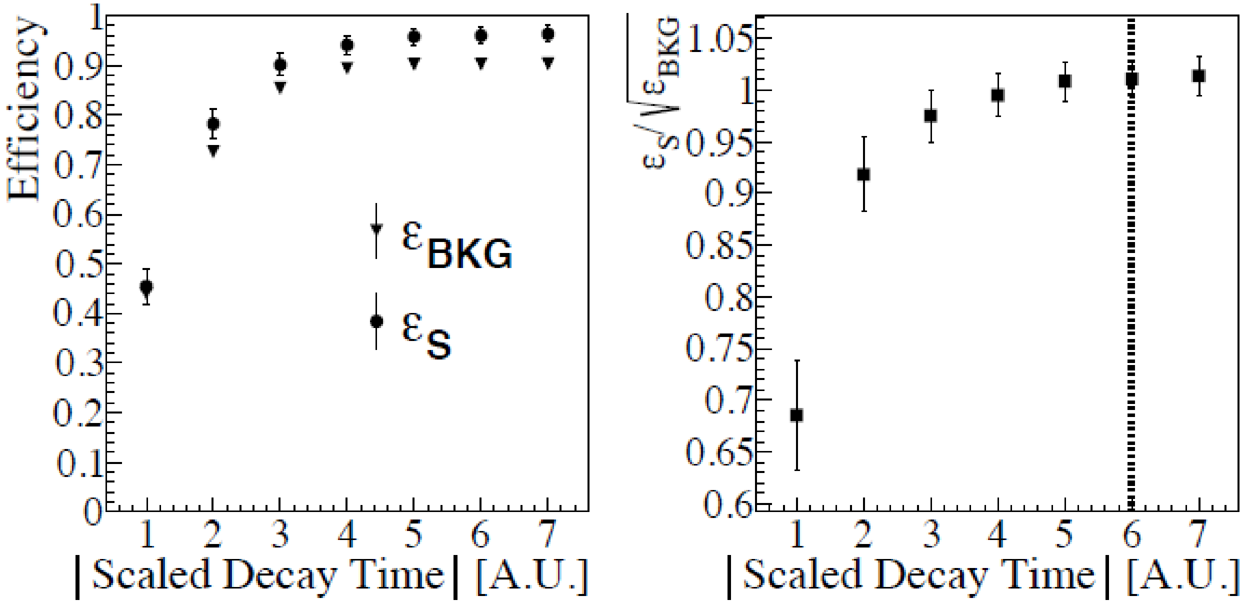
Major contribution is the crystal quality (average baseline FWHM ~5 keV)

Shape parameters cut



Remove energy-dependency of the shape parameters for energy-independent cuts

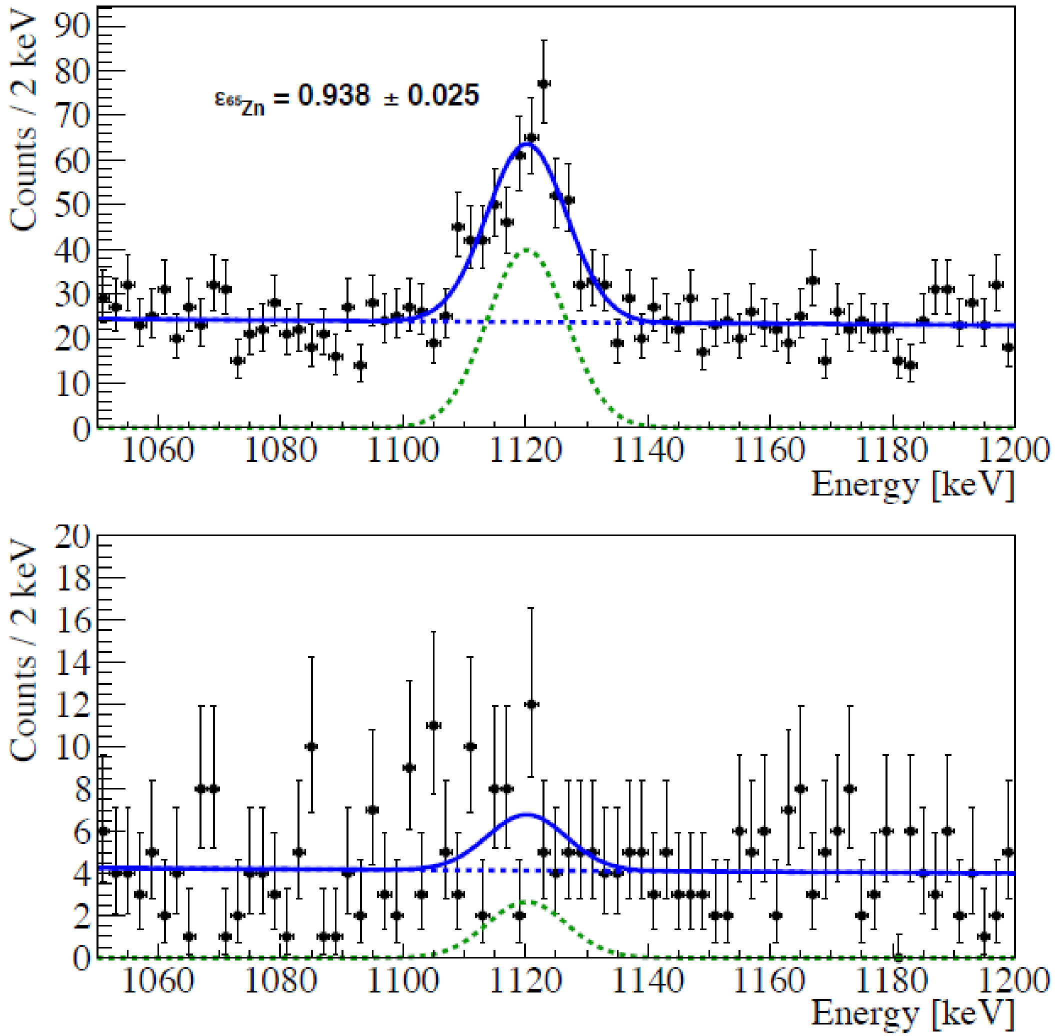
Efficiency and signal/noise as figure of merit to choose cut level



Evaluation of efficiency

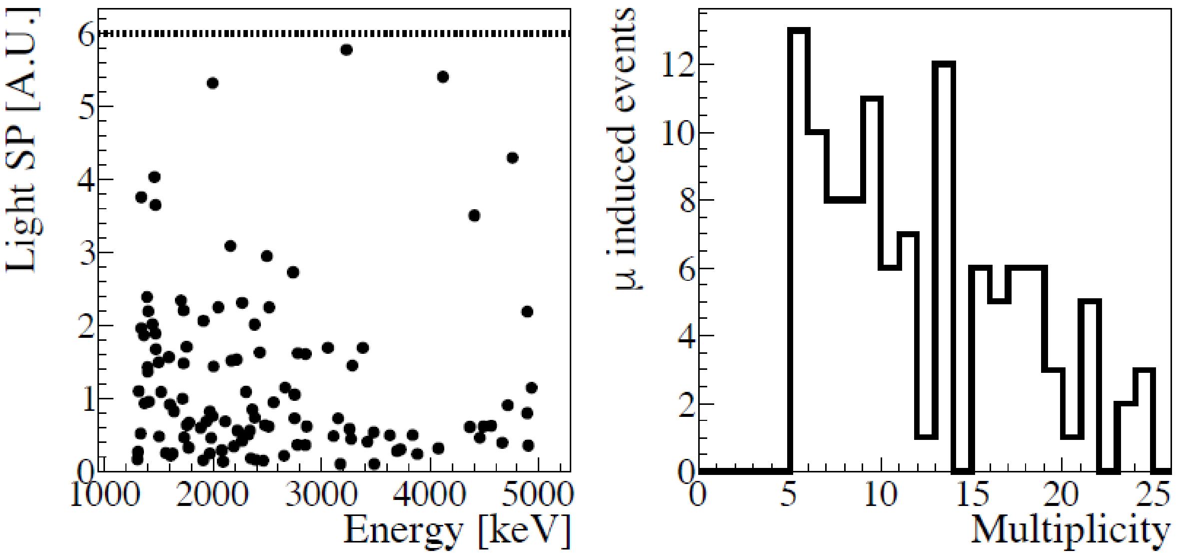
Heat

- Fit of ^{65}Zn Line before/after cuts applied

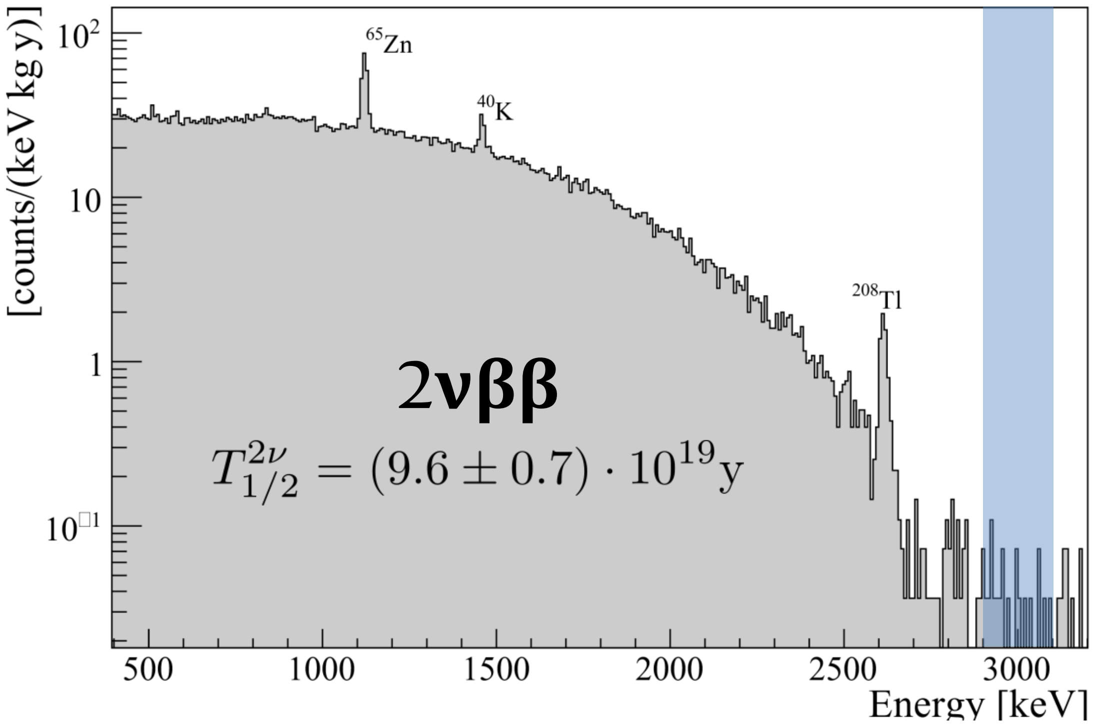


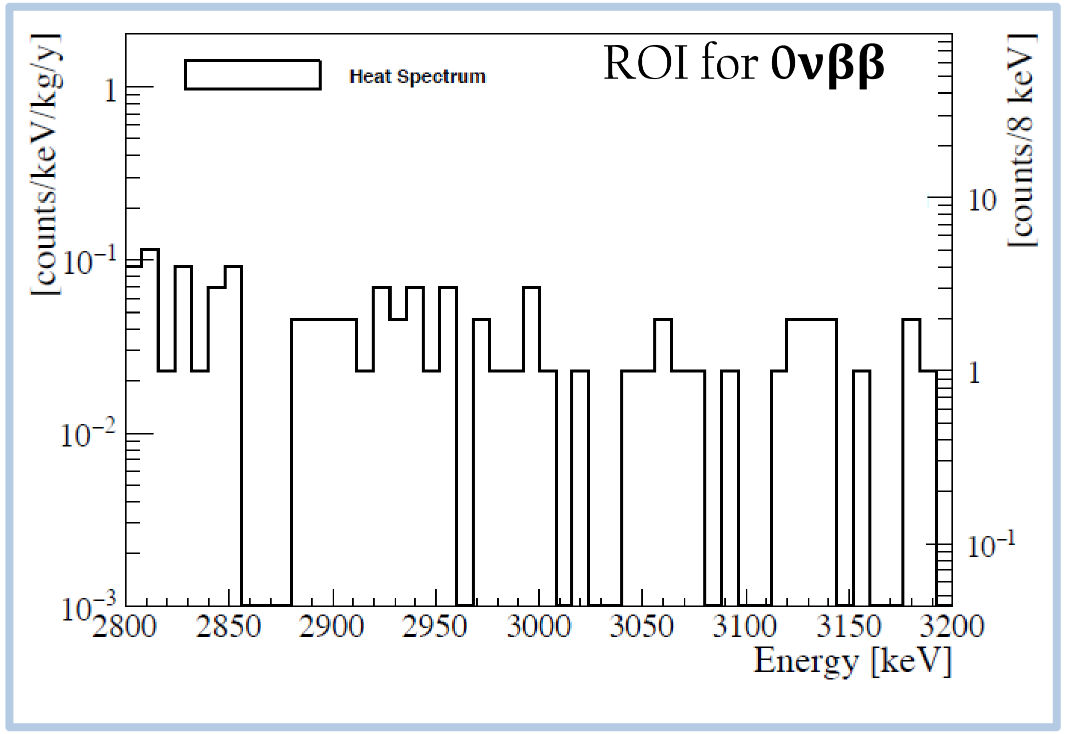
Light

- Cut on events with M>6
  - Muonic showers, almost pure beta/gamma sample



0νββ search





- ^{65}Zn: cosmogenically activated
- ^{40}K and ^{208}Tl: natural radioactivity
- **2νββ is the dominant background**

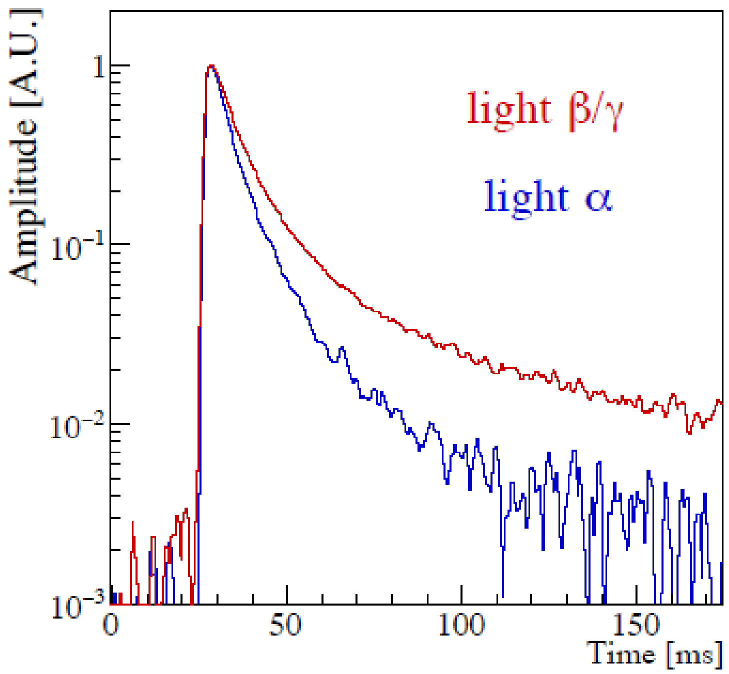
Basic Selections

- Rejection of "non-particle-like" events through pulse shape on thermal pulses
- Anti-coincidence between crystals (ΔT=20ms)
  - Multiplicity selection

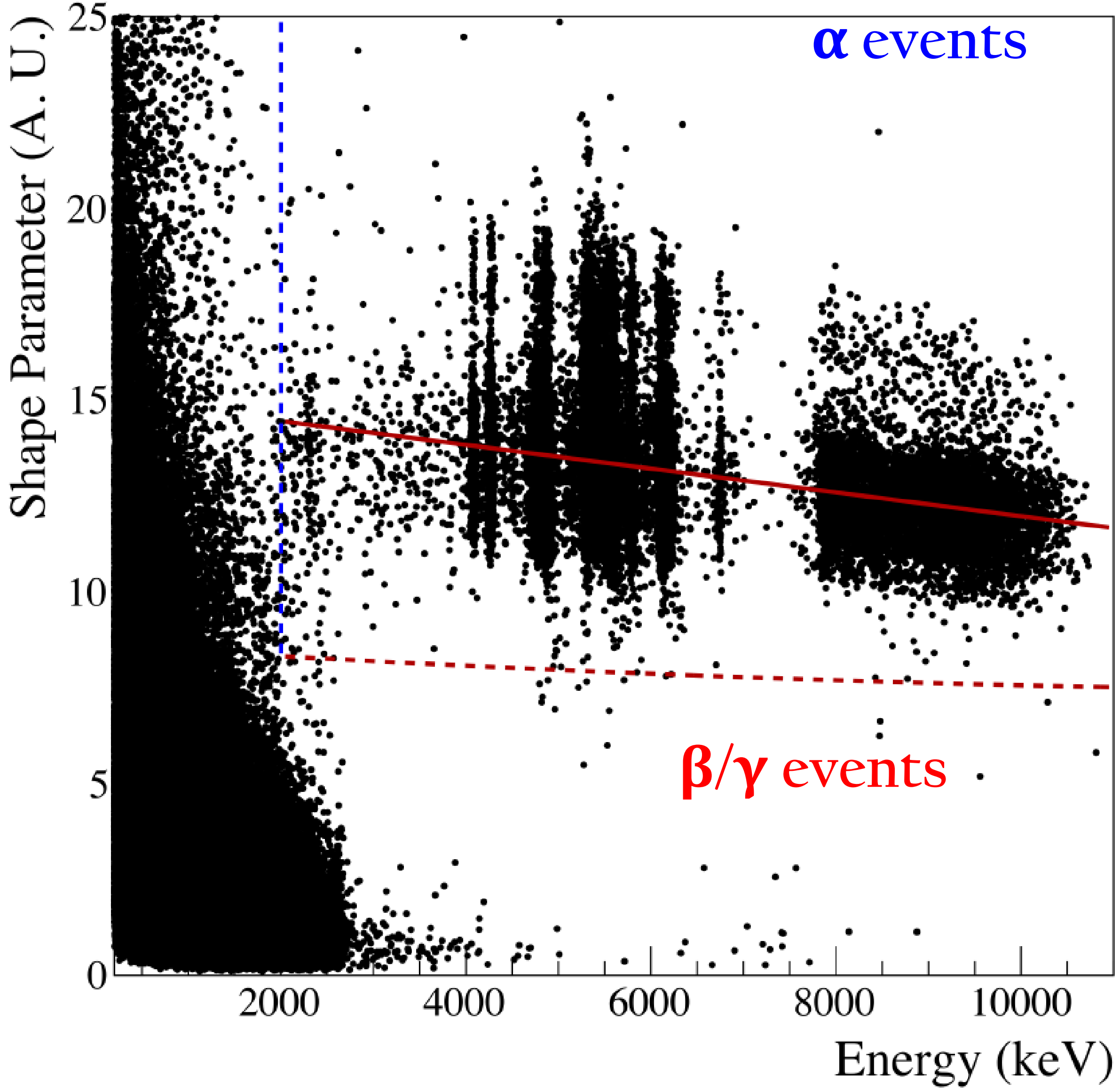
$$\mathrm{BKG} = (3.2 \pm 0.4) \cdot 10^{-2}\ \mathrm{cnts/(keV \cdot kg \cdot y)}$$

Background – Alpha Rejection

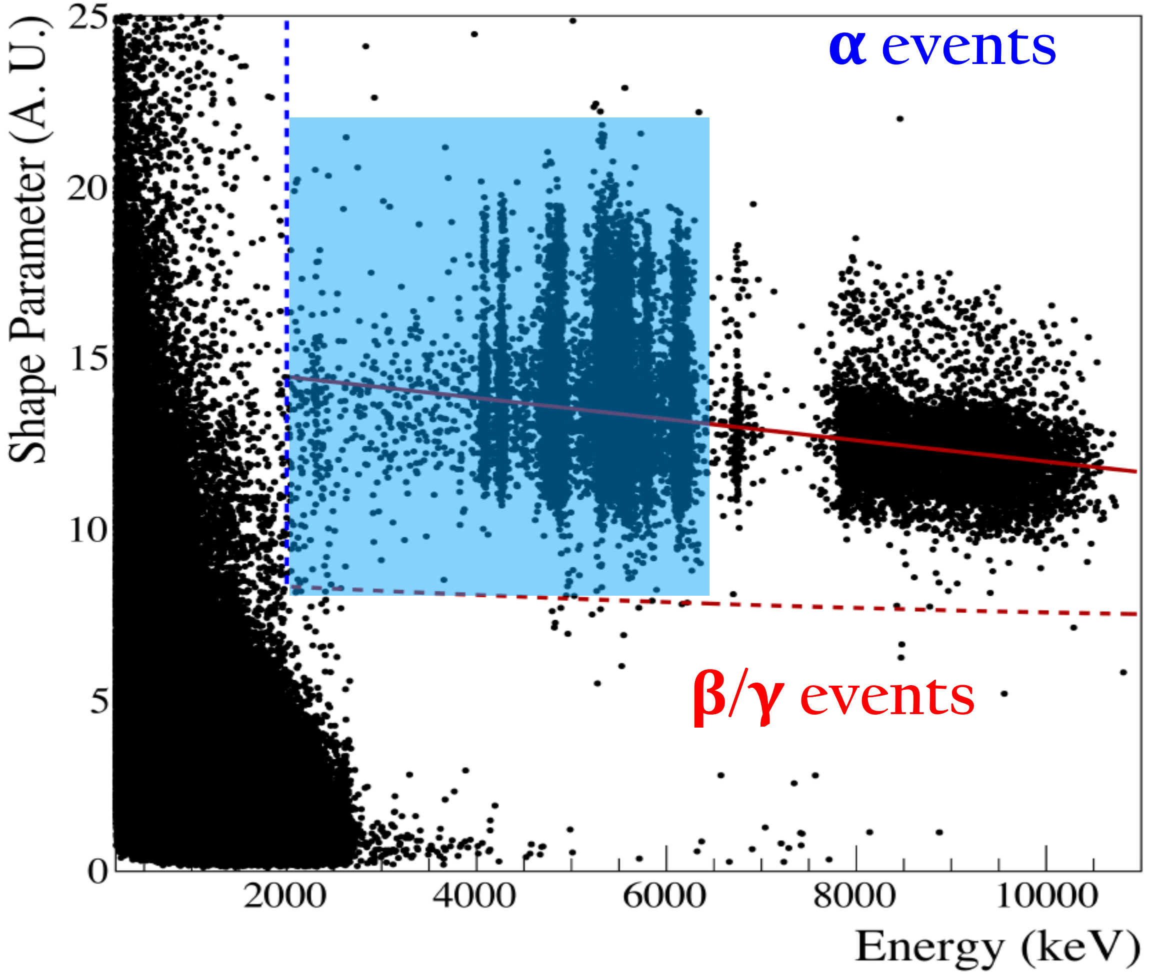
Light Signal depends on particle type



Selection based on light shape parameter

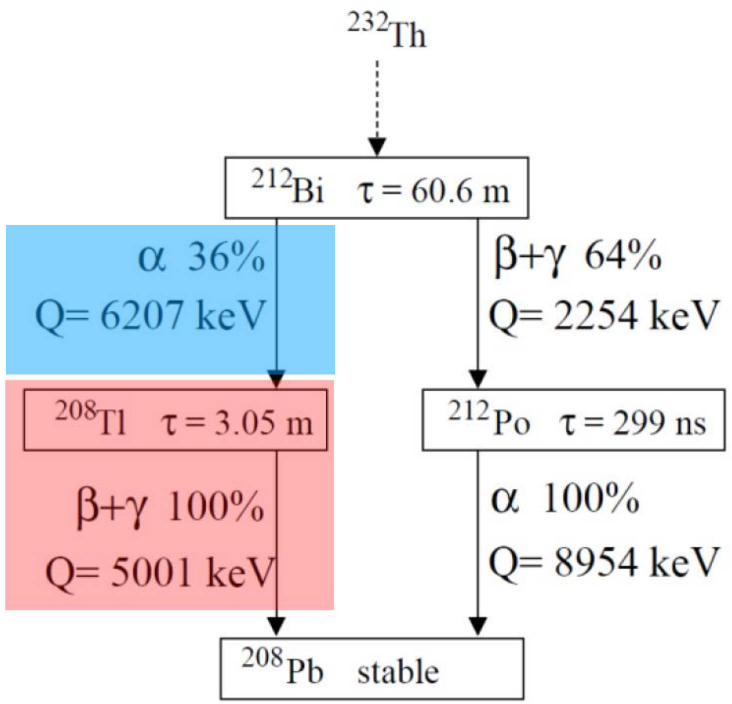


Background – Delayed coincidences rejection



Selection made

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



Veto any event succeeding a ^{212}**Bi α event** in a 7 half-life window

- α pulse shape
- 2.0 MeV < Energy < 6.5 MeV
    - Both peak and surface events

Background model

- A full model is needed to undestand the background components

EXPERIMENTAL DATA

Particle type
α events
β/γ events

Multiplicity (M)
Crystals triggered in 20ms

Combined with a **Bayesian analysis**

BACKGROUND SOURCES

ZnSe crystals
- **Bulk**
- **Surface**
  - O(10mm)
  - O(10nm)

Reflective Foil
- **Bulk**
- **Surface**
  - O(10nm)

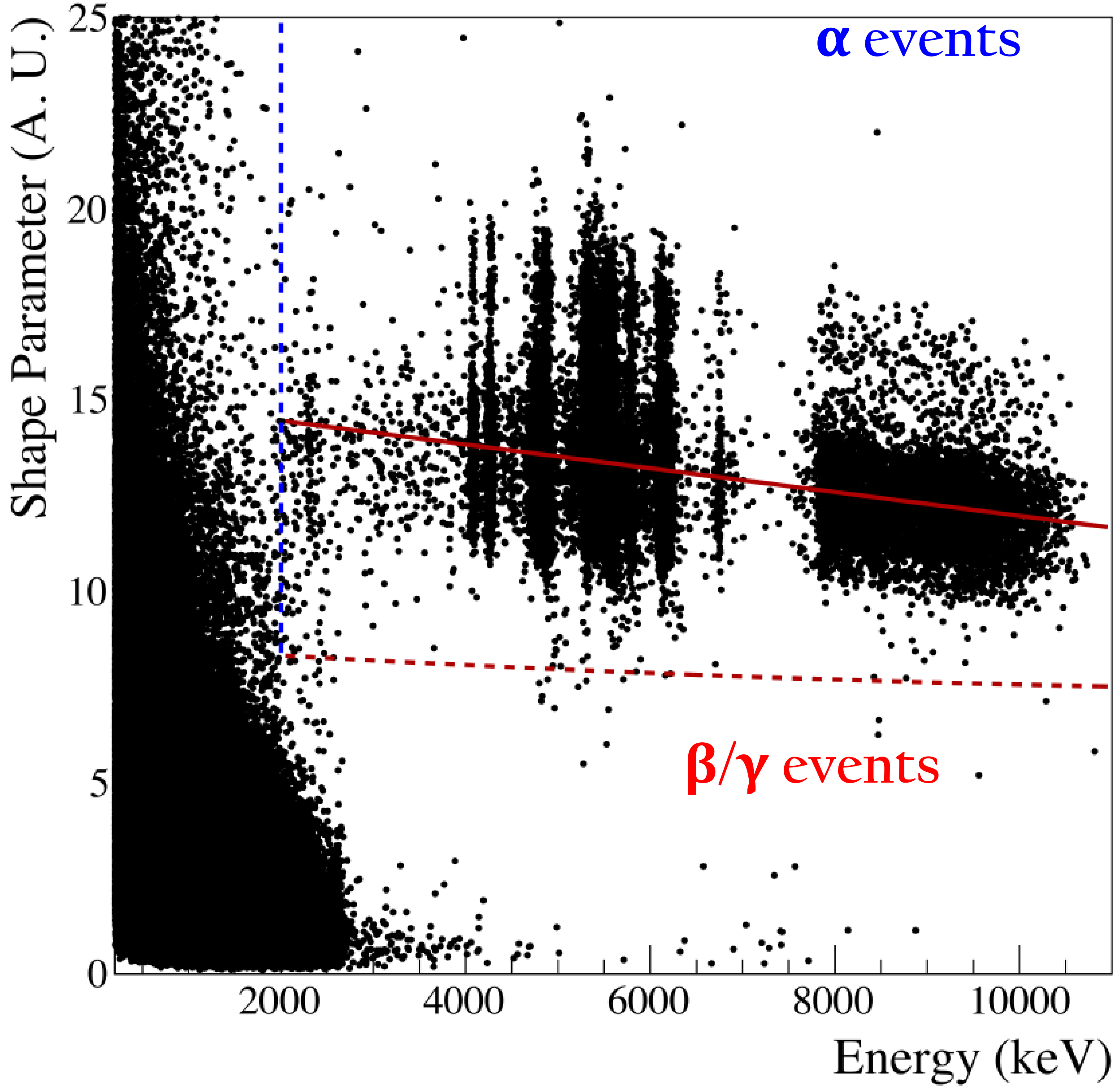
Muons
- High Multiplicity

Cryostat
- **Bulk**
- Cu Holder
- CryoInt
- Roman Lead
- Cryo Ext

Shape cut for Background Model

$$\mathrm{SP} = \frac{1}{\omega_r}\sqrt{\sum_{i=i_M}^{i_M+\omega_r}(y_i - A\cdot S_i)}$$

y_i = filtered light pulse
A = maximum amplitude
S_i = filtered average pulse
i_M = position of the maximum and
w_r = right width at half maximum of S_i



Optimized cut:

$$\mathrm{SP} = \mu_\alpha(E) - 3 \times \sigma_\alpha(E)$$

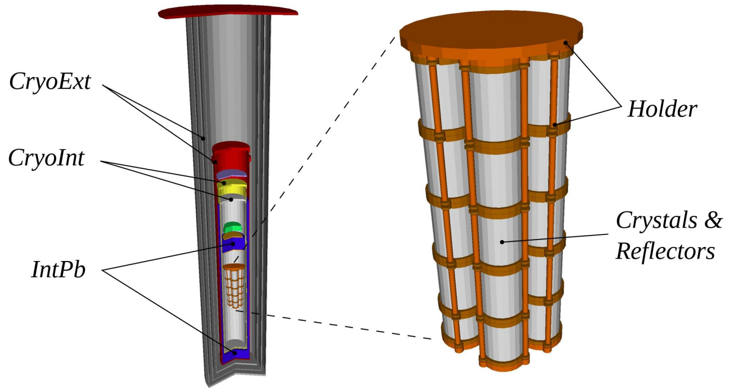
Parameter calculates for SP>6 (pure beta gamma)

Total Fit Results

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

(^{a}) *CryoInt* sources include also a minor contribution from *Holder* bulk contaminations.
(^{b}) *ExtPb* is used to represent also the *CryoExt* sources, that exhibit degenerate spectra.
(^{c}) *Reflectors* include also a contribution from light detectors, and from copper surface and other parts directly facing the ZnSe crystals.

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	$(3.7 \pm 0.2) \times 10^{-8}$



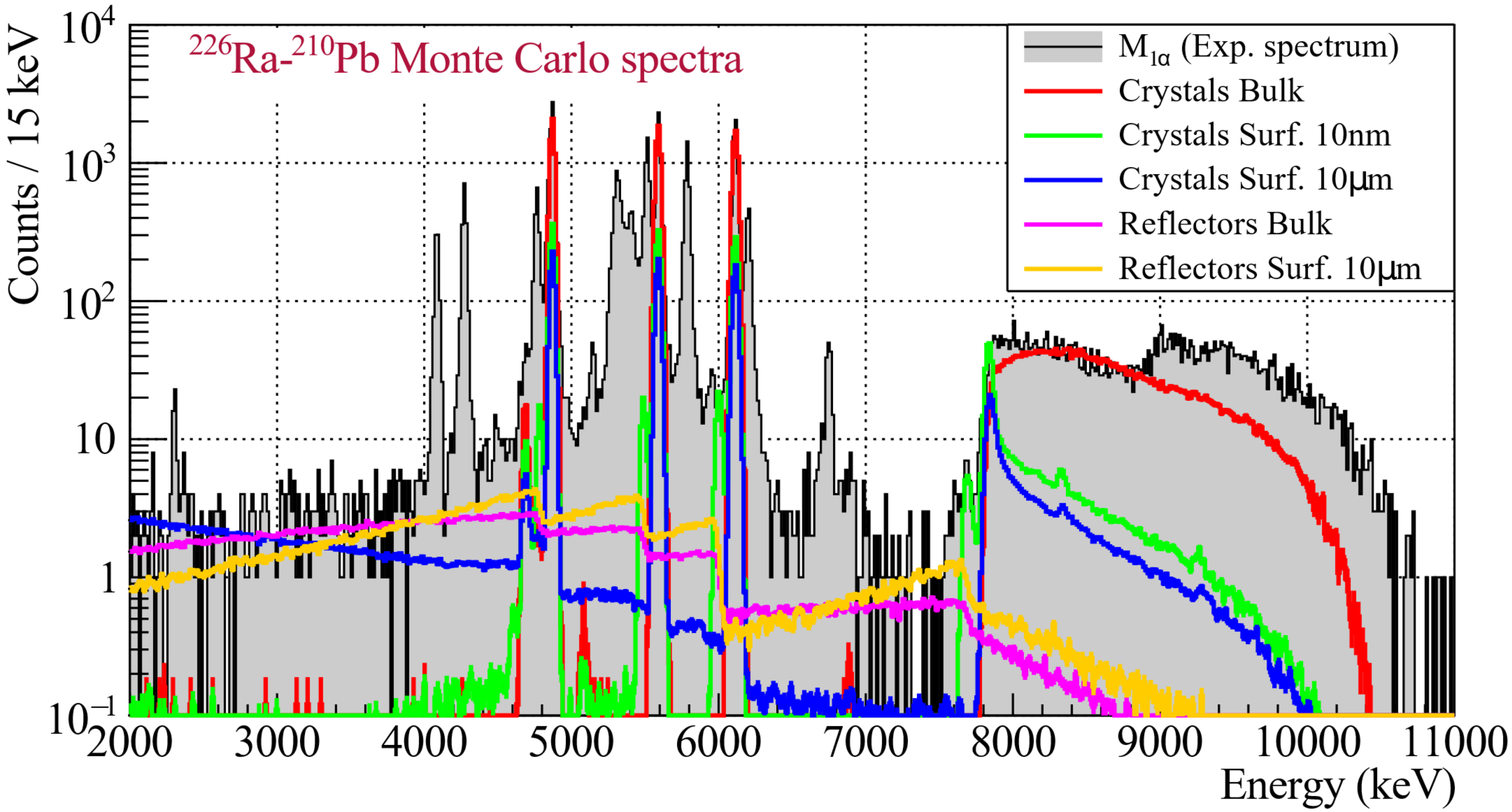
Surface
Exponential profile

ROI contaminations

After time veto of 7 livetimes

Component	ROI_{bkg} rate (10^{-4}counts/(keV kg yr))	Source	ROI_{bkg} rate (10^{-4}counts/(keV kg yr))
Crystals	$11.7 \pm 0.6\ ^{+1.6}_{-0.8}$	^{232}Th– bulk	$3.4 \pm 0.6 \pm 0.1$
		^{232}Th–surf	$3.4 \pm 0.5\ ^{+1.0}_{-0.7}$
		^{238}U–surf	$4.9 \pm 0.3\ ^{+1.3}_{-0.3}$
Reflectors & Holder	$2.1 \pm 0.3\ ^{+2.2}_{-1.0}$	^{232}Th	< 3.3
		^{238}U	$1.8 \pm 0.3\ ^{+1.4}_{-0.9}$
Cryostat & Shields	$5.9 \pm 1.3\ ^{+7.2}_{-2.9}$	^{232}Th	$3.5 \pm 1.3\ ^{+7.4}_{-3.3}$
		^{238}U	$2.4 \pm 0.4\ ^{+4.1}_{-0.7}$
Subtotal	$19.8 \pm 1.4\ ^{+6.6}_{-2.7}$		
Muons	$15.3 \pm 1.3 \pm 2.5$		
$2\nu\beta\beta$	6.0 ± 0.3 ($< 3 \times 10^{-6}$ counts/(keV kg yr) in [2.95–3.05] MeV range)		
Total	$41 \pm 2\ ^{+9}_{-4}$		
Experimental	$35\ ^{+10}_{-9}$		

Alpha vs Bulk



- Different impact on the continuum