The 27th International Workshop on Weak Interactions and Neutrinos

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FINAL RESULTS OF THE CUPID-0 PHASE I EXPERIMENT

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On behalf of the CUPID-0 collaboration

CUPID-0 FOR CUPID (CUORE UPGRADE WITH PARTICLE ID)

CUPID is a proposed 0νββ experiment based on **scintillating bolometers**.
Its mission is to discover **0νββ decay** if $m_{\beta\beta} > 10$ meV.

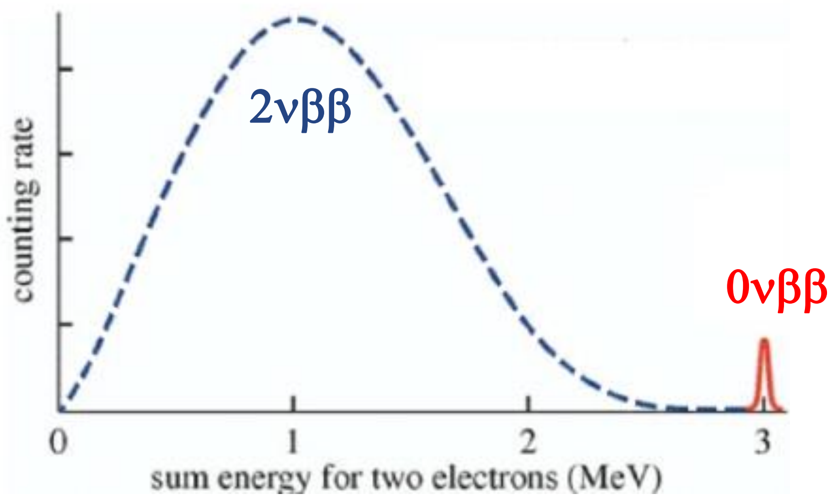
TECHNICAL CHALLENGES

- Detector mass in the range of several hundred kg of the ββ isotope

  ➡ **Isotopic enrichment**

- Background close to zero at the ton×year exposure scale

  ➡ **Active background rejection**
  and improved material selection



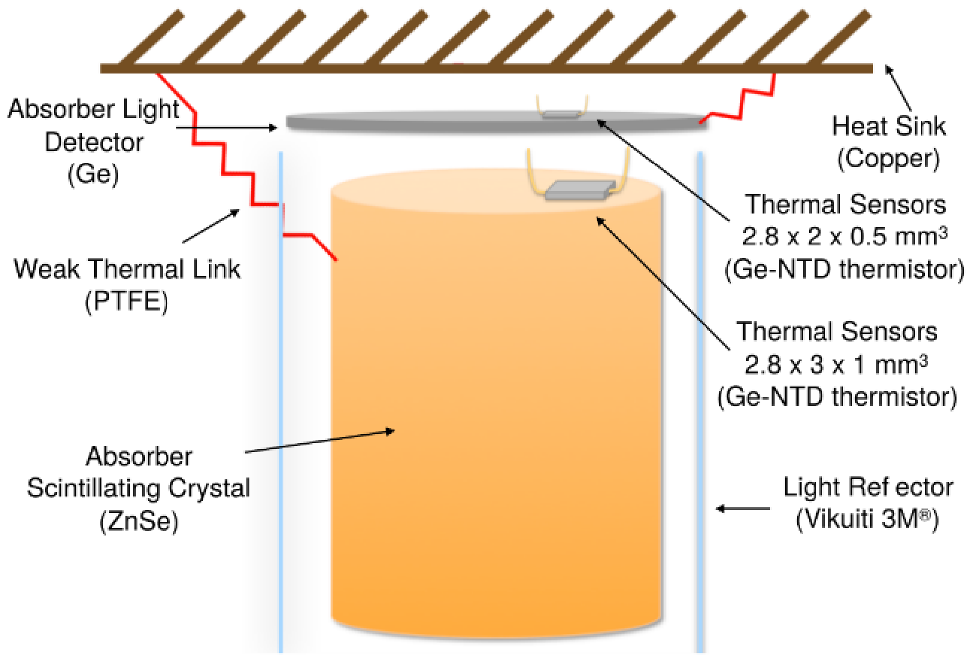
- **Energy resolution** of a few keV (FWHM) around 0νββ Q-value

ββ energy

CUPID-0 is the first demonstrator of the new technologies that will be implemented in CUPID and it is also a competitive 0νββ decay 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



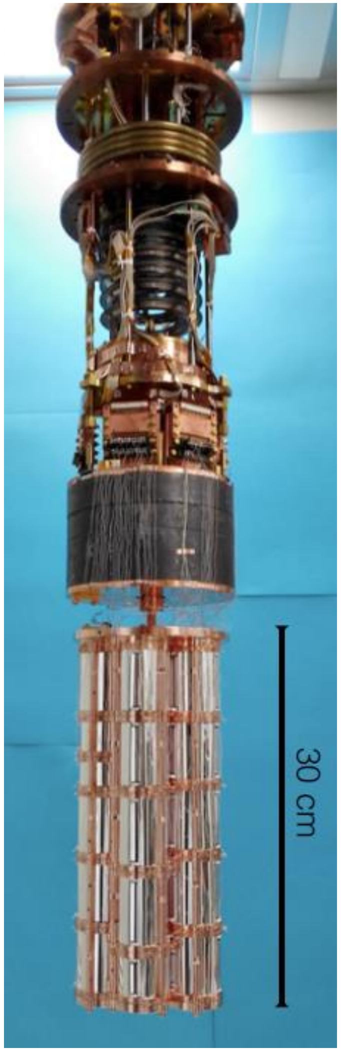
Detector Features

- High energy resolution $\mathcal{O}$(1/1000)
- High detection efficiency (source = detector)
- **Particle IDentification**

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

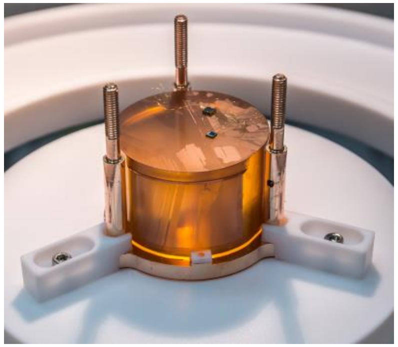
- α background: identification and rejection
- γ/β background: ββ isotope with large Q-value

THE CUPID-0 DETECTOR

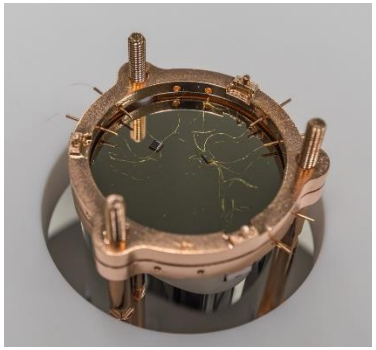


Array of scintillating bolometers for the investigation of ^{82}Se $0\nu\beta\beta$ (Q = 2997.9 ± 0.3 keV).

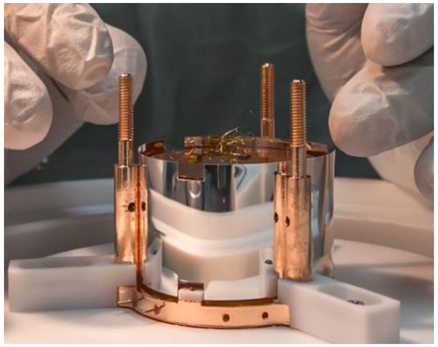
- 95% enriched $Zn^{82}Se$ bolometers
- 10.5 kg of ZnSe, 5.17 kg of ^{82}Se (3.8×10^{25} $\beta\beta$ nuclei)
- Ge bolometers at top/bottom of crystals to detect scintillation
- NTD thermistors to measure energy depositions
- Reflecting foils to enhance light collection
- High radiopure copper holder structure



ZnSe crystal



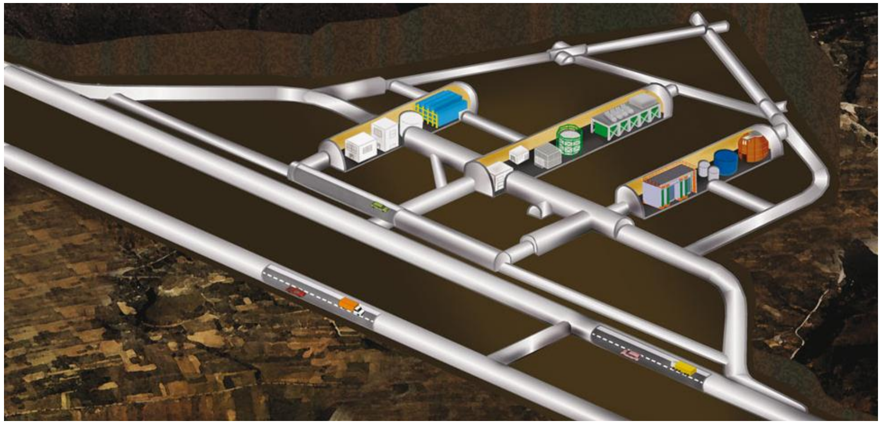
Ge light detector



Reflecting foil

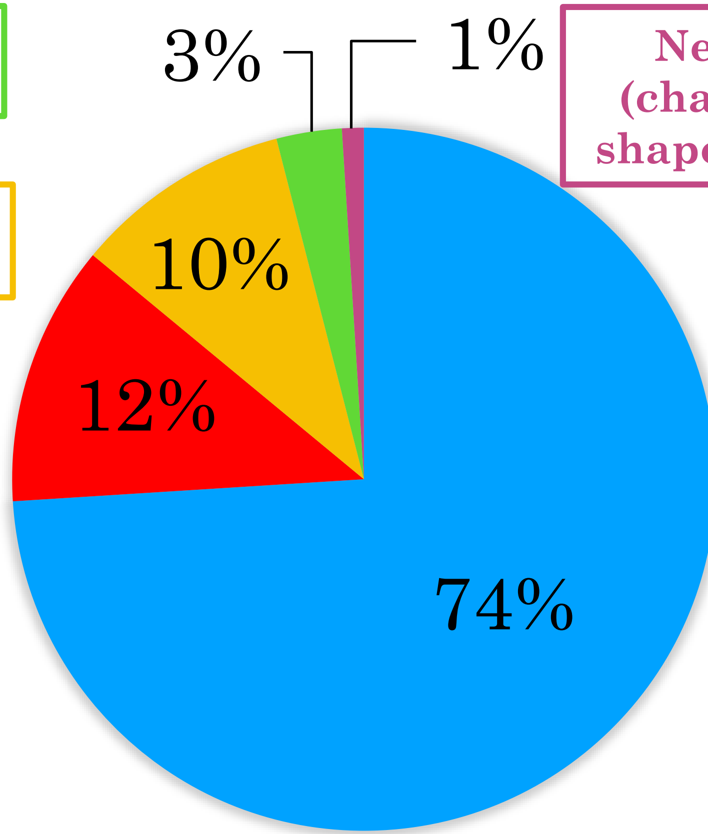
CUPID-0 @ LNGS

- Deep underground location at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, 1400 m of rock (~3600 m.w.e.)
- Installed in the cryostat previously used for Cuoricino and CUORE-0 experiments



CUPID-0 DATA TAKING (PHASE I)

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



^{56}Co Energy Calibration

^{232}Th Energy Calibration

System maintenance

Neutron calibration (characterization of β/γ shape parameters at RoI)

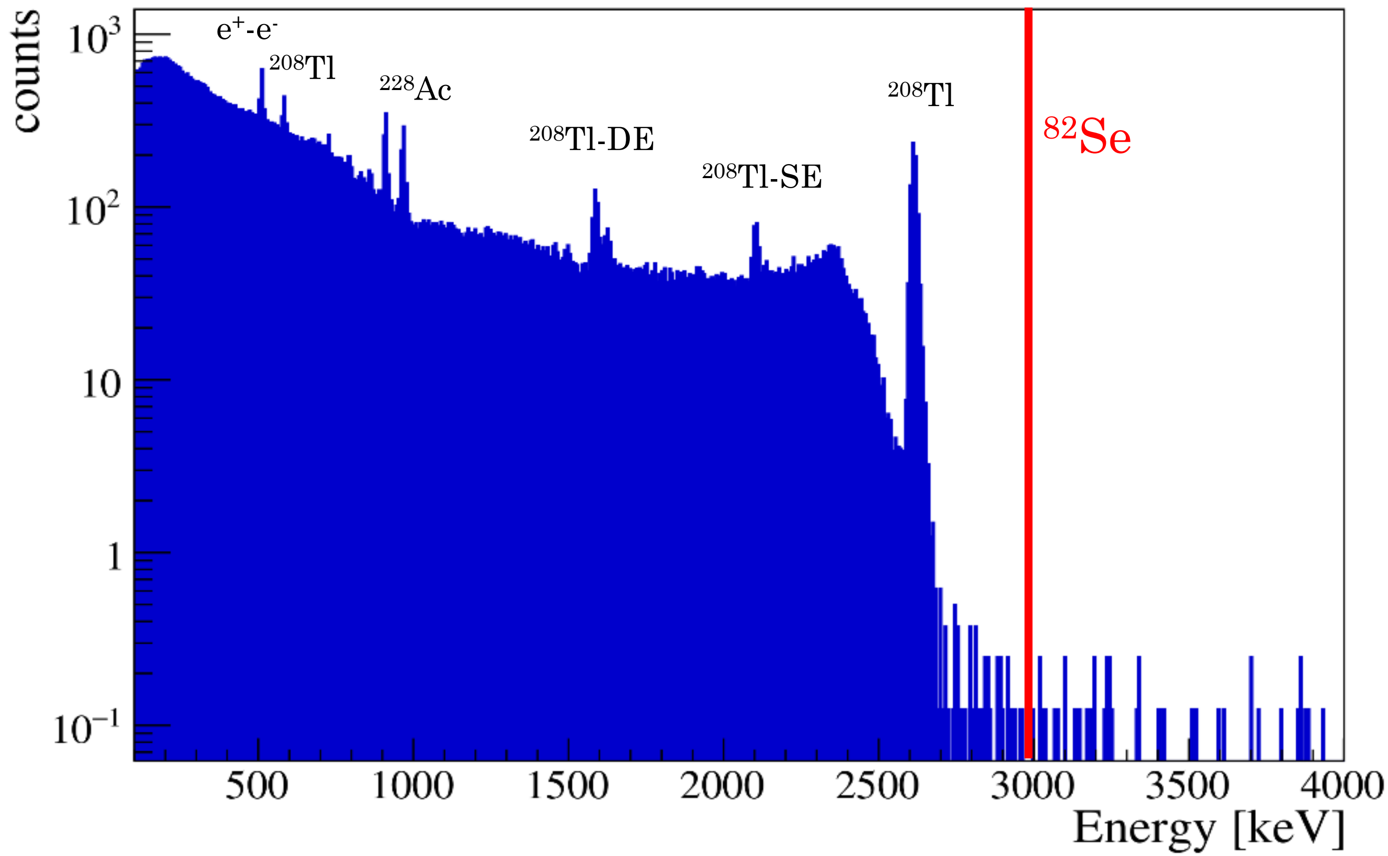
ββ physics

ZnSe exposure: 9.95 kg×yr

^{82}Se exposure: 5.29 kg×yr

DETECTOR CALIBRATION WITH ^{232}TH

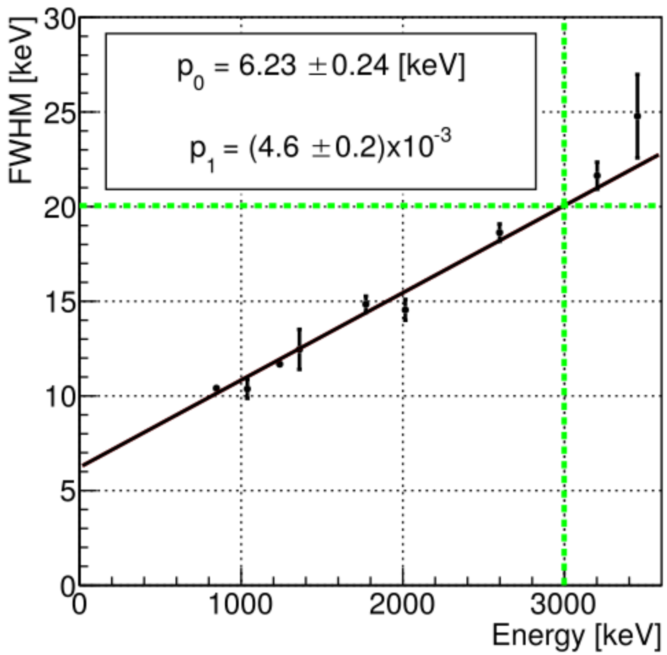
- ^{232}Th sources are periodically deployed beside the cryostat for calibration of heat and intercalibration of light detectors

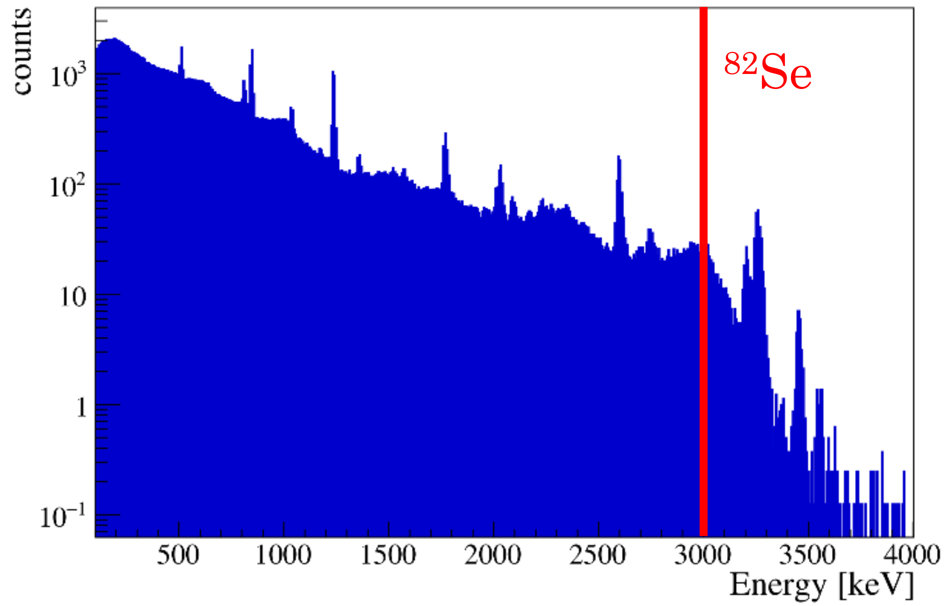


Detector Calibration with ^{56}Co

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

- check the goodness of energy reconstruction
- evaluate the energy resolution at ^{82}Se $Q_{\beta\beta}$





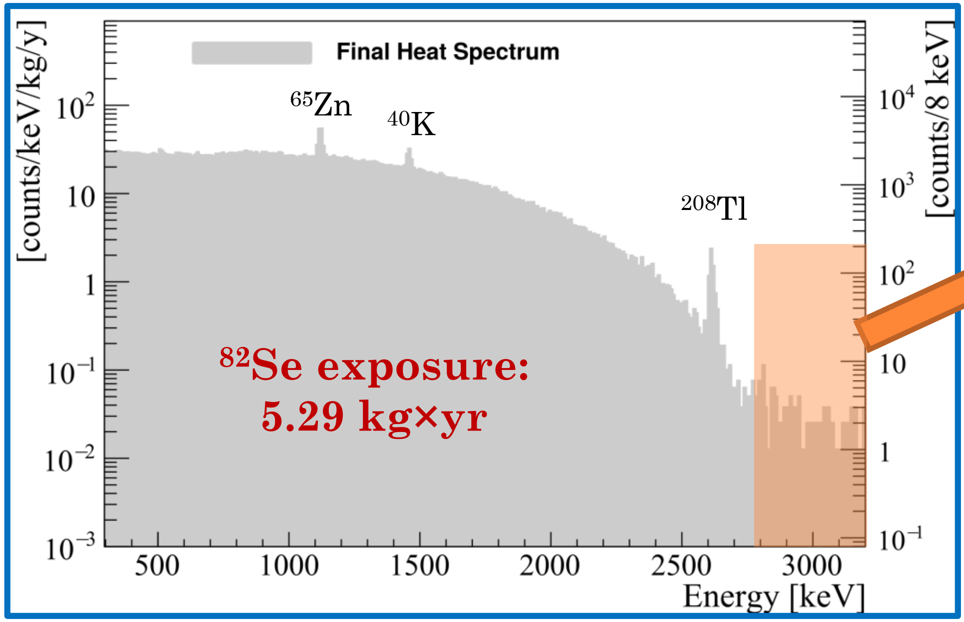
The exposure-weighted harmonic mean **FWHM energy resolution** at ^{82}Se $Q_{\beta\beta}$ is equal to:

(20.05 ± 0.34) keV

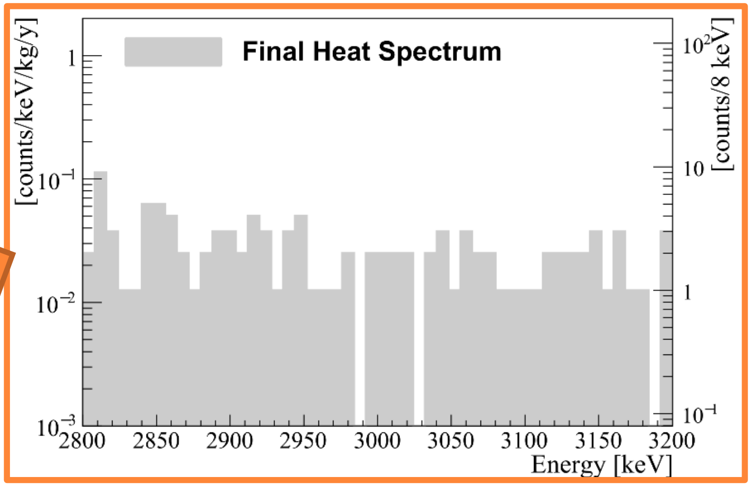
0νββ SEARCH: HEAT SPECTRUM PRODUCTION

- **Anti-coincidence** → tag&reject events depositing energy in more than one ZnSe crystal within a ±20ms window
- Rejection of **pile-up** (1 sec before and 4 sec after trigger)
- Rejection of "non-particle" events through **pulse shape analysis**

ββ physics spectrum

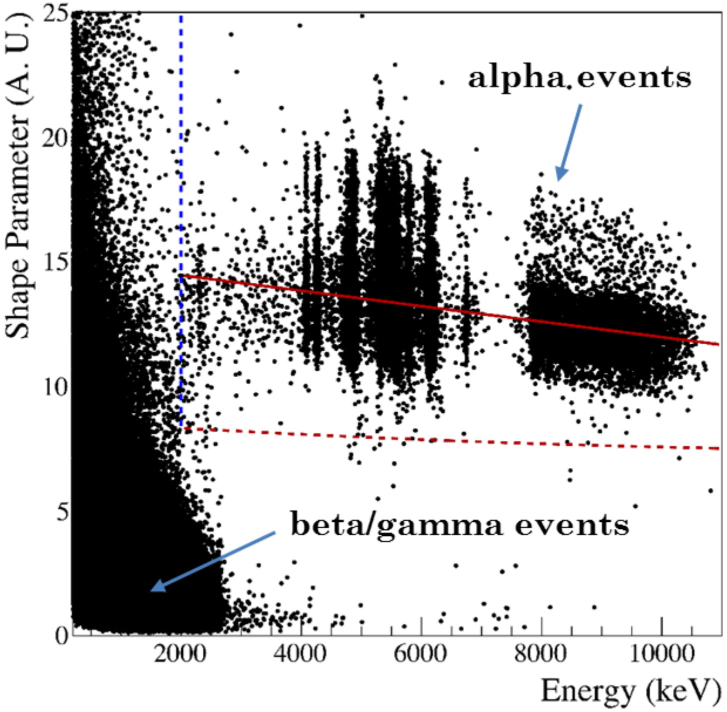


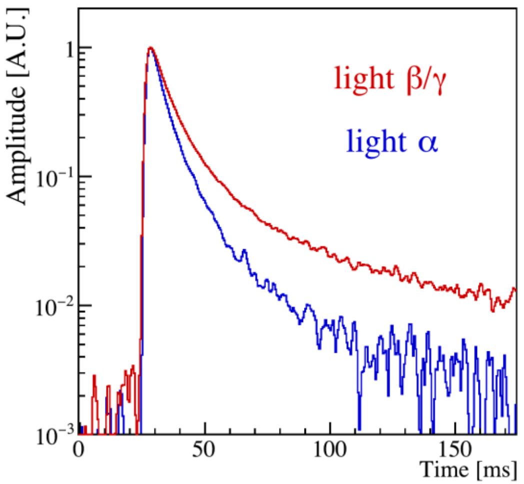
0νββ RoI

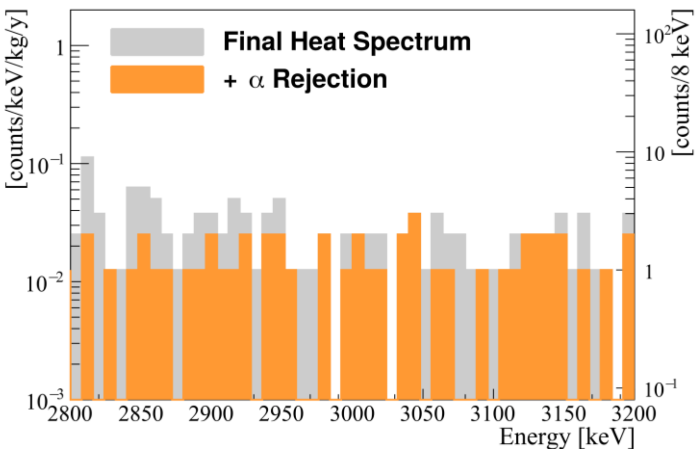


$0\nu\beta\beta$ SEARCH: REJECTION OF α PARTICLES

- Rejection of α events based on the shape of the light pulse





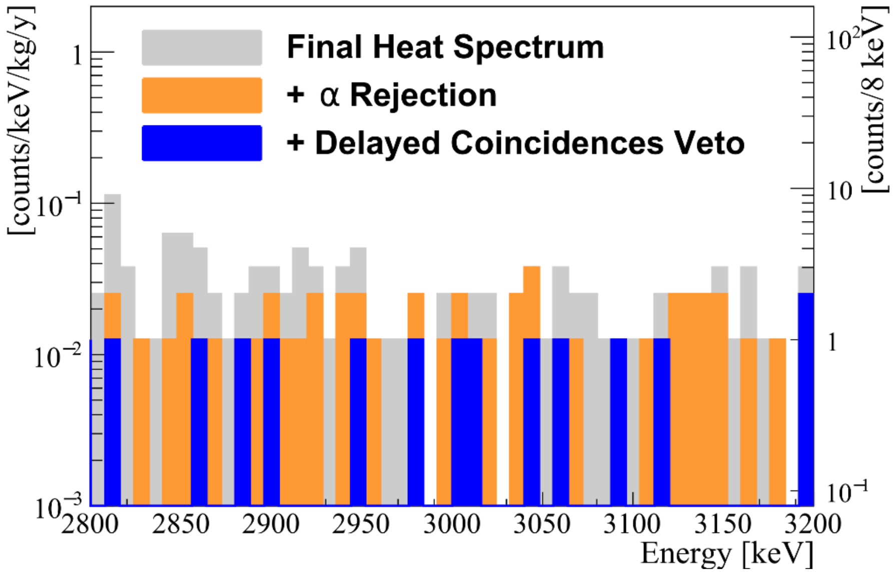


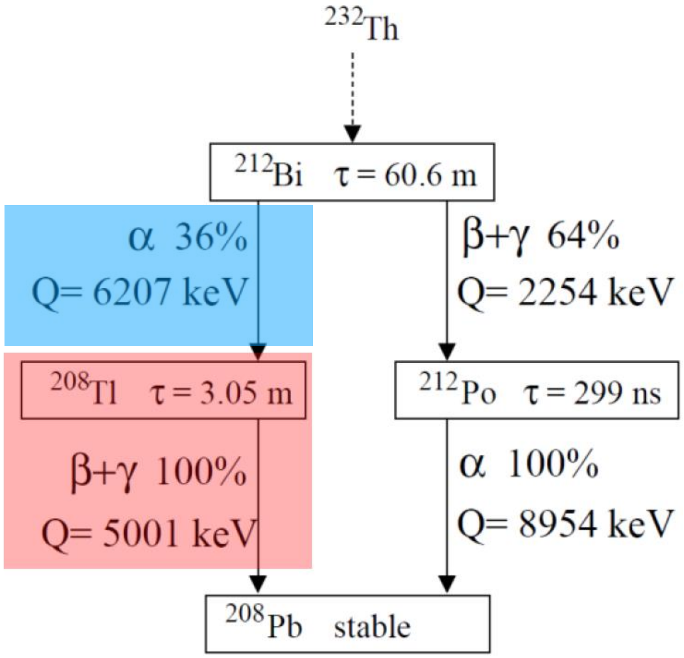
- mean value of α particle SP ($\mu_\alpha(E)$)
- acceptance threshold = $\mu_\alpha(E) - 3 \cdot \sigma_\alpha(E)$
- energy below which the PID is not applied

$0\nu\beta\beta$ SEARCH: REJECTION OF ^{208}TL EVENTS

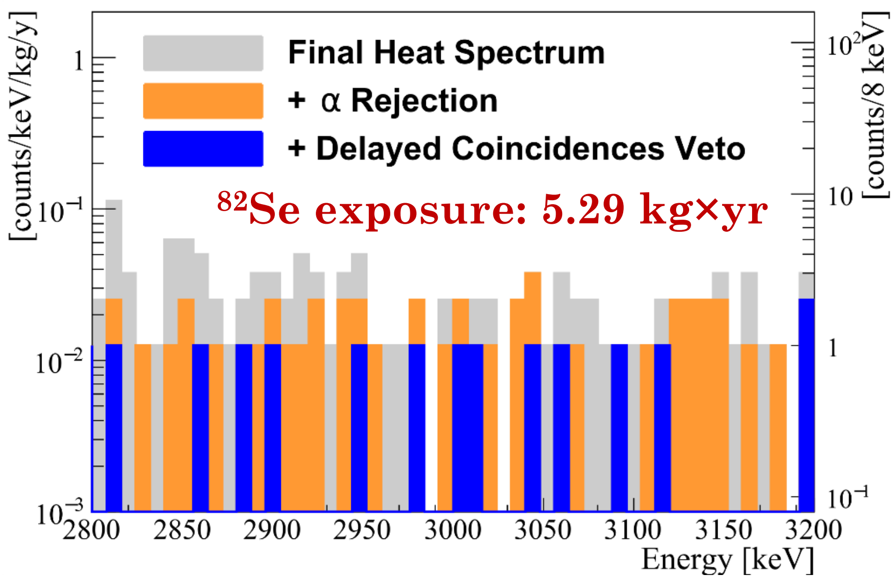
Analysis of $\alpha - \beta/\gamma$ delayed coincidences:

- ^{208}Tl β/γ events are preceded by ^{212}Bi α events
- We veto any event preceded by a primary ^{212}Bi α event within 7 half-life time window
- ^{212}Bi events are selected among α events with energy in the range 2 – 6.5 MeV





0νββ SEARCH: 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 range [2.8 – 3.2] MeV:

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

Lowest background achieved with bolometric experiments.

No evidence of 0νββ signal

Best half-life limit on ^{82}Se 0νββ

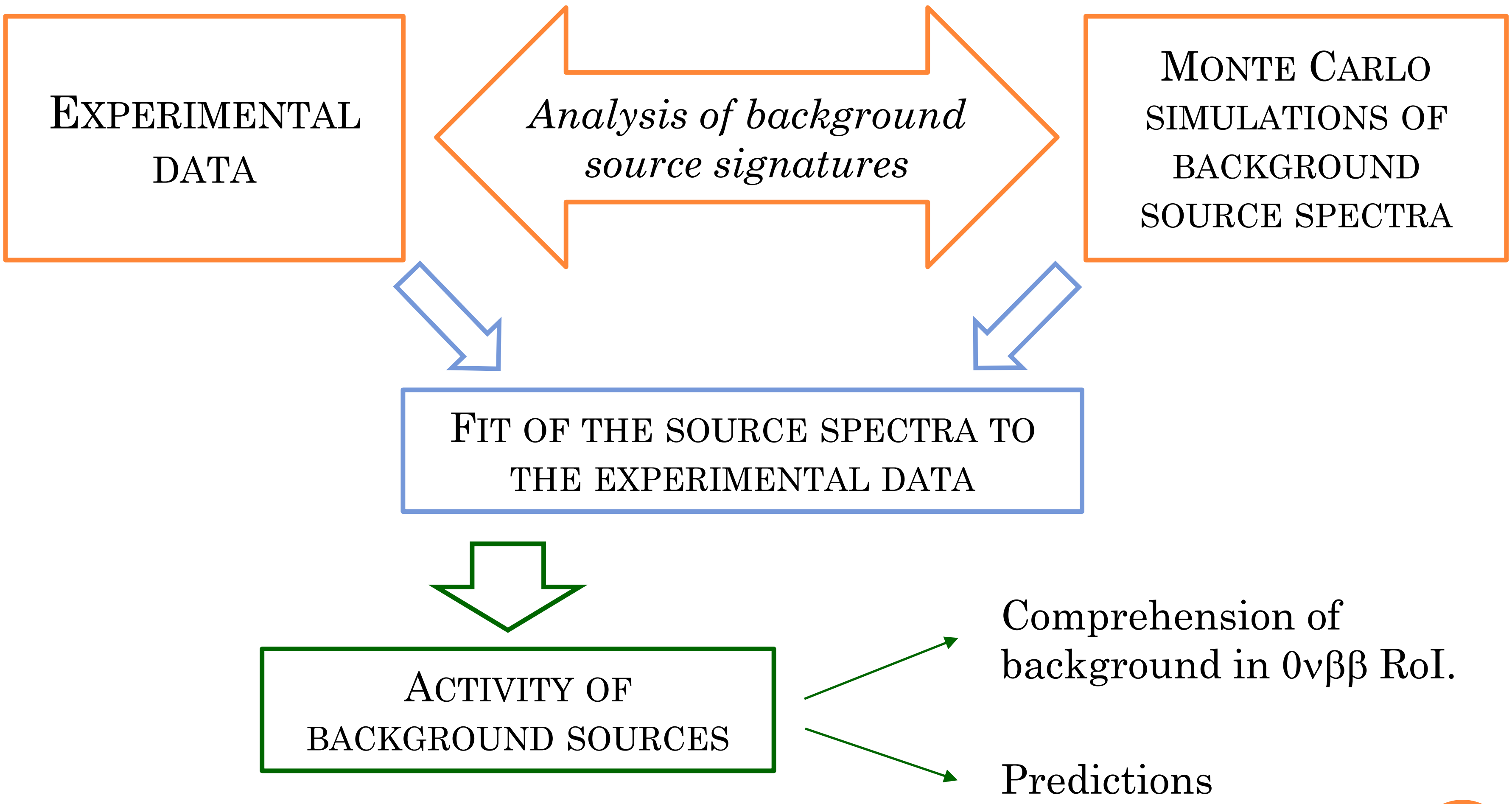
$$T^{0\nu}_{1/2} > 3.5 \cdot 10^{24} \text{ yr (90\% C.I.)}$$

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

range due to the nuclear matrix element calculations

BACKGROUND MODEL

[arXiv:1904.10397](https://arxiv.org/abs/1904.10397)



BACKGROUND MODEL: EXPERIMENTAL DATA

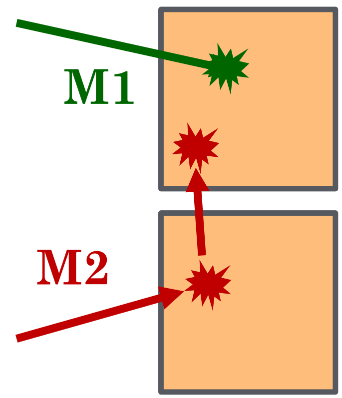
- Experimental data divided according to **multiplicity** and **particle type**

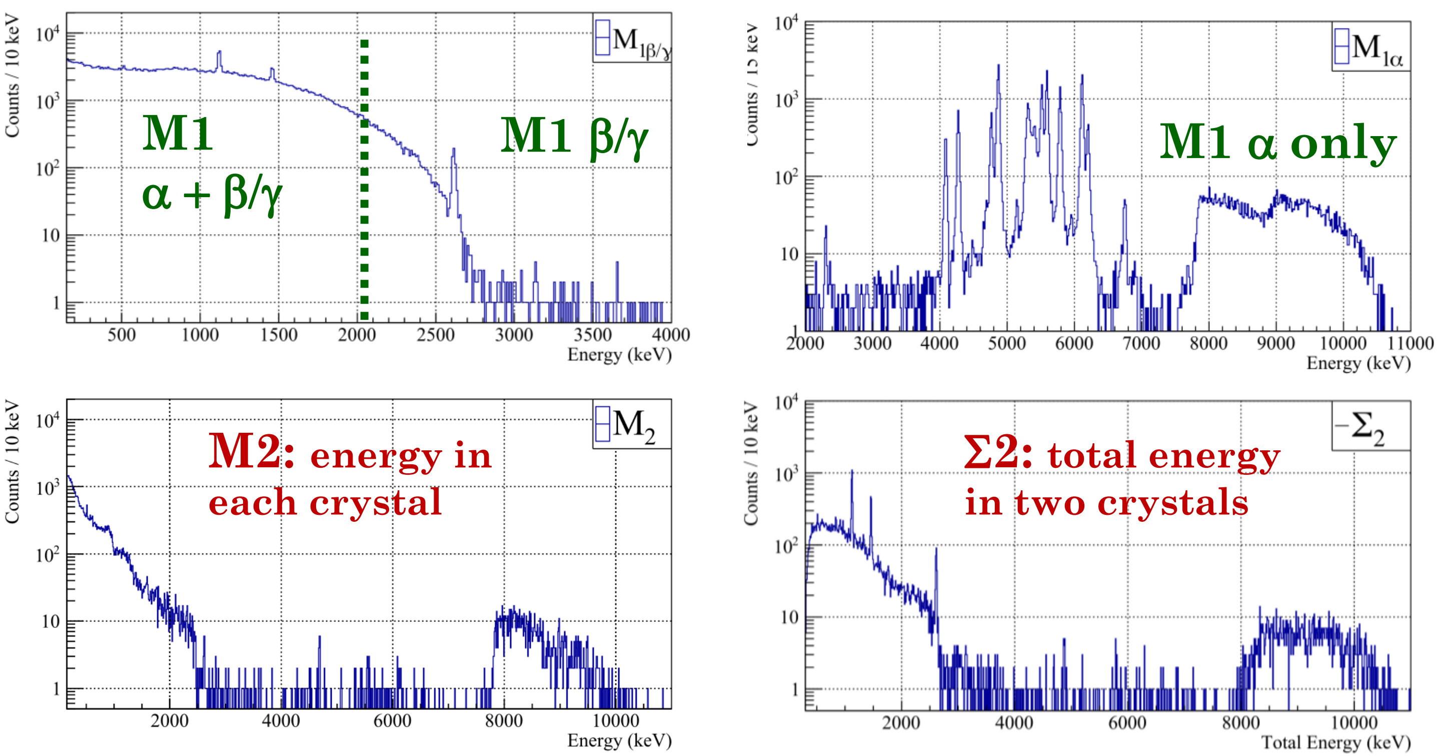
  → we build 4 spectra

- Analysis of **γ** and **α** lines in the spectra.

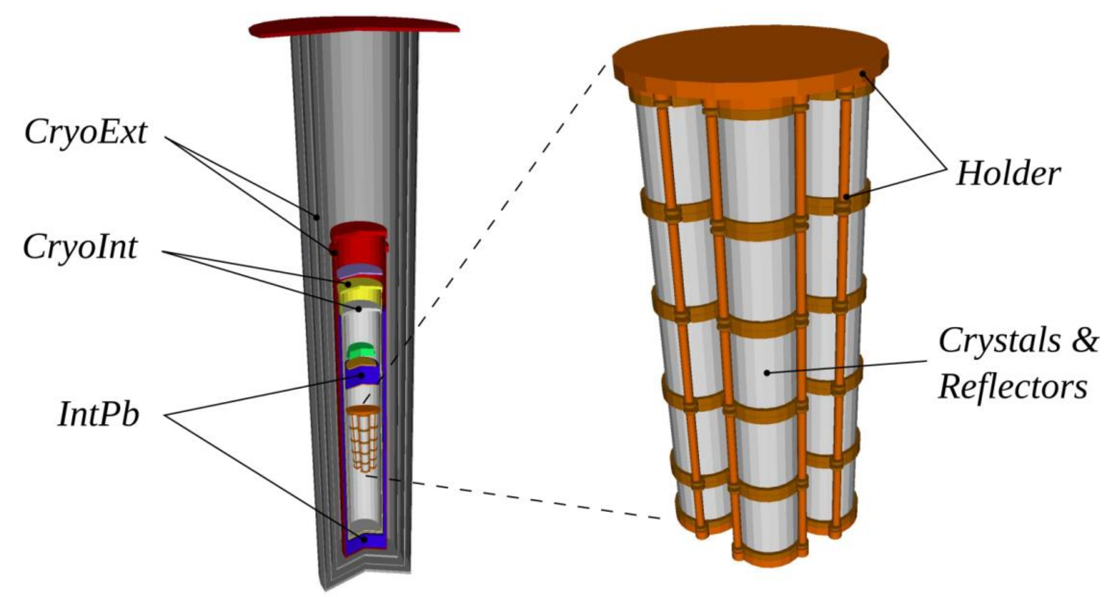
Multiplicity (M)

Time-coincidence window: 20ms





Background model: MC simulations

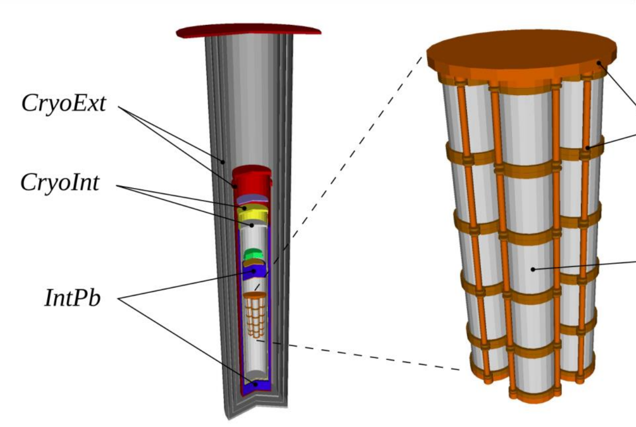


- Monte Carlo simulations (Geant4) of background sources
- CUPID-0 geometry modelled with high detail
- Reproduction of detector features (coincidences, resolution, particle ID, thresholds, …)

Background model: sources

Background model uses 33 sources:

- different contaminants (^{232}Th and ^{238}U decay chains, ^{40}K, cosmogenic activation, …)
- different positions in the experimental setup
- Muons



Background sources

Internal/near sources to fit M1α spectrum

- **Crystals**: bulk / shallow surface $\mathcal{O}$(10nm) / deep surface $\mathcal{O}$(10μm)
- **Reflectors & Holder surface**: shallow surface $\mathcal{O}$(10nm) / deep surface $\mathcal{O}$(10μm)

Surface: exponential profile

External sources

- **CryoInt**: 50mK and 600mK cryostat internal shields & holder bulk
- **IntPb**: ancient roman lead shield
- **CryoExt**: IVC, OVC, superinsulation, main bath & External Lead shield

BACKGROUND MODEL: BAYESIAN FIT

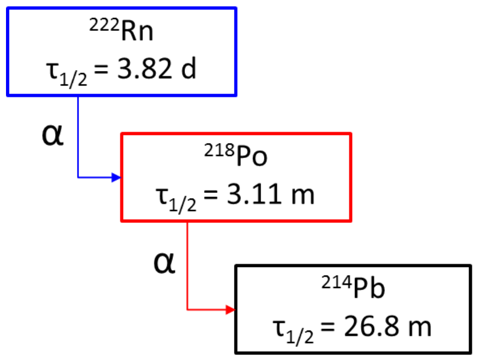
- We perform a simultaneous **Bayesian fit** to M1α, M1β/γ, M2, and Σ2 spectra to determine source activities (i.e. MC normalizations)
- We use Markov Chain MC to sample the Joint PDF of fit parameters
- ***Priors*** are exploited to include additional information from previous experiments/radioassay measurements and from special analyses of CUPID-0 data:
  - Muons → normalized to M>3 events
  - Analysis of α–α delayed coincidences to get information about positions of crystal contaminations.

Given a ***parent*** event @ Q-value (P_Q), the probability to observe a time-correlated ***daughter*** event @ Q-value (D_Q):

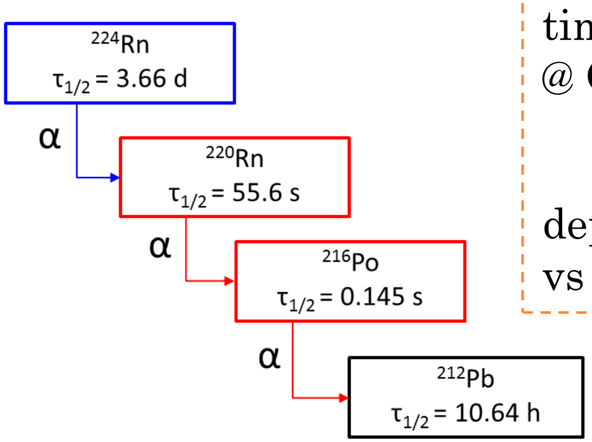
$$P(D_Q \mid P_Q)$$

depends on source position (bulk vs surface).

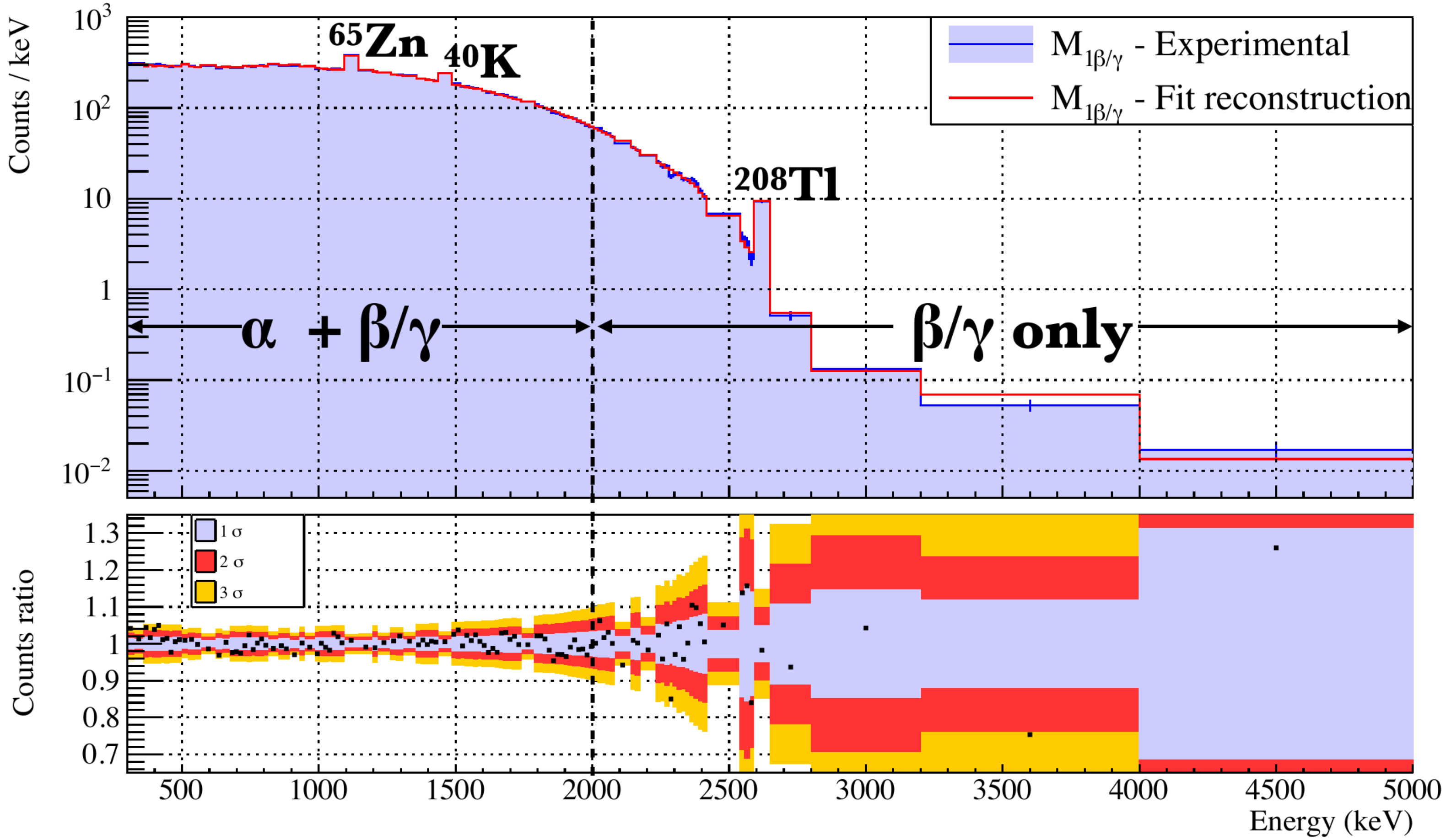
^{238}U CHAIN



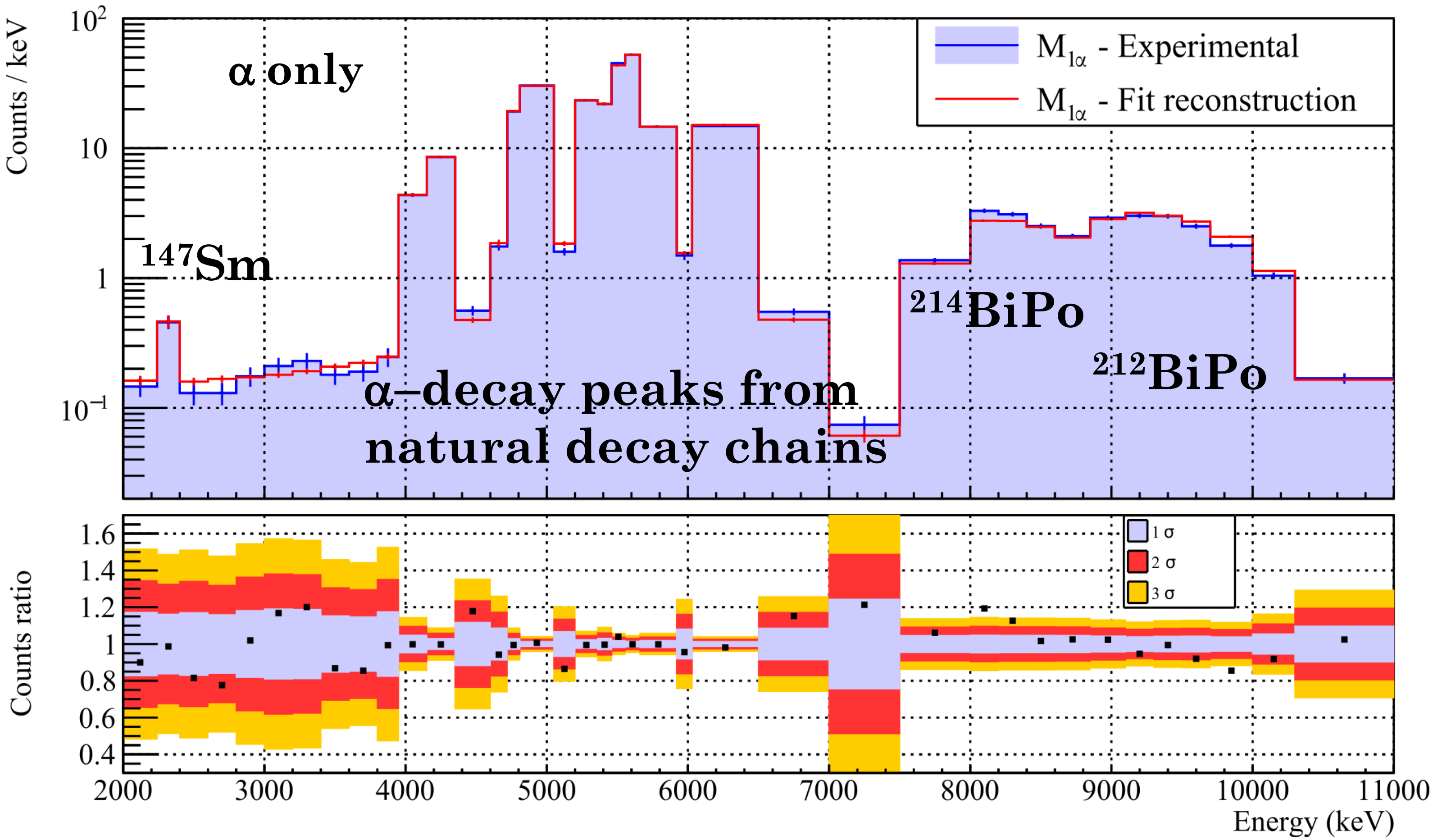
^{232}TH CHAIN



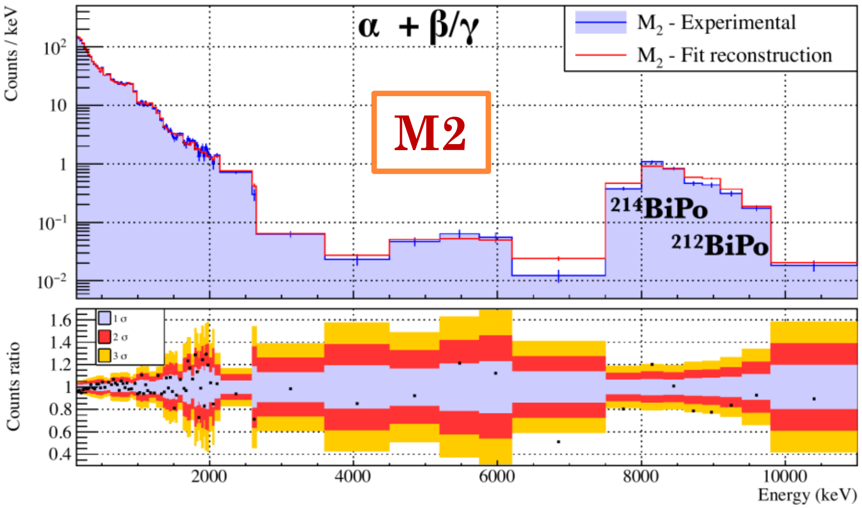
Background model: fit result M1 β/γ

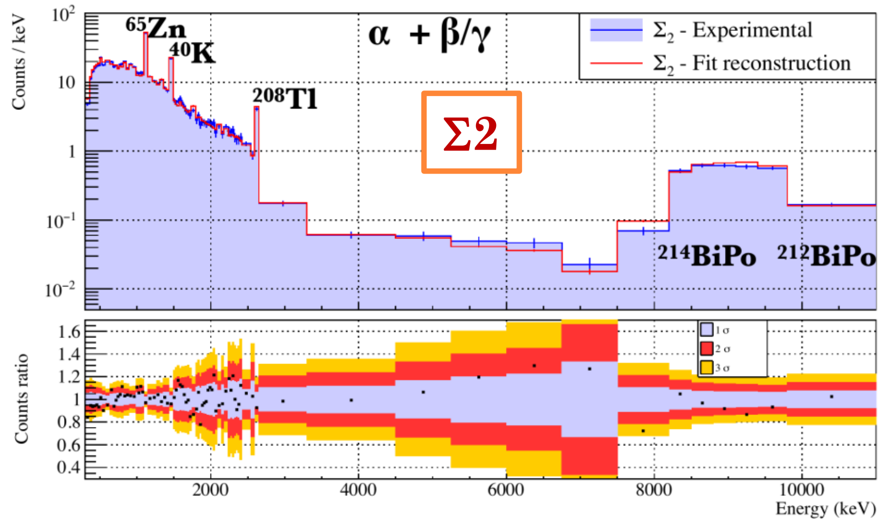


BACKGROUND MODEL: FIT RESULT M1 α

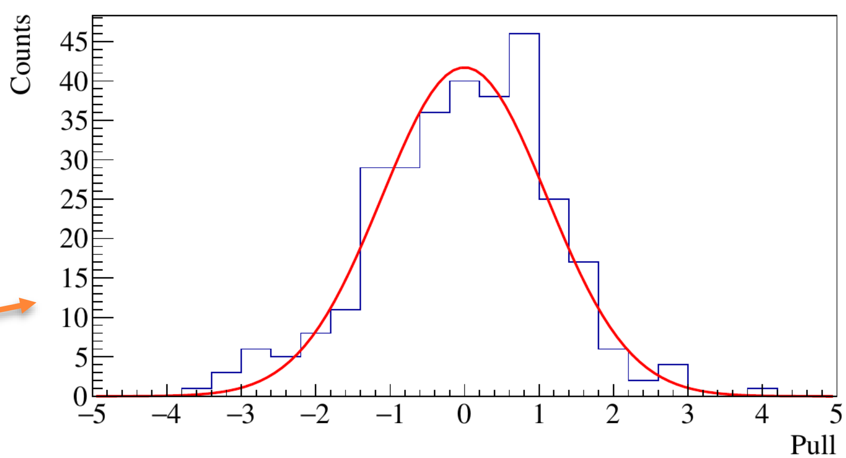


BACKGROUND MODEL: FIT RESULT M2 AND Σ2





- Peaks and continuum are well modelled
- Some differences in BiPo pile-up events, due to imperfect energy reconstruction
- Distribution of fit residuals compatible with a Gaussian with $\mu = 0$ and $\sigma = 1$.



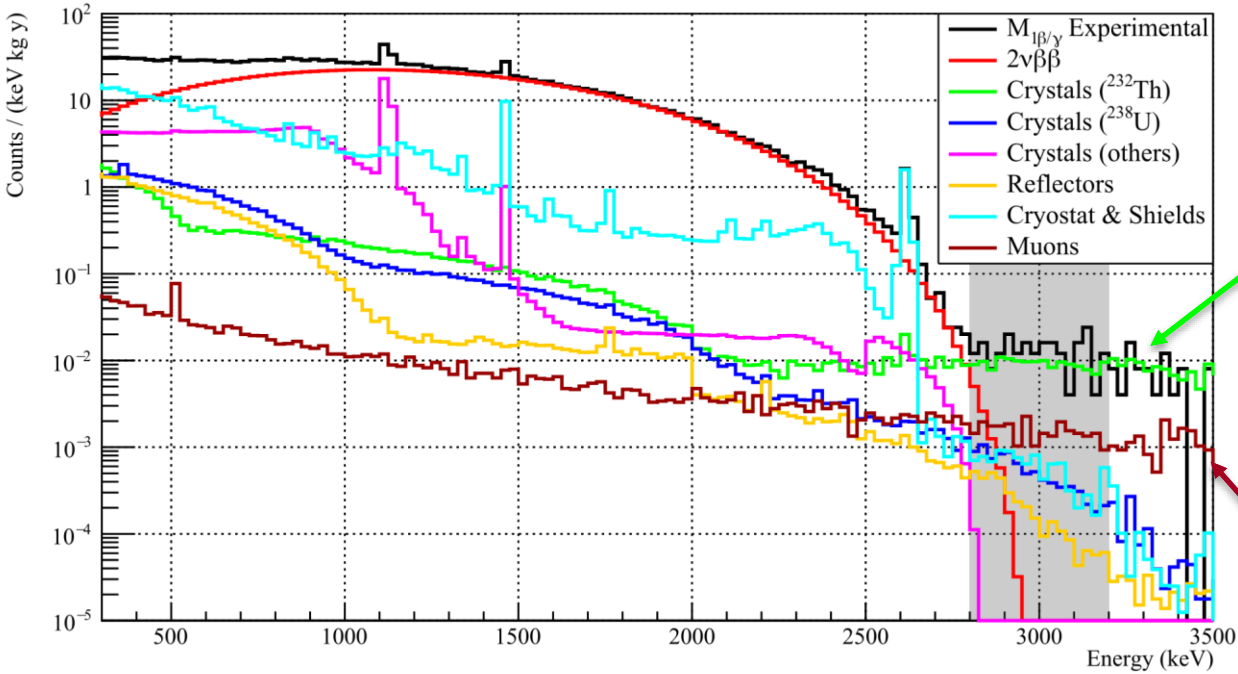
BACKGROUND MODEL: RESULTS

arXiv:1904.10397

Background sources contributing to the M1β/γ reconstruction, grouped by position and contaminant:

2νββ is the dominant contribution

Possibility to perform detailed study on this decay (paper in preparation)



^{232}Th in Crystals is the main contribution in RoI because rejection of ^{208}Tl events is not applied here

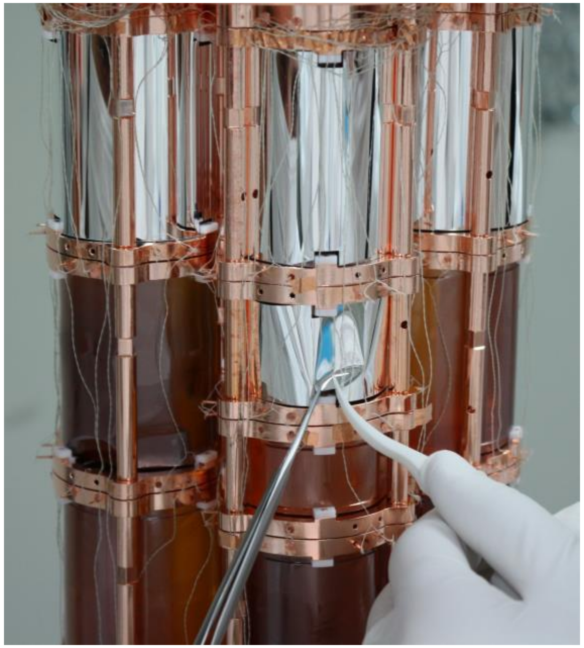
After delayed coincidences cut

Muons give ~44% of residual background rate in RoI

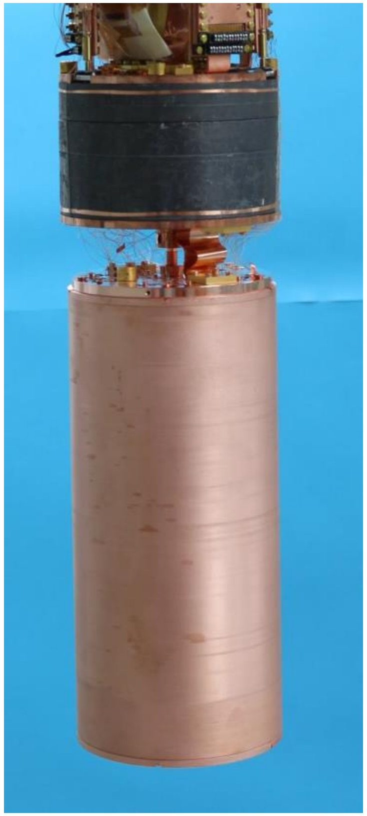
Other background sources in crystals, reflectors, cryostat & shields, contributing to the RoI at a level of a few 10^{-4} counts/(keV kg y)

CUPID-0 Phase II: upgrades

- Muons are 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!!!!!



SUMMARY AND FUTURE PERSPECTIVES

- CUPID-0 is the first large array of enriched scintillating bolometers
- CUPID-0 Phase I → ZnSe exposure: 9.95 kg·y
- Excellent background index in the ^{82}Se 0νββ RoI:

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

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

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

- Background model: information on background sources and best measurement of ^{82}Se 2νββ decay (paper in preparation)
- CUPID-0 Phase II → better understanding of background sources

Thanks for your attention!!!