Background studies for the CROSS, CUPID-Mo and CUPID neutrinoless double beta decay experiments

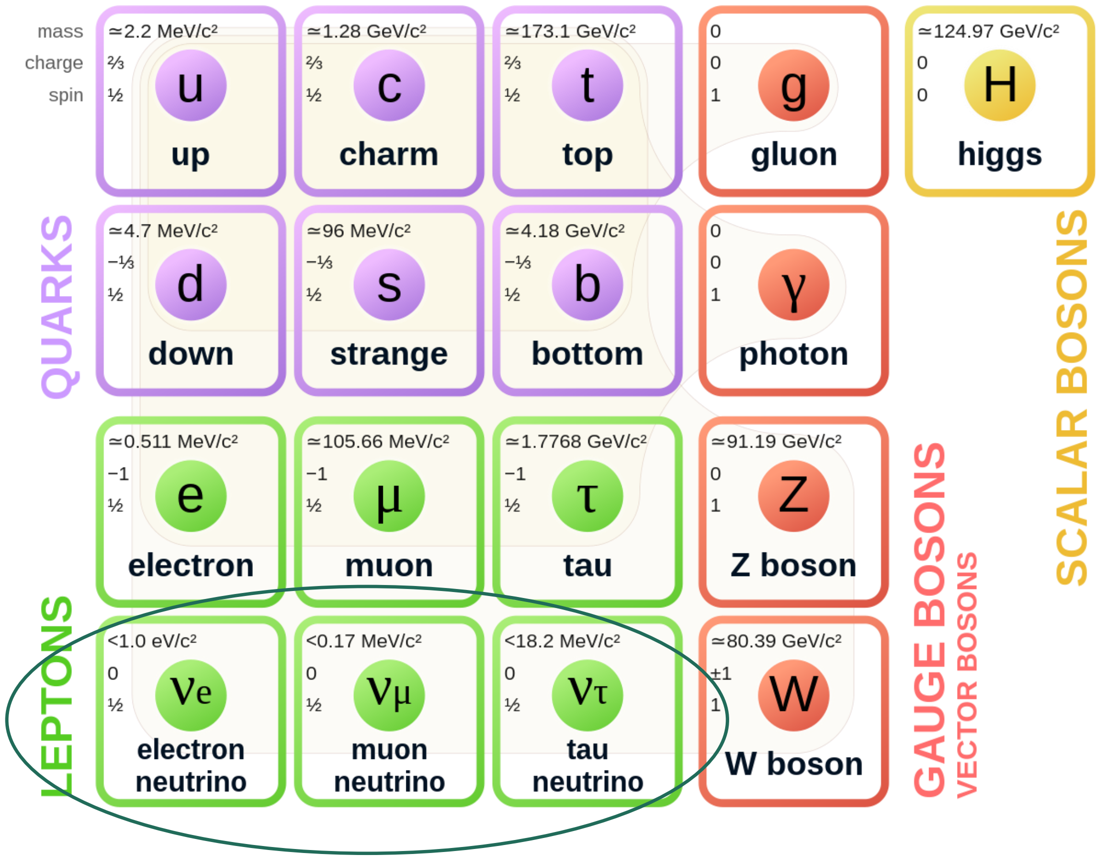
LÉONARD IMBERT

PHENIICS FEST

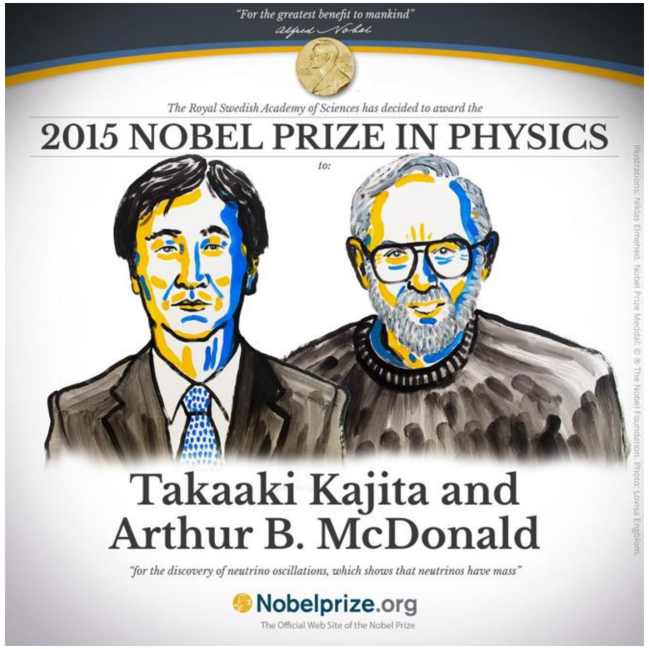
20/05/2022

Neutrino

- Neutral particle
- Massless in the Standard Model



- Neutrino oscillation
  - Require massive neutrinos



- What is the mass of the neutrinos ?
- How do neutrinos get their masses ?
- What is the nature of the neutrino ?

Double Beta Decay

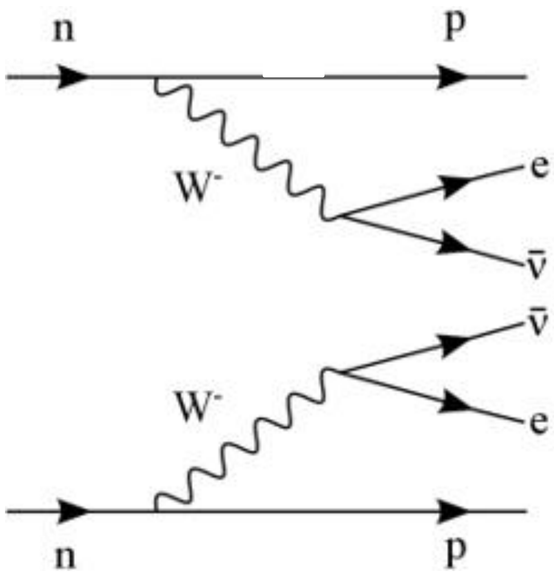
- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}_e$ 2νββ
- Standard Model process
  - Possible when single beta decay is not energetically possible
- Observed for 9 isotopes

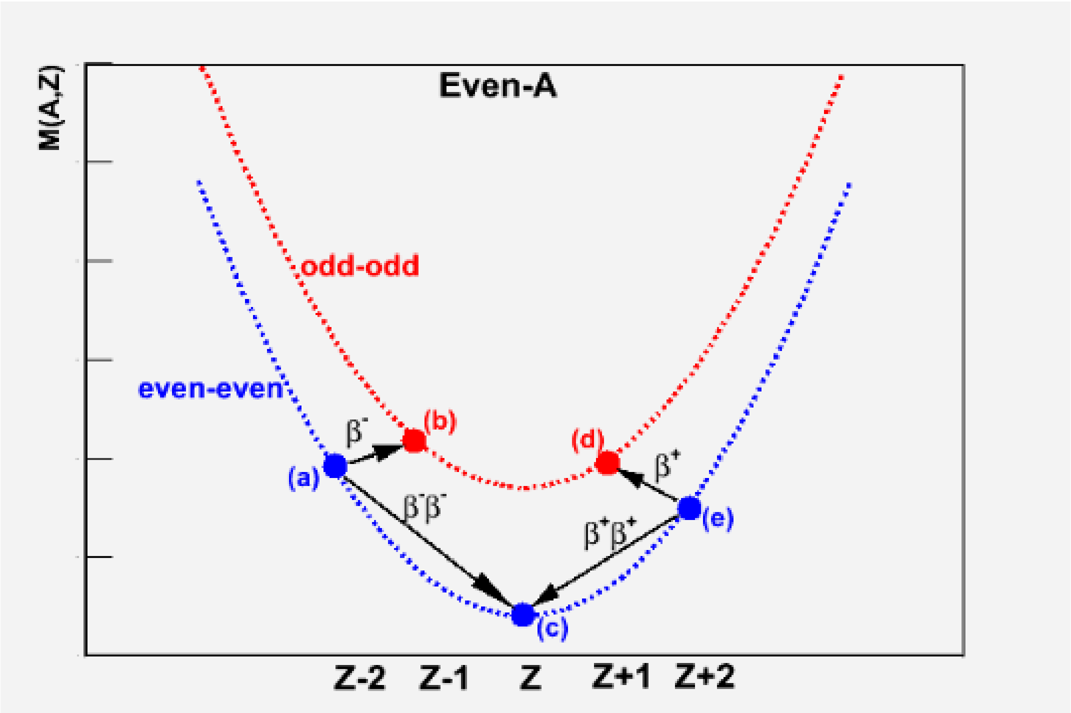
SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*
(Received May 20, 1935)

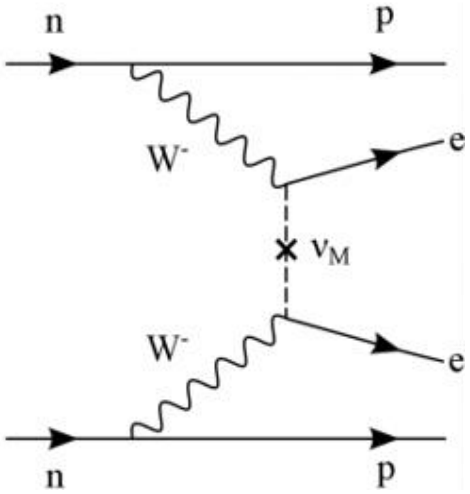
From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.





Neutrinoless Double Beta Decay

- Hypothetical decay
- $(A, Z) \rightarrow (A, Z+2) + 2e^-$ $\quad \mathbf{0\nu 2\beta}$
- **Lepton number violation ΔL = 2**
- Majorana neutrino $\nu = \bar{\nu}$



TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

Nuovo Cimento 14(1937)171-184

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

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

Space phase factor :
Known and calculated to good accuracy

Nuclear Matrix Element :
Differences between different nuclear models

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

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

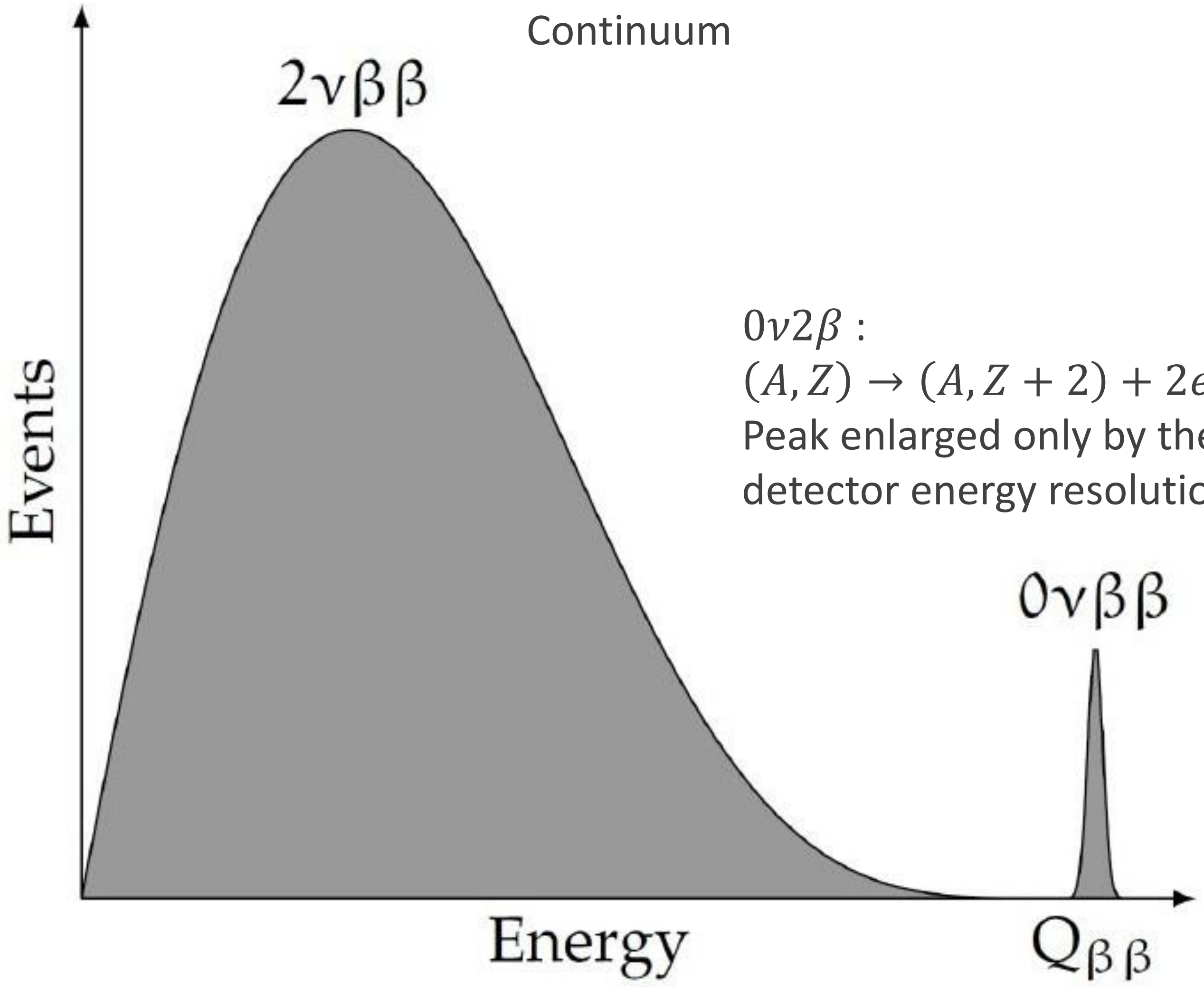
Effective Majorana mass :

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

Searching for $0\nu2\beta$

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

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

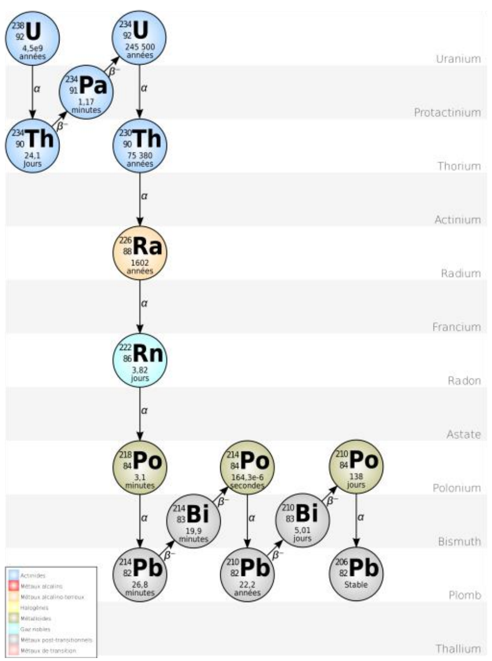


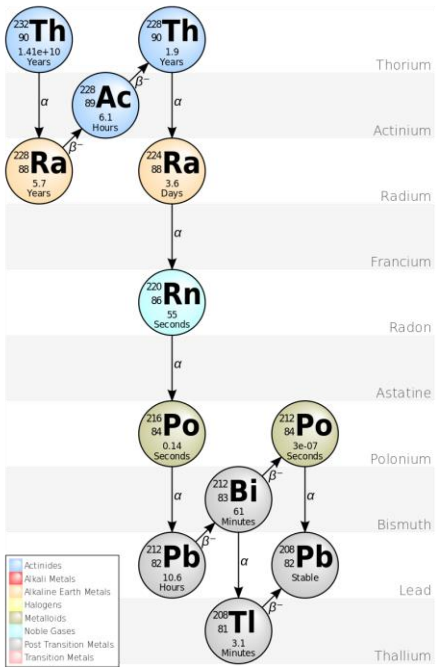
$0\nu2\beta$:
$(A,Z) \rightarrow (A,Z+2) + 2e^-$
Peak enlarged only by the detector energy resolution

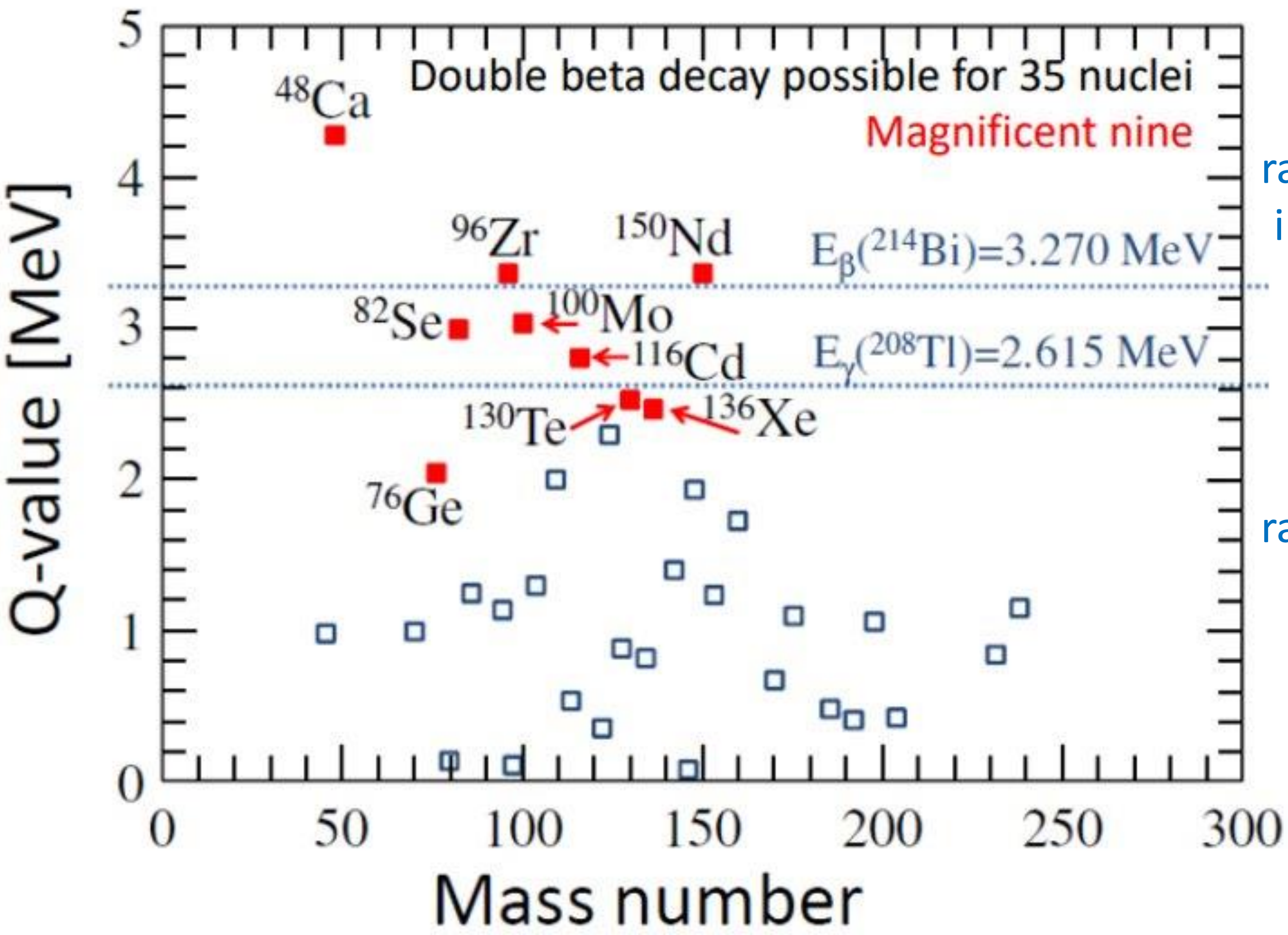
- Requires :
  - Low background in the ROI (around the $Q_{\beta\beta}$)
  - Good energy resolution

Experimental challenge

- $Q_{\beta\beta}$ is an important factor for the background
- Main background is coming from **natural radioactivity**
  - α, β, γ particles
  - Decay chains of ^{238}U and ^{232}Th





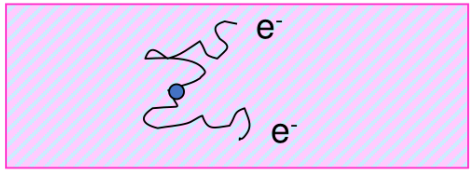


End of natural radioactivity induced by ^{214}Bi

End of γ natural radioactivity

Bolometric technique

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

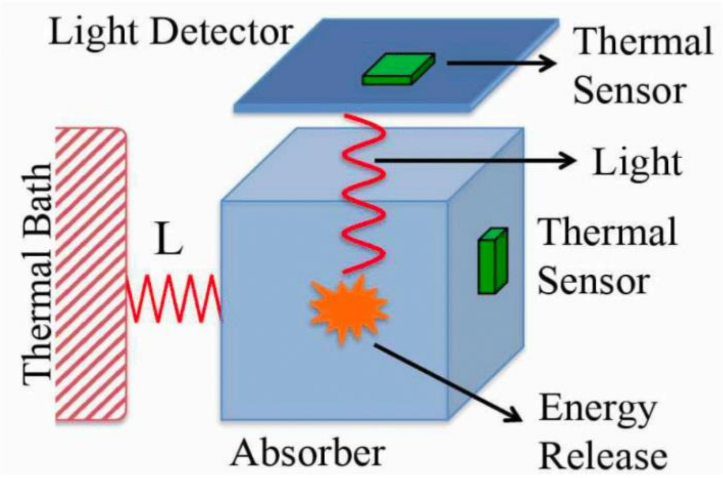


Source ≡ Detector

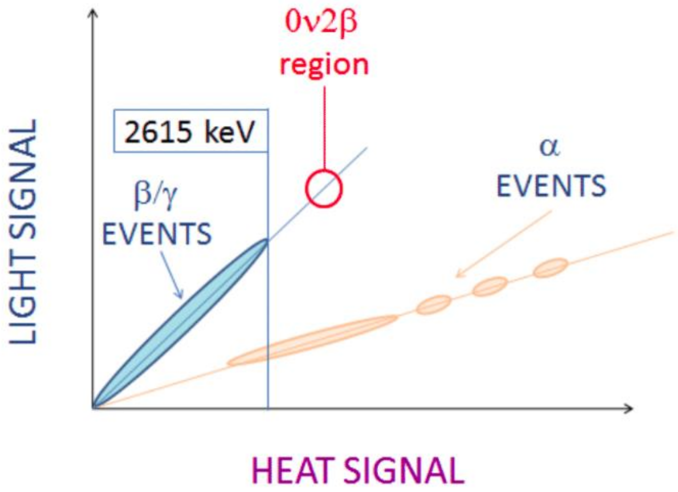
- Good energy resolution

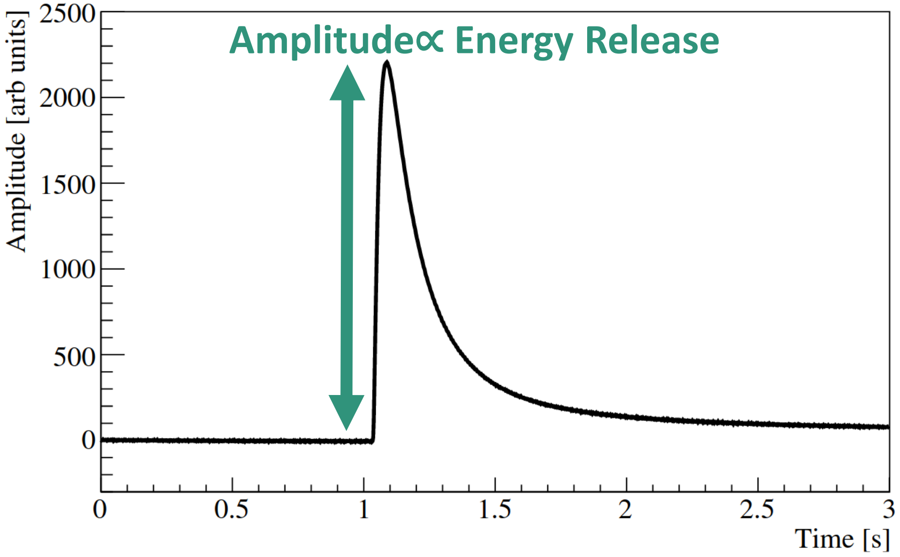
- Scintillating bolometers
  - **Discriminations between β/γ and α particles**
  - Heat and Light signals

Scintillating Bolometer

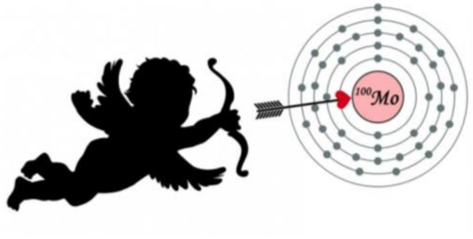


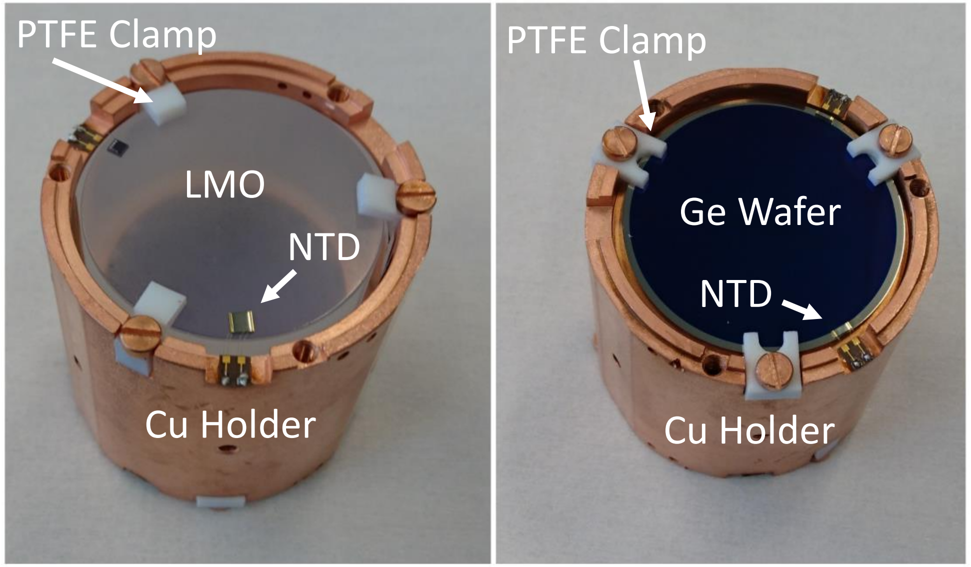
Particle Identification





CUPID-Mo





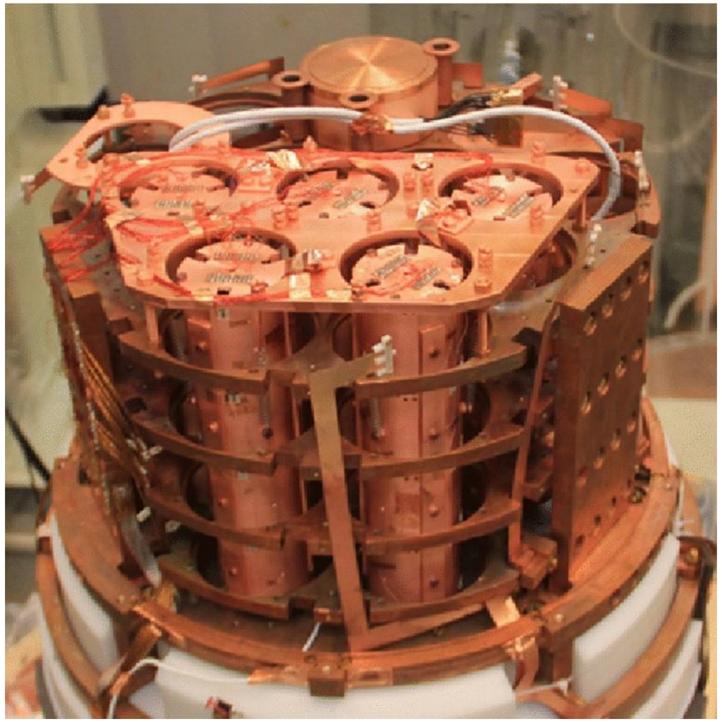
Demonstrator for the next generation ton scale experiment CUPID

Installed at Laboratoire Souterrain de Modane (LSM)

^{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



World leading limit on ^{100}Mo 0νββ :

- **$T_{1/2} > 1.8 \times 10^{24}$ years**
- **$m_{\beta\beta}$ < (280 – 490) meV**

arXiv:2202.08716
Submitted to EPJC

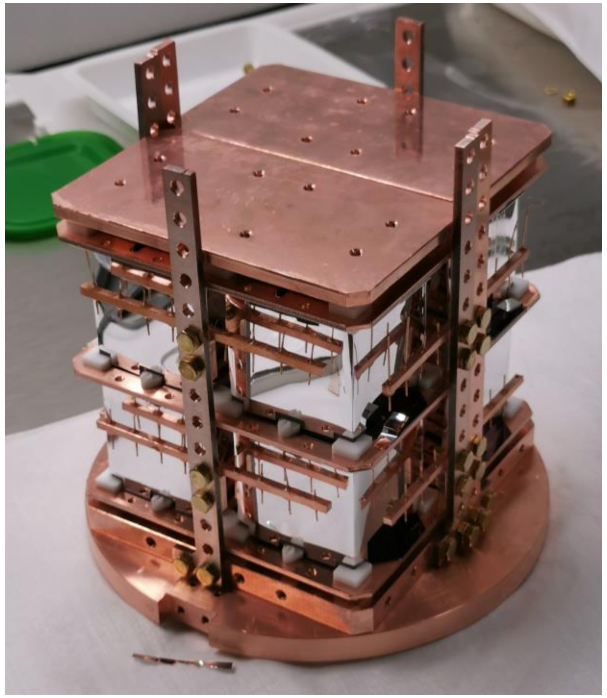
CUPID

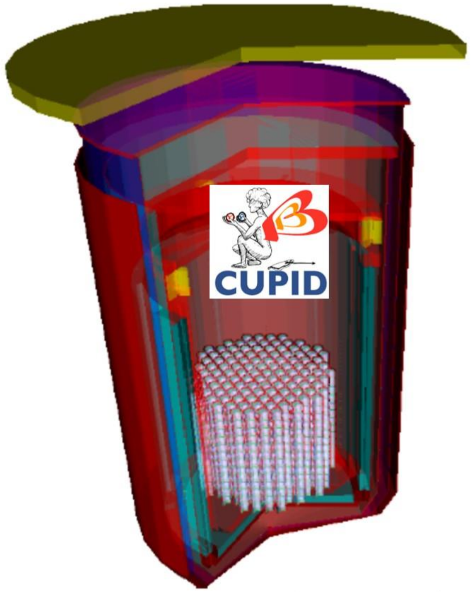
Next bolometric ton scale experiment for 0νββ

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

α rejection using light signal

Background Index goal : 10^{-4} counts/keV/kg/yr





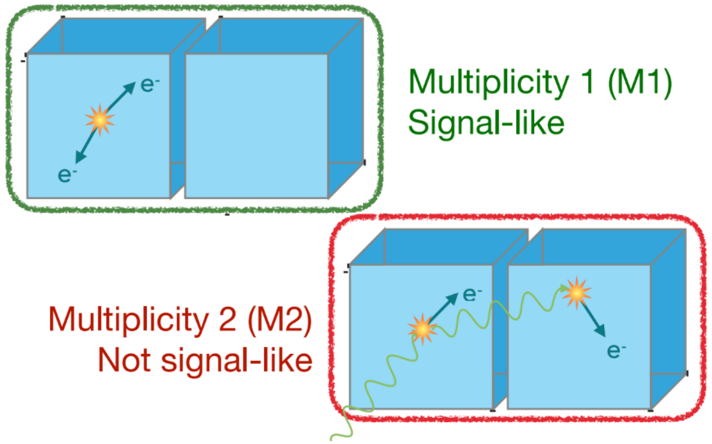
0νββ sensitivity goal

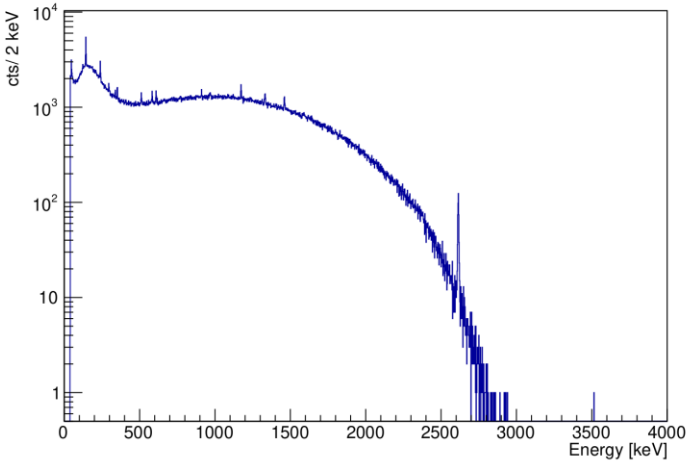
- $T_{1/2}$ ~ 10^{27} years
- $m_{\beta\beta}$ ~ 12 - 20 meV

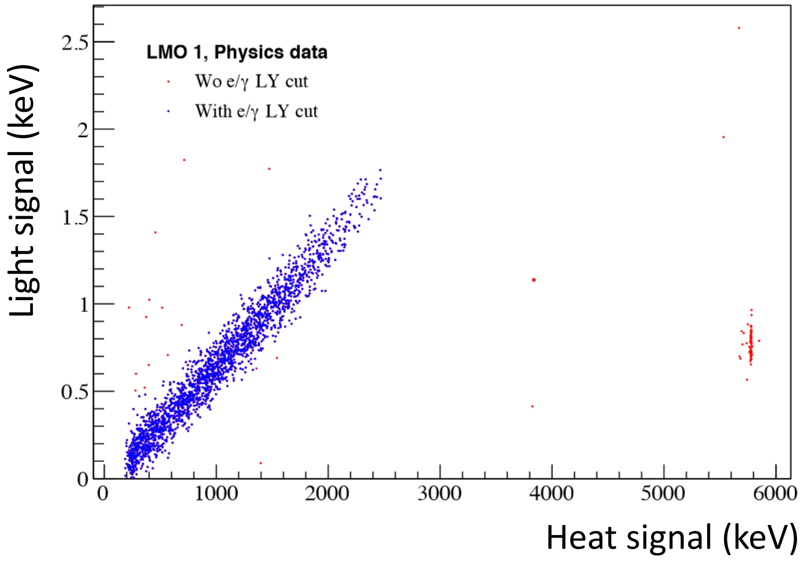
CUPID-Mo Data production

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

- Important Cuts
  - Multiplicity : Number of events above our energy threshold within a +/- 10 ms time window
    - $M_{1,\beta/\gamma}$
      - Events in one detector identified as β/γ
      - 0νββ signal like
    - M_2
      - Coincidences between two crystals
      - Constrains levels of external contaminations
    - $M_{1,\alpha}$
      - M_1 events & Energy > 3 MeV
      - Constrain levels of contaminations for crystals and reflectors
      - Permits differentiation between bulk and surface events for crystals
  - Light Detector
    - Reject alpha particles







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

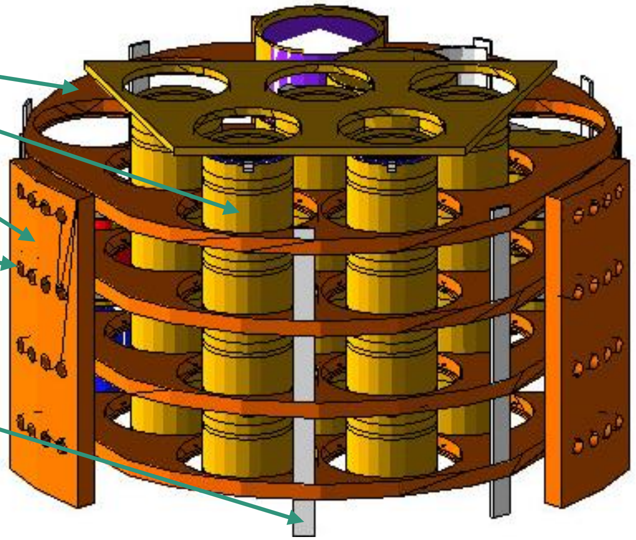
CUPID-Mo simulations

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

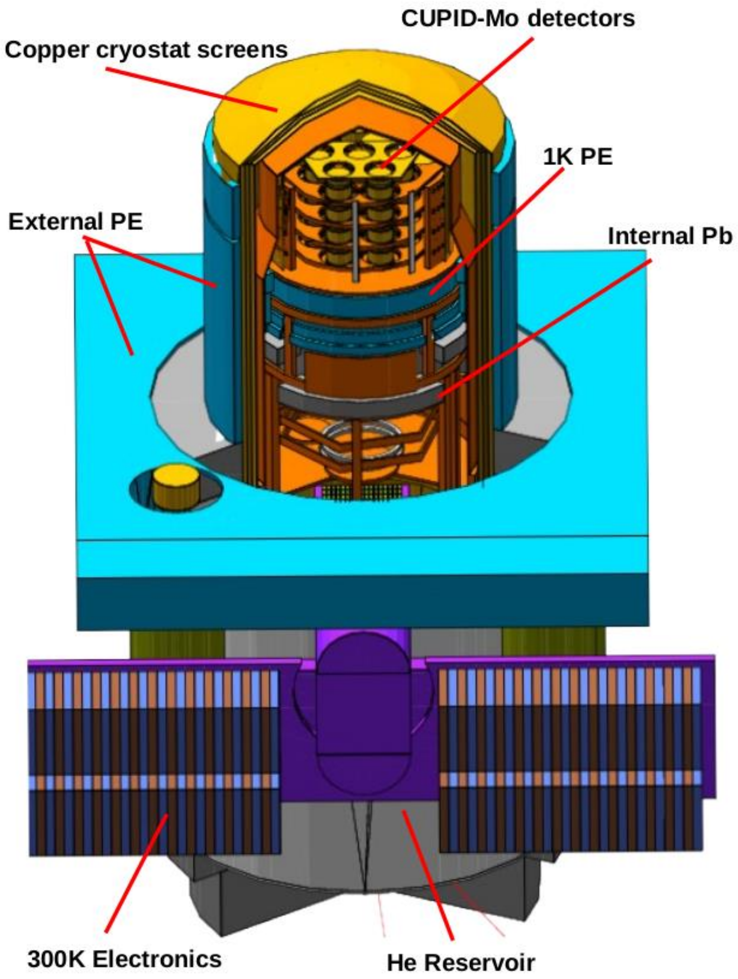
Surface component :
Exponential density profile $e^{-x/\lambda}$

10mK sources
- Copper internal
- Springs
- Screws
- Kapton connectors
- Kapton cables

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

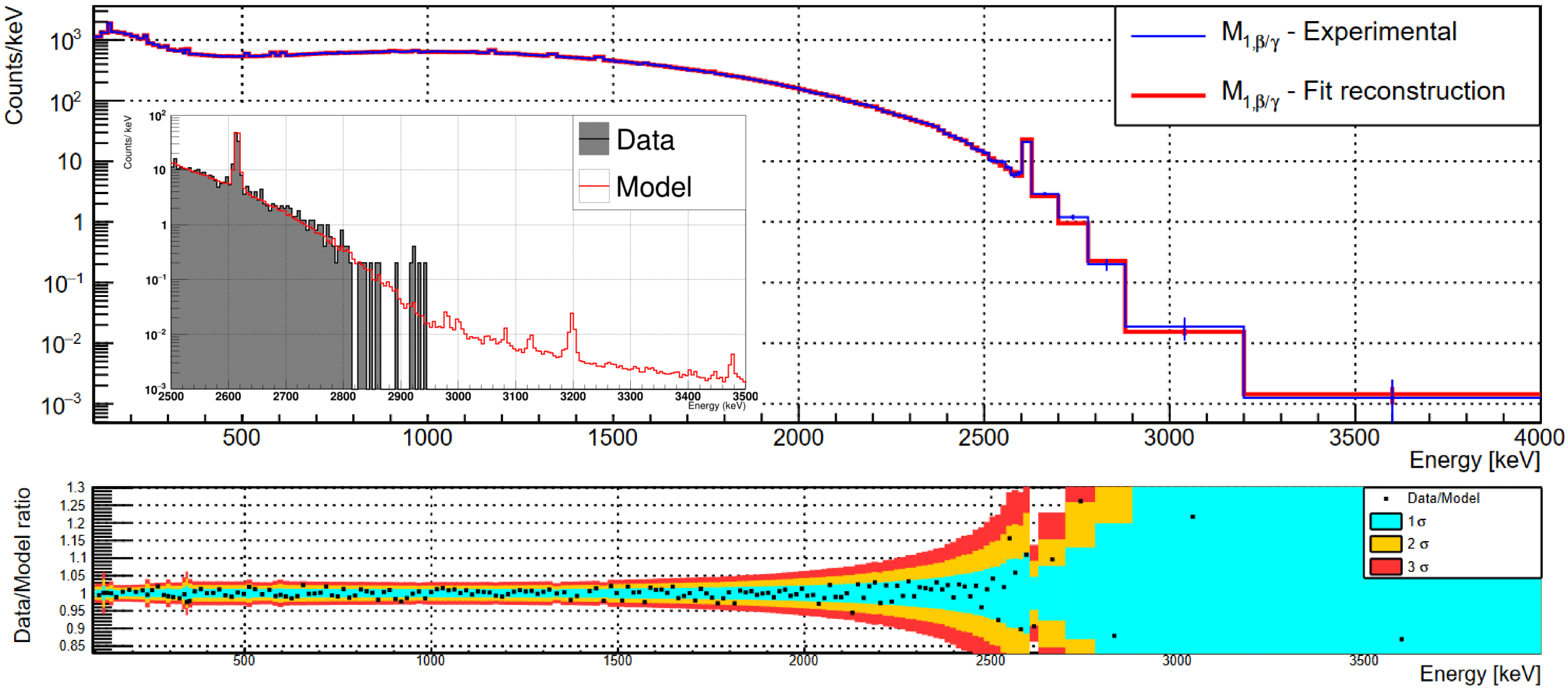


Geant4 Rendering of the CUPID-Mo detectors



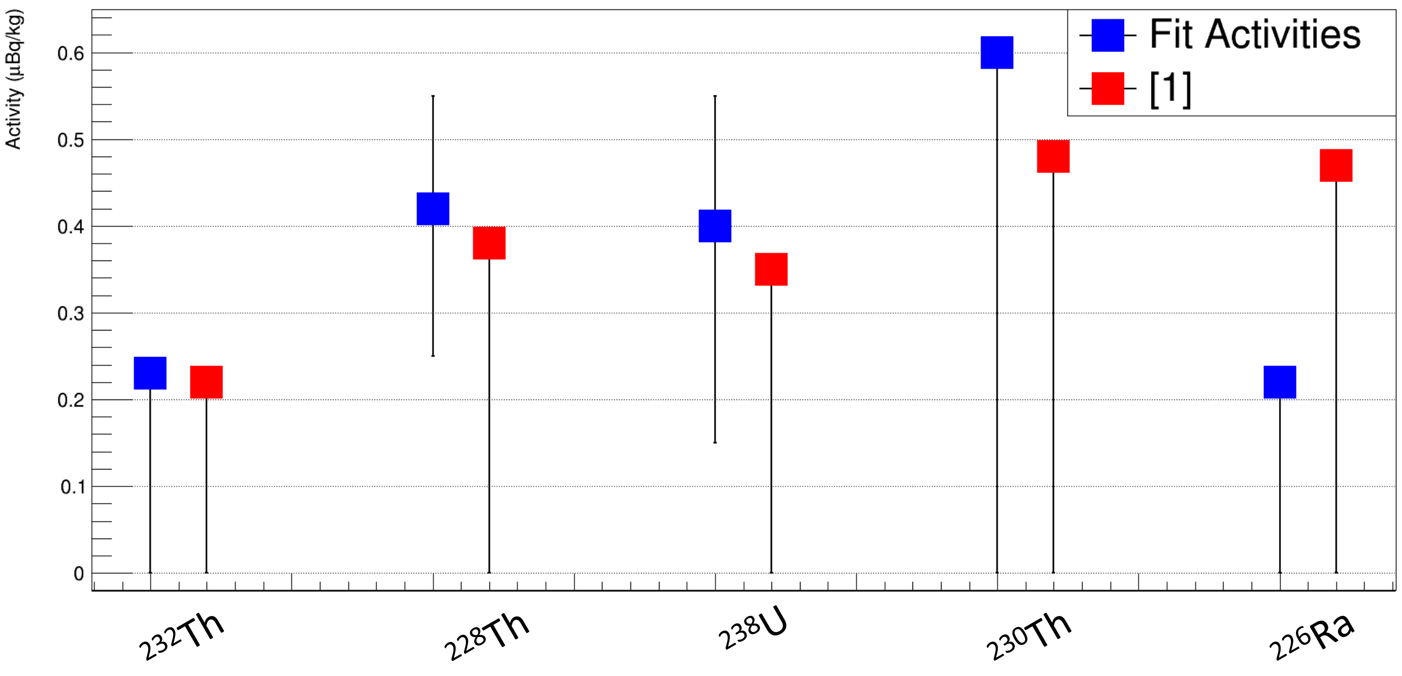
Geant4 Rendering of the Edelweiss set up with the CUPID-Mo detectors as implemented in the simulations

Results

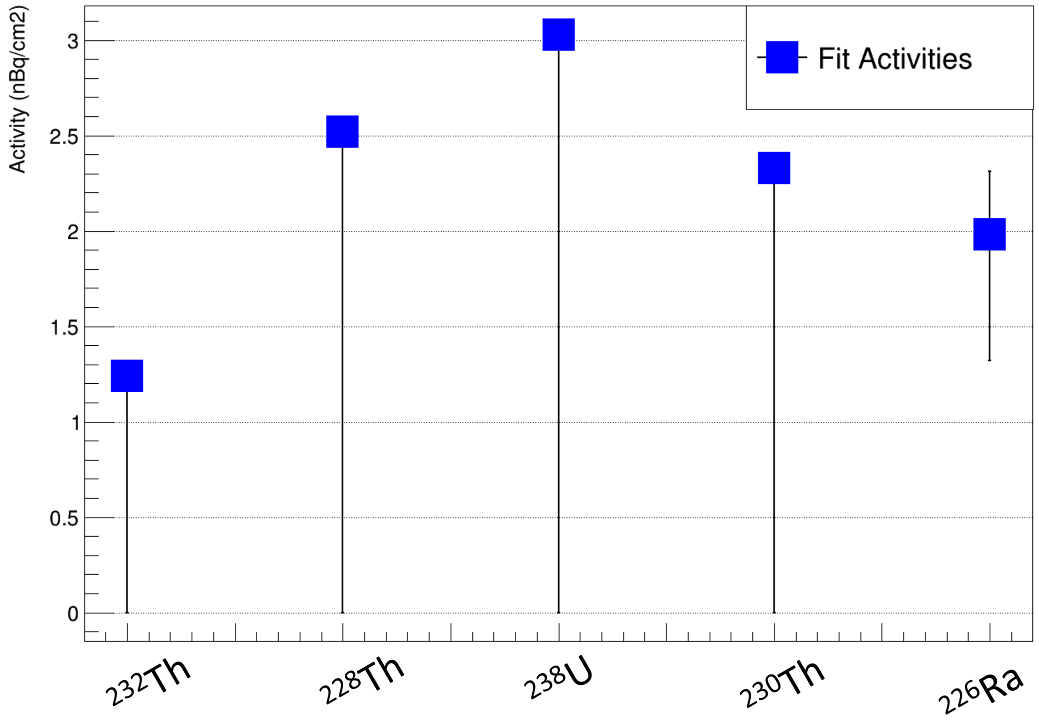

Counts/keV
$M_{1,\beta/\gamma}$ - Experimental
$M_{1,\beta/\gamma}$ - Fit reconstruction
Data
Model
Counts/ keV
Energy (keV)
Energy [keV]
Data/Model ratio
Data/Model
1σ
2 σ
3 σ
Energy [keV]

Results

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



Crystal Bulk Activities



Crystal Surface Activities

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

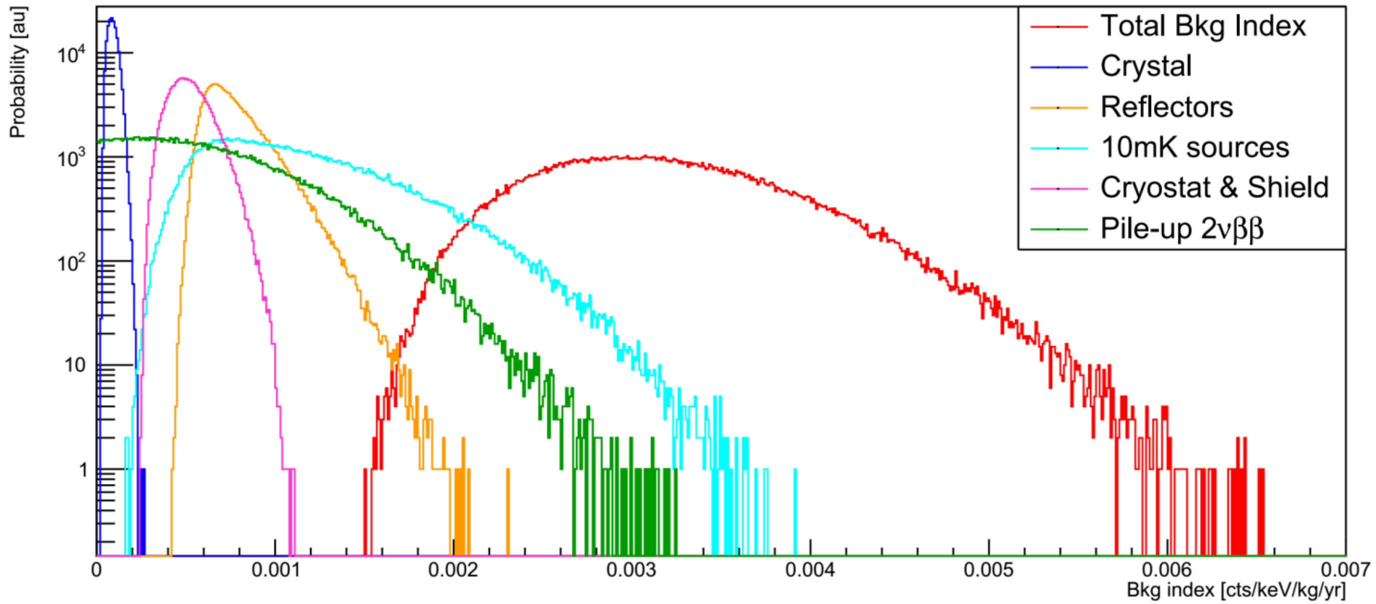
λ = 10 nm

We derive the crystal bulk and surface activities from the fit

The crystal bulk contaminations from the ^{238}U and ^{232}Th chains are all below 1 µBq/kg

These levels of contaminations are compatible with the CUPID background index goal

Results



Probability Density Function of the Background Index

From the fit we derive the number of counts in the region of interest that is defined as 3034 +/- 15 keV

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

We can extract the background index coming from the crystals :

8.4 x 10^{-5} cts/keV/kg/yr

Extrapolation for CUPID :

~2 x 10^{-5} cts/keV/kg/yr << CUPID Background Index Goal (10^{-4} cts/keV/kg/yr)

Contaminations of crystals are compatible with the CUPID background index goal

Summary

- We have developped a full background model of the CUPID-Mo experiment

- A robust background model allows several further studies
  - In particular the extraction of the ^{100}Mo 2νββ lifetime

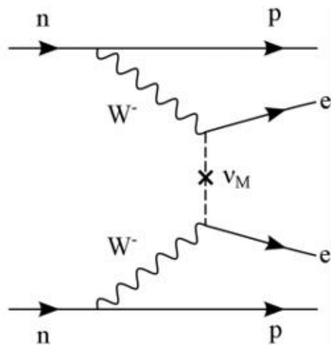
- Background index of the CUPID-Mo experiment : $3.0^{+0.7}_{-0.6} \times 10^{-3}$ cts/keV/kg/yr

- Low crystal bulk and surface activities
- Compatible with the CUPID background index goal

BACK-UP

Neutrinoless Double Beta Decay

- Hypothetical decay
- $(A, Z) \rightarrow (A, Z+2) + 2e^-$ **$0\nu2\beta$**
- **Lepton number violation ΔL = 2**
- Majorana neutrino $\nu = \bar{\nu}$



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

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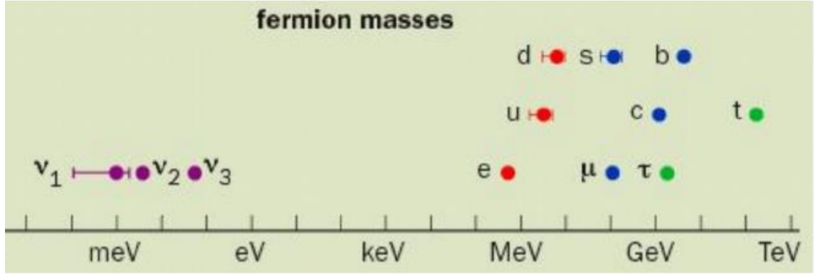
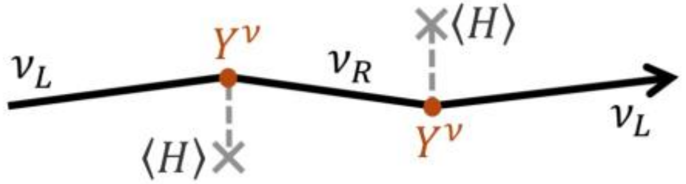
Dirac mass

$$\mathcal{L} \supset Y_\nu^{ij} L_i N_j \phi = M_D^{ij} \nu_i N_j$$

Small Yukawa coupling :

$$m_\nu / \Lambda_{EW} \leq 10^{-12}$$





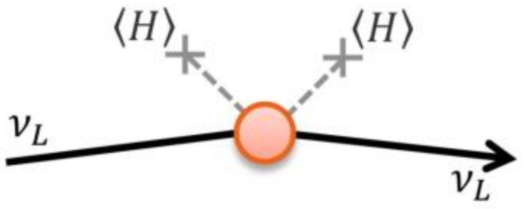
Majorana mass

$$\mathcal{L} \supset Y_\nu^{ij} L_i N_j \phi + M^{ij} N_i N_j$$
$$= M_D^{ij} \nu_i N_j + M_M^{ij} N_i N_j$$

$$M_\nu = \begin{pmatrix} \delta m_\nu^{1loop} & M_D \\ M_D^T & M_M \end{pmatrix}$$

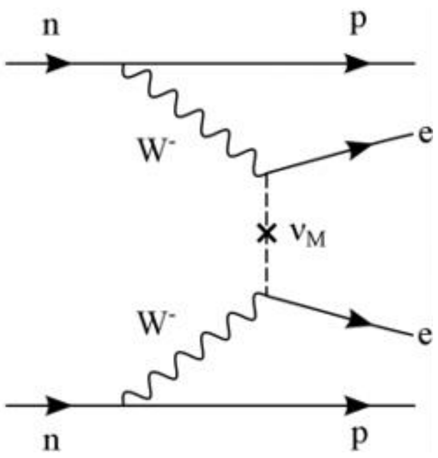
Diagonalisation with $M_M >> M_D$:

See-saw type 1

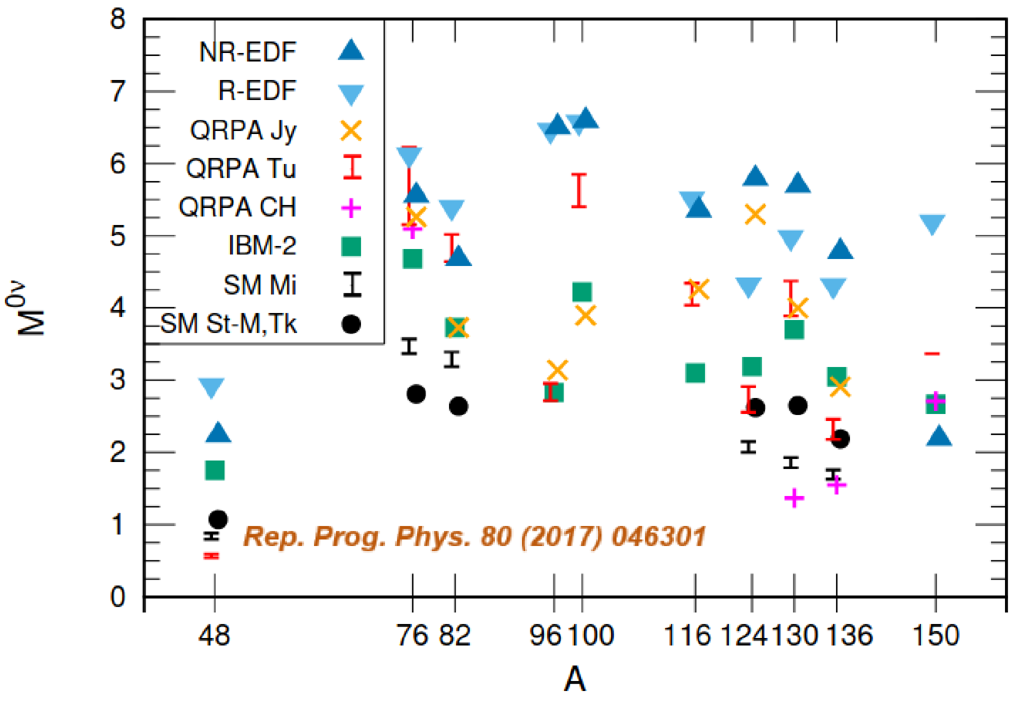


$\nu \simeq \nu_L + \theta v_R^c$	$m_\nu \simeq \frac{M_D^2}{M_M}$	mainly **active** $SU(2)_L$ doublet states with **light** masses
$N \simeq \nu_R + \theta^T v_L^c$	$m_N \simeq M_M$	mainly **sterile** singlet states with **heavy** masses

Light Majorana neutrino exchange

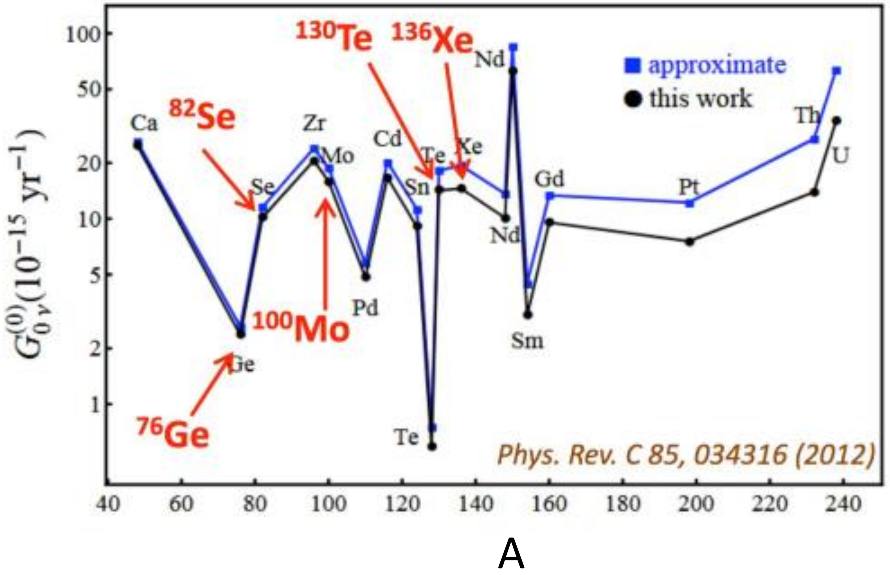


$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}\, g_A^4\, M^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$



Space phase factor :

Known and calculated to good accuracy



Nuclear Matrix Element :

- Differences between different nuclear models

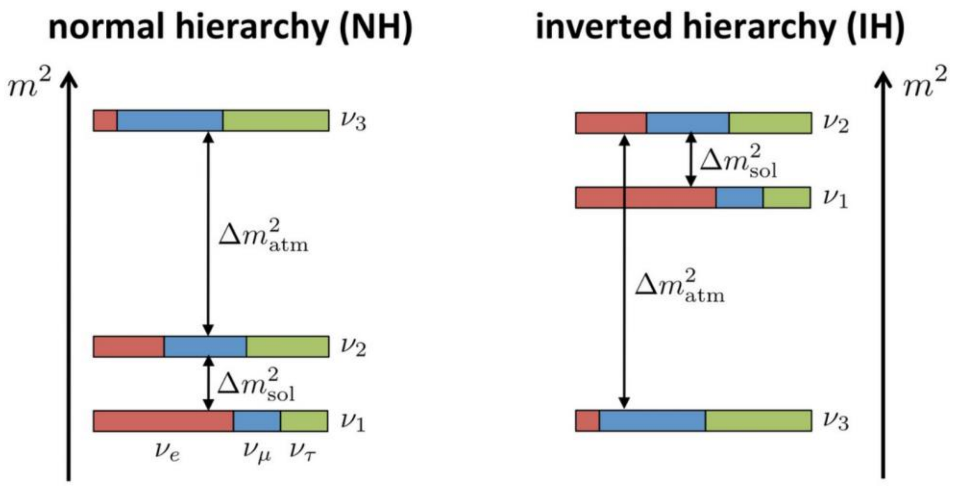
Weak axial-vector coupling strenght :

- Question of g_A quenching under study

Effective Majorana mass :

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

Where we are



Best current limits :

KamLAND-Zen on ^{136}Xe :

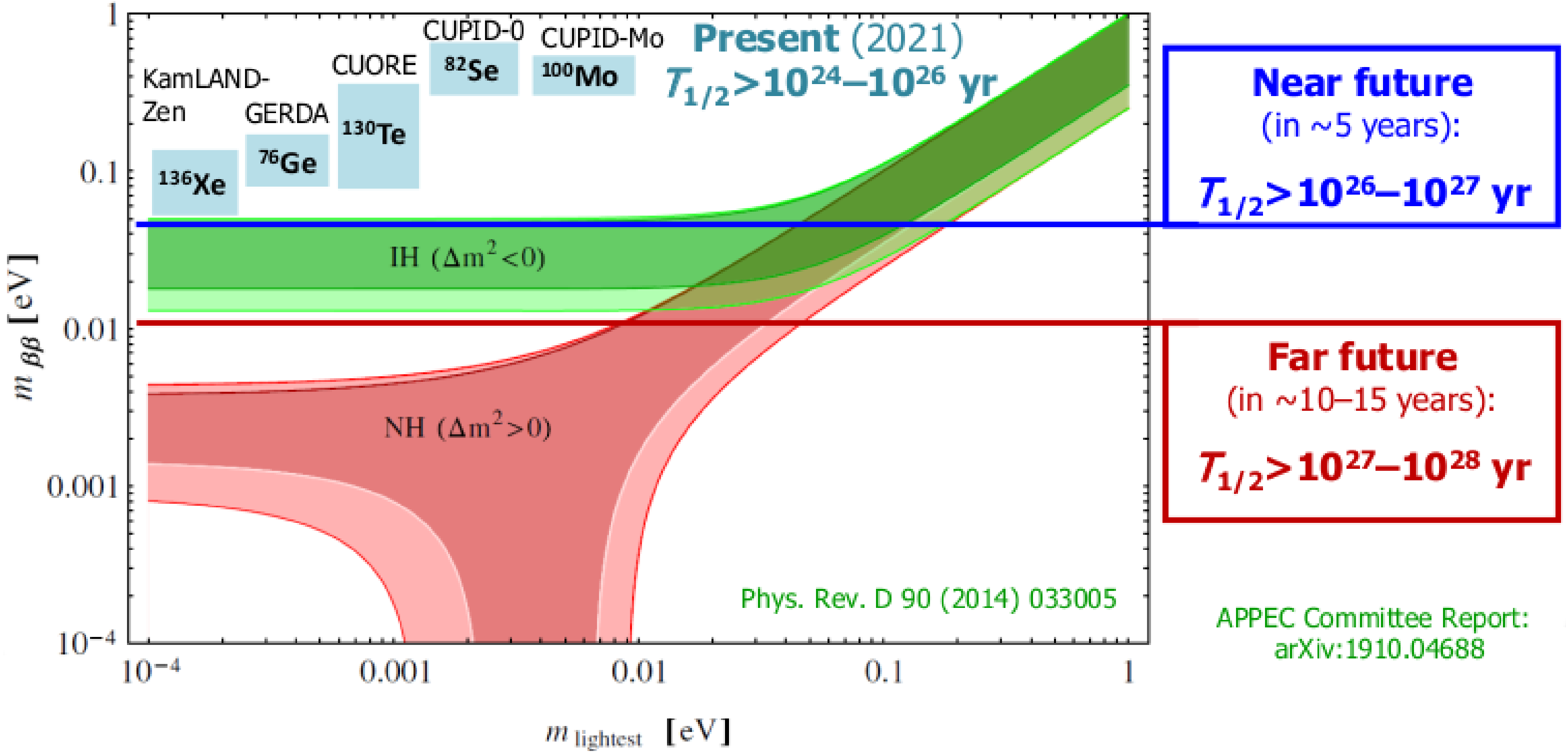
- $T_{1/2} > 1.07 \times 10^{26}\ yr$
- $m_{\beta\beta} < 61\ - 165\ meV$

arXiv:1605.02889
PRL 117, 082503 (2016)

GERDA on ^{76}Ge :

- $T_{1/2} > 1.8 \times 10^{26}\ yr$
- $m_{\beta\beta} < 79\ - 180\ meV$

arXiv:2009.06079
PRL 125, 252502 (2020)



APPEC Committee Report:
arXiv:1910.04688

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

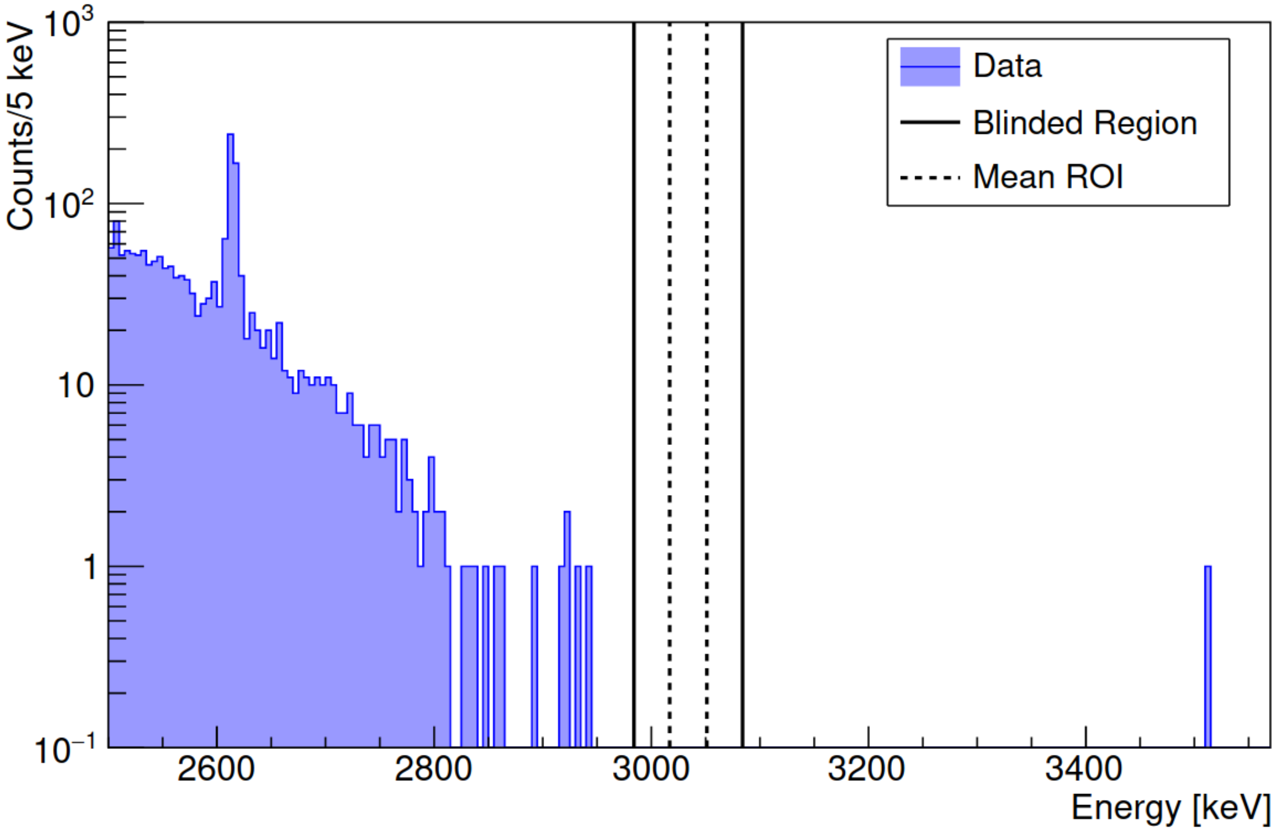
Limit on $T_{1/2}^{0\nu\beta\beta}$ of ^{100}Mo

- 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 :

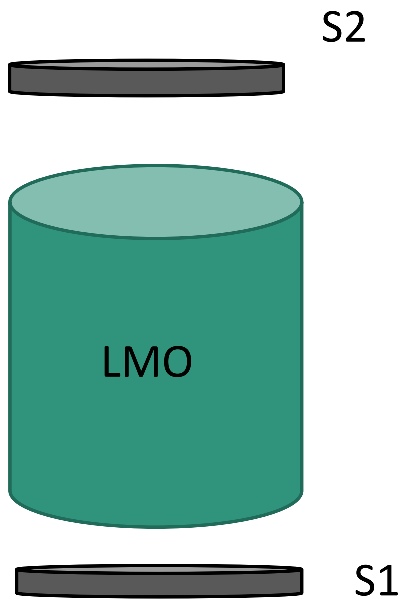
$T_{1/2} > 1.8 \times 10^{24}$ y (90% CI)

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

arXiv:2202.08716
Submitted to EPJC

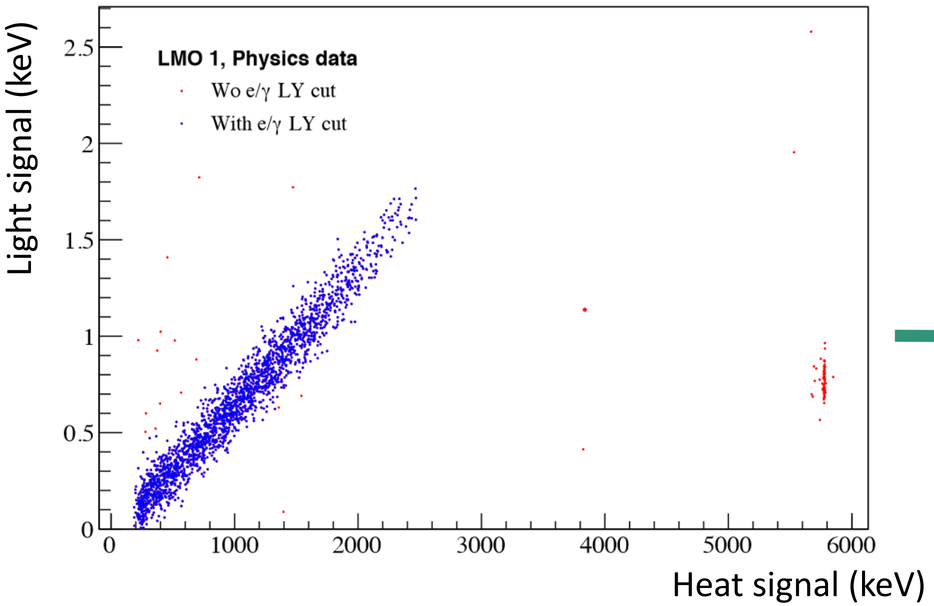


Light Detector Cut

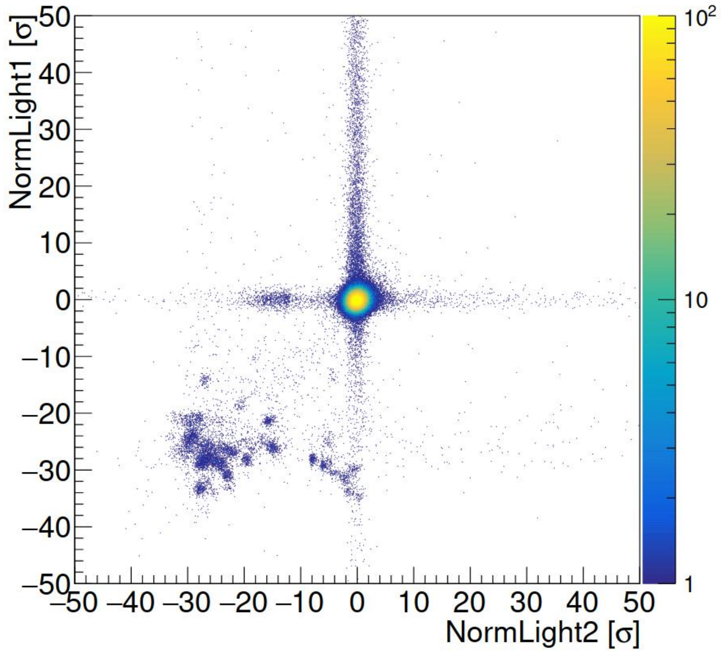


Goal : Apply a unique cut on all the data to remove α particles

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



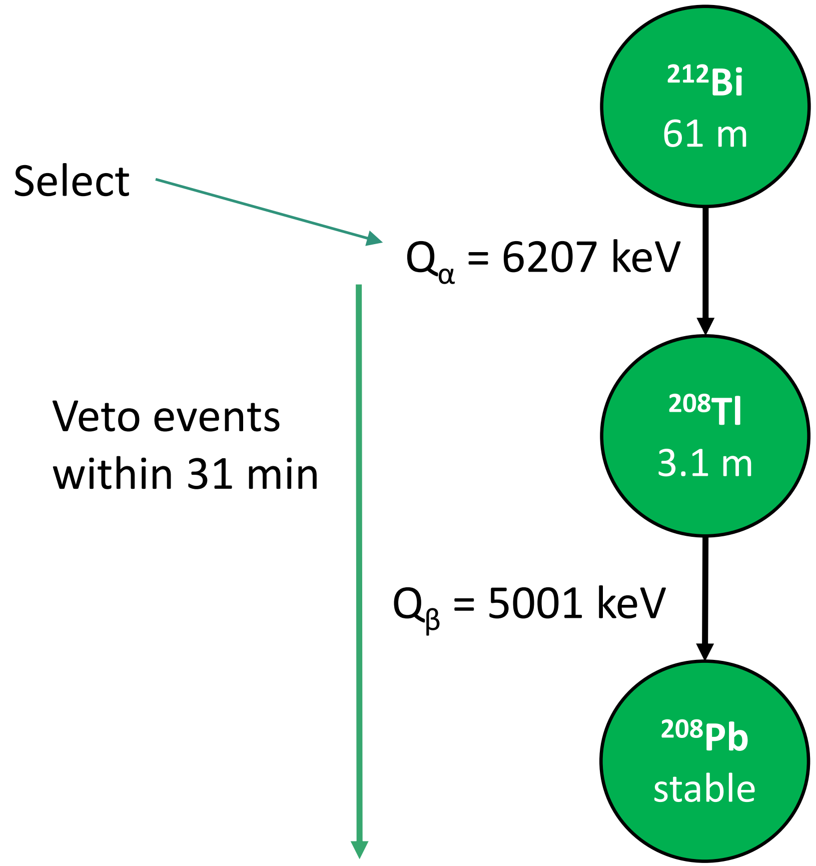
Normalization



Delayed coincidences

Thorium chain :

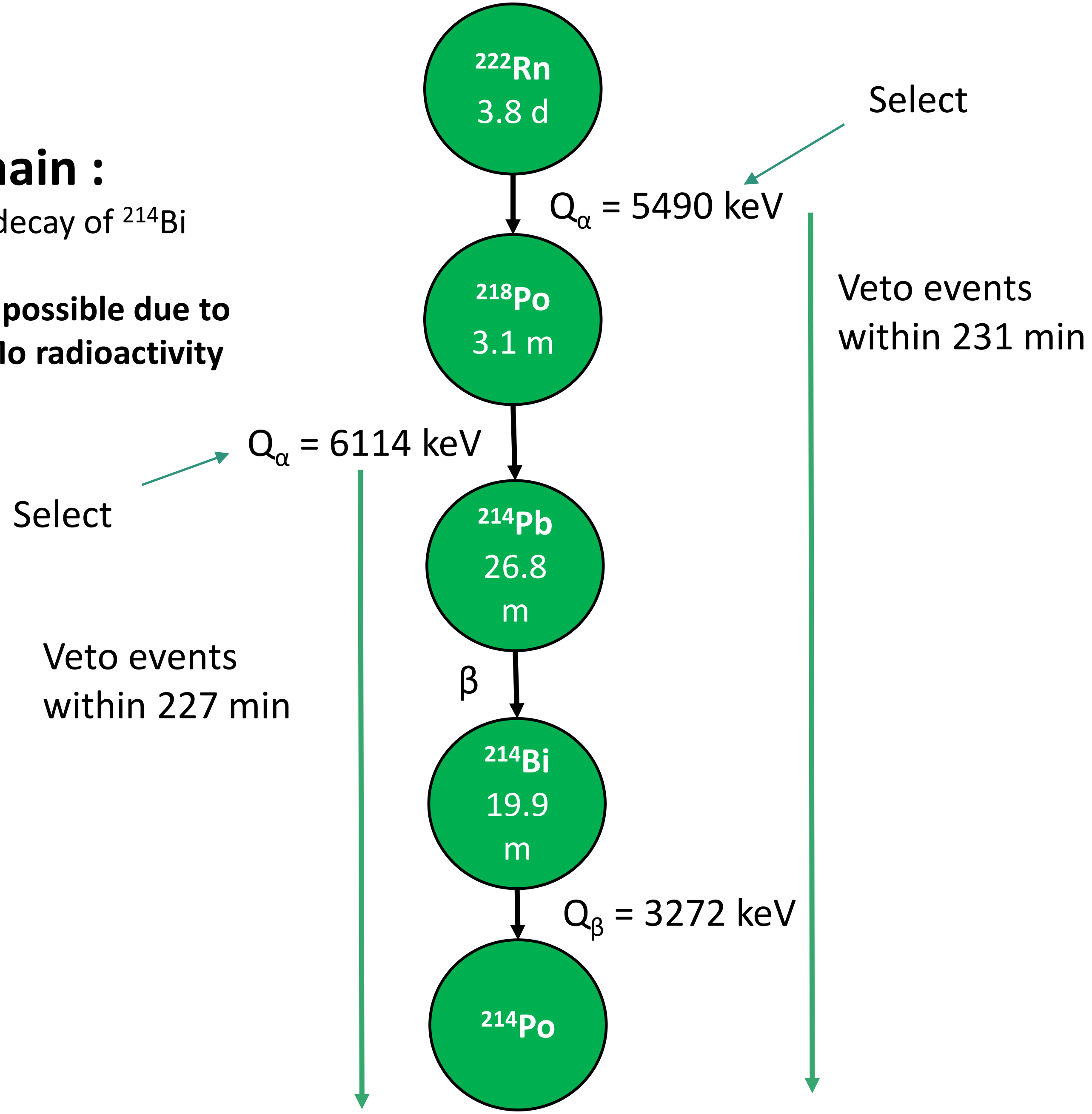
Goal : remove β decays of ^{208}Tl from the crystals



Uranium chain :

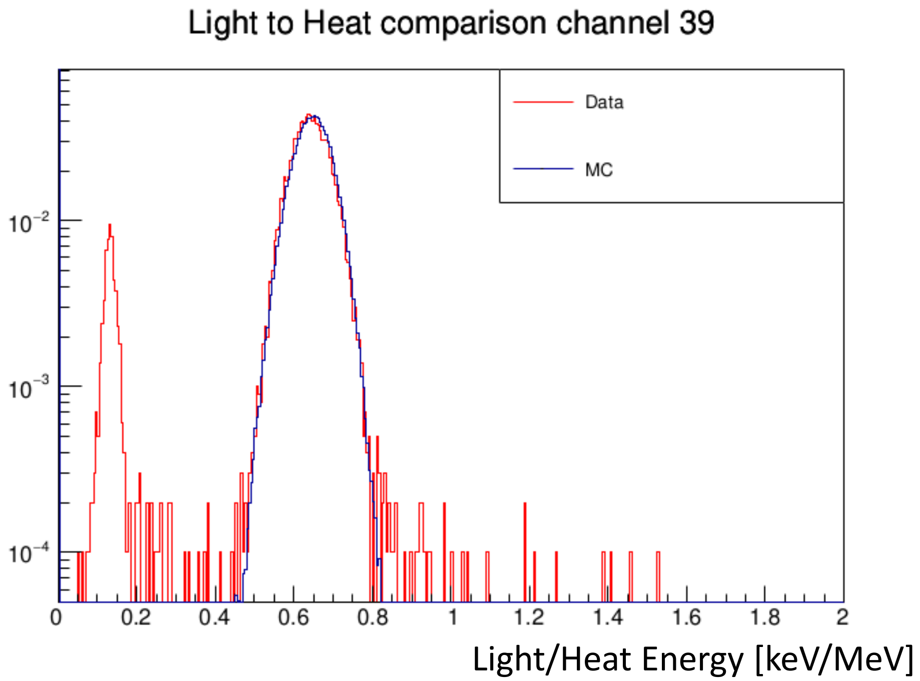
Goal : remove β decay of ^{214}Bi from the crystals

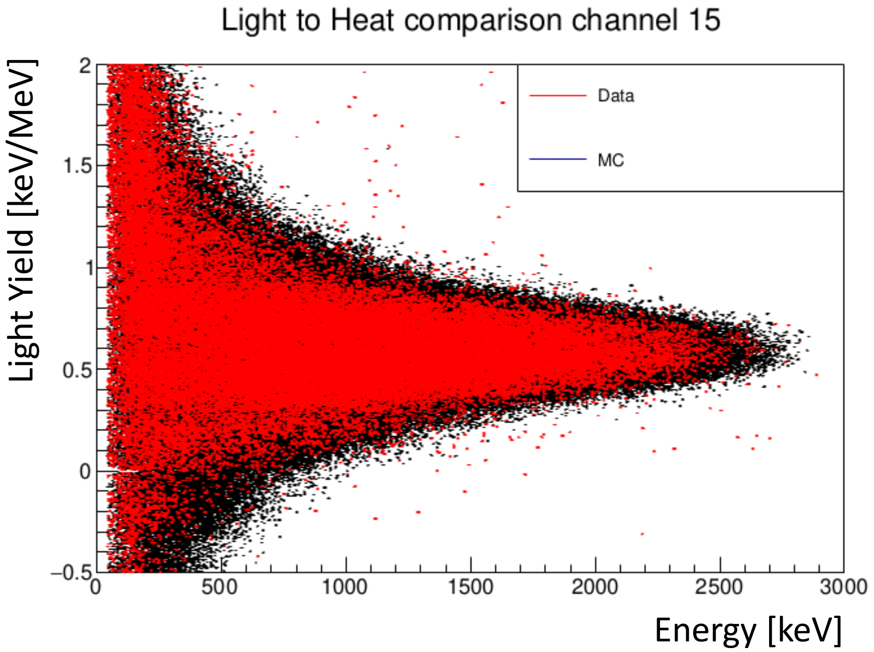
Novel analysis is possible due to the low CUPID-Mo radioactivity



Detector response model

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

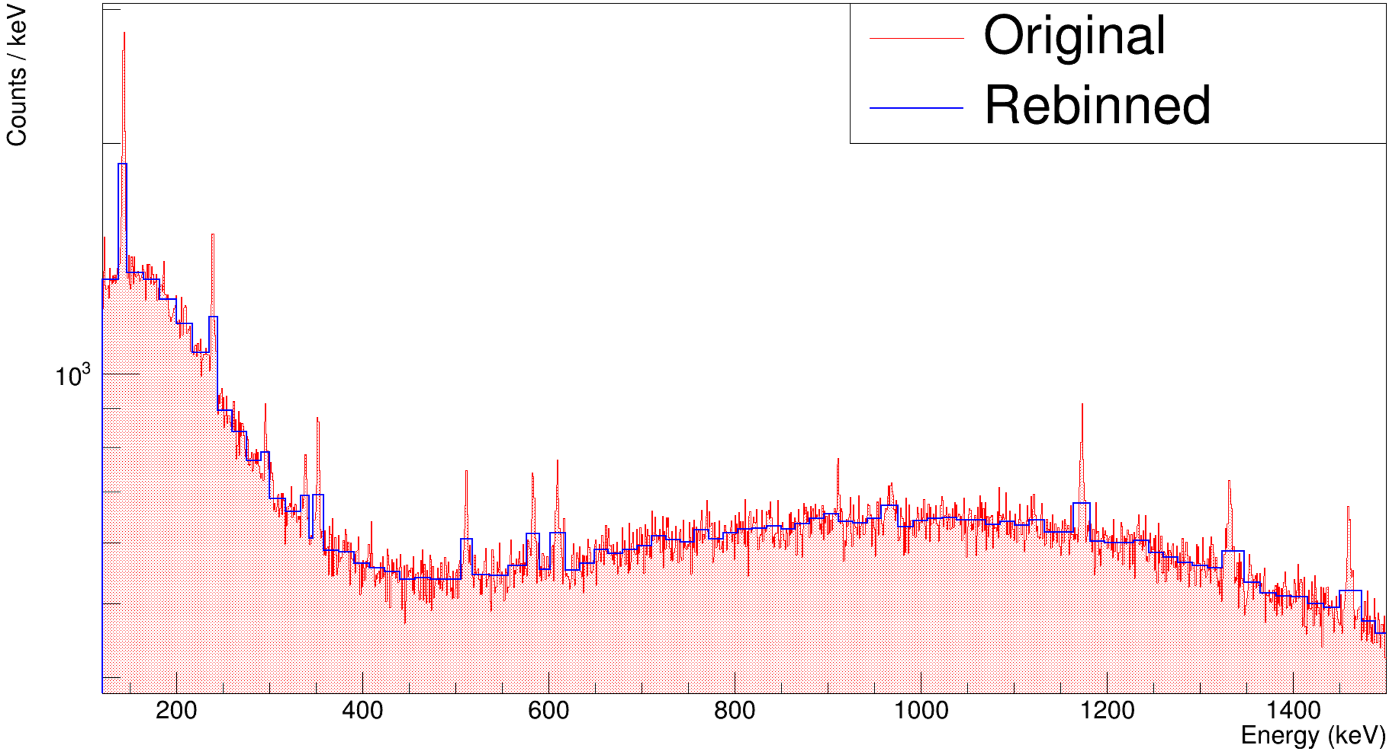




- We compute :
  - Multiplicity
  - Delayed coincidences
  - Light Detector signal
    - For each deposited energy in the crystal we generate randomly a scintillation light
    - This scintillation light is generated according to the light distribution in the data

Final reference fit

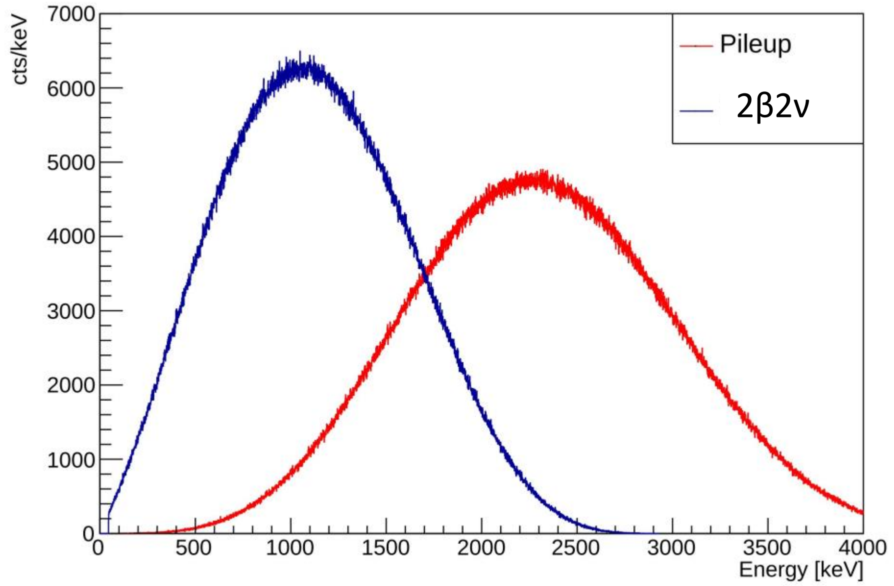
- Fit performed with a Bayesian analysis using Just Another Gibbs Sampler (JAGS)
- Parameters of the model tell us the radioactive contamination of the various components
- A robust background model allows for several further physics studies



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 $2\beta2\nu\ 0_1^+$:

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

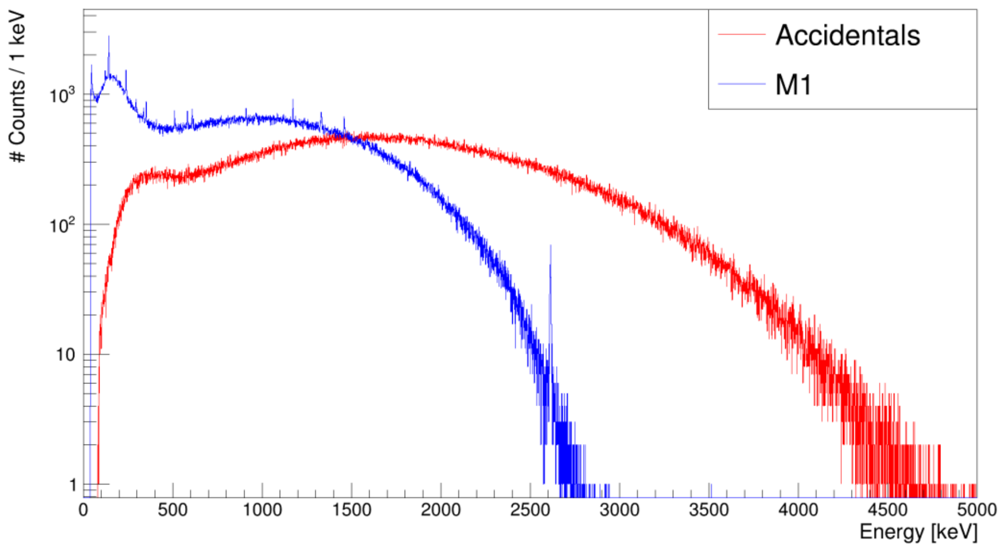
Barabash, A. S. AIP Conference Proceedings. Vol. 2165. No. 1. AIP Publishing LLC, 2019.

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

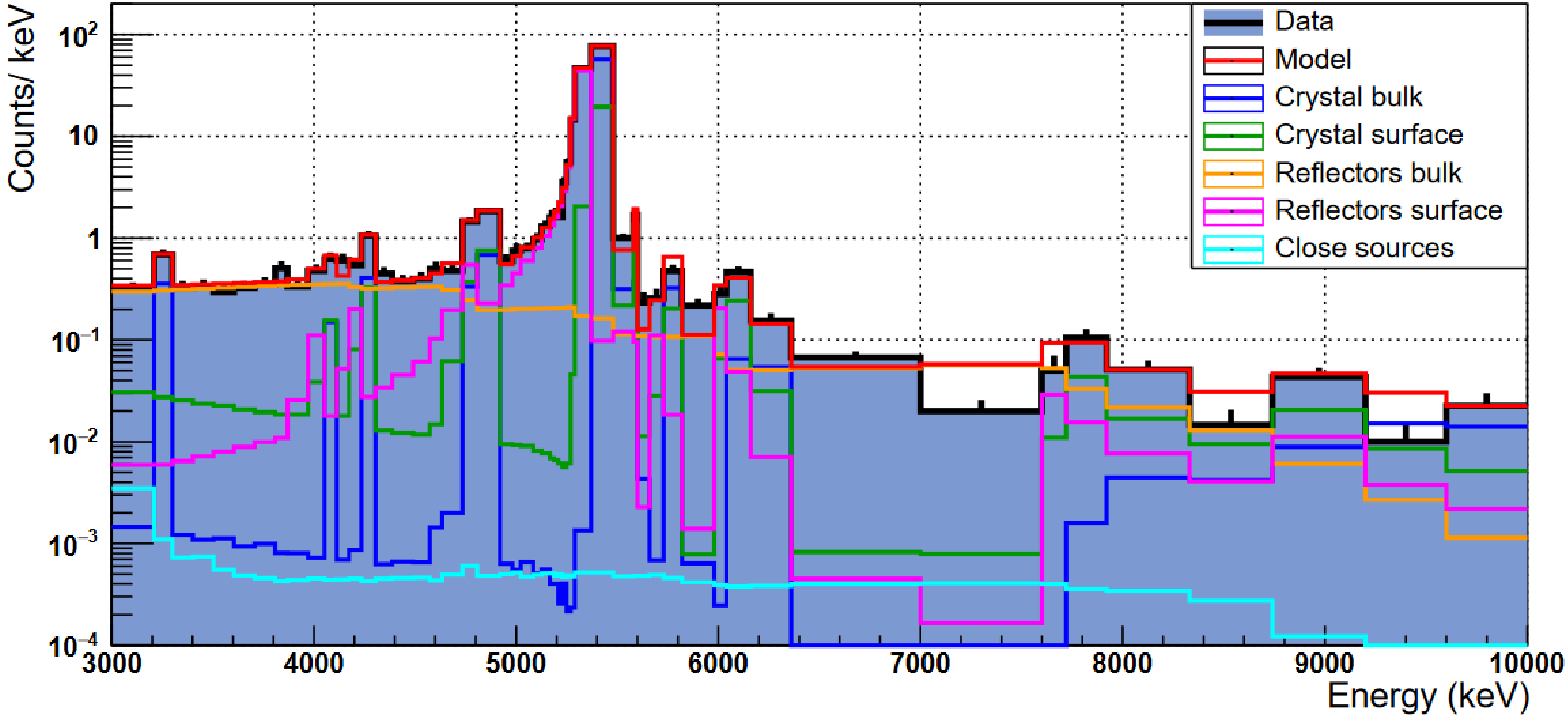
$$N_{random} \propto N_{M1}^2 \times \Delta t$$ ← time window of the multiplicity

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

Activities of Springs :

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

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



Backgrounds of CUPID-Mo / CUPID

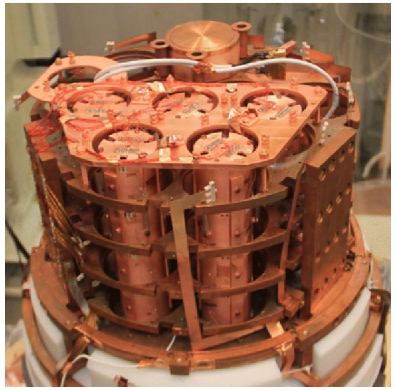
CUPID-Mo

Laboratoire souterrain de Modane (LSM)

Edelweiss cryostat

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

Closed structure



CUPID - Next bolometric ton scale experiment for 0νββ

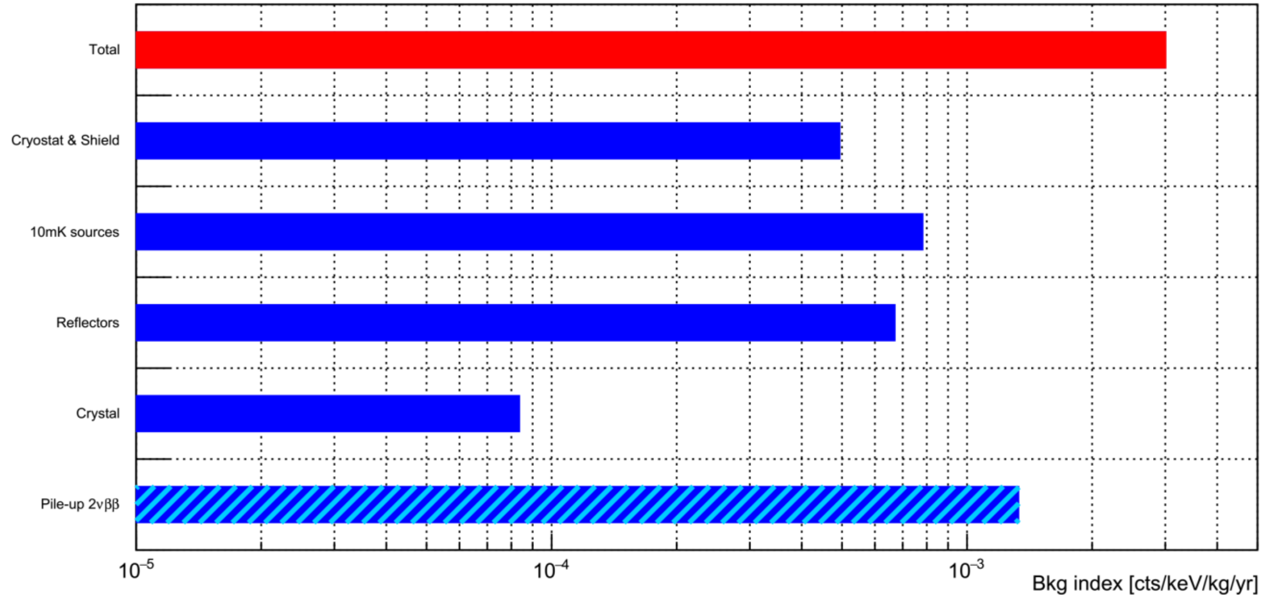
Laboratori Nazionali del Gran Sasso (LNGS)

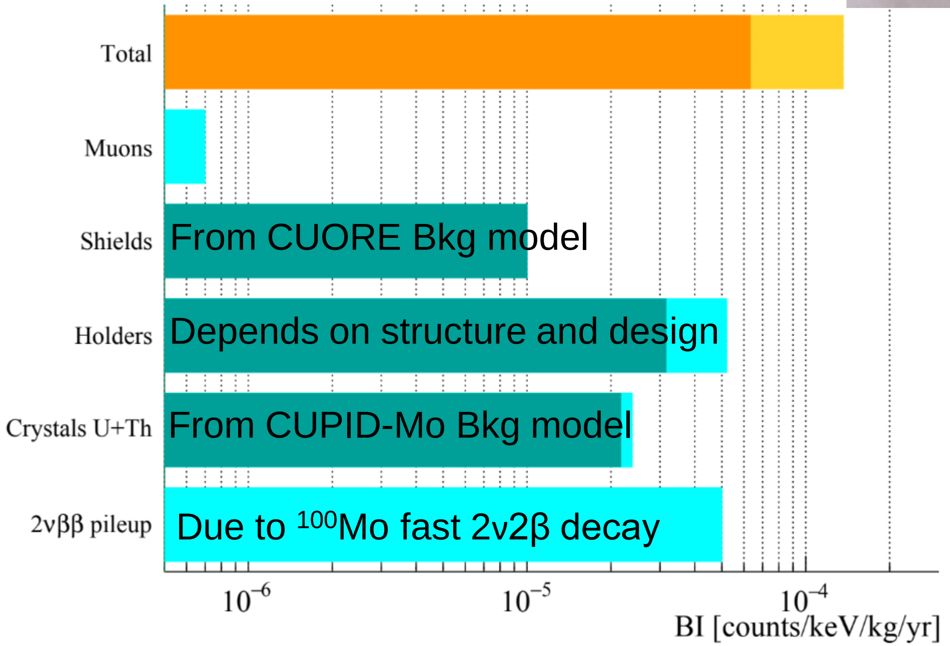
CUORE cryostat

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

Open structure

Background Index Goal = 10^{-4} ckky





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

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

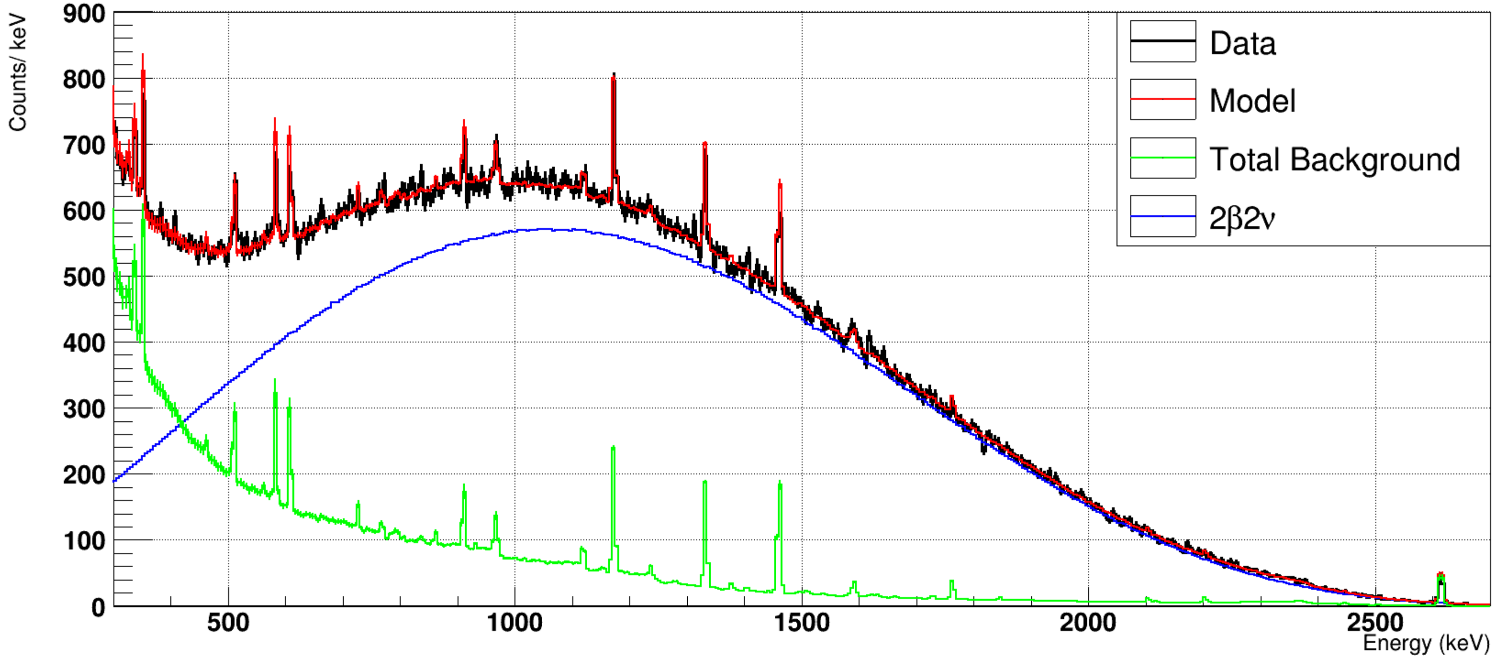
Previous measurements : Uncertainty = $^{+2.9\%}_{-2.4\%}$ **arXiv:1912.07272**

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

Decay process of ^{100}Mo 2νββ

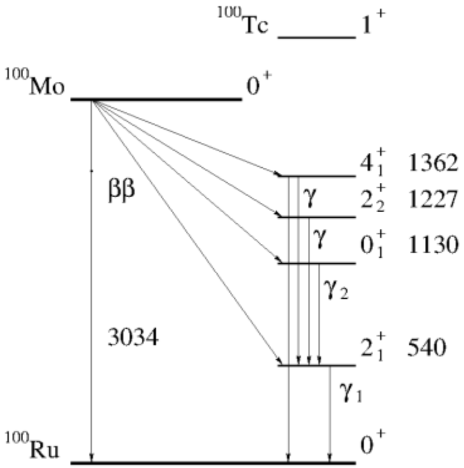
The process of ^{100}Mo 2νββ is not established

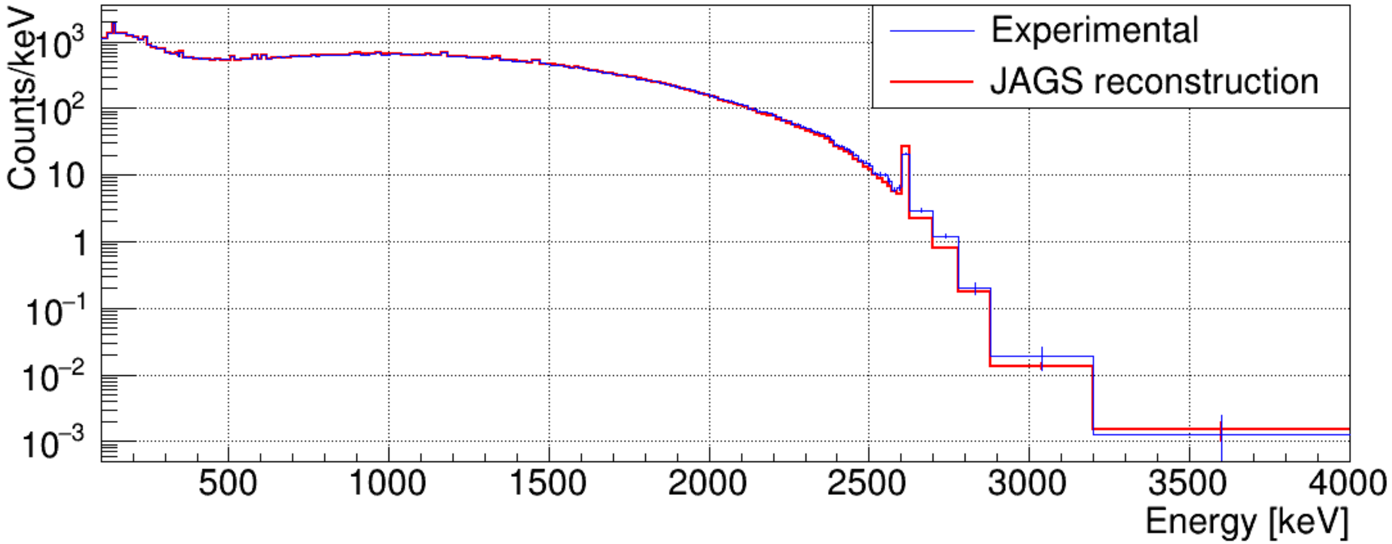
SSD Intermediate state :

- 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