Background studies for CUPID-Mo and CUPID $0\nu\beta\beta$ experiments

LÉONARD IMBERT

P2IO MEETING

11/04/2022

Neutrinoless double beta decay

2νββ

- 2n -> 2p + 2e⁻ + 2$\overline{\nu}_e$
- Standard Model process
- Possible for 35 nuclides
  - Even-Even nucleus
  - Observed for 9 isotopes

0νββ

- Hypothetical decay
- 2n -> 2p + 2e⁻
- **Lepton number violation ΔL = 2**
- Majorana neutrino $\nu = \bar{\nu}$

- Majorana neutrino is needed in leptogenesis to explain the matter/antimatter asymmetry

Space phase factor :
- Known and calculated to good accuracy

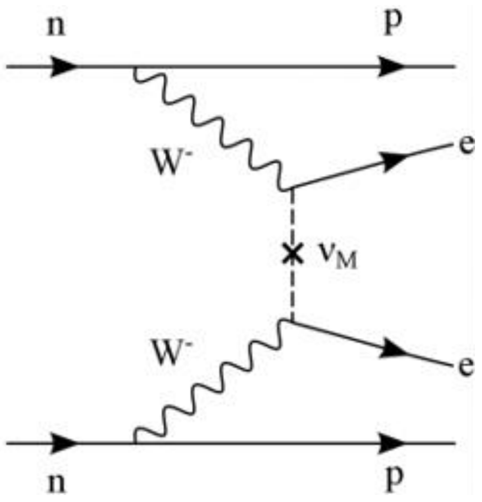
Weak axial-vector coupling strenght :
- Question of g_A quenching under study

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}\, g_A^4\, M^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Nuclear Matrix Element :
- Differences between different nuclear models

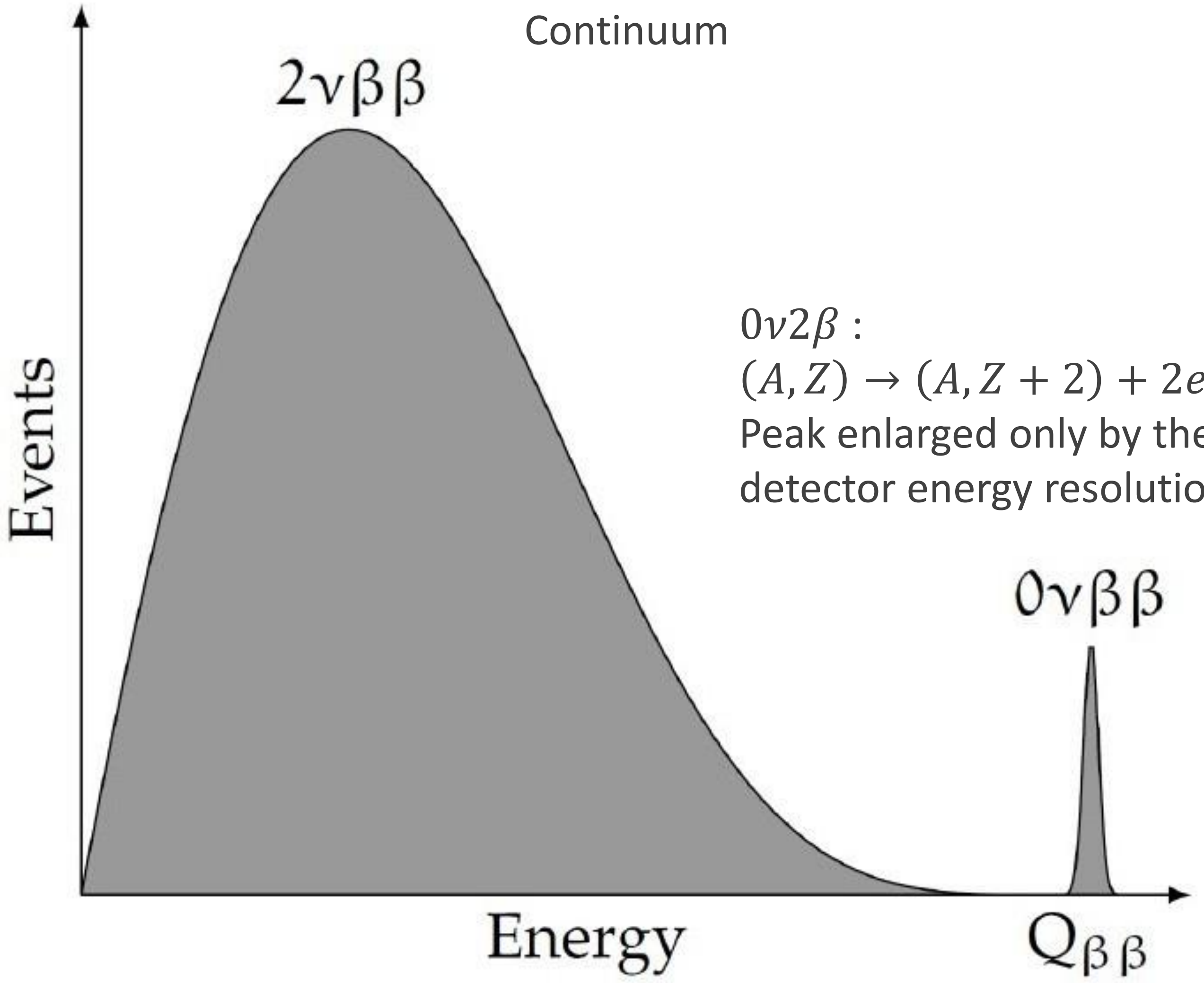
Effective Majorana mass :

$$m_{\beta\beta} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$



Searching for $0\nu2\beta$

$2\nu2\beta$:
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$
Continuum

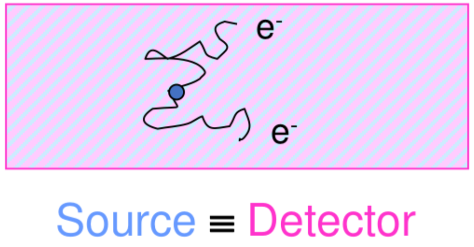


$0\nu2\beta$:
$(A,Z) \rightarrow (A,Z+2) + 2e^-$
Peak enlarged only by the detector energy resolution

The shape of the two-electron sum-energy spectrum enables to distinguish between the 0ν (new physics) and the 2ν decay modes

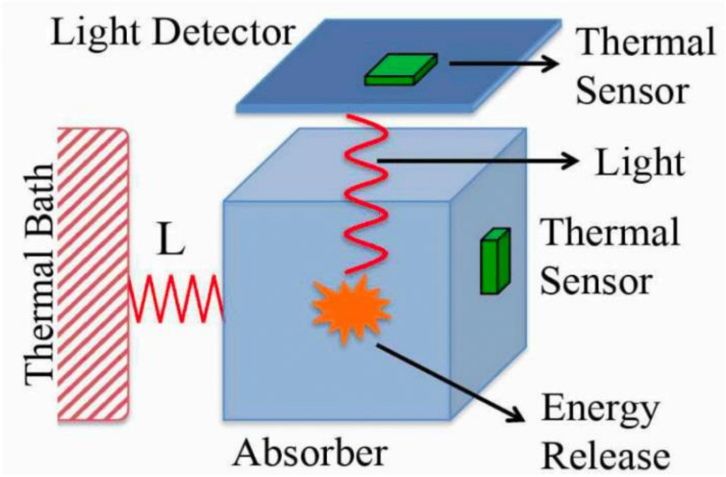
- Requires :
  - Low background in the ROI (around the $Q_{\beta\beta}$)
  - Good energy resolution

Bolometric technique

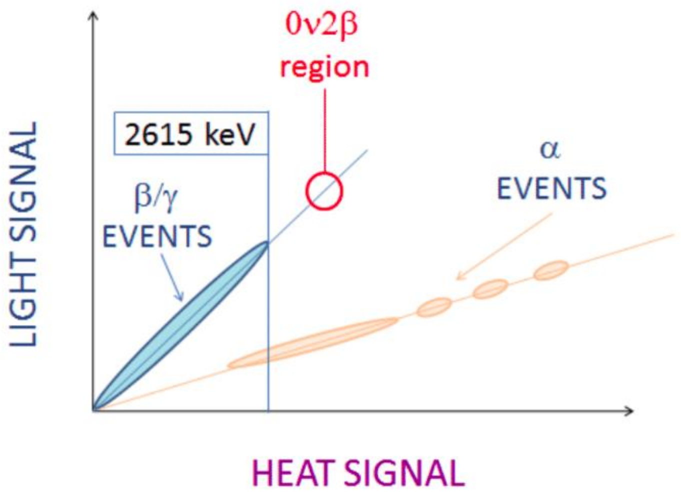


- Crystals cool down to ~ 10-20 mK
- Detector = source
  - High detection efficiency
- Good energy resolution

Scintillating Bolometer



Particle Identification



- Scintillating bolometers
  - Discriminations between β/γ and α particles
  - Heat and Light signals

CUPID-Mo

Demonstrator for the next generation ton scale experiment CUPID

Installed at Laboratoire Souterrain de Modane (LSM)

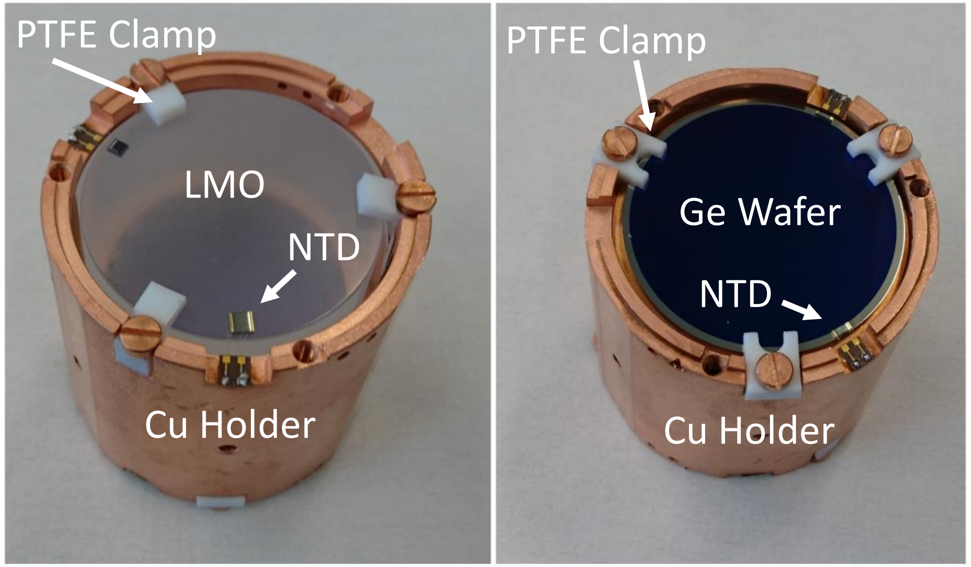
Installed in EDELWEISS cryostat

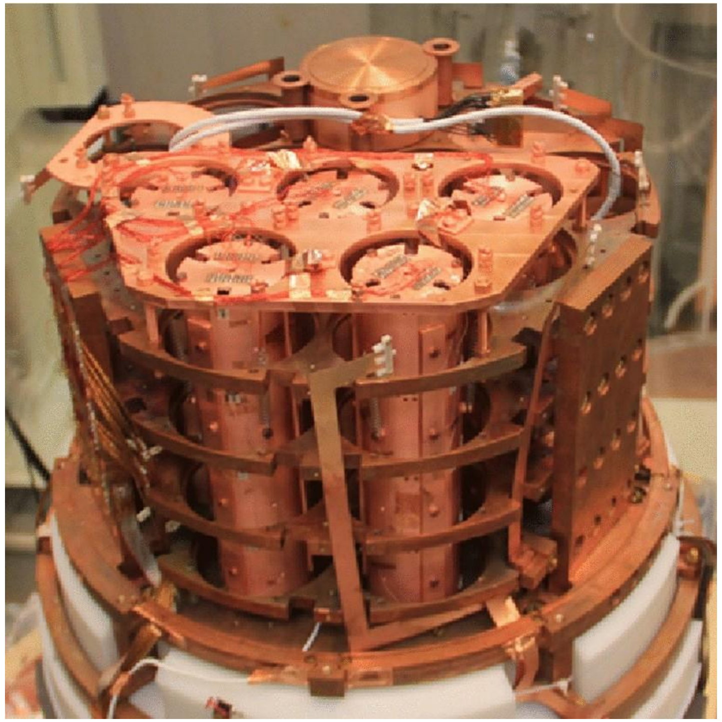
^{100}Mo $Q_{\beta\beta}$ = 3034 keV

20 $Li_2{}^{100}MoO_4$ scintillating bolometers

- 0.2 kg $Li_2{}^{100}MoO_4$ cylindrical crystals
- ^{100}Mo enrichment ~ 97 %
- Ge wafers as Light Detectors (LD)
- NTD Ge thermistors
- Copper holders, PTFE supports, Reflecting foils

- Materials radioactivity have been measured by HPGe or ICPMS





CUPID-Mo Data production

Exposure : 2.71 kg.year acquired between March 2019 and June 2020

Trigger (Optimal trigger) [1]

→ Amplitude from optimal filter (maximises SNR)

→ Thermal gain stabilization from ^{208}Tl (2615 keV)

↓ Calibration
Crystal : Th/U source
LD : ^{60}Co source producing Mo X-rays

← Cuts
- Light Detector
- Coincidences
- Pulse Shape

← Total efficiency after cuts [2]
(88.43 +/- 1.80) %

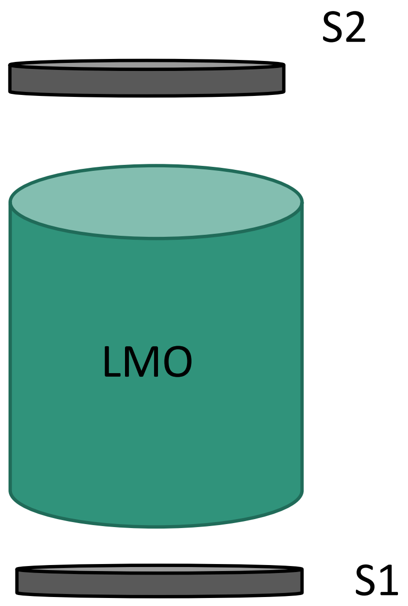
[1] : CUORE Phys. Rev. Lett. 124.122501

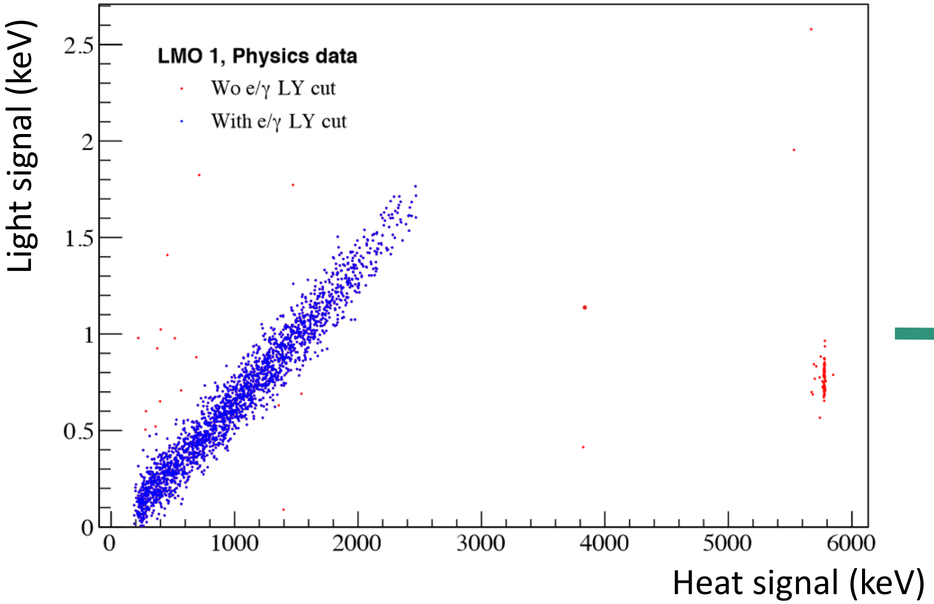
[2] : exposure weighted average

Light Detector Cut

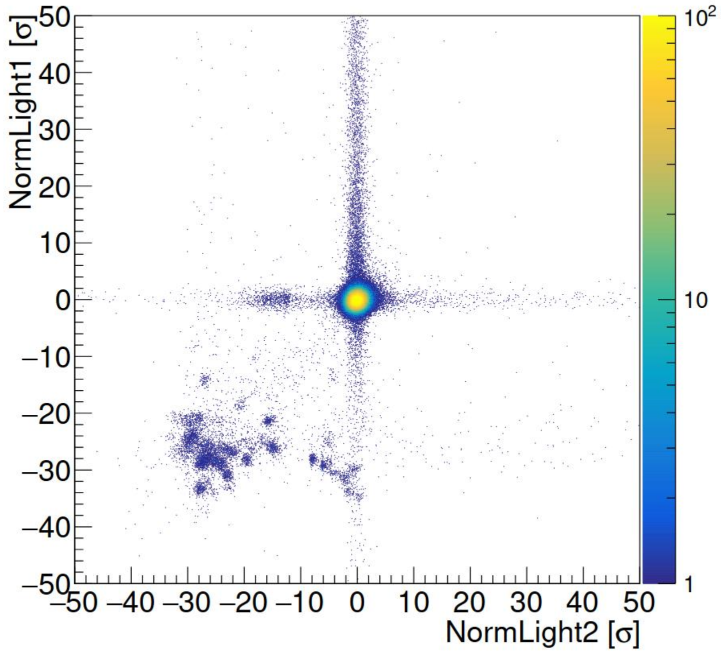
Goal : Apply a unique cut on all the data to remove α particles

1. Extraction of the 2 Light Detectors signals
2. Normalize each signal in the Light Detector by :
   a) The Energy (light is proportional to heat)
   b) The Light Detector (each one has its own performances)
   c) The Dataset (acquisition conditions can affect performances)
3. Apply the cut





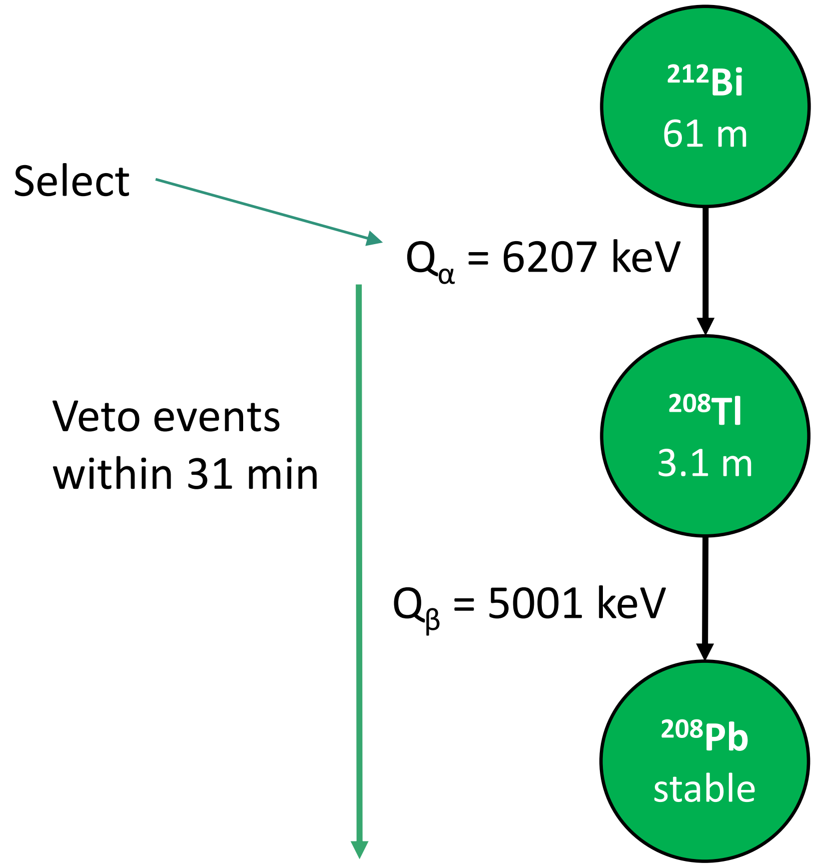
Normalization



Delayed coincidences

Thorium chain :

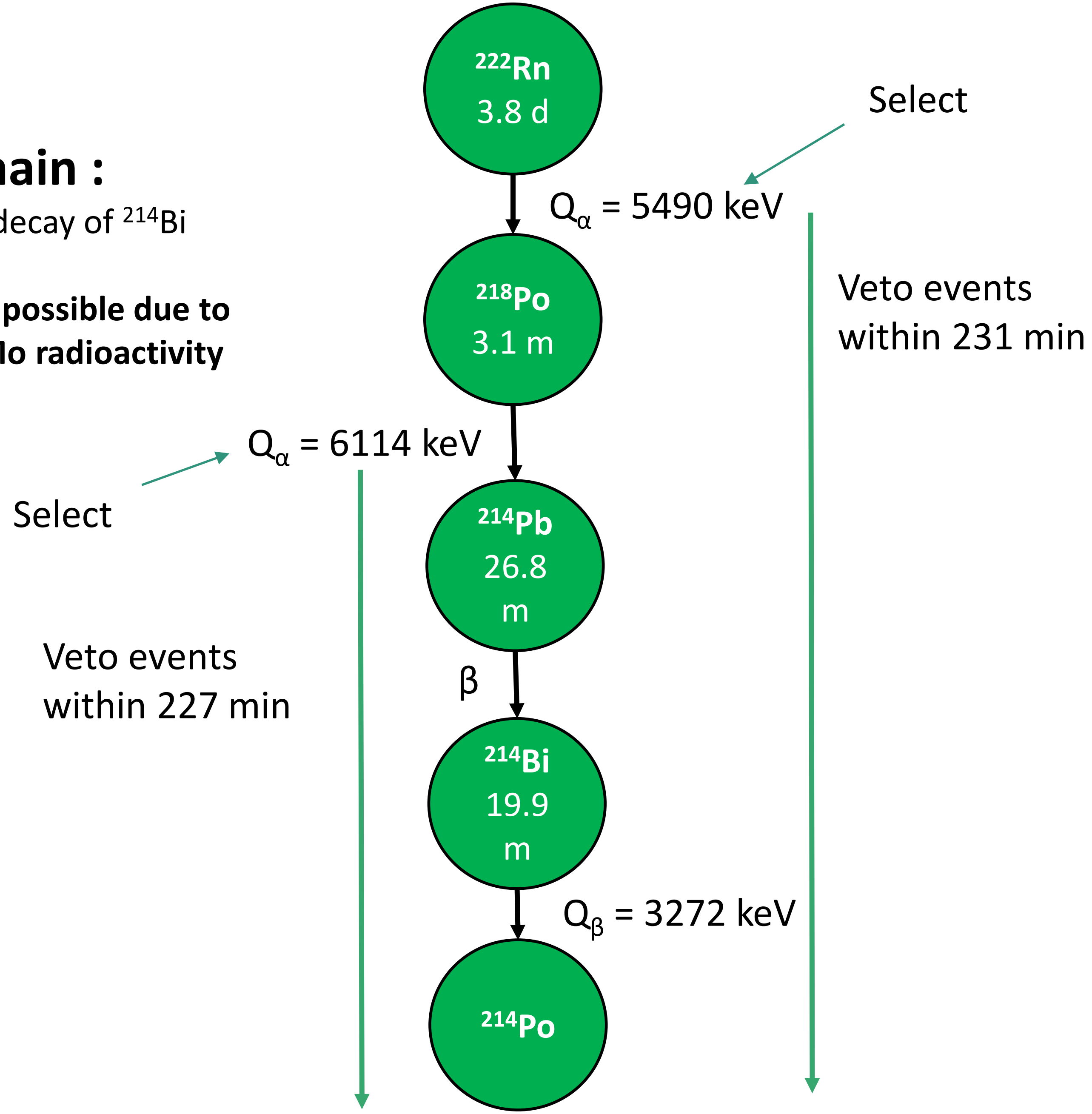
Goal : remove β decays of ^{208}Tl from the crystals



Uranium chain :

Goal : remove β decay of ^{214}Bi from the crystals

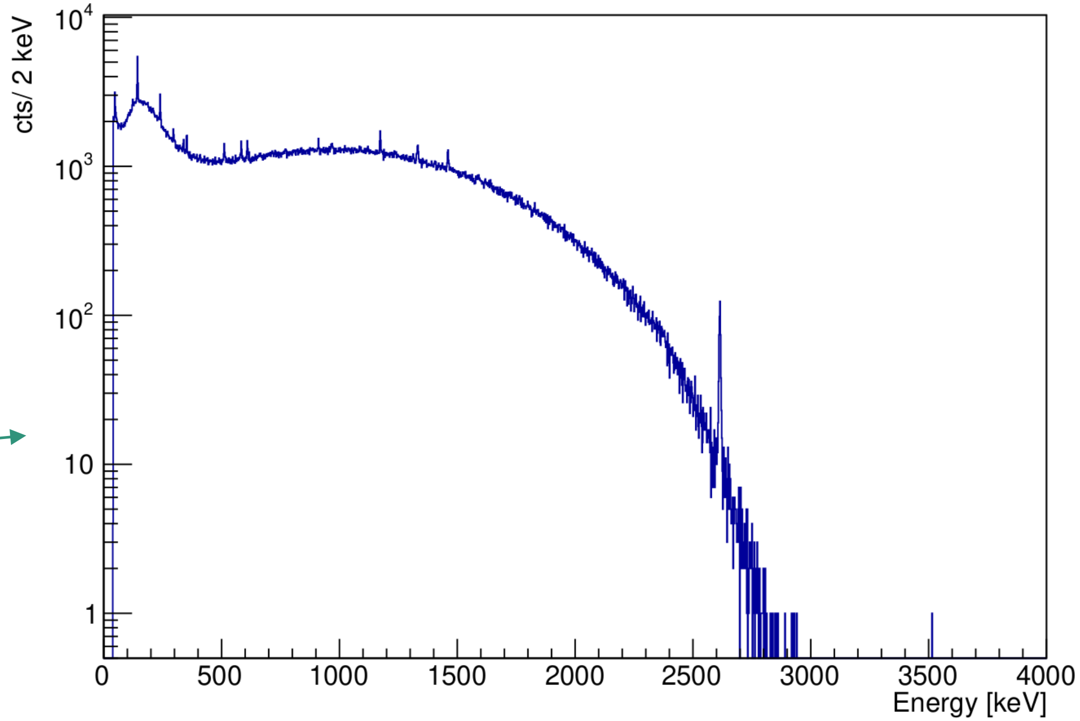
Novel analysis is possible due to the low CUPID-Mo radioactivity

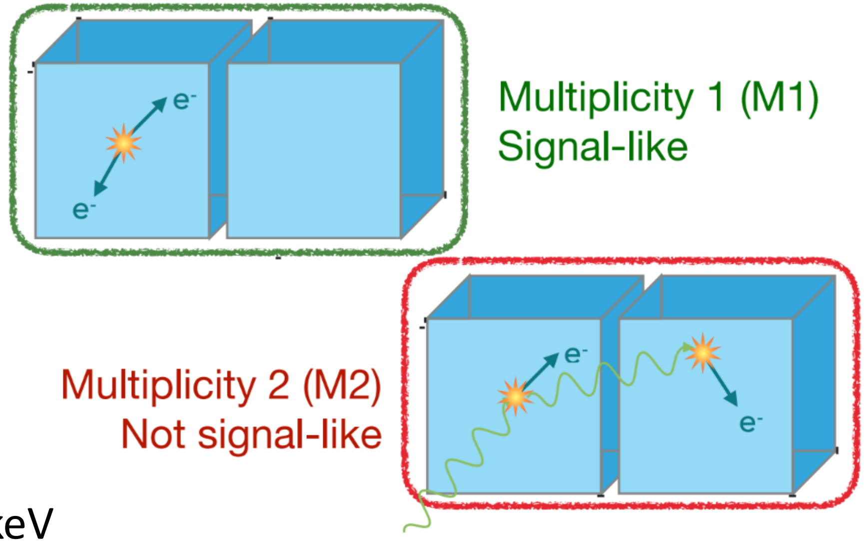


Multiplicity

- Number of events above our energy threshold[1] within a +/- 10 ms time window

- $M_{1,\beta/\gamma}$
  - Events in one detector identified as β/γ
  - $0\nu\beta\beta$ signal like
- M_2
  - Coincidences between two crystals
  - Constrains levels of external contaminations
- $M_{1,\alpha}$
  - M_1 events & E > 3 MeV
  - Constrain levels of contaminations for crystals and reflectors
  - Permits differentiation between bulk and surface events for crystals





[1] 40 keV

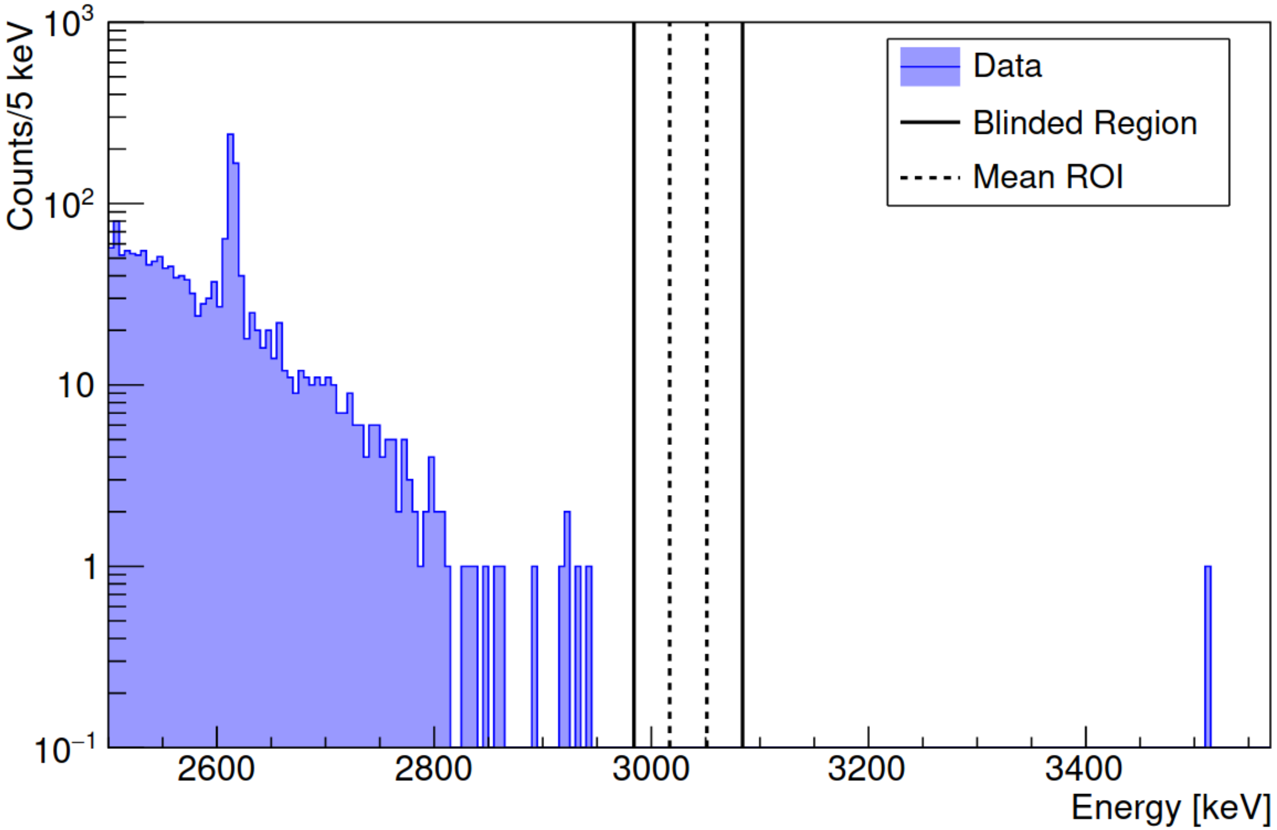
Limit on $T_{1/2}^{0\nu\beta\beta}$ of ^{100}Mo

- Blinding performed by masking events in an energy range of +/- 50 keV around $Q_{\beta\beta}$
- Exposure : 2.71 kg×year of data (1.47 kg×year for ^{100}Mo)
- After application of all cuts : 0 events in the ROI
- Bayesian counting analysis in ROI and sidebands leads to :

$T_{1/2} > 1.8 \times 10^{24}$ y (90% CI)

$m_{\beta\beta} <$ (280 - 490) meV

arXiv:2202.08716
Submitted to EPJC



Background model

Goal : Describe the experimental data by a linear combination of the MC spectra

- MC simulations used as input for a global fit of the data

- Simultaneous fit of $M_{1,\beta/\gamma}$, M_{2sum}, $M_{1,\alpha}$ spectra

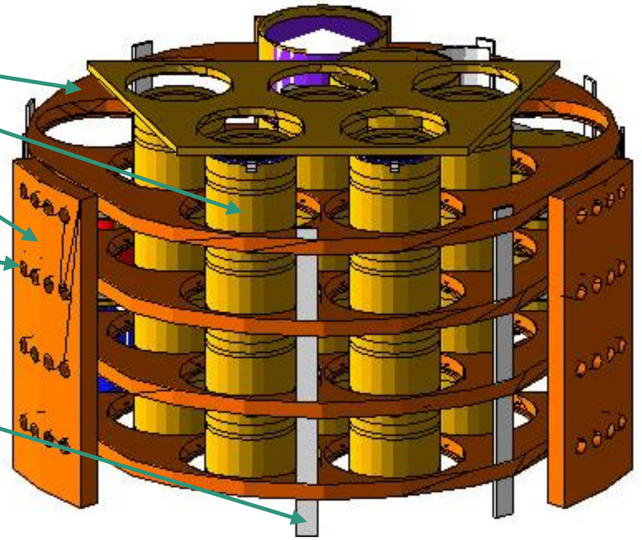
CUPID-Mo simulations

- Geant 4 based program
- Decays are generated in :
  - Crystal bulk and surface
  - Reflector bulk and surface

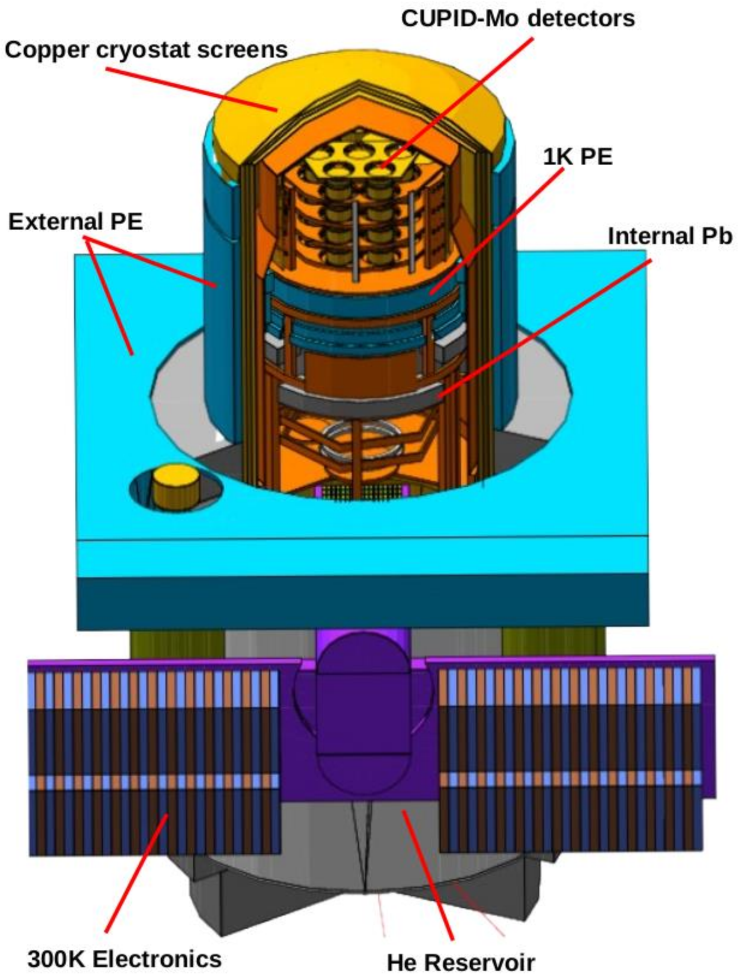
Surface component :
Exponential density profile $e^{-x/\lambda}$

Close sources
- Copper internal
- Springs
- Screws
- Kapton connectors
- Kapton cables

Cryostat and shield
- Copper screens
- Screen 300K
- Polyethylene internal



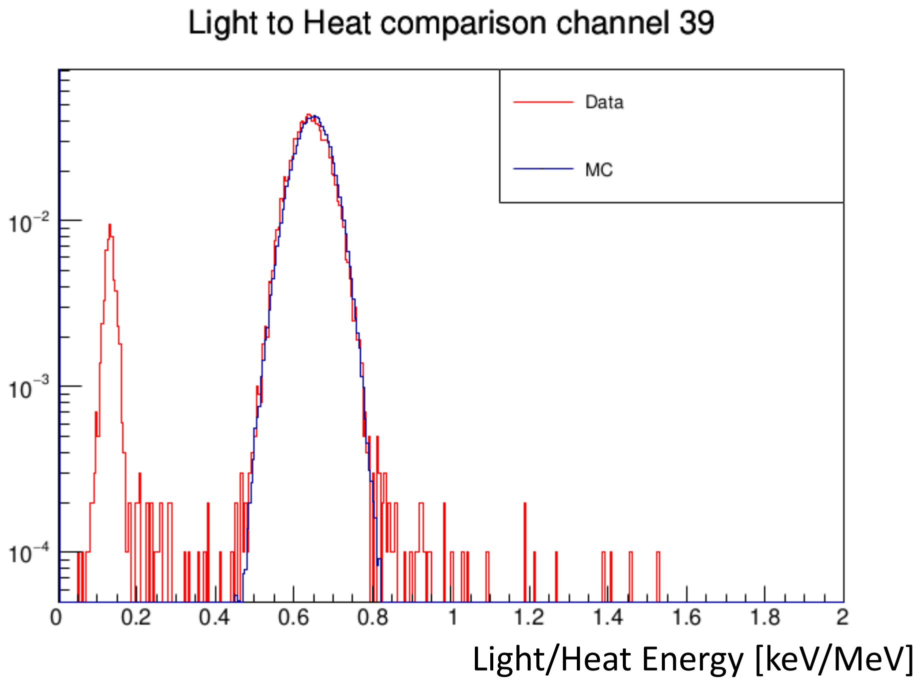
Geant4 Rendering of the CUPID-Mo detectors

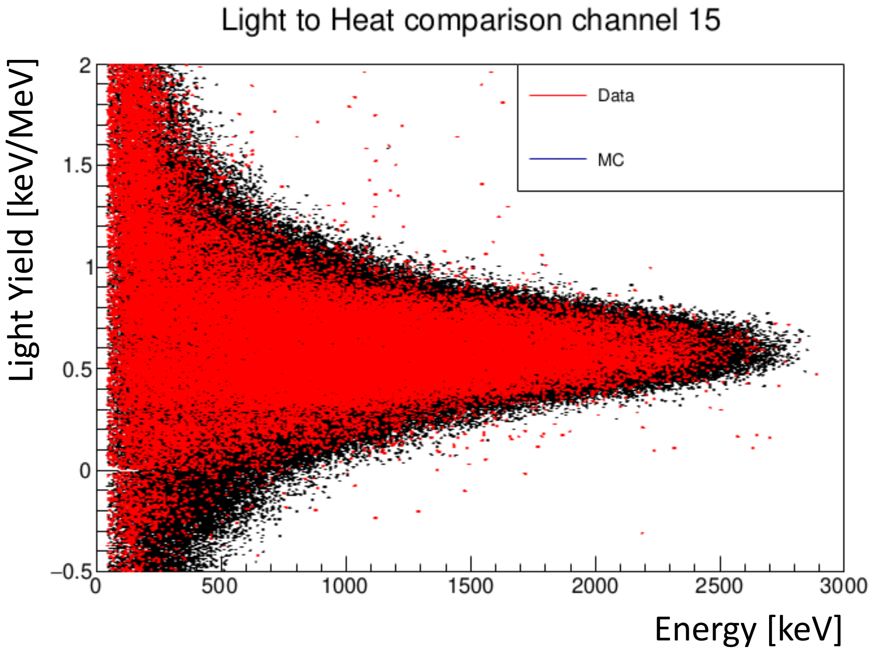


Geant4 Rendering of the Edelweiss set up with the CUPID-Mo detectors as implemented in the simulations

Detector response model

- Detector effects convolved into Monte-Carlo spectra
  - Energy resolution
  - Efficiency

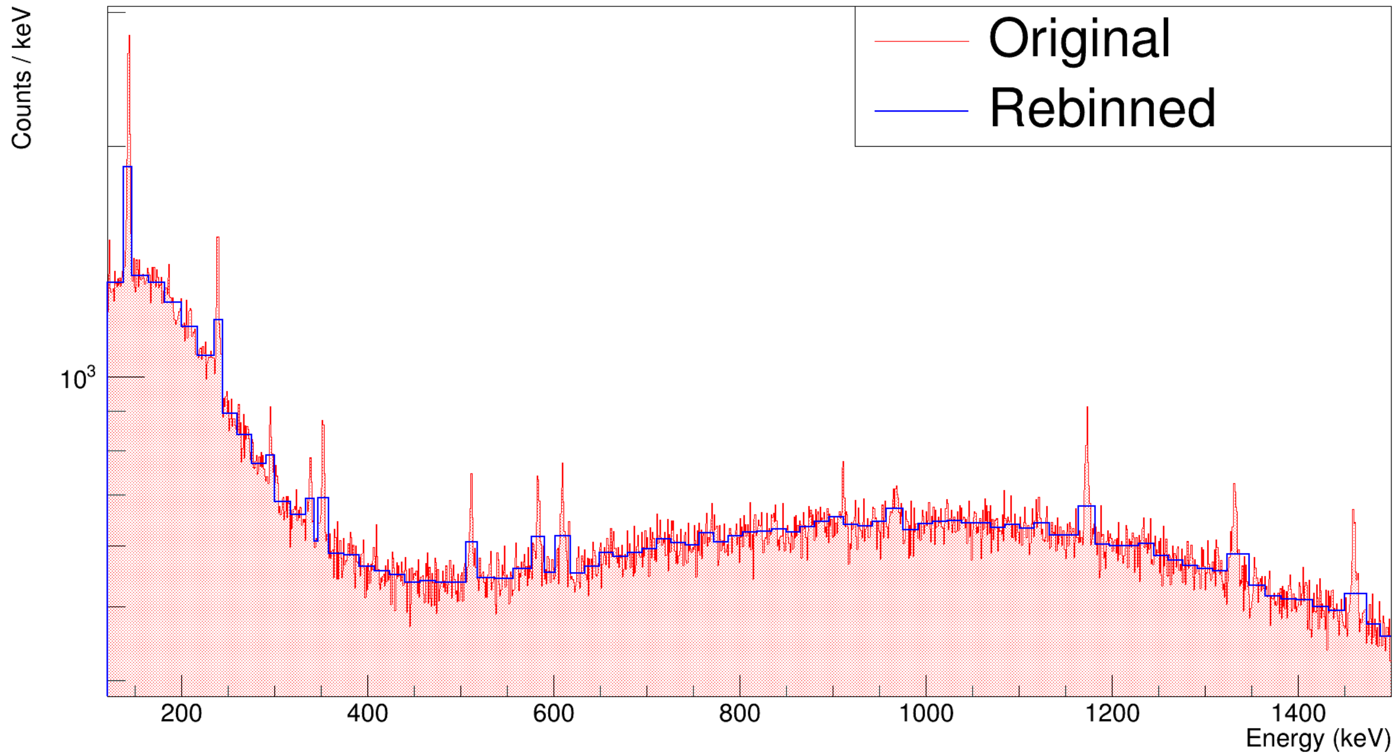




- We compute :
  - Multiplicity
  - Delayed coincidences
  - Light Detector signal
    - For each deposited energy in the crystal we generate randomly a scintillation light
    - This scintillation light is generated according to the light distribution in the data

Final reference fit

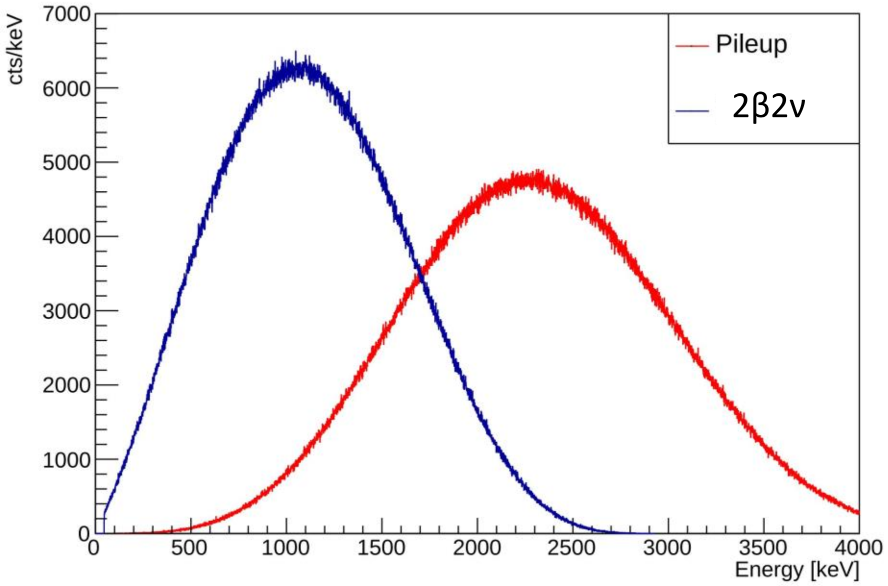
- Fit performed with a Bayesian analysis using Just Another Gibbs Sampler (JAGS)
- Parameters of the model tell us the radioactive contamination of the various components
- A robust background model allows for several further physics studies



Parameters :

- Variable binning
- Peaks are fully contained in one bin
- $M_{1,\beta/\gamma}$
  - Interval : [100 ; 4000] keV
- M_{2sum}
  - Interval : [400 ; 4000] keV
- $M_{1,\alpha}$
  - Interval : [3000 ; 10 000] keV

Priors : Final Reference Fit



Excited state 2β2ν 0_1^+ :

- $T_{1/2}$ = (6.7 +/- 0.5) 10^{20} years

Barabash, A. S. AIP Conference Proceedings. Vol. 2165. No. 1. AIP Publishing LLC, 2019.

Pile-up :

- Spectrum is generated by random selection of 2 events in the 2β2ν spectrum

$$\Gamma_{pileup} \propto \Gamma_{single}^2 \times \Delta t_{eff}$$ ← time resolution of the detector

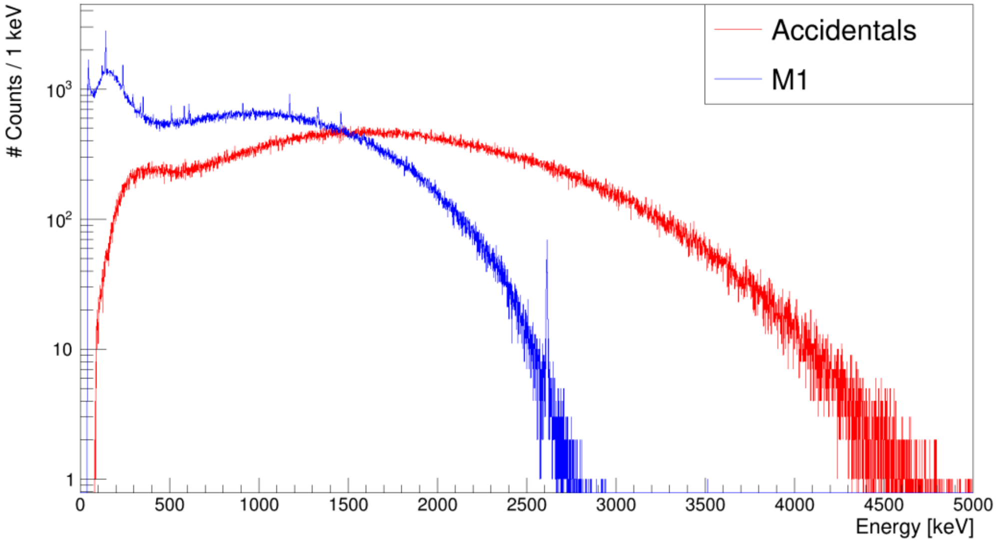
- In calibration data : $\Delta t_{eff} < 7ms$ (90% C.I.)

Accidentals :

- Spectrum is generated by random selection of 2 events in the $M_{1,\beta/\gamma}$ spectrum

$$N_{random} \propto N_{M1}^2 \times \Delta t$$ ← time window of the multiplicity

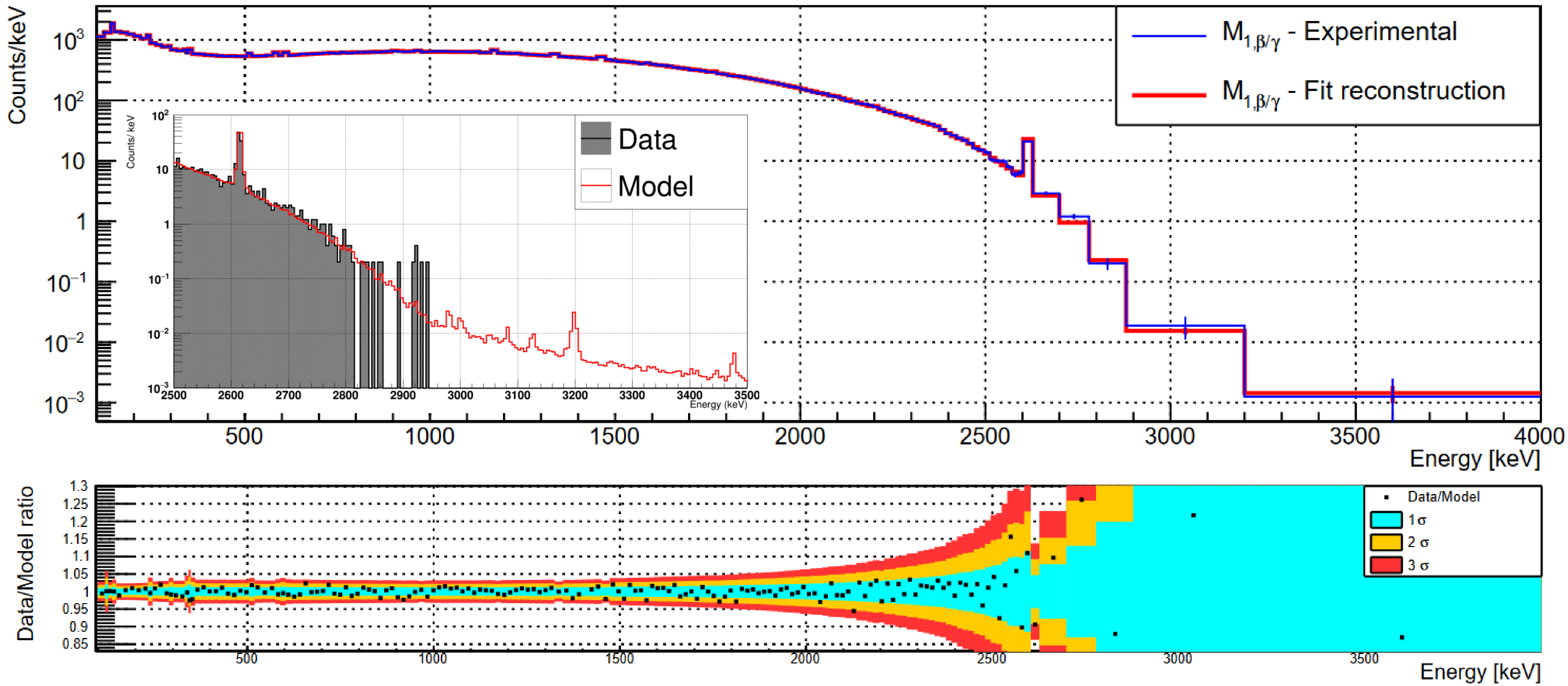
- $N_{accidentals} = 620\ \pm 25$ events



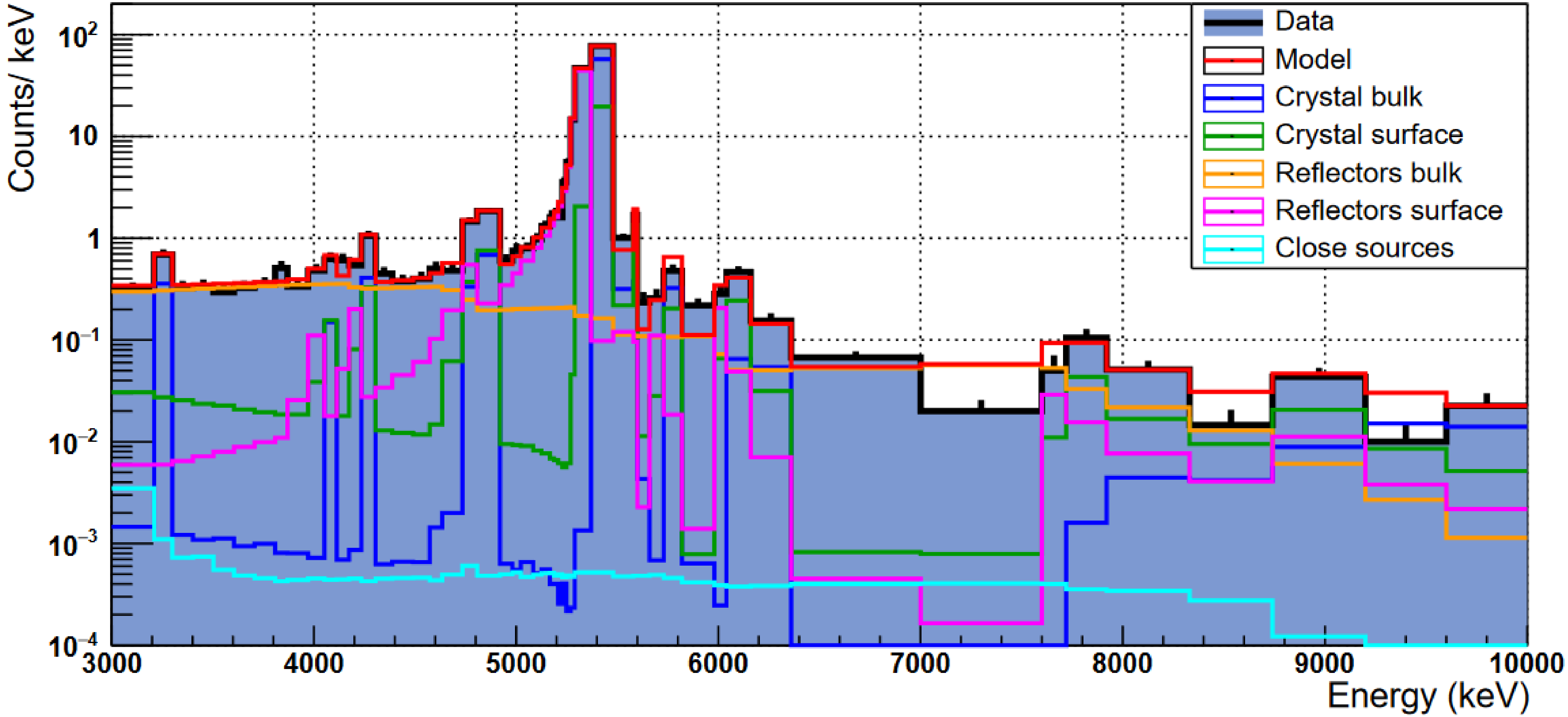
Activities of Springs :

- ^{40}K : 3600 +/- 400 mBq/kg
- ^{226}Ra : 11 +/- 3 mBq/kg
- ^{228}Th: 21 +/- 5 mBq/kg

Results : $M_{1,\beta/\gamma}$

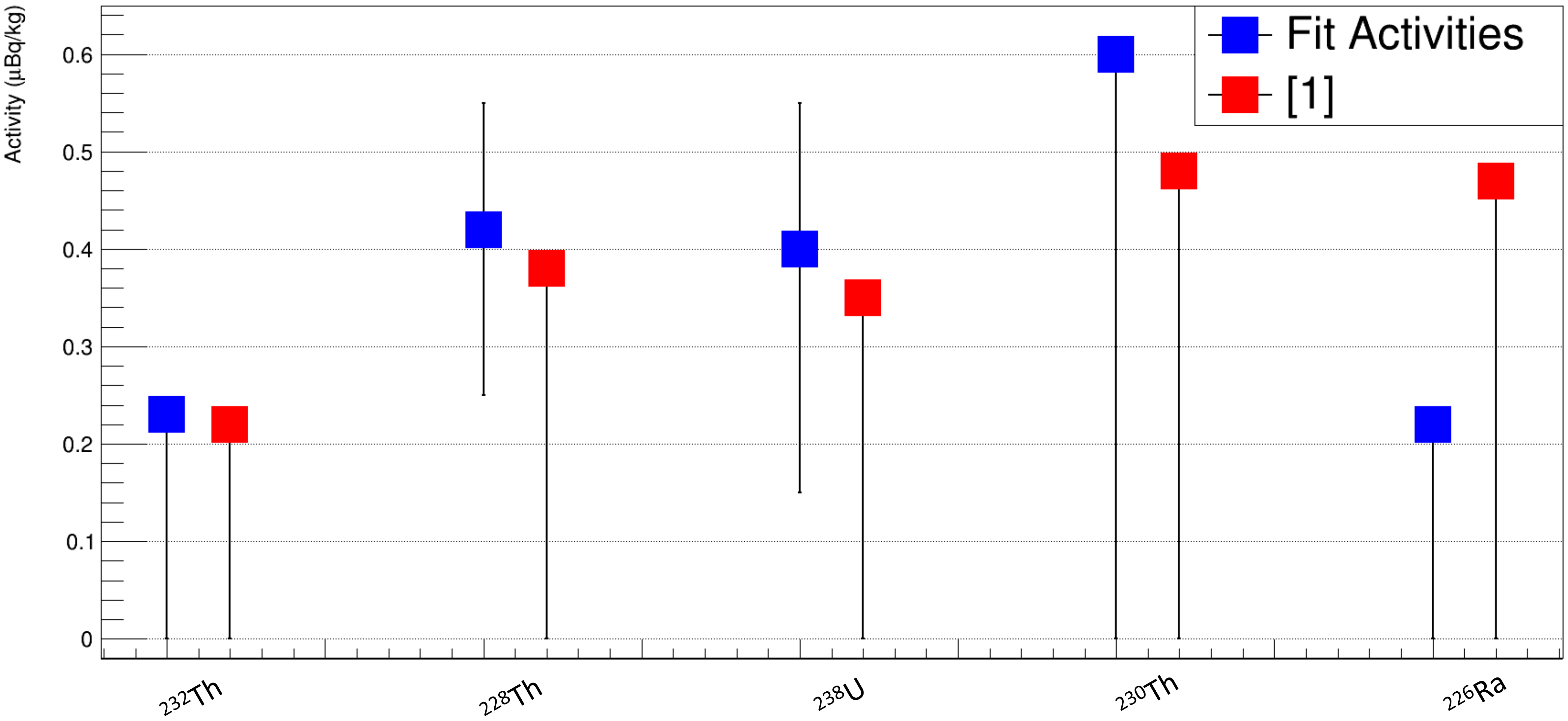


Background components : $M_{1,\alpha}$



Crystal bulk activities

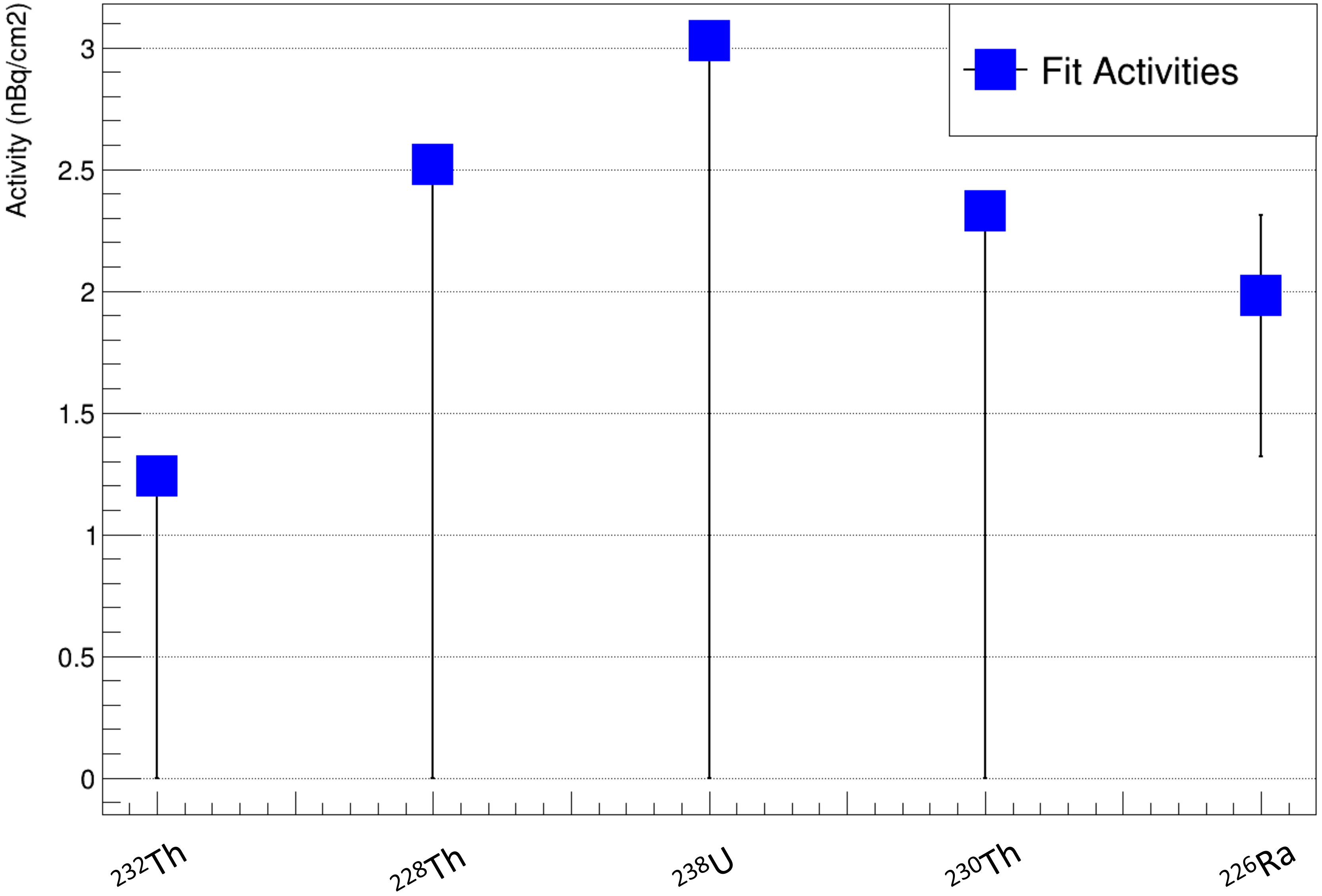
[1] : D. Poda [CUPID-Mo collaboration]. (Neutrino 2020), June 22–July 02 (2020)



Crystal surface activities

Surface component :

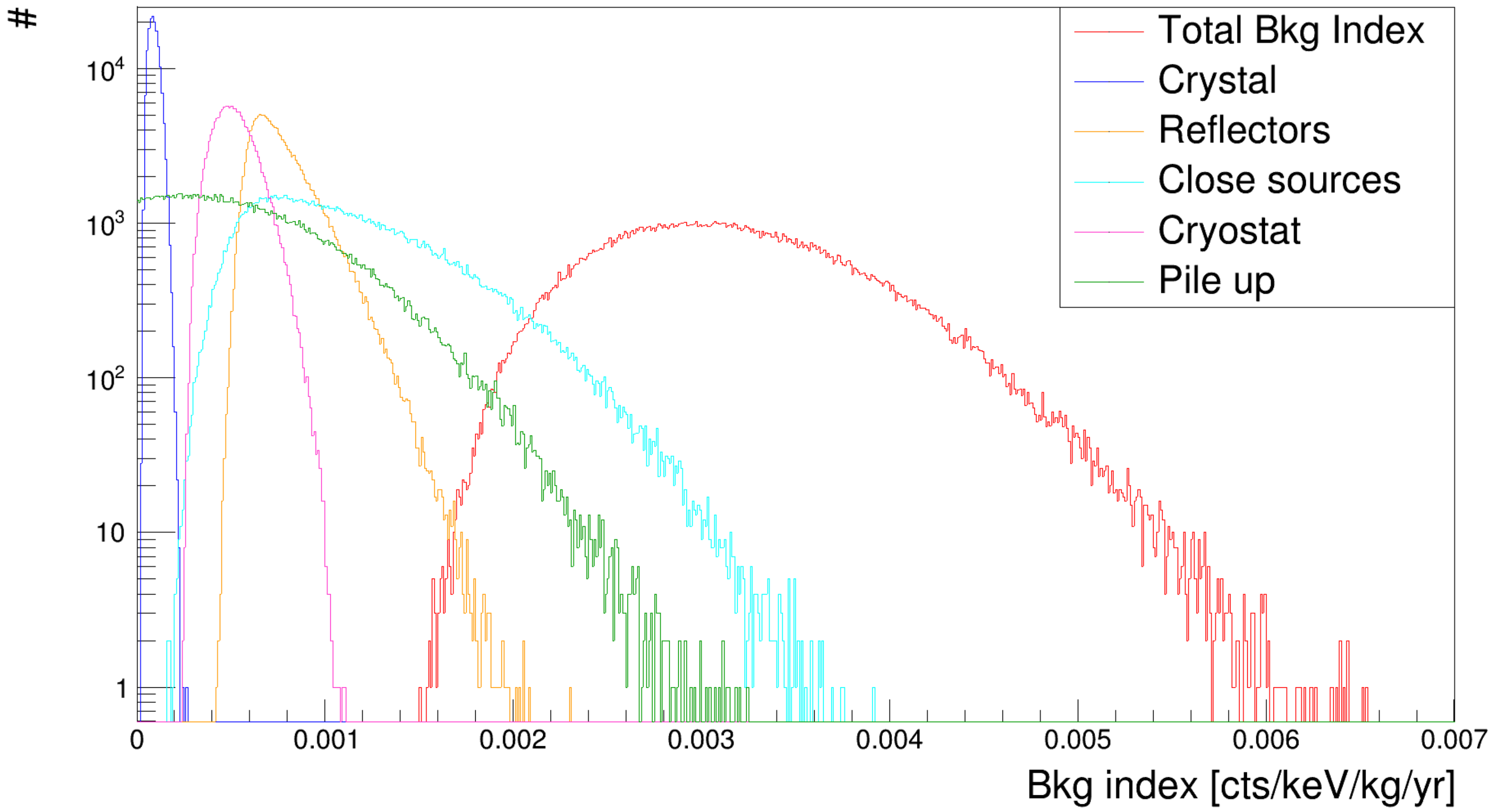
- Exponential density profile $e^{-x/\lambda}$
- λ = 10 nm



Background Index

Background index in 3034 +/- 15 keV :

$$3.0^{+0.7}_{-0.6} \times 10^{-3} \text{ counts / keV / kg / year}$$



Backgrounds of CUPID-Mo / CUPID

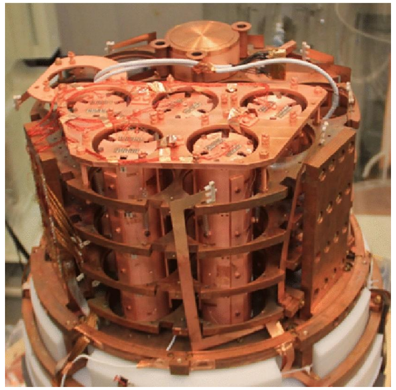
CUPID-Mo

Laboratoire souterrain de Modane (LSM)

Edelweiss cryostat

20 $Li_2{}^{100}MoO_4$ crystals

Closed structure



CUPID - Next bolometric ton scale experiment for 0νββ

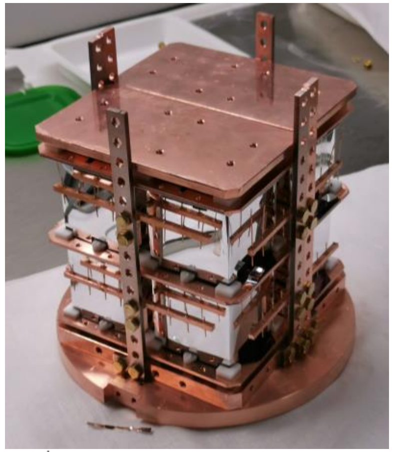
Laboratori Nazionali del Gran Sasso (LNGS)

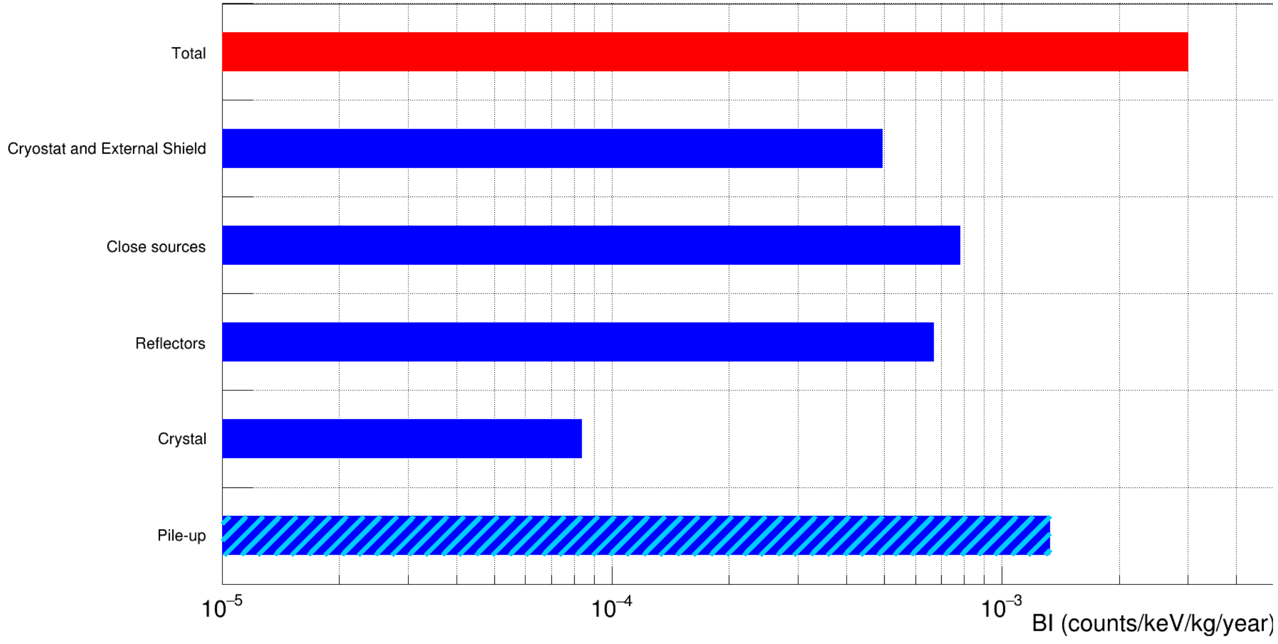
CUORE cryostat

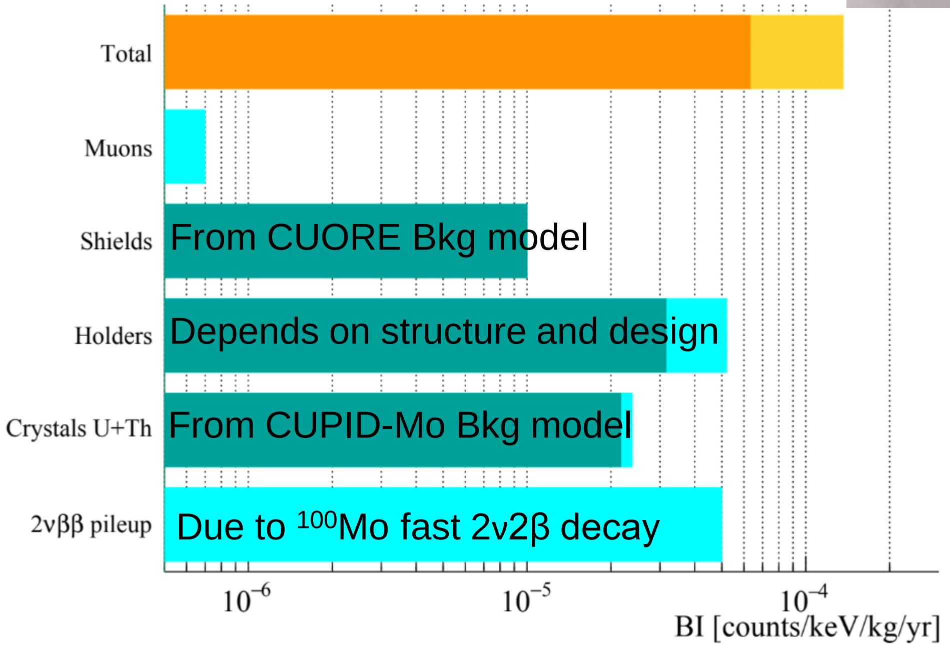
~ 1500 $Li_2{}^{100}MoO_4$ crystals

Open structure

Background Index Goal = 10^{-4} ckky







Decay process of ^{100}Mo 2νββ

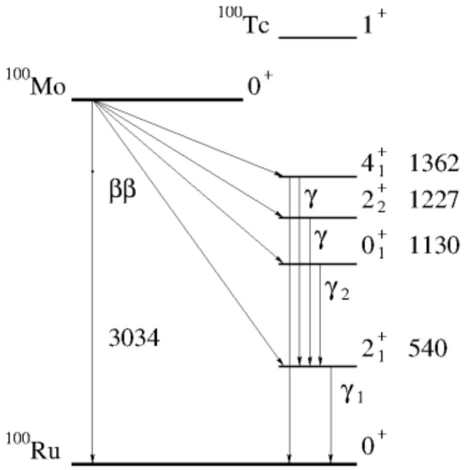
The process of ^{100}Mo 2νββ is not established

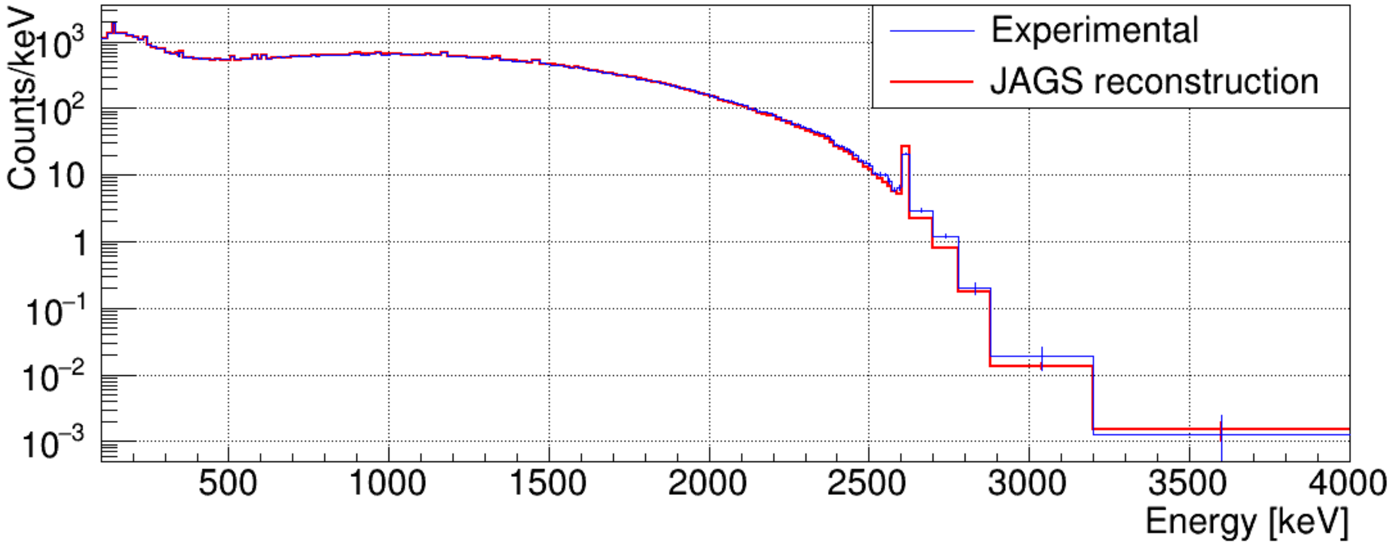
SSD Intermediate state :

- Ground state of ^{100}Tc

HSD Intermediate state :

- Include higher states of ^{100}Tc





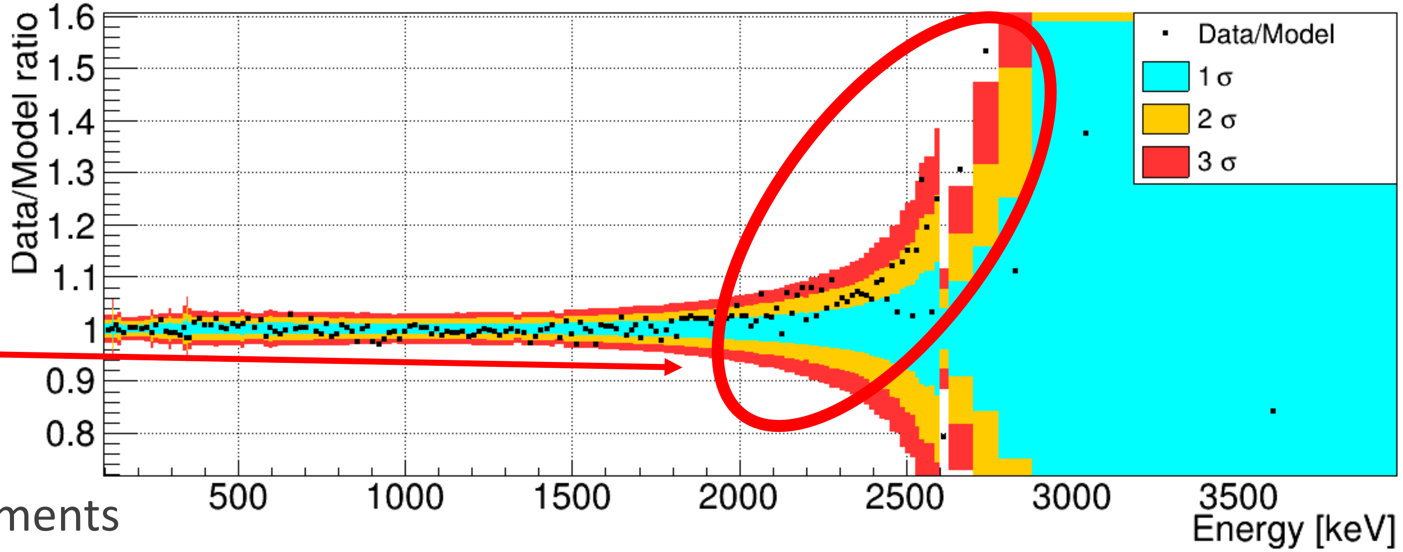
Models can be distinguished by the shape of ^{100}Mo 2νββ

The two models were parameterized according to Jenni Kotila

The **HSD model is clearly disfavoured** from the fit

Experimentally **we favoured the SSD model**

This is in agreement with observations of other experiments



Determination of the ^{100}Mo 2νββ half life

Thanks to the robust background model one can extract the $T_{1/2}^{2\nu\beta\beta}$

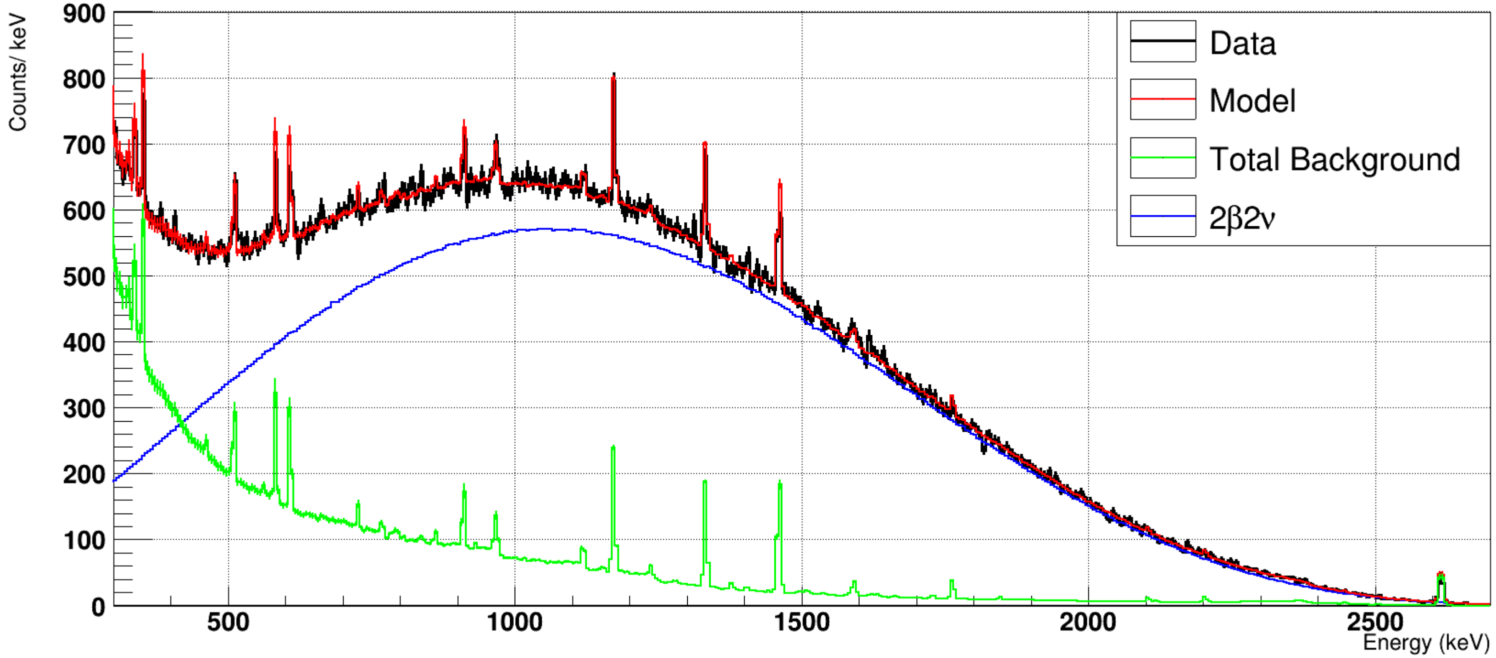
Previous measurements : Uncertainty = $^{+2.9\%}_{-2.4\%}$ **arXiv:1912.07272**

Blinded analysis : From our reference fit we extract the normalization coefficient (that we don't translate in terms of half life)

Statistical uncertainty = +/- 0.3 %

We estimate the systematic uncertainties induced by :

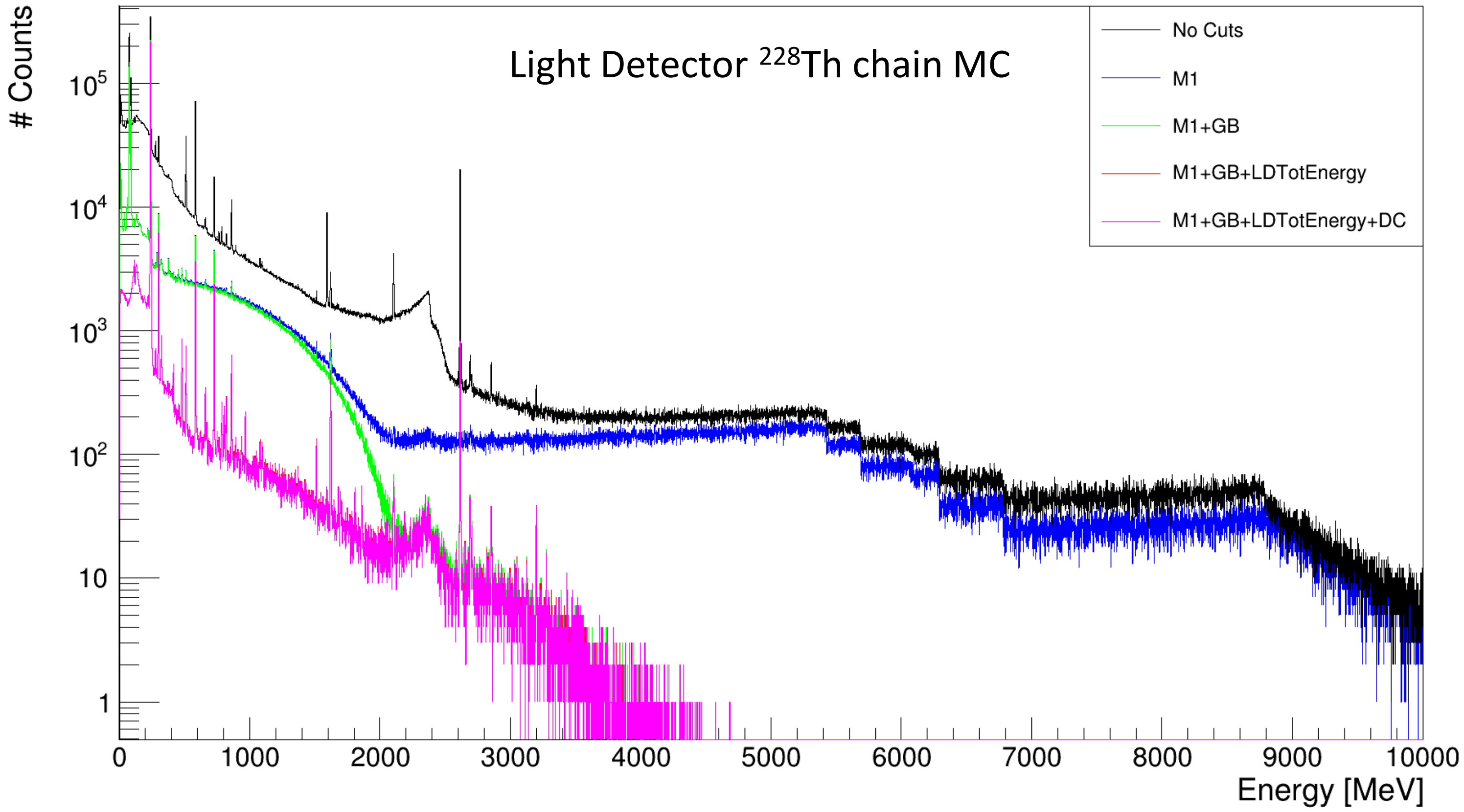
1. The $M_{1,\beta/\gamma}$ range : Syst = 0.3 %
   - [200 ; 4000]
   - [500 ; 4000]
2. The choice of binning : Syst = 0.4 %
   - 1 keV fixed binning
   - 2 keV fixed binning
   - 20 keV fixed binning
3. Statistical fluctuations in the MC : Syst = 0.1 %
4. Choice of sources : Syst = 0.2 %



We have to estimate the uncertainty coming from efficiency that is expected to be ~ 1%
With such errors we could achieve the most precise measurements of ^{100}Mo 2νββ half life up to date

MC simulations for CUPID

- Agata
  - GEANT4 code developed by the collaboration
  - Including the baseline geometry of CUPID
- Detector response
- MC Simulations
  - Estimate expected backgrounds, in particular in region of interest



- Working on maximum activities that we can accept for some components close to the crystals to achieve our background index goal (10^{-4} ckky)
- This will guide the method and the time needed to measure the radioactivity of such components

Summary

Paper will be soon published

CUPID-Mo :

- Lowest background index for bolometric experiment was observed : $\mathbf{3.0^{+0.7}_{-0.6}} \times \mathbf{10^{-3}}$ ckky

- Low crystal bulk and surface contaminations
- Compatible with CUPID Background Index Goal

Writing paper will start soon

- SSD model is favoured for 2νββ

- The most precise measurement could be achieved for the 2νββ half life of ^{100}Mo

CUPID :

- Working on MC simulations to extract the maximum activities that can be accepted
- Will update the geometry in the Agata code with the updated version of the tower design of CUPID

BACK-UP

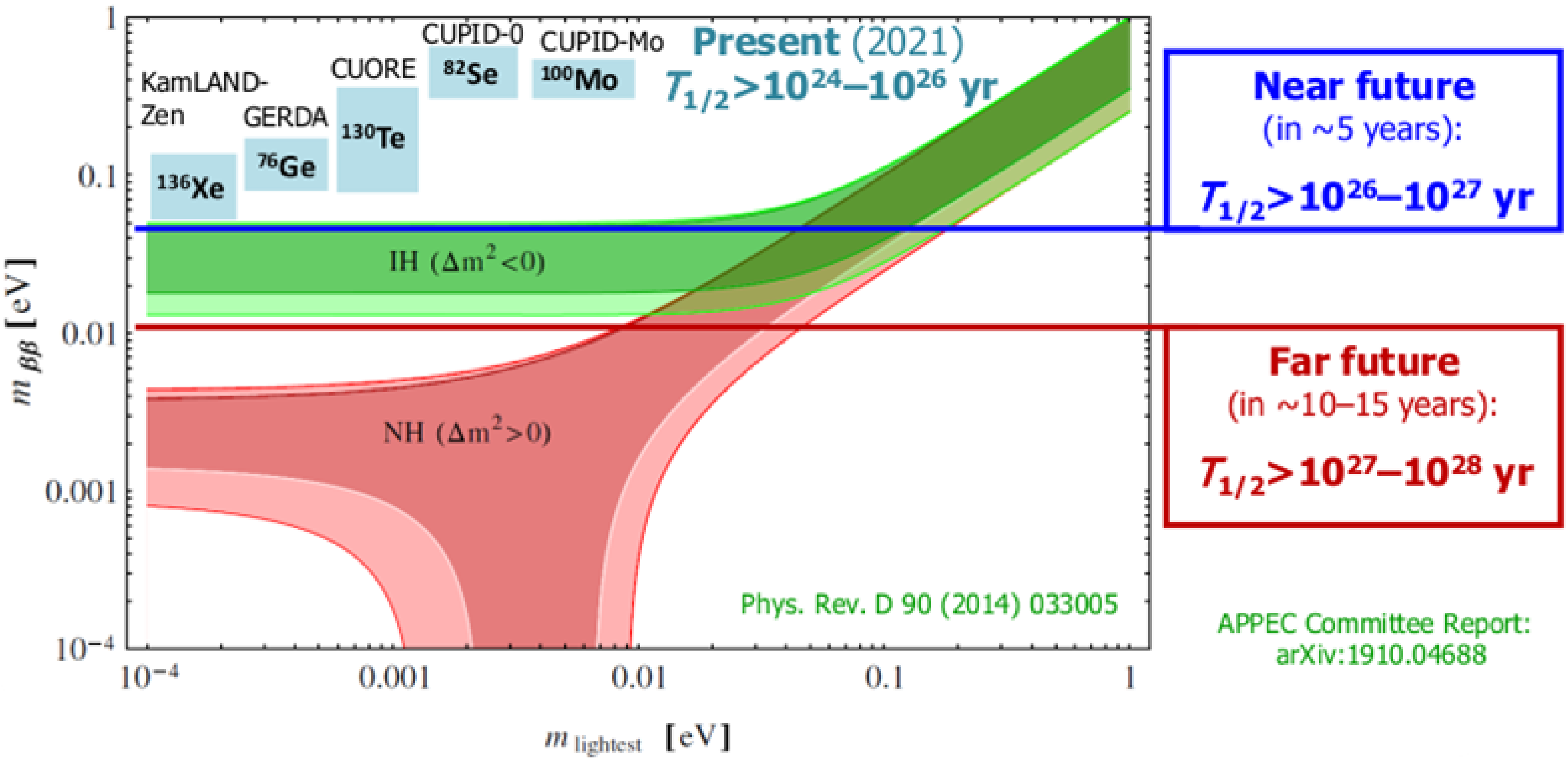
Where we are

Best current limits :

KamLAND-Zen on ^{136}Xe :

- $T_{1/2} > 2.3 \times 10^{26}\ yr$
- $m_{\beta\beta} < 36\ - 156\, meV$

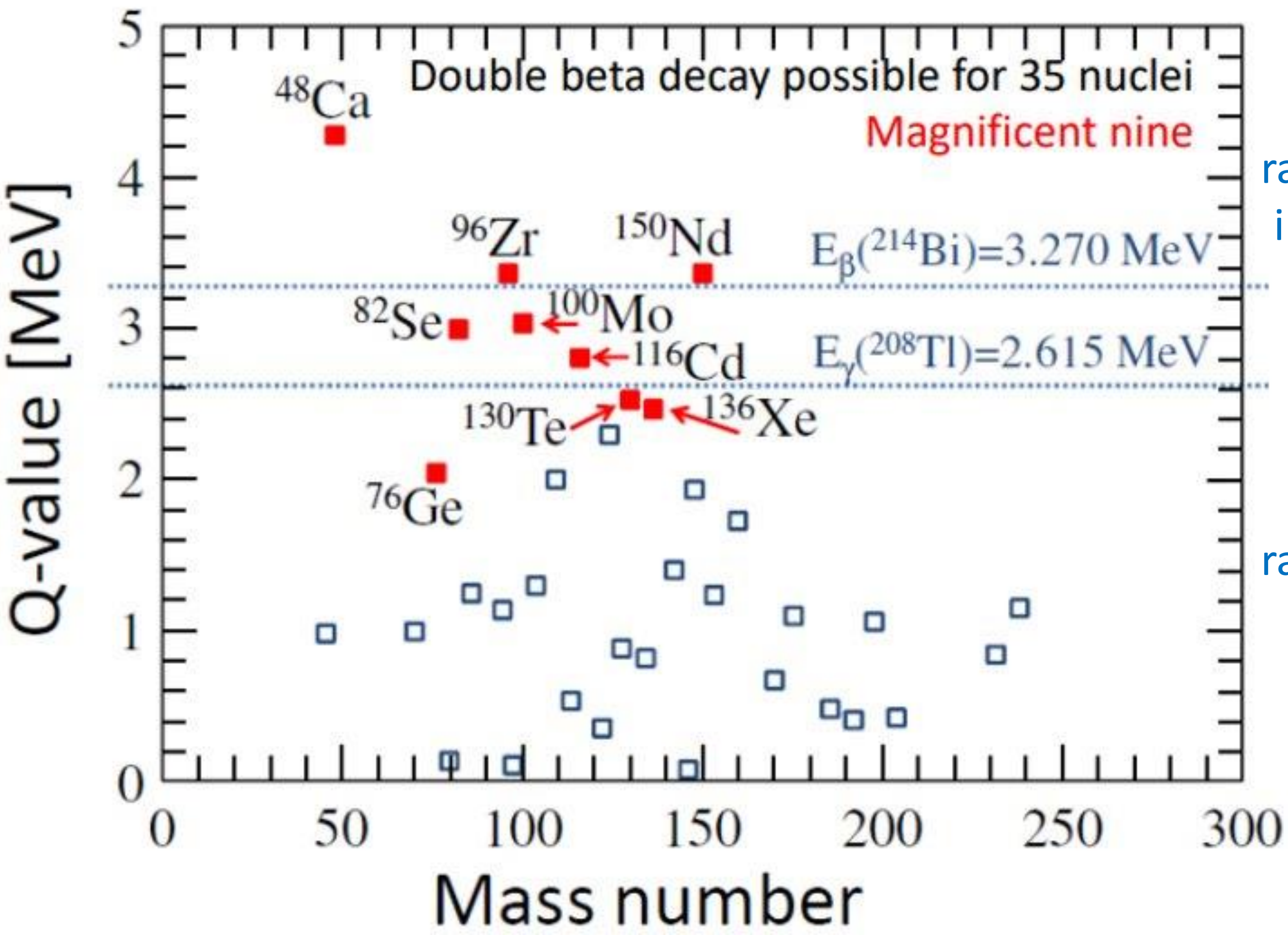
arXiv:2203.02139



Experimental challenge

- $Q_{\beta\beta}$ is an important factor
  - Phase space $G_{0\nu} \propto Q^5$
  - Background

- Main background is coming from **natural radioactivity**
  - α, β, γ



End of natural radioactivity induced by ^{214}Bi

End of γ natural radioactivity

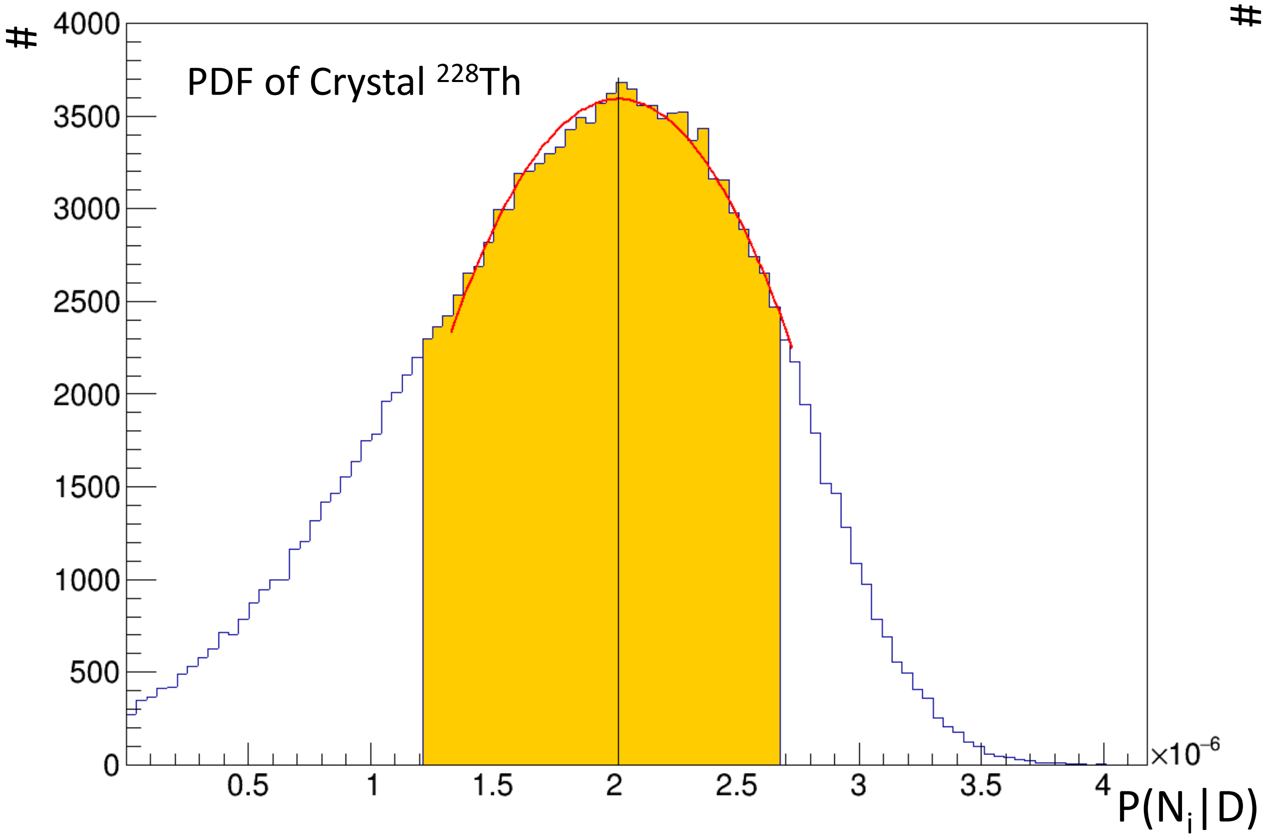
Extraction of activities from Probability Density Function

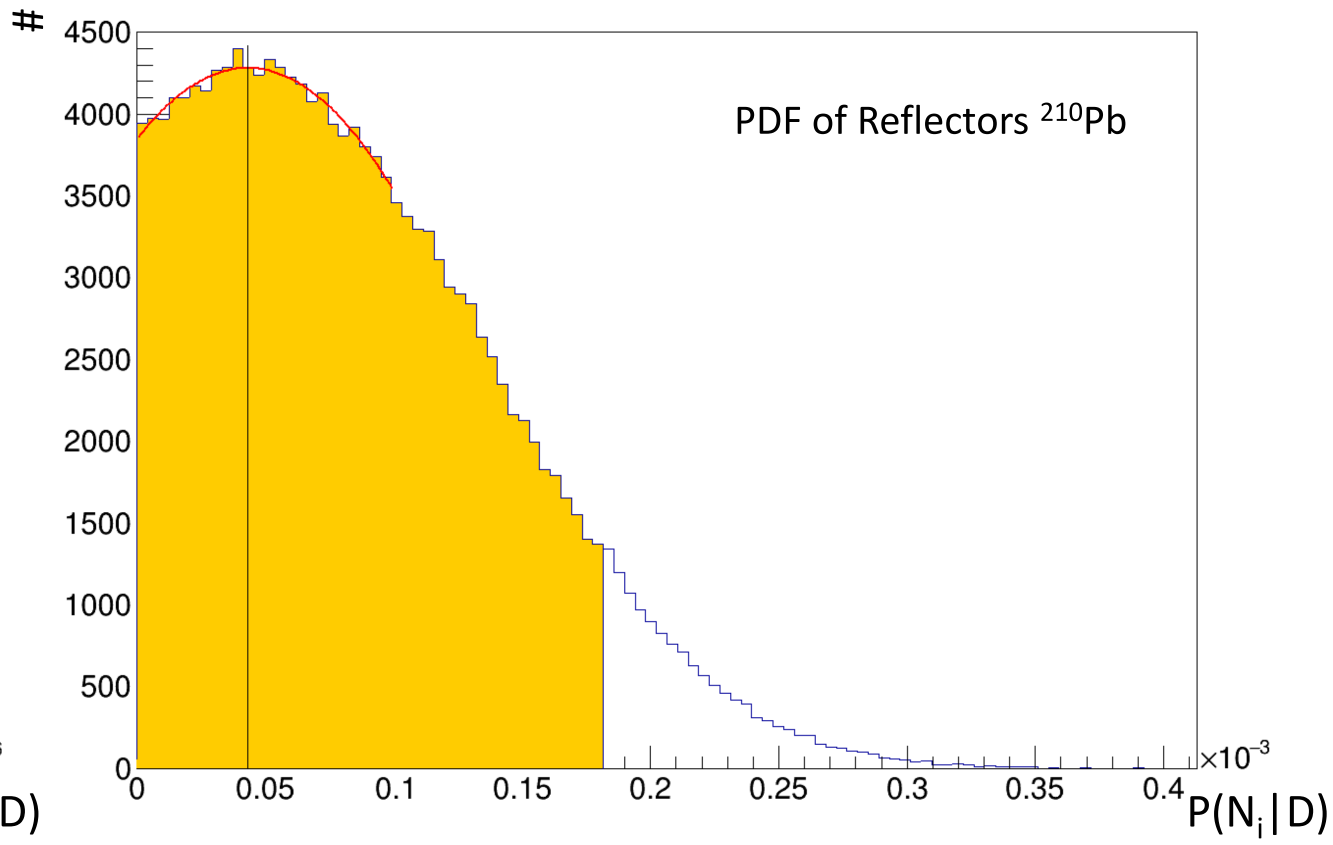
For each marginalised distributions

- Use the mode as our point estimate
- Compute the smallest 68.3 % interval around the mode

If the smallest 68.3 % interval is compatible with 0

- Compute an 90% upper limit





We can convert these point estimates and their associated errors (or limits) to activities