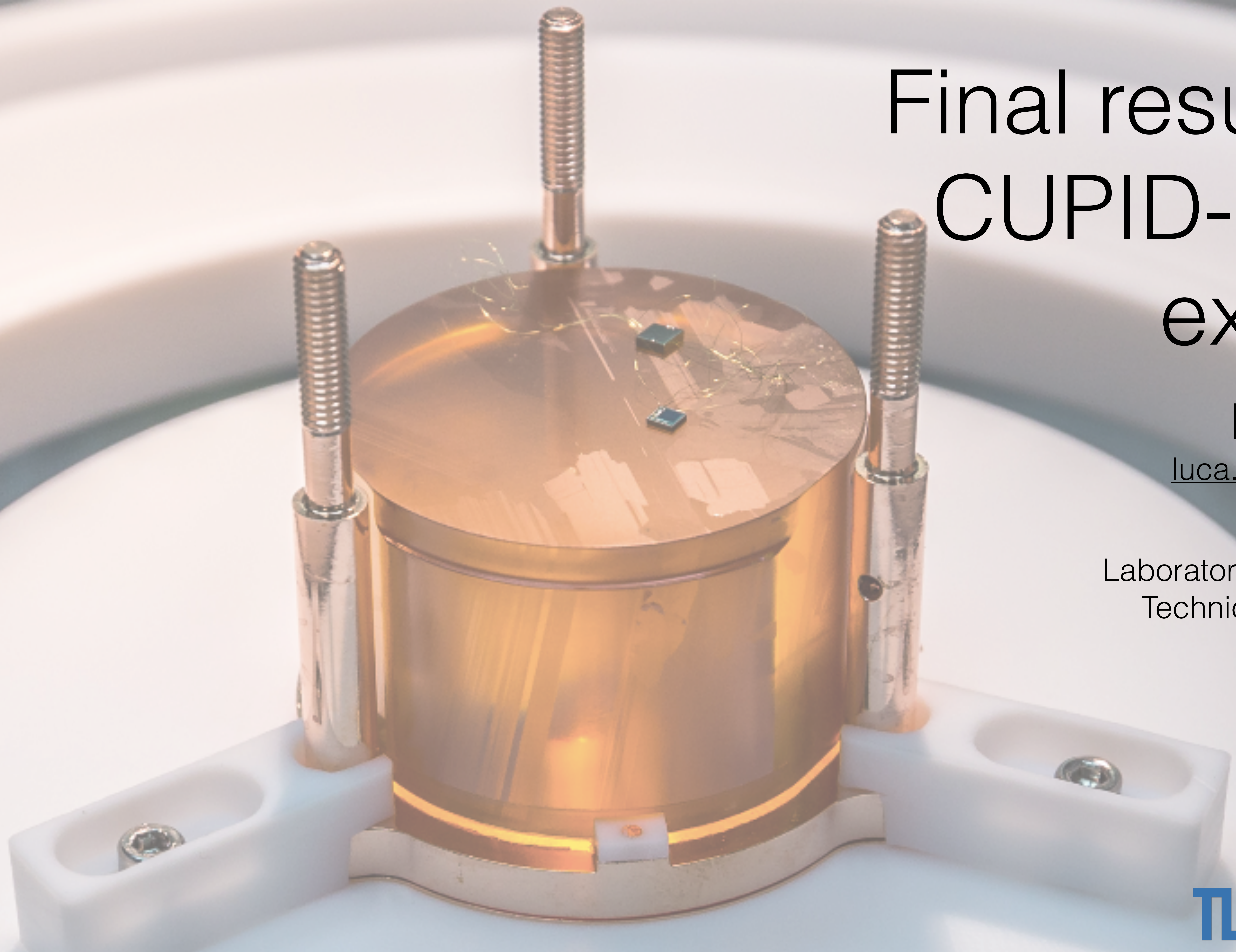

# Final results of the CUPID-0 Phase I experiment


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European Physical Society - HEP2019 10-17 JULY 2019 - Ghent, Belgium

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# Outline

- $0\nu\beta\beta$ motivations
- The cryogenic calorimetric technique
- CUPID-0
  - Detector design and construction
  - Detector performance
  - Results

# 0νββ implications

0νββ at the level of nucleons:

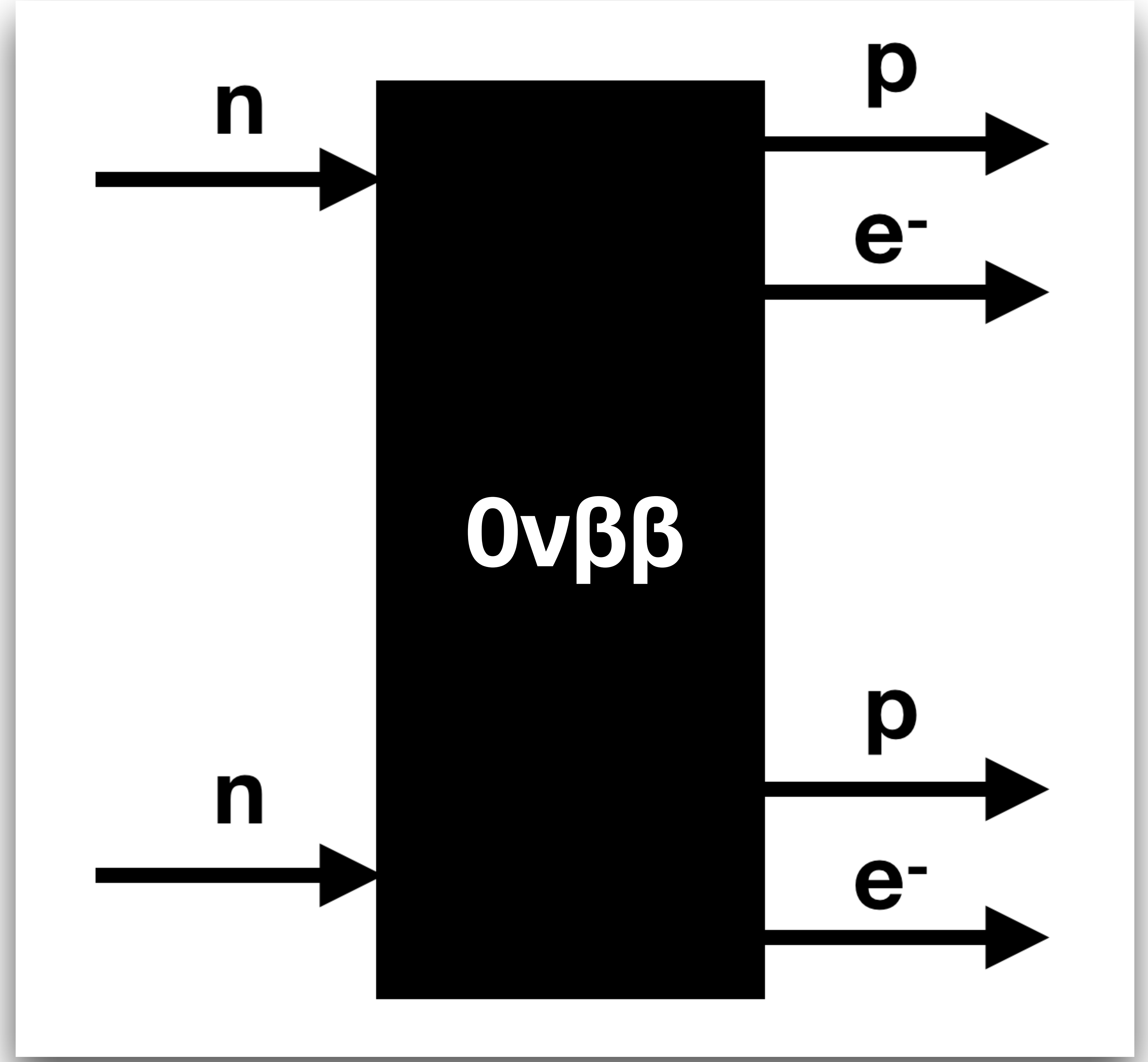
$$2n \rightarrow 2p + 2e^-$$

- need letpon-number-violating physics beyond the SM (ΔL=2)
- 2 leptons are produced out of energy: **matter creation** ("leptogenesis")

Fundamental process (strong implications):

- Baryo/Leptogenesis requires the violation of baryon number and lepton number (*B*−*L* is the only conserved quantity)

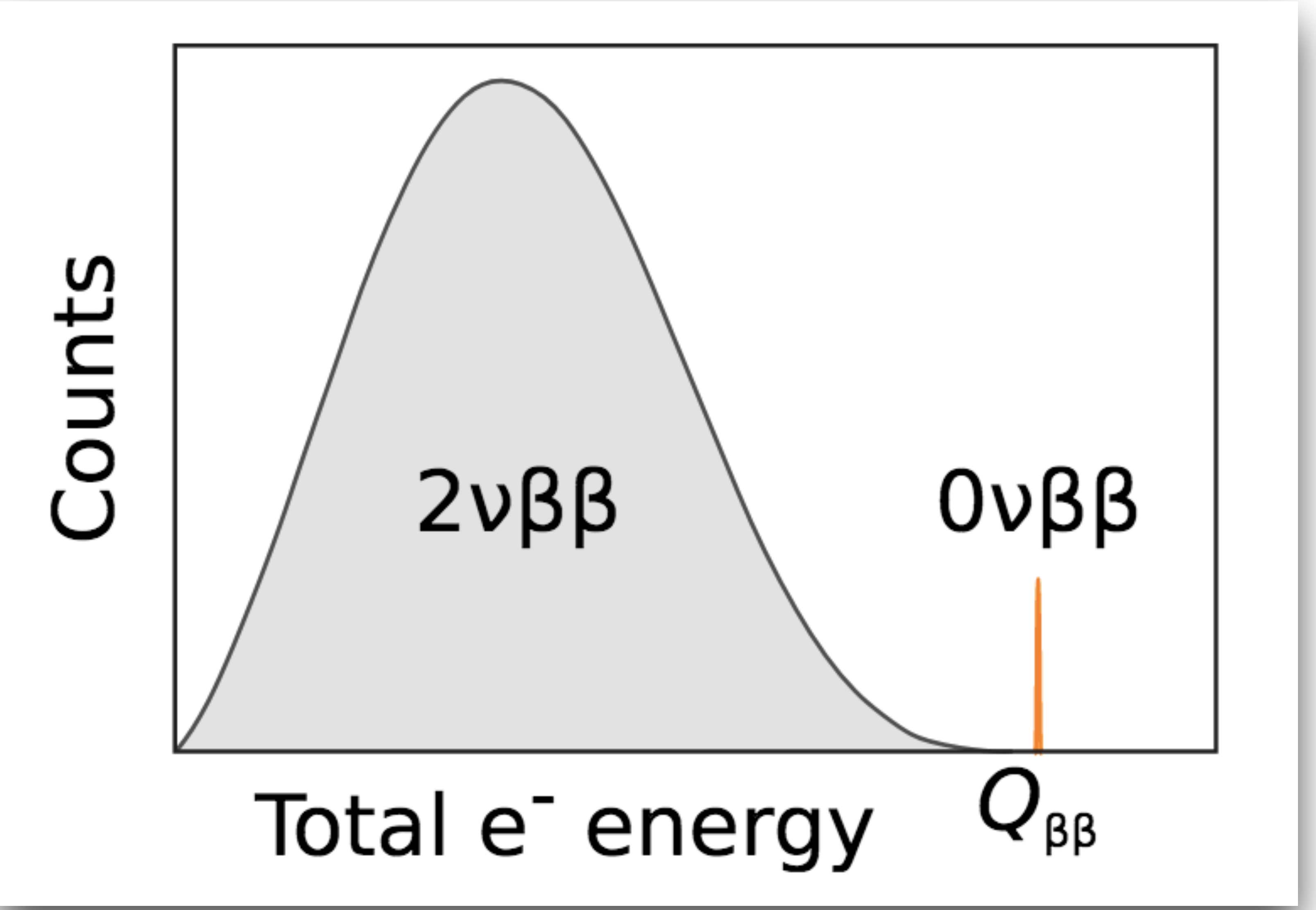
0νββ ⇹ proton decay



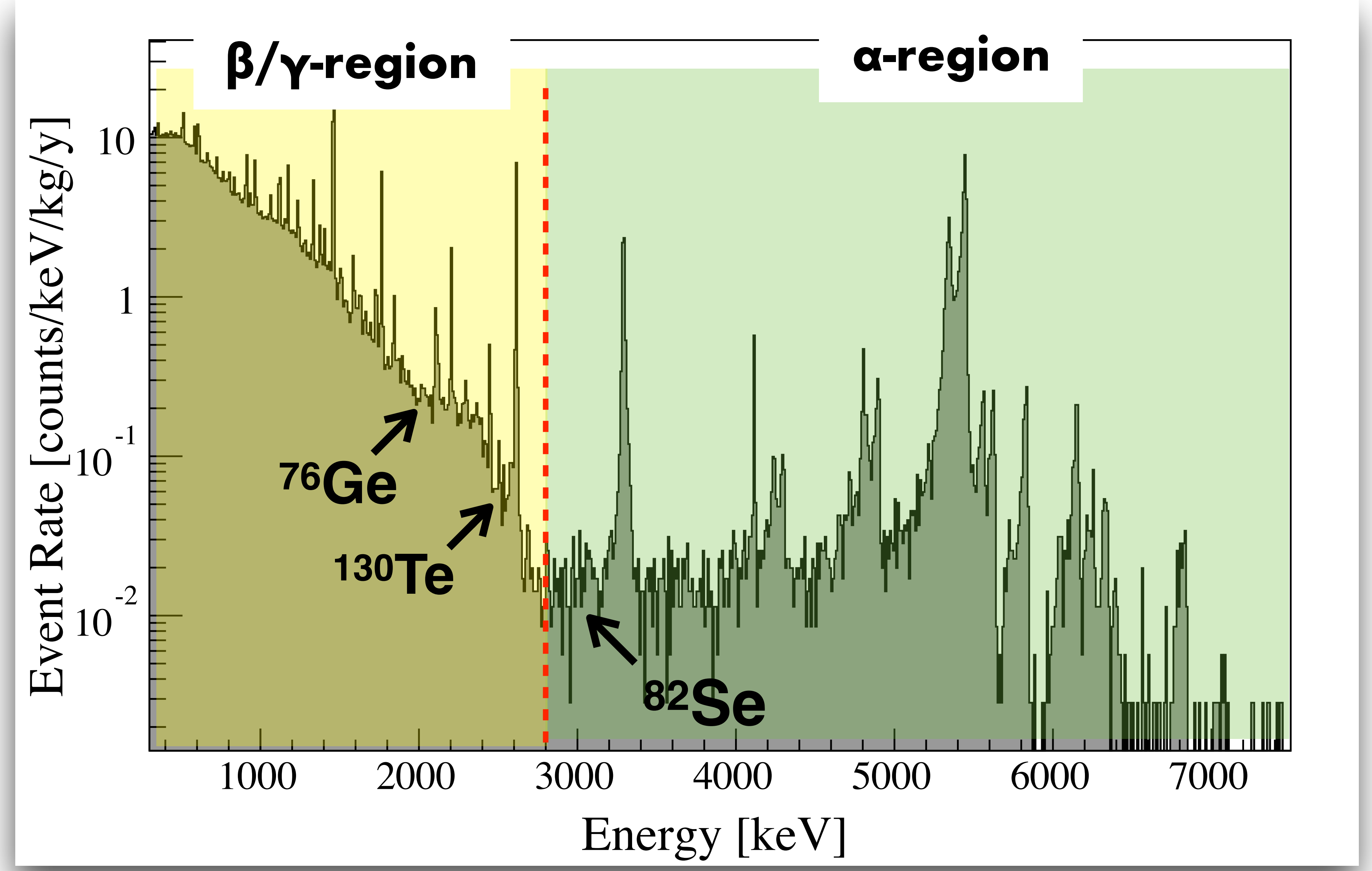
# Expected signal

- Signal: peak at the sum-energy (Q) of the two electrons (2-3 MeV depending on the isotope)
- Backgrounds: natural radioactivity in the detector proximity, cosmic rays, ...
- $0\nu\beta\beta$ Half-life : <u>limits</u> in the range of >$10^{26}$ y

Computed energy spectrum

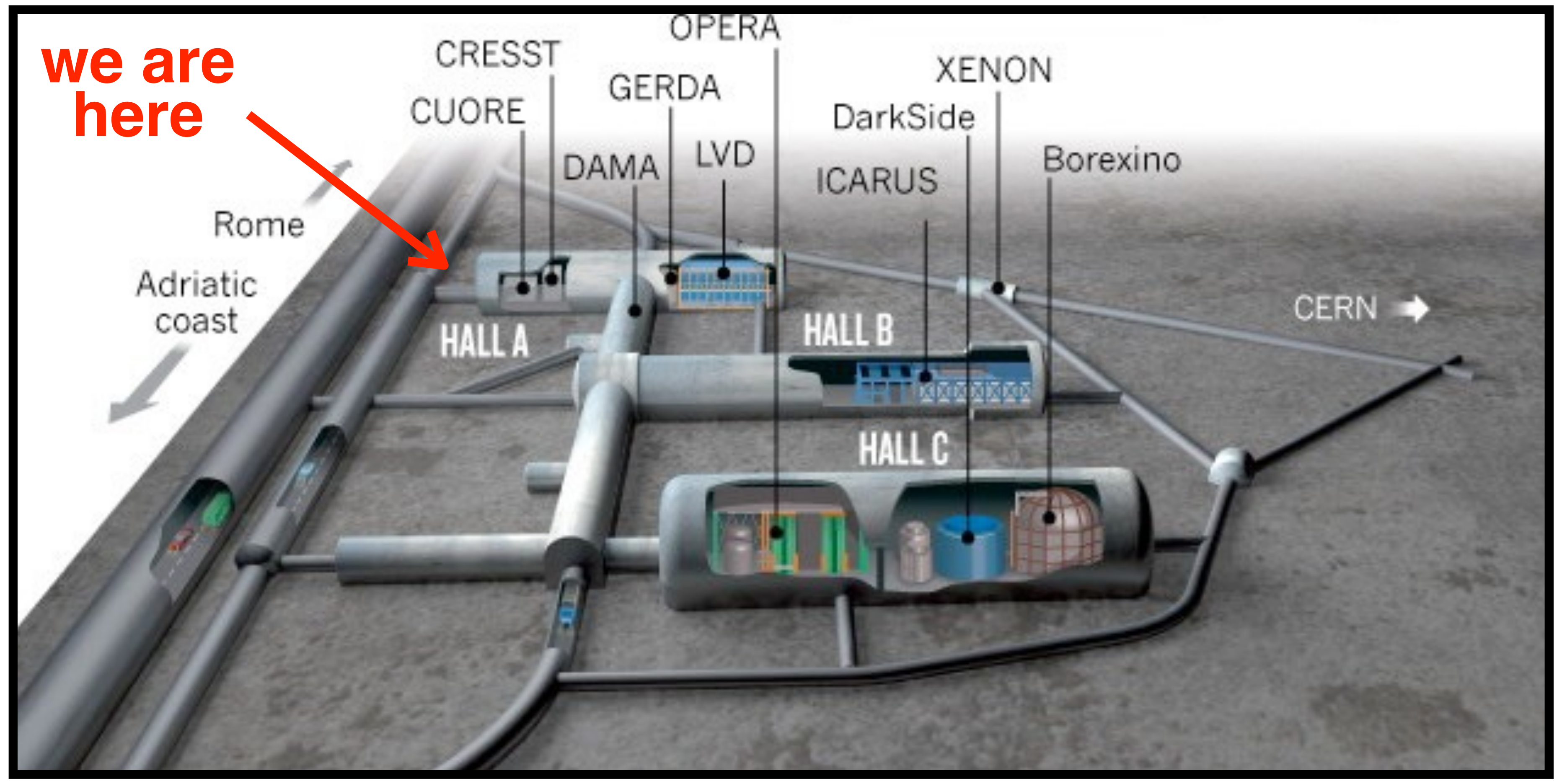



Energy spectrum from natural radioactivity



# The Gran Sasso underground facility

Laboratori Nazionali
del Gran Sasso
INFN, Italy


Unique site for low background physics

Experimental location:

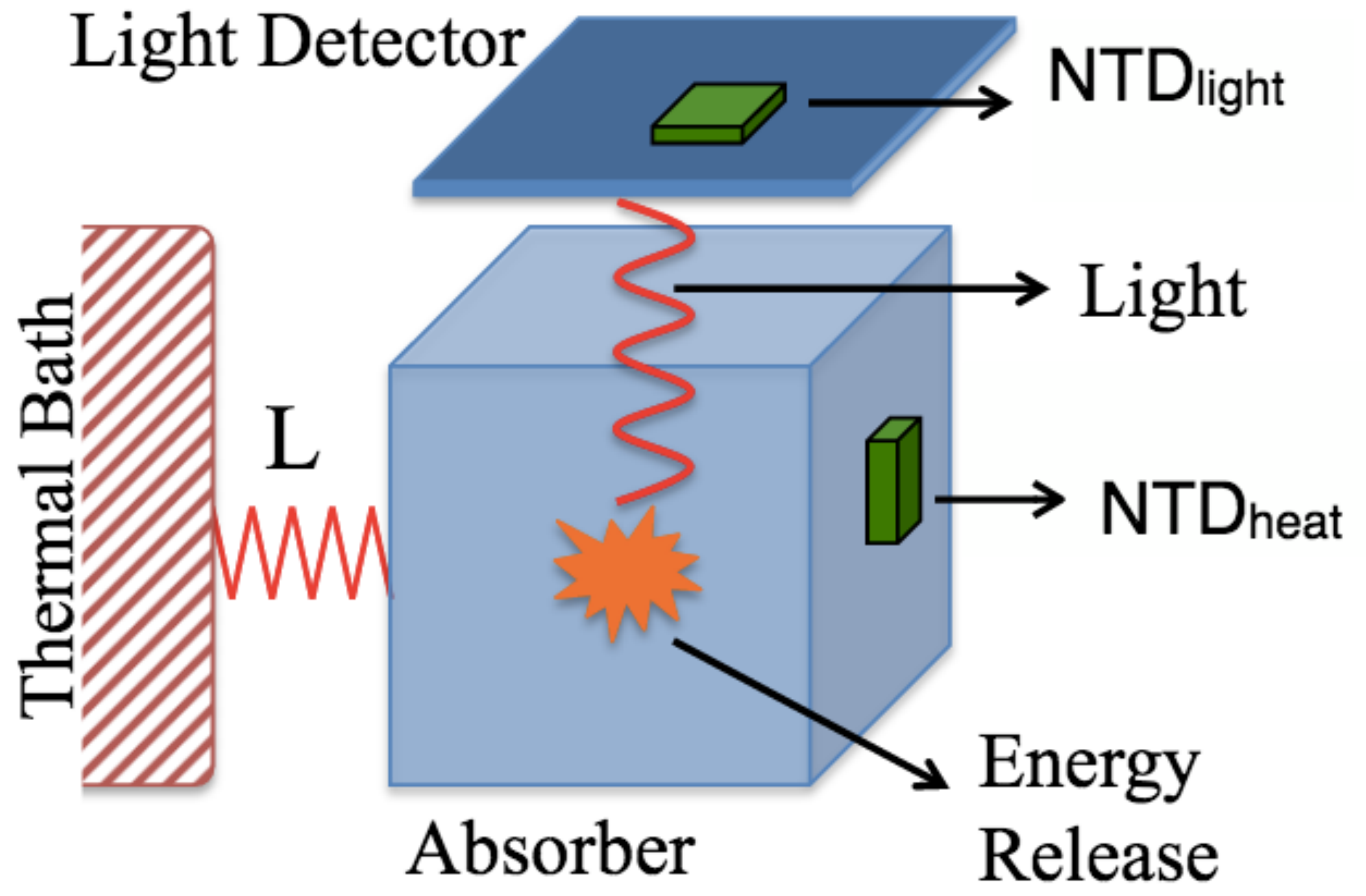
- Average depth 3600 m w.e.
- Muon flux $2.6\times10^{-8}$ $\mu/s/cm^2$
- Neutrons < 10 MeV: $<10^{-6}$ $n/s/cm^2$

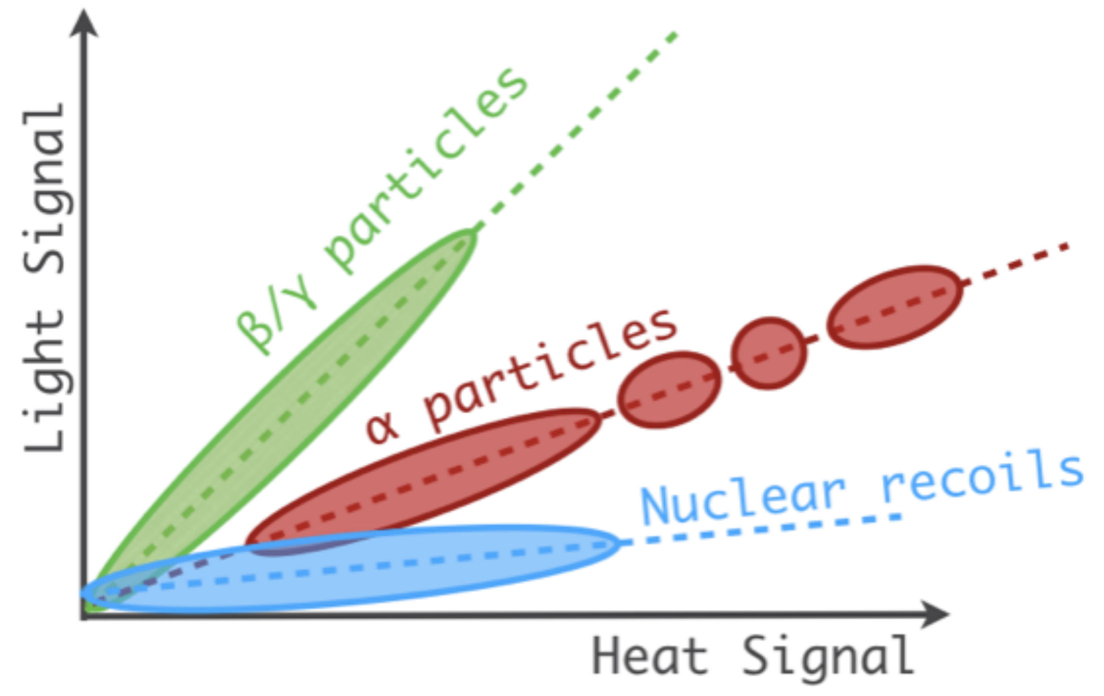
# Scintillating bolometers

A bolometer is a highly sensitive calorimeter operated @ 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




The simultaneous read-out of **HEAT** and **LIGHT** allows particle identification

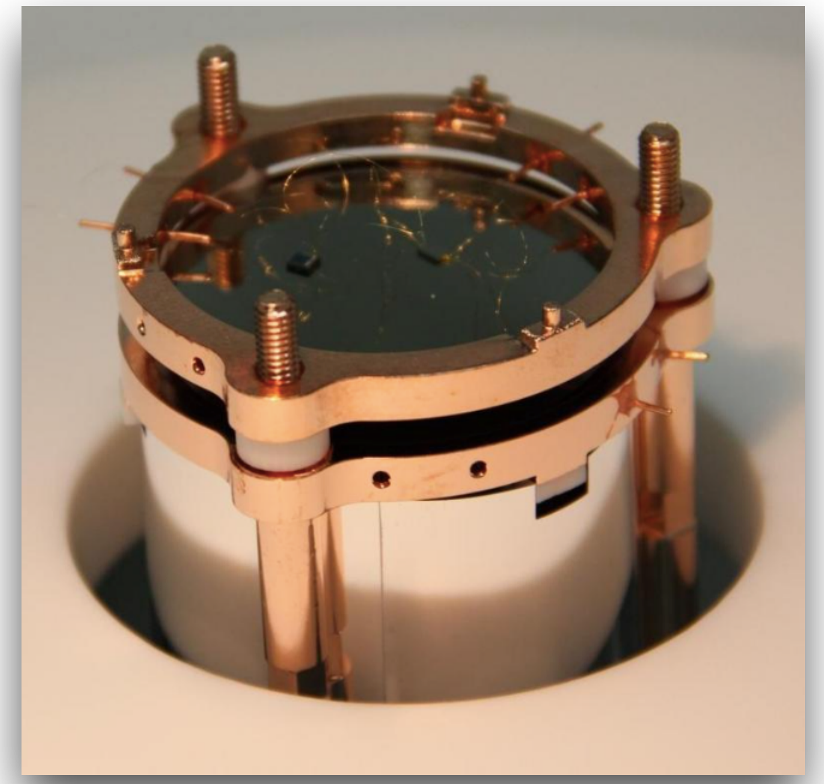
- ↓ Fully active detectors
- ↓ Slow thermal signal O(5 seconds)
- ↑ High energy resolution O(1/1000)
- ↑ High detection efficiency (source = detector)
- ↑ **Particle ID**

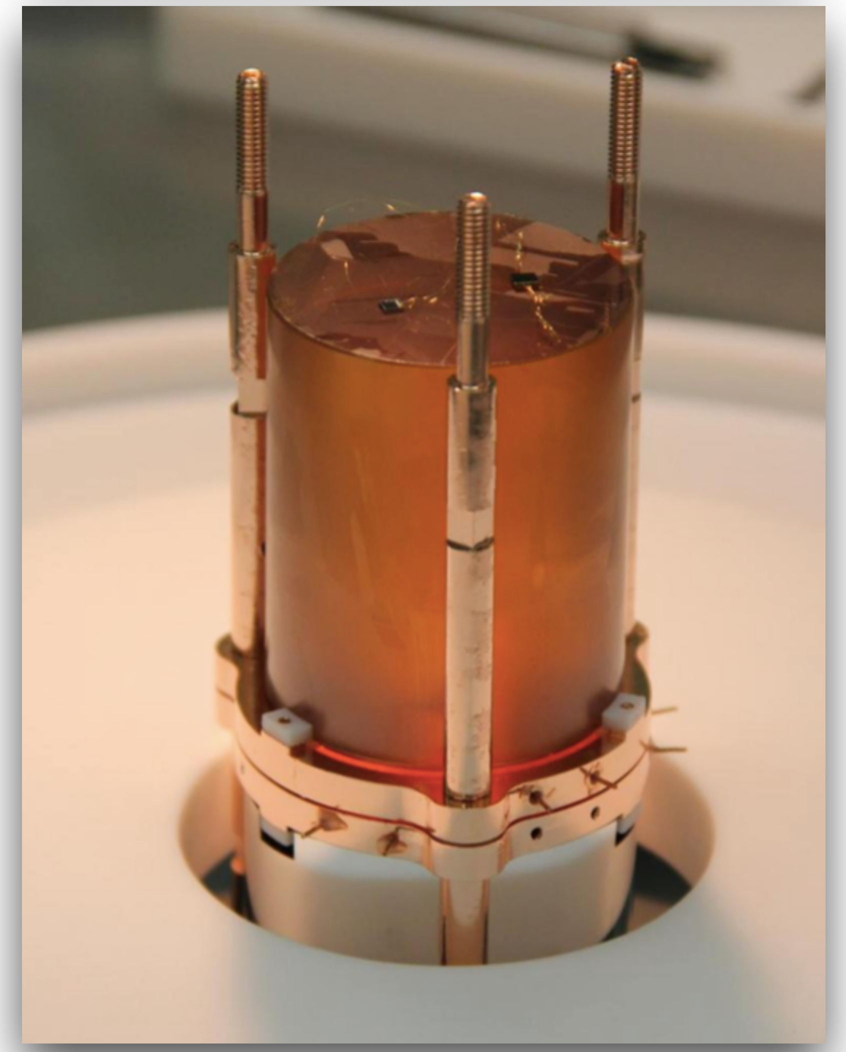
A **background-free experiment** is possible:
α-background: identification and rejection

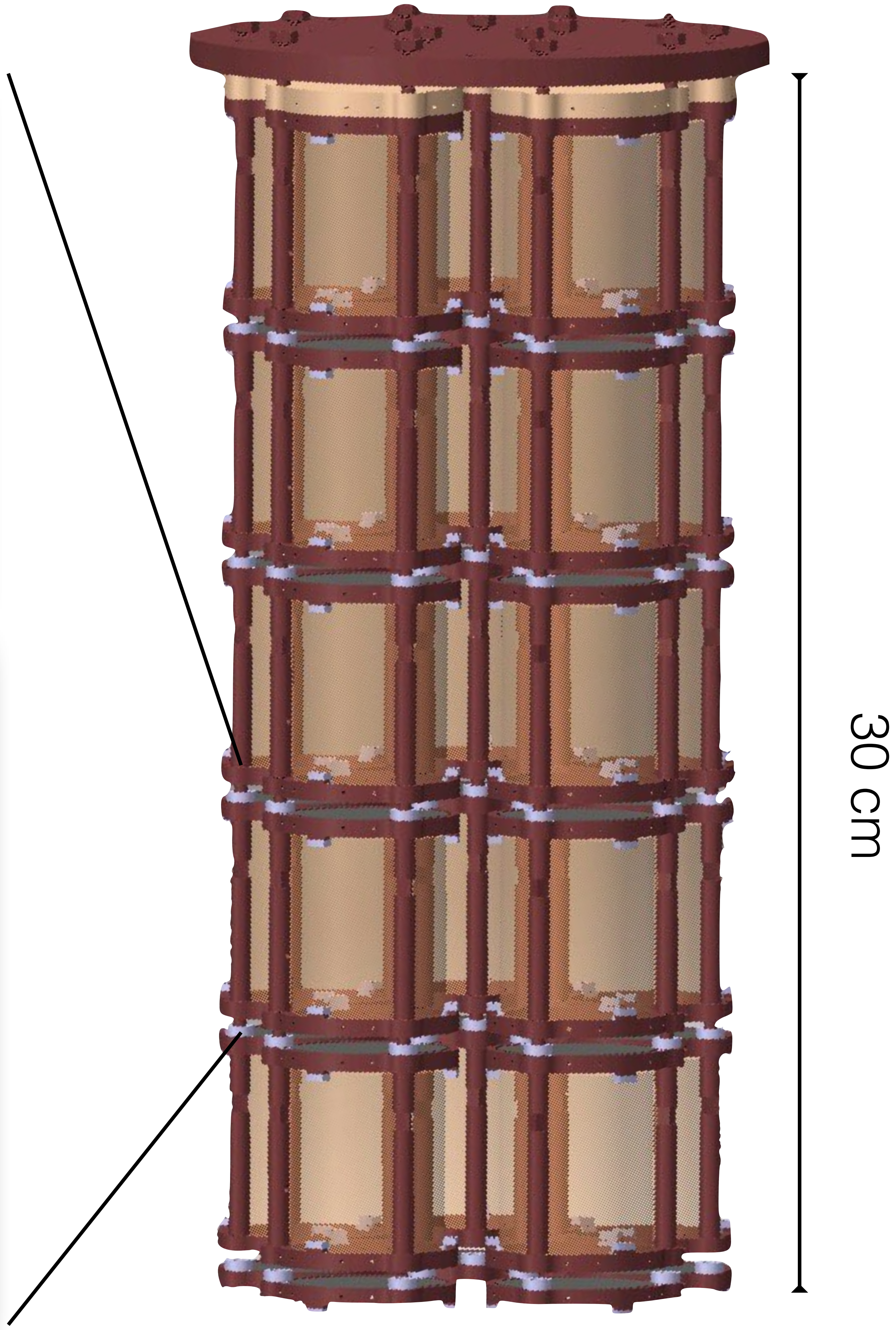
# CUPID-0

CUPID-0 is the first array of scintillating bolometers
for the investigation of $^{82}Se$ $0\nu\beta\beta$

- $^{82}Se$ Q-value 2998 keV
- 95% enriched $Zn^{82}Se$ bolometers
- 26 bolometers (24 enr + 2 nat) arranged in 5 towers
  - 10.5 kg of ZnSe
  - 5.17 kg of $^{82}Se$ -> $N_{\beta\beta} = 3.8 \times 10^{25}$ ββ nuclei
- Light Detector: Ge wafer operated as cryogenic detector
- Simplest modular detector ➜ scale up
  - Copper structure (ElectroToughPitch)
  - PTFE holders
  - Light Reflector (VIKUITI 3M)





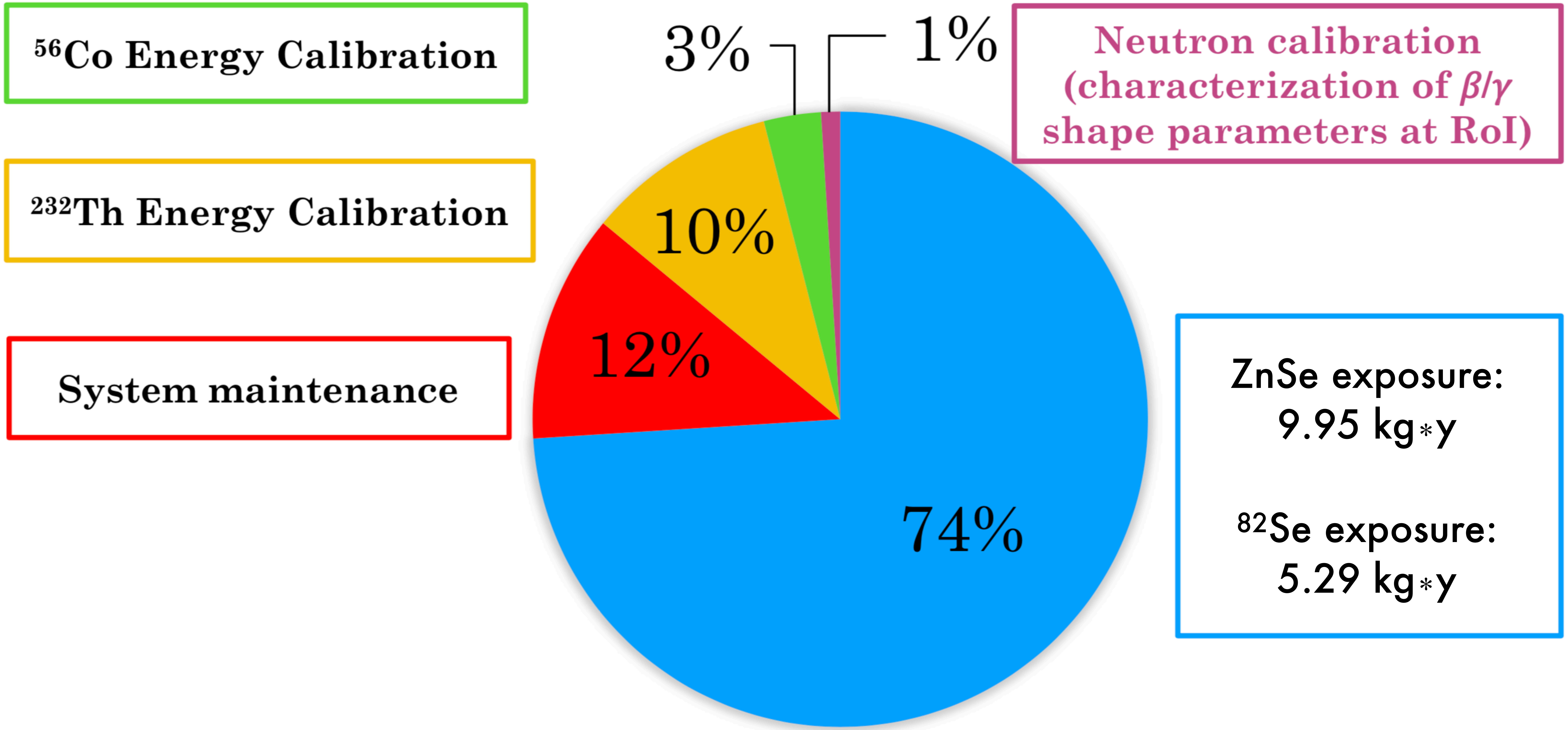





CUPID-0 Coll., Eur. Phys. J. C (2018) 78:428.

# Data taking

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




ZnSe exposure:
9.95 kg$*$y

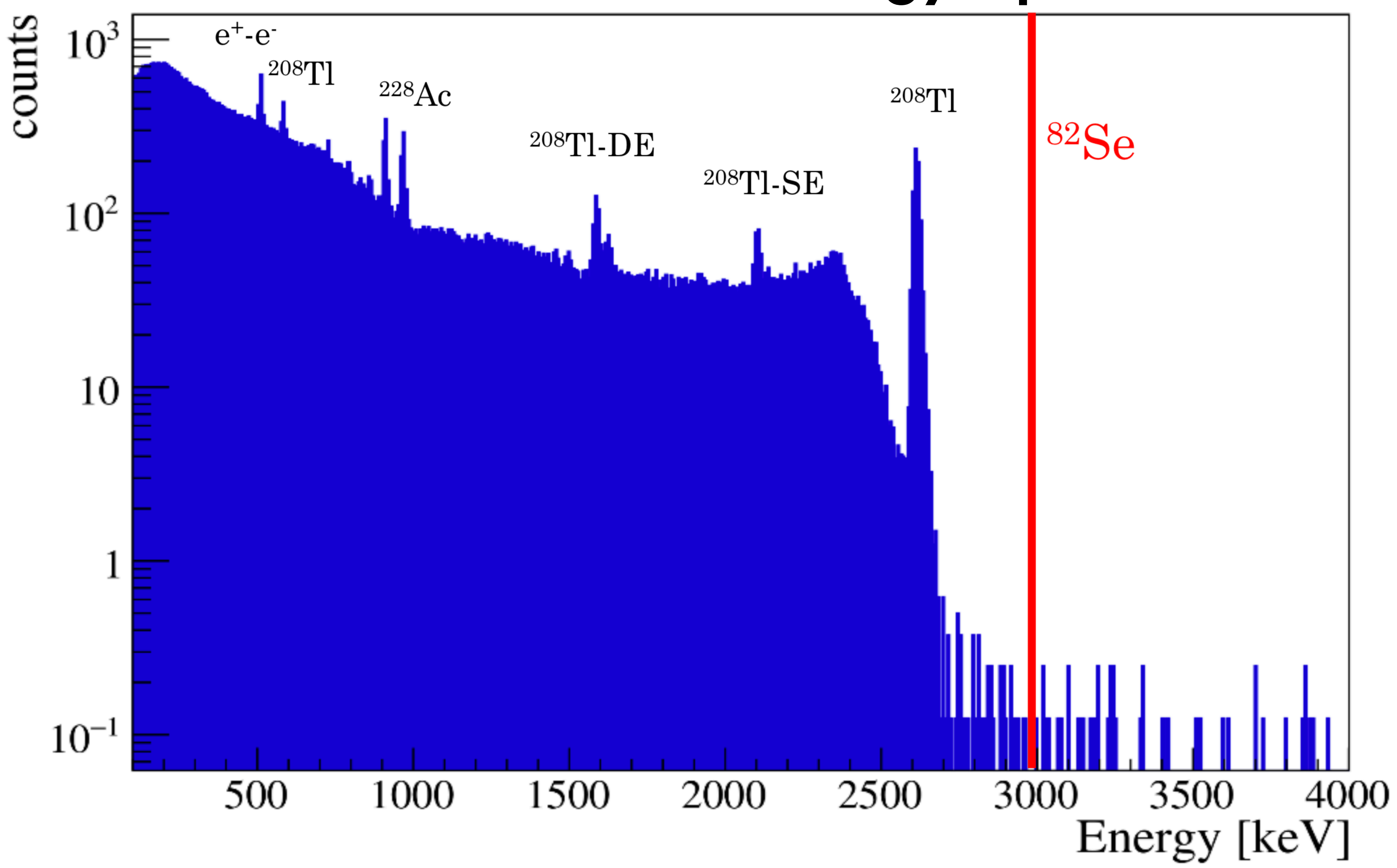
$^{82}$Se exposure:
5.29 kg$*$y

# Detector energy calibration

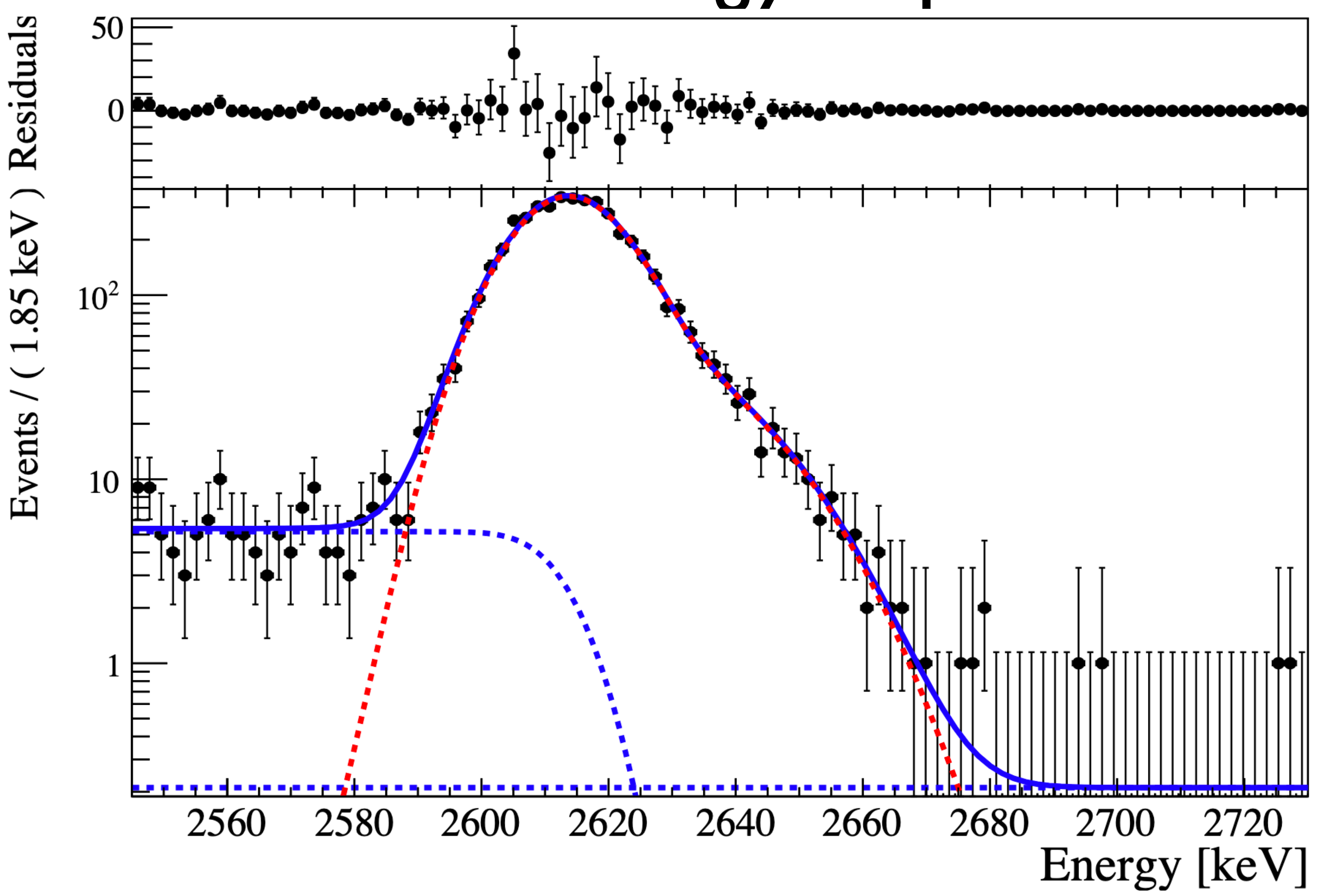
Detector energy calibration using $^{232}$Th and $^{56}$Co gamma-radioactive sources:

- Evaluation of the energy resolution at $^{82}$Se $Q_{\beta\beta}$ (2998 keV)
- Study on the energy reconstruction

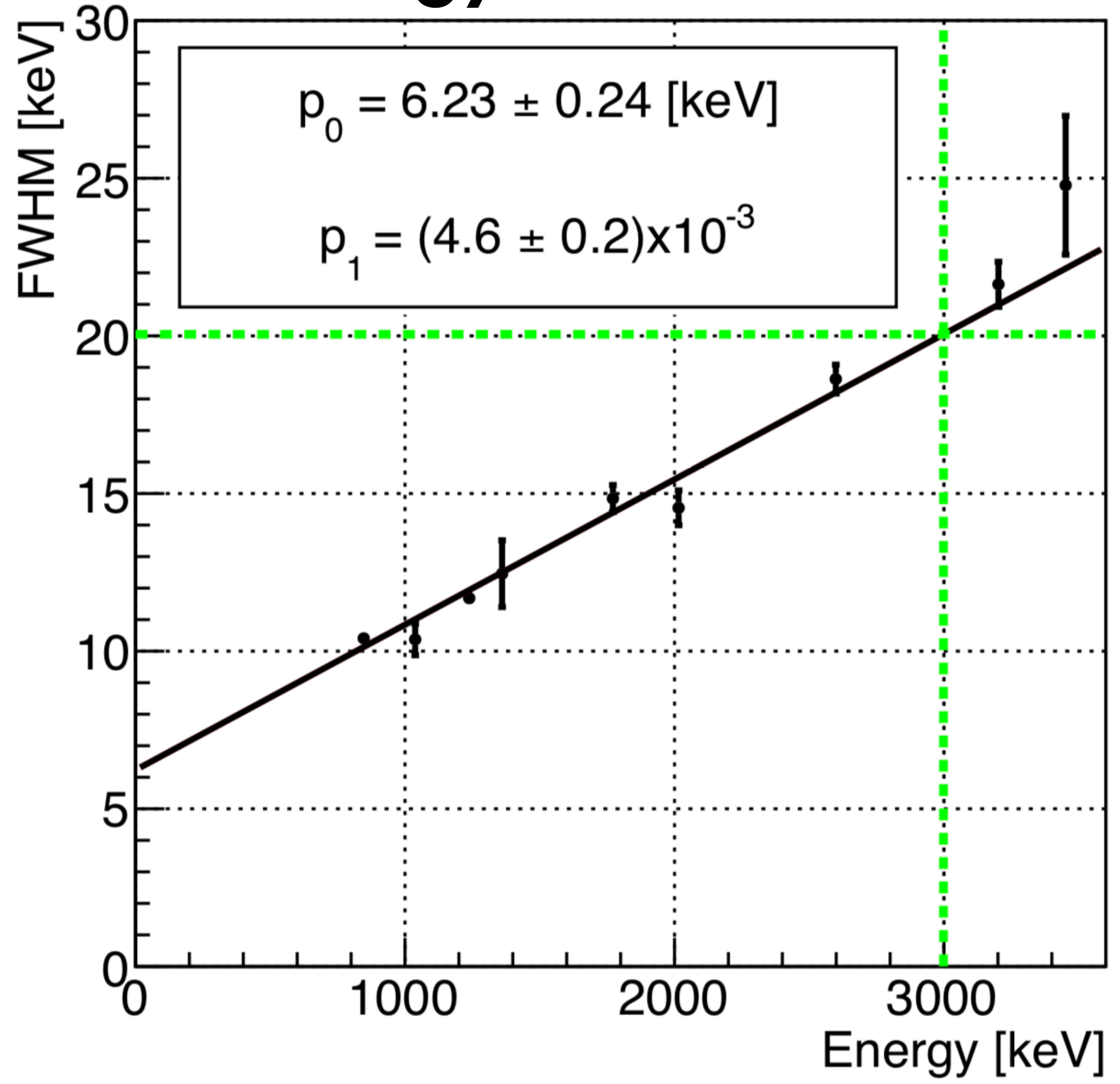
Total calibration energy spectrum




Detector energy response




Energy resolution




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

(20.05±0.34) keV

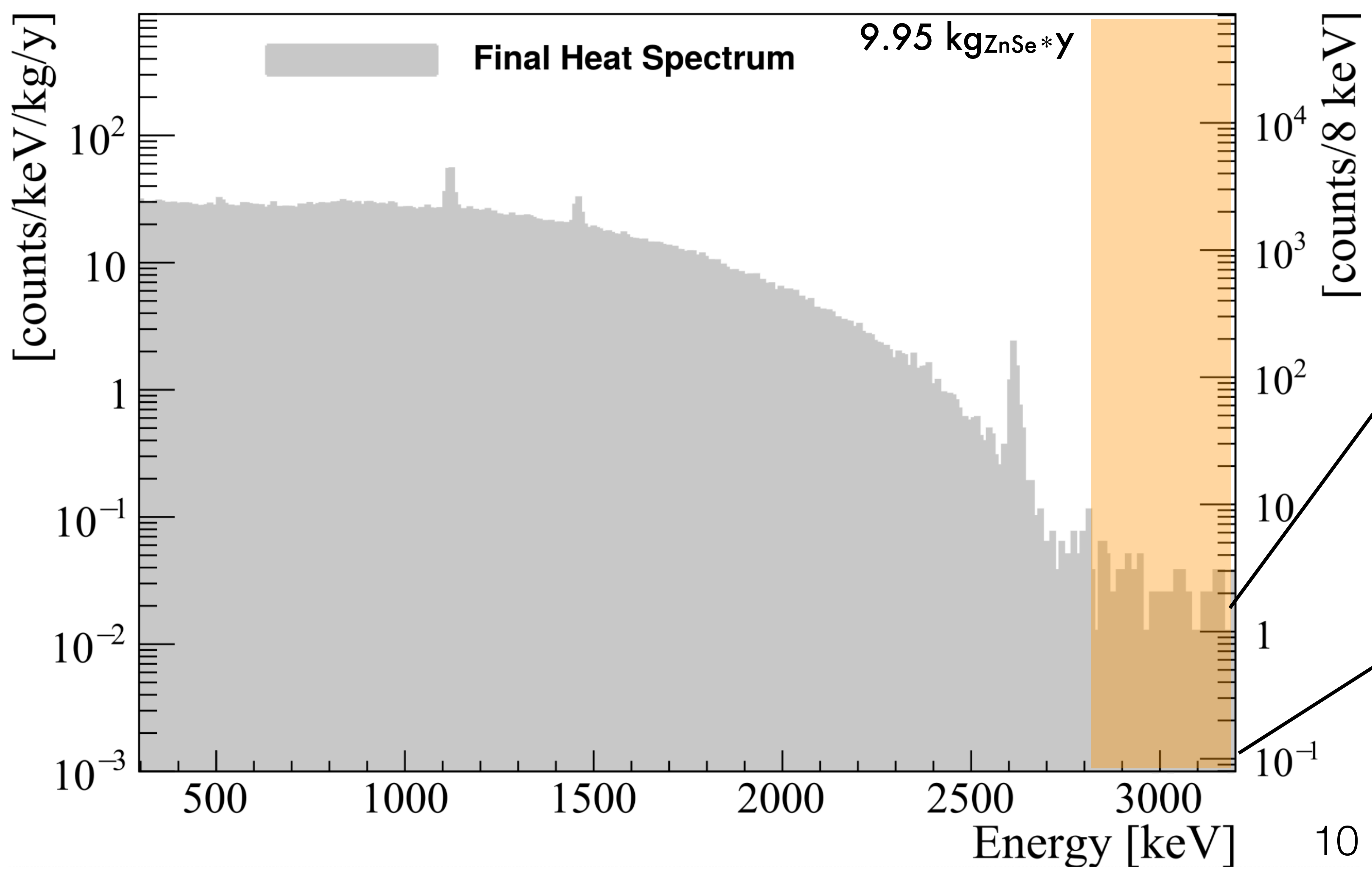
# 0νββ search: heat spectrum

Single energy deposition at 3 MeV in 1 crystal

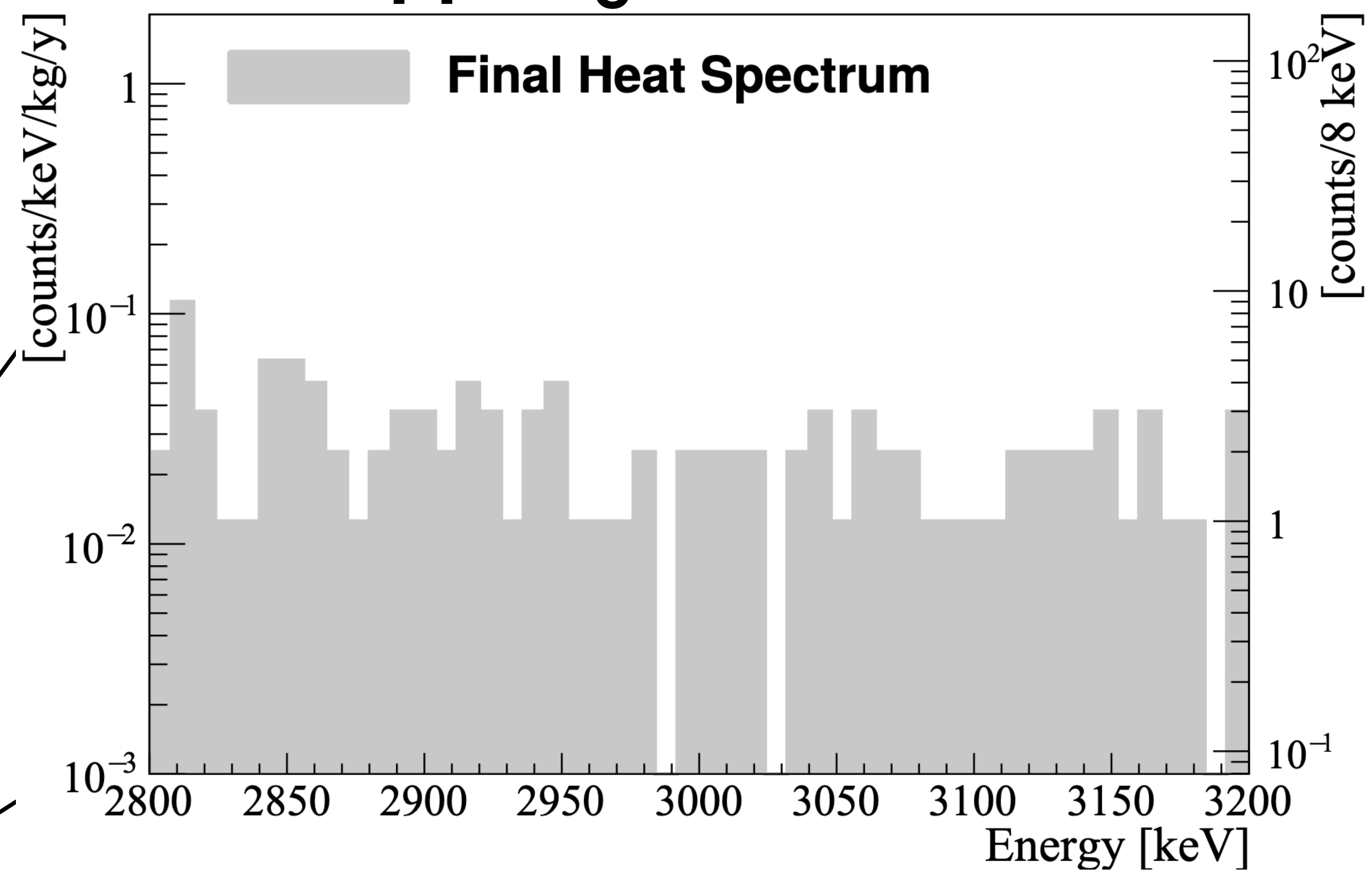
DATA SELECTION:

- *Rejection of Non-particle* events through **Pulse Shape Analysis**
- **Anti-coincidence**: reject energy deposit in more than one ZnSe crystal within a ±20ms window
- Rejection of **pile-up** (1 sec before and 4 sec after trigger)

ββ total energy spectrum



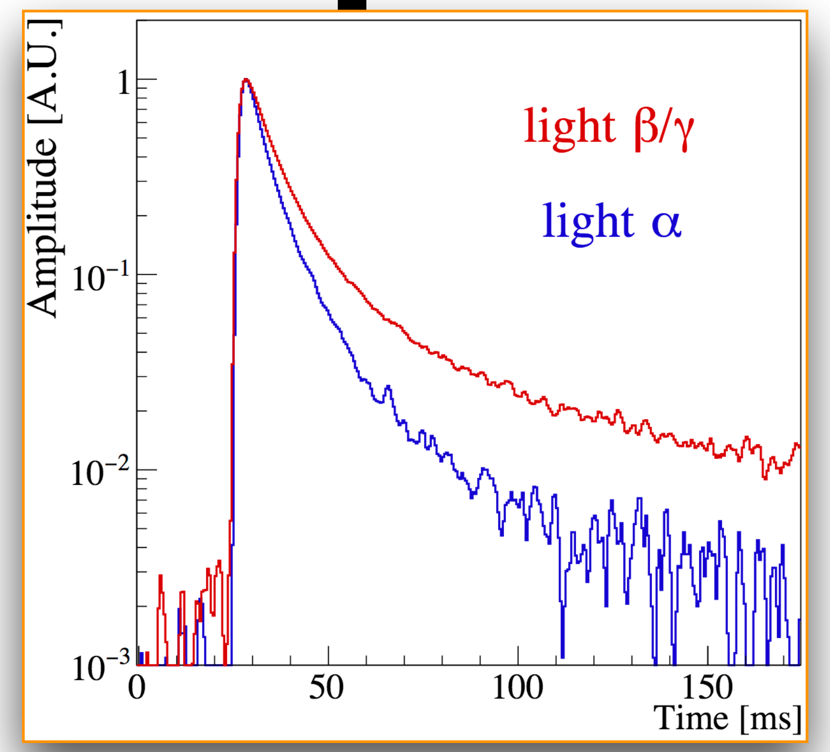

0νββ Region of interest



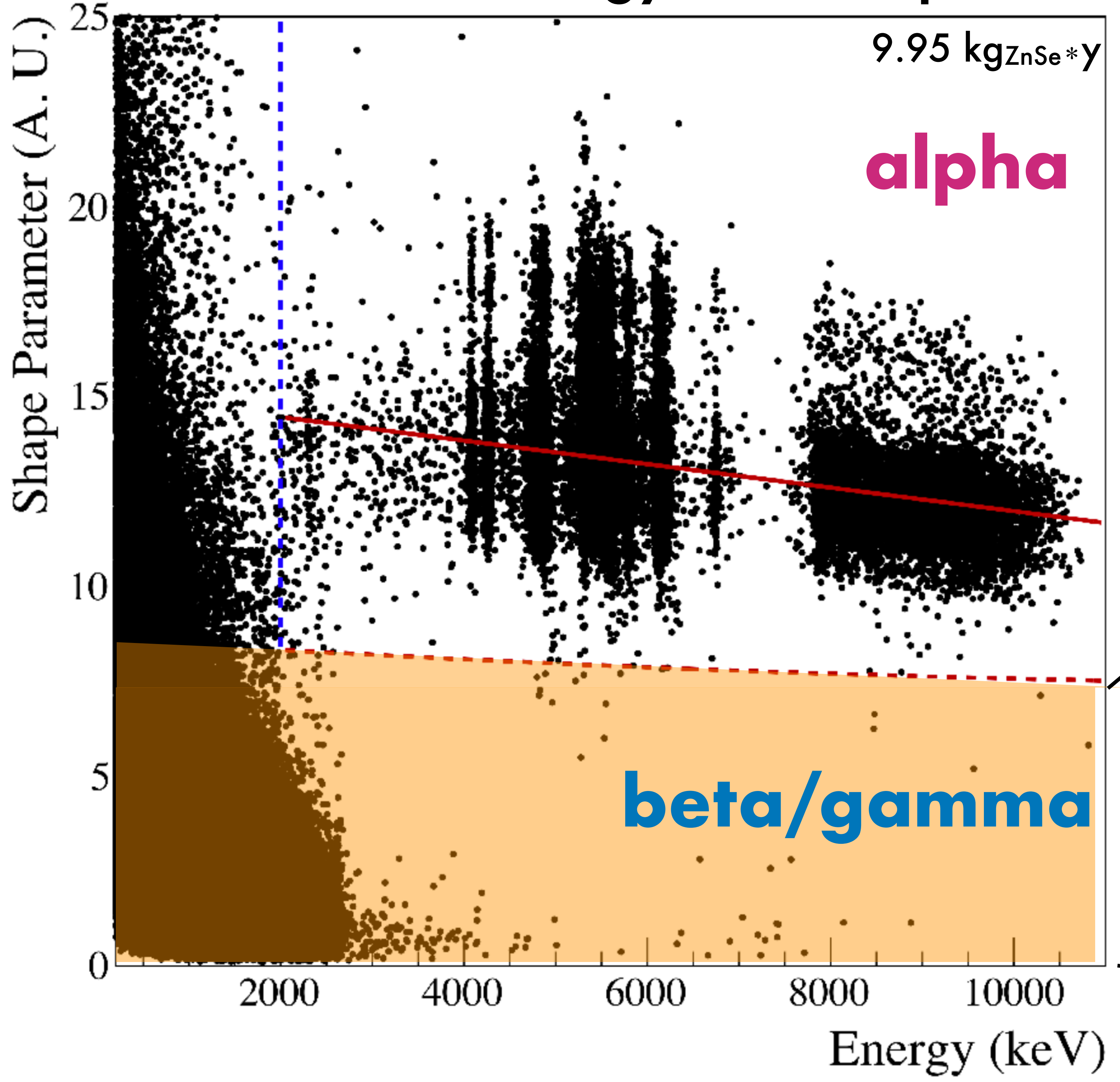

Background in the RoI: **3.2*10$^{-2}$ c/keV/kg/y**

# 0νββ search: alpha particle rejection

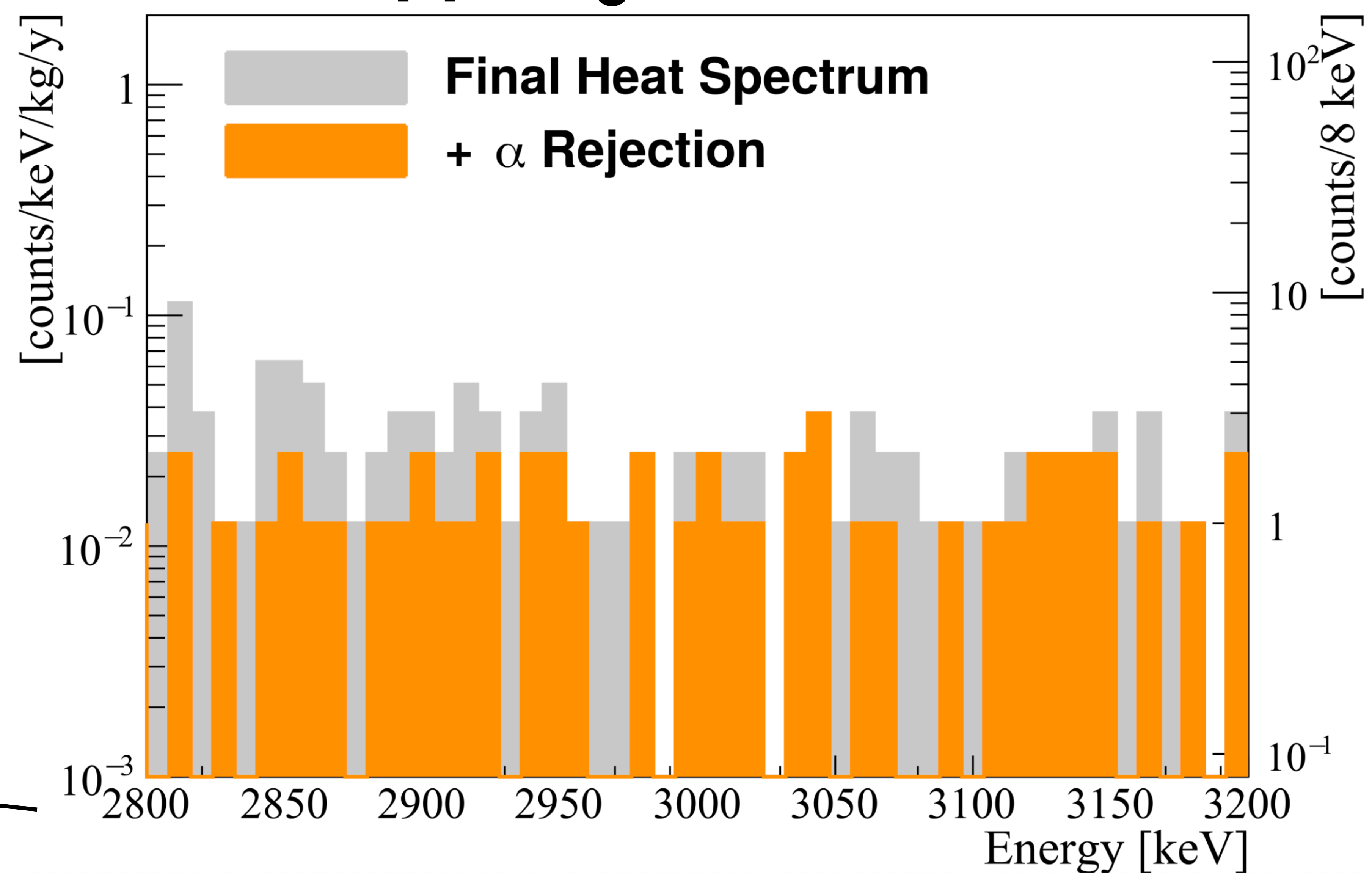
Rejection of α particle interactions: **Pulse shape analysis of light channel**




ββ total energy scatter plot




0νββ Region of interest

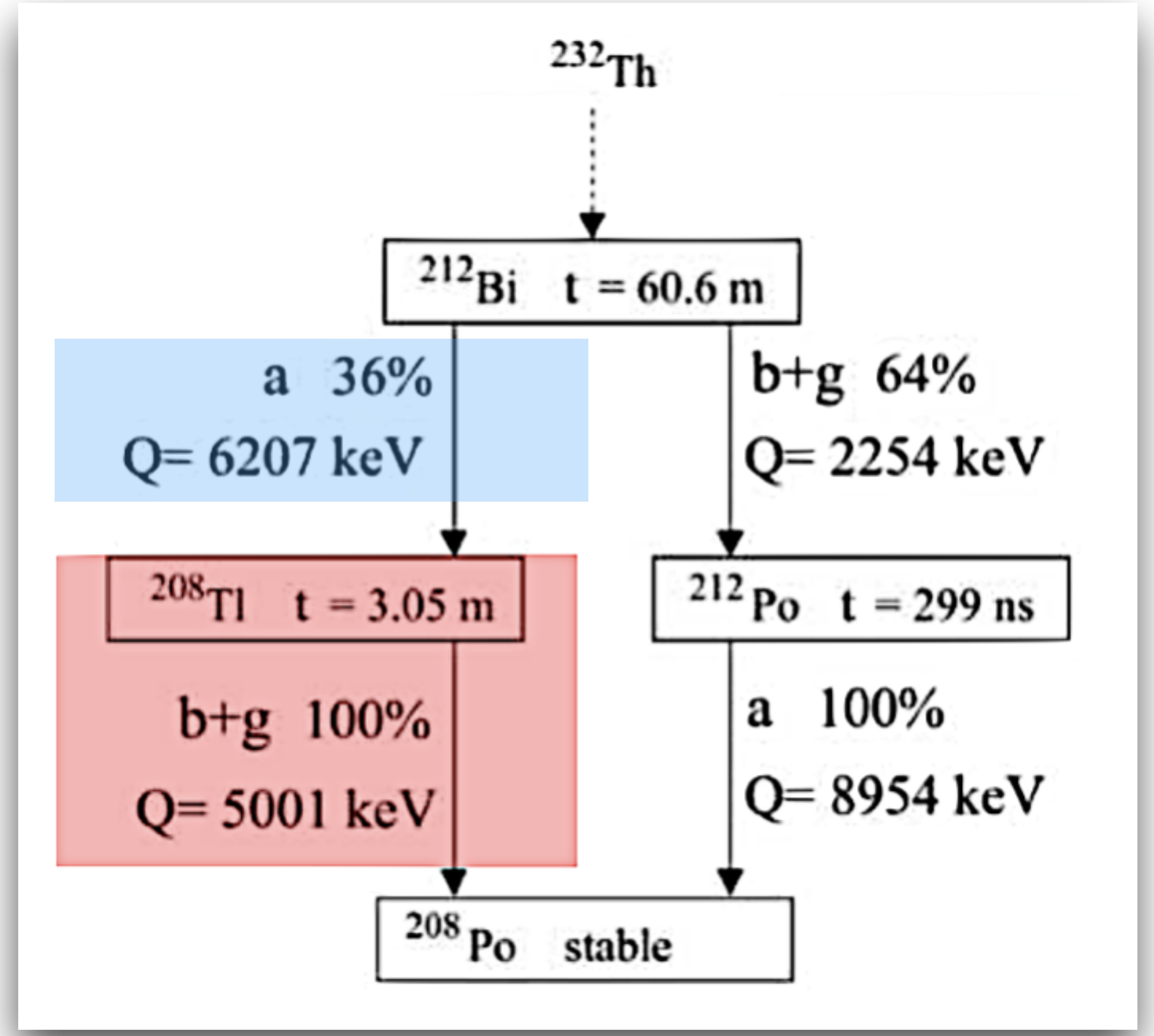



- mean value for alpha particles SP($\mu_\alpha$(E))
- acceptance treshold = $\mu_\alpha(E) - 3\sigma_\alpha(E)$
- energy below which the PID is not applied

Background in the RoI: **$1.3 * 10^{-2}$ c/keV/kg/y**

# 0νββ search: high energy β rejection

Rejection of **α-related events**:
Delayed alpha coincidence $^{212}Bi$ - $^{208}Tl$



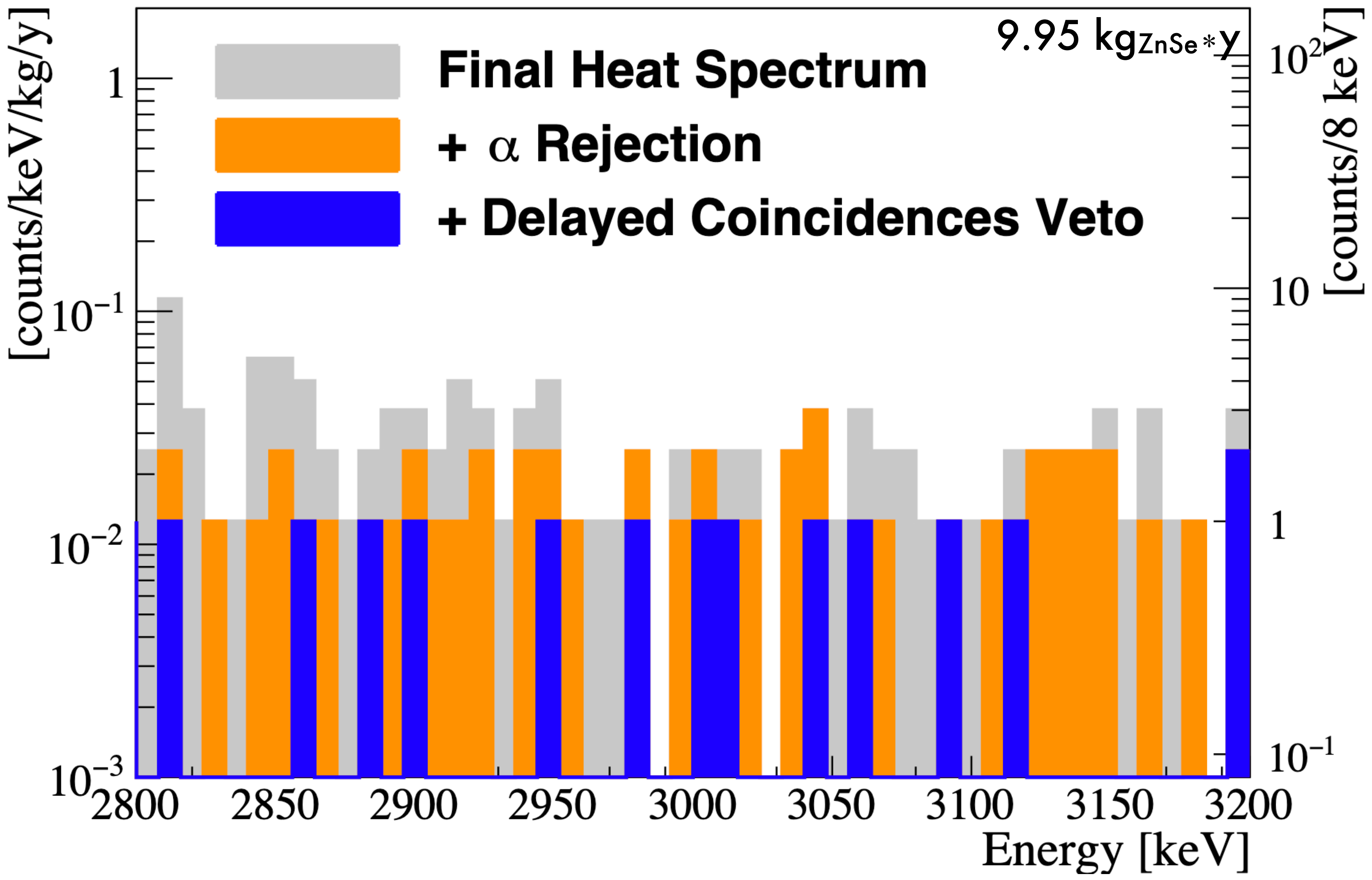

$^{212}Bi$ α event are selected in a range of (2.5-6)MeV

For each $^{212}Bi$ α event the detector is disabled for $7\tau_{1/2}$ (21min).

↓

Rejection of high energy γ from $^{208}Tl$.

0νββ Region of interest




Background in the RoI: **3.5∗10$^{-3}$ c/keV/kg/y**

**Lowest background ever achieved with cryogenic detectors**

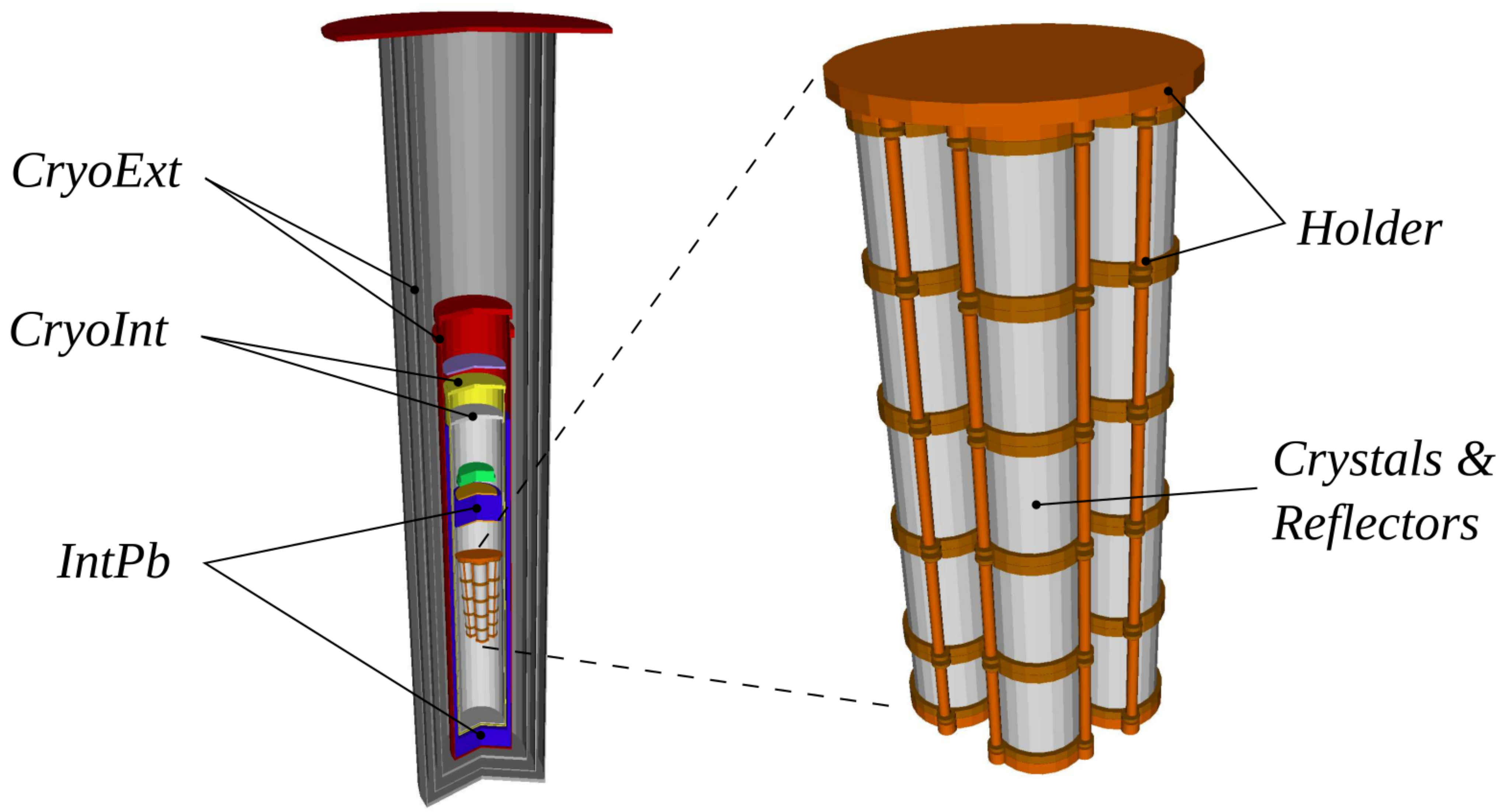
# Background model

Development of Monte Carlo simulation code (based on Geant4) for background sources studies

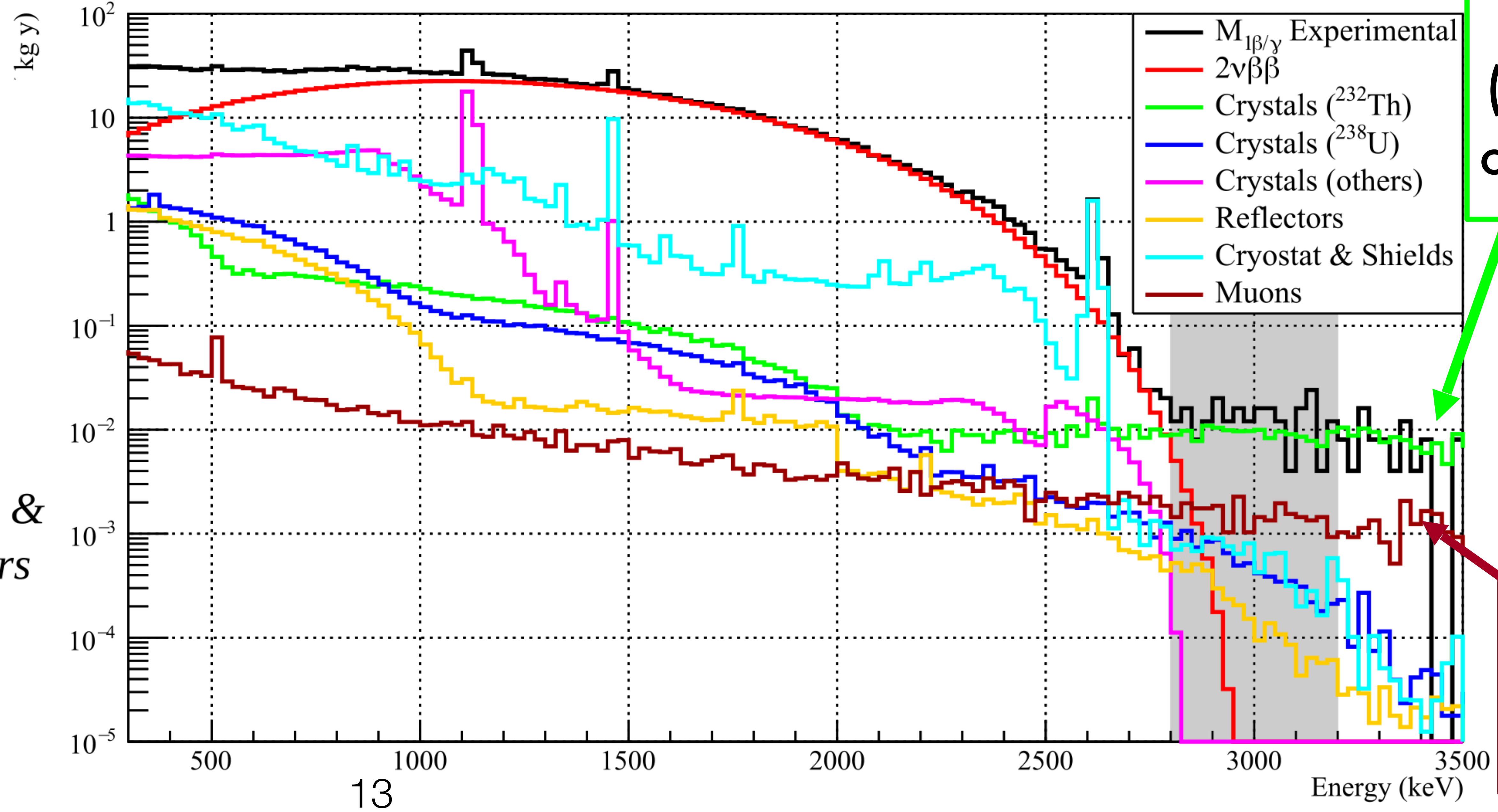
- Highly detailed model of CUPID-0 detector geometry
- Reproduction of detector features (coincidences, resolution, particle ID, thresholds, ...)

Background model uses >30 sources:

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




Total background energy reconstruction



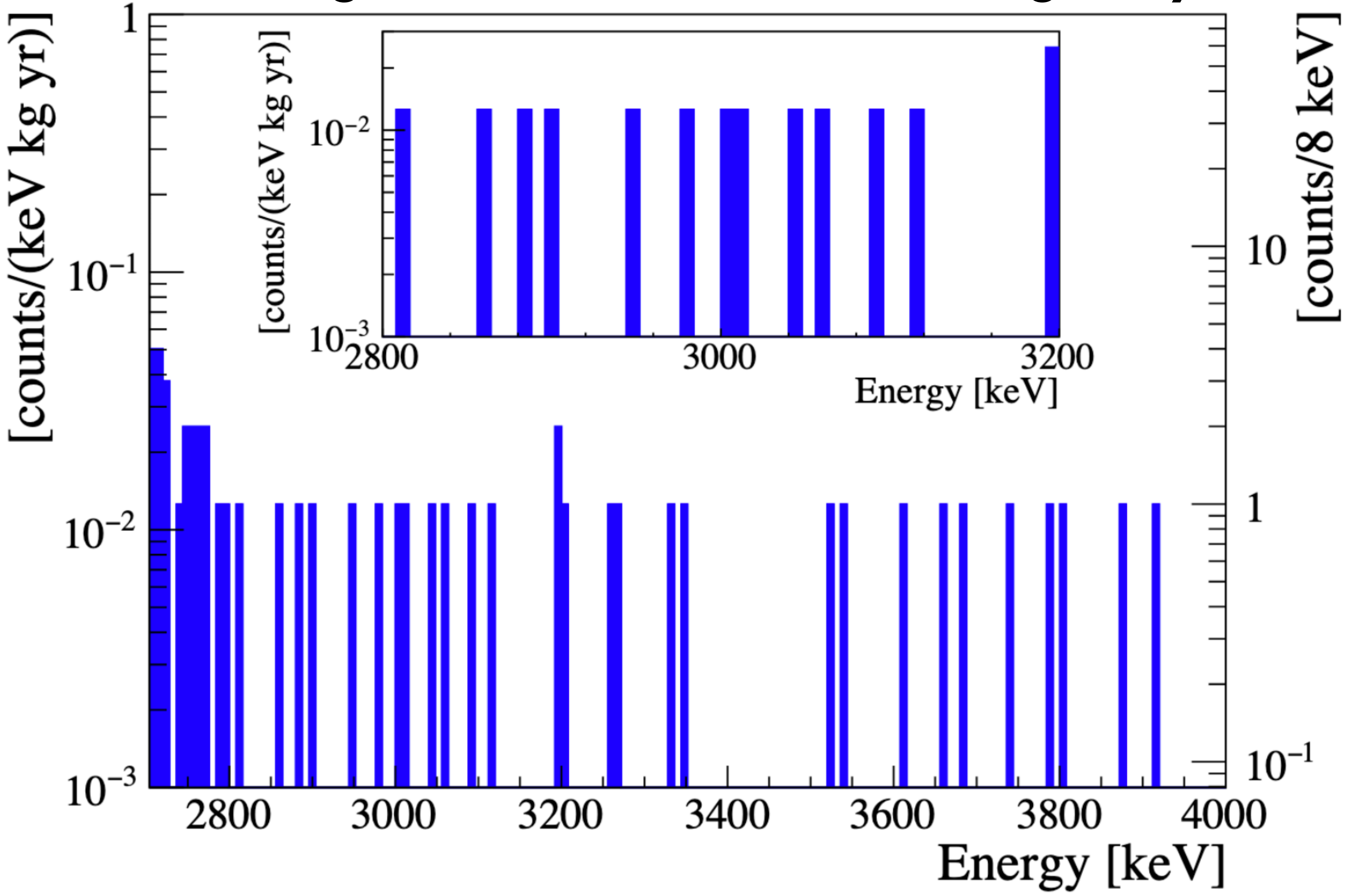

$^{232}Th$ in Crystals is the main contribution (delayed coincidence of $^{208}Tl$ is not applied)

*After delayed coincidences cut*

44% of residual background rate in RoI are muons

# Results on 0νββ search

0νββ Region of interest (9.95 $kg_{ZnSe} * y$)




| | |
|---|---|
| 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 %** |

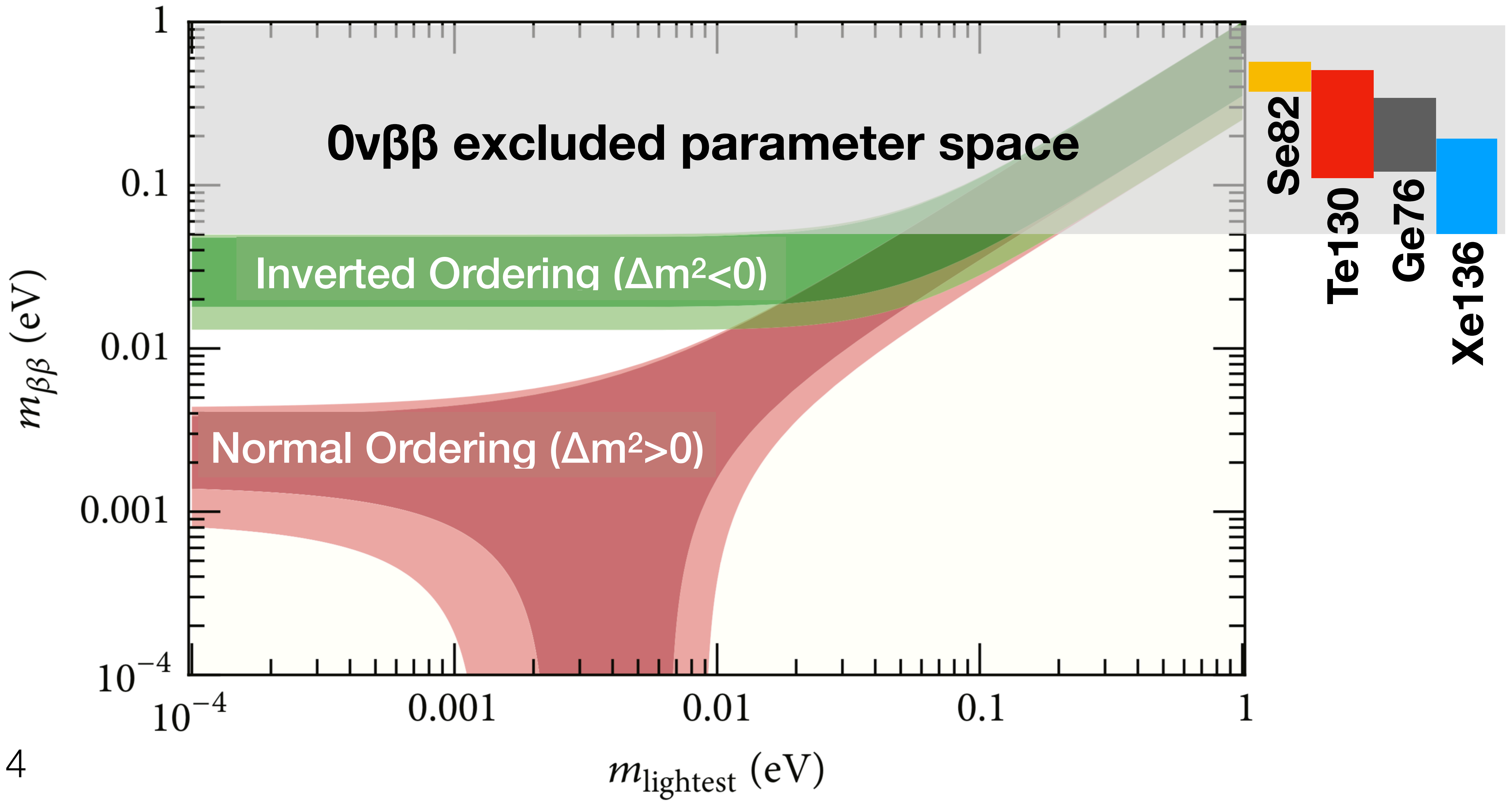
UEML Simultaneous fit over the datasets
No evidence of 0νββ

**Best half-life limit on $^{82}$Se: $T^{0\nu} > 3.5 * 10^{24}$ yr (90%C.I.)**

Corresponding to a neutrino mass limit

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

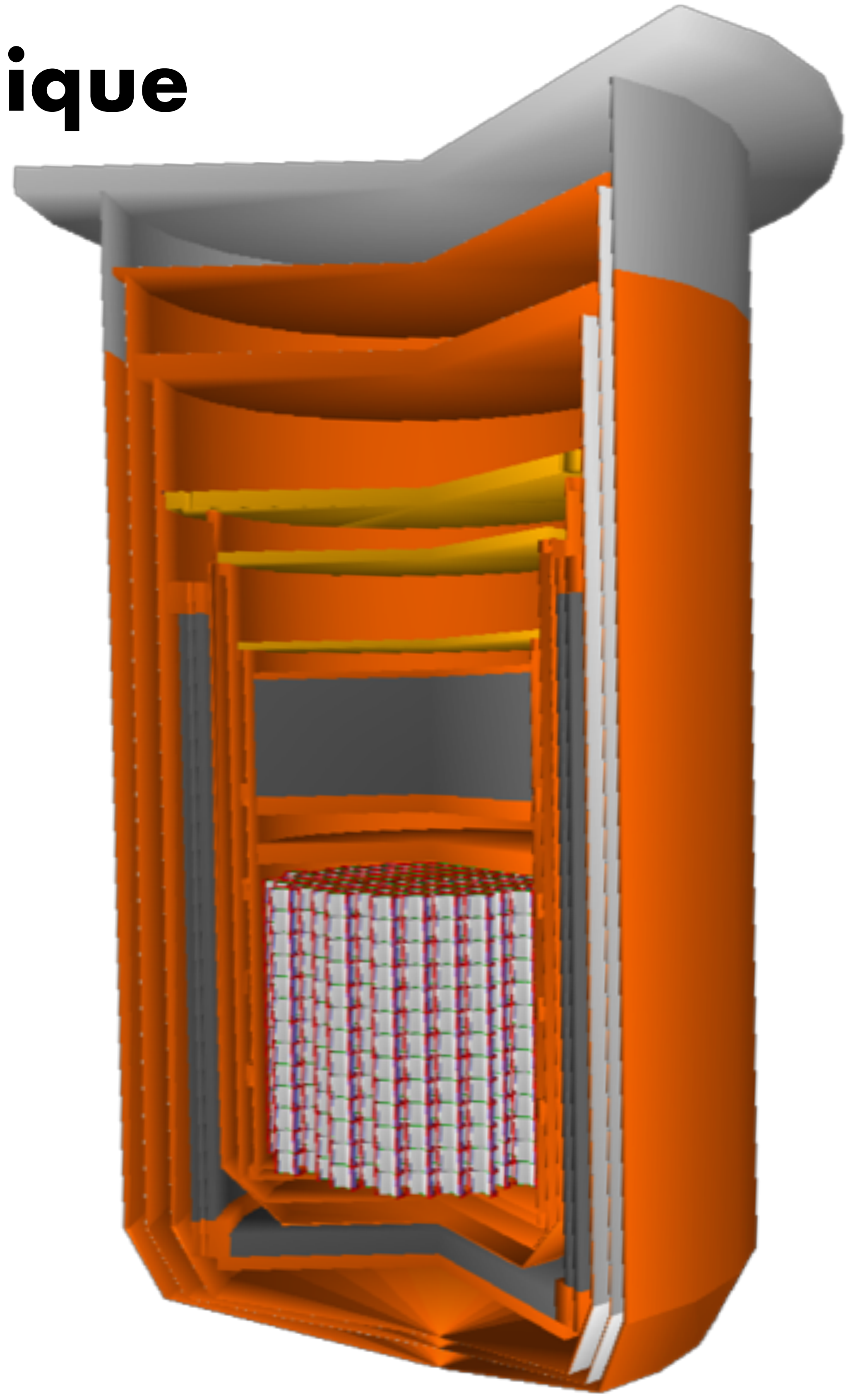
* depending on the Nuclear Matrix Element adopted



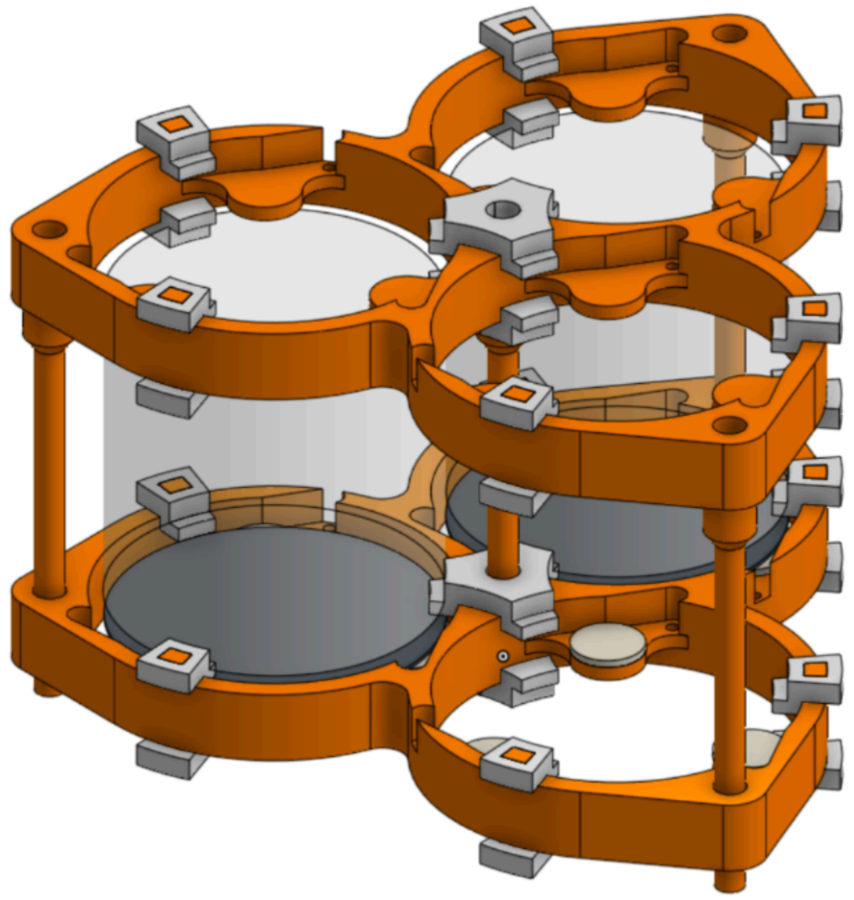
# The future: CUPID

Cuore Upgrade with Particle ID

- Goal: explore the entire inverted ordering neutrino mass region down to 10 meV
- How: merge the **CUORE cryogenic infrastructure** with **CUPID-0 particle ID technique**



- Highly enriched $Li_2{}^{100}MoO_4$ crystals
- Large array of 1500 $Li_2MoO_4$ crystals + LDs
- Total detector mass about 250 kg of $^{100}Mo$
- Operation in almost null-background conditions: $10^{-4}$ c/keV/kg/y



TDR and construction readiness by 2021

Conservative, Mature, Data Driven Baseline Design

# Conclusions

- 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: $3.5 * 10^{-3}$ c/keV/kg/y
- Best half-life limit on $^{82}$Se 0νββ decay: $T^{0\nu} > 3.5 * 10^{24}$ yr (90%C.I.)
- CUPID-0 Phase II→ validation of current background model
- We are currently shaping CUPID collaboration and project