Physics results from CUPID-Mo exploiting the new background model

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P2IO MEETING

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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

Space phase factor :

- Known and calculated to good accuracy

Weak axial-vector coupling strenght :

- Question of g_A quenching under study

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

Effective Majorana mass :

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

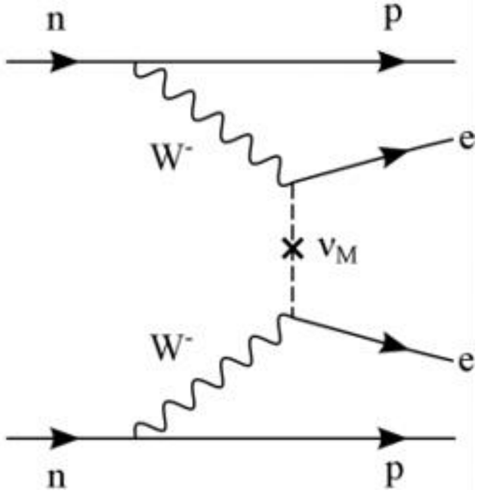
Nuclear Matrix Element :

- Differences between different nuclear models

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

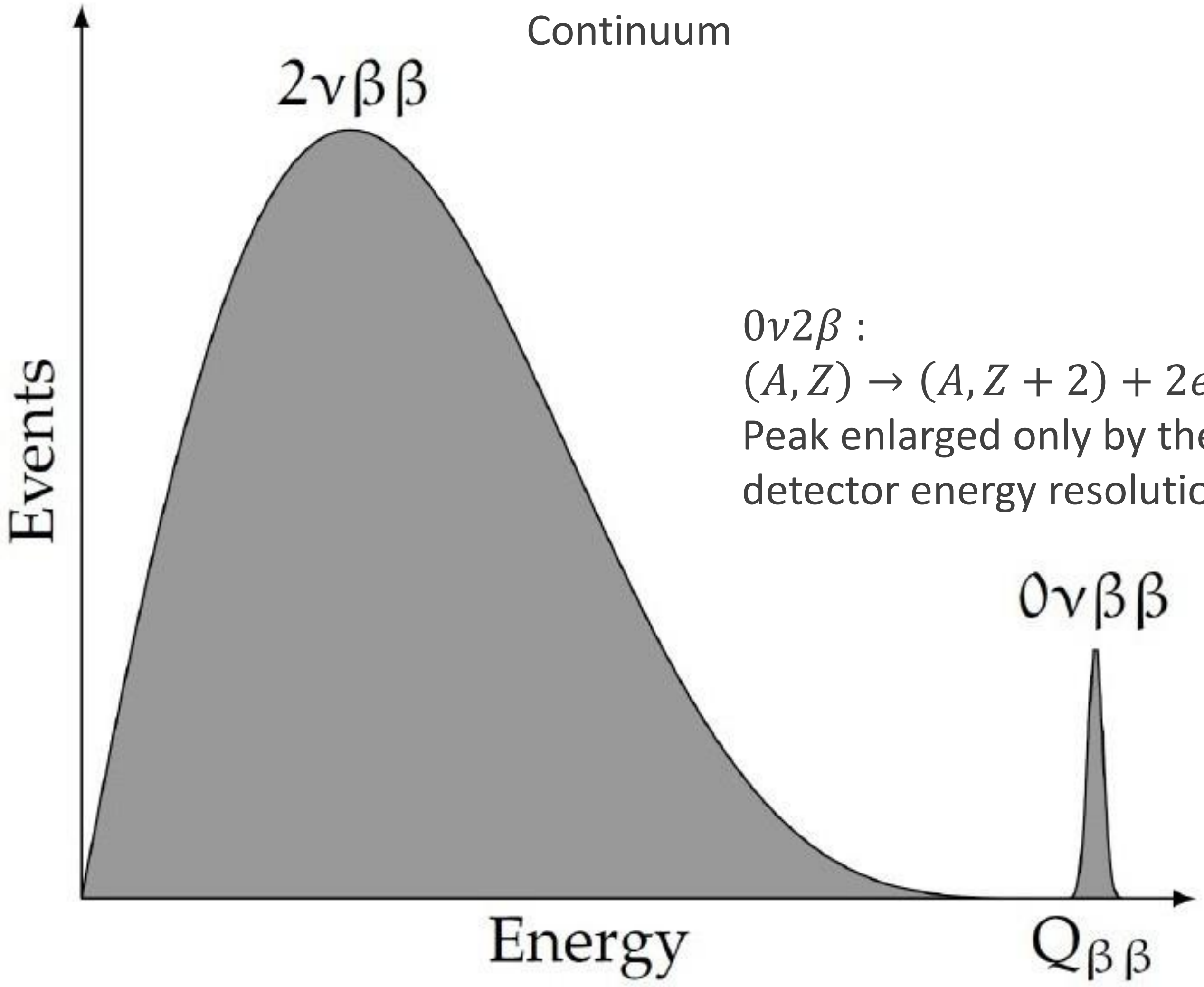


Searching for $0\nu2\beta$

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

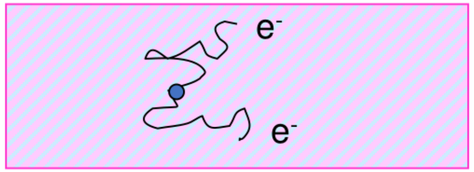
- Requires :
  - Low background in the ROI (around the $Q_{\beta\beta}$)
  - Good energy resolution

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



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

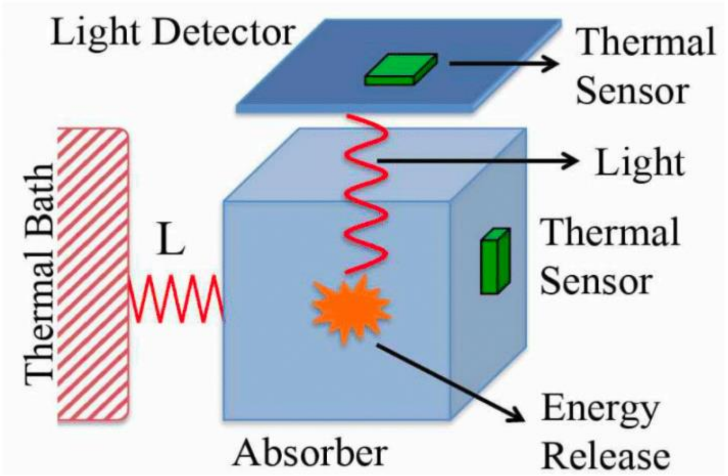
Bolometric technique



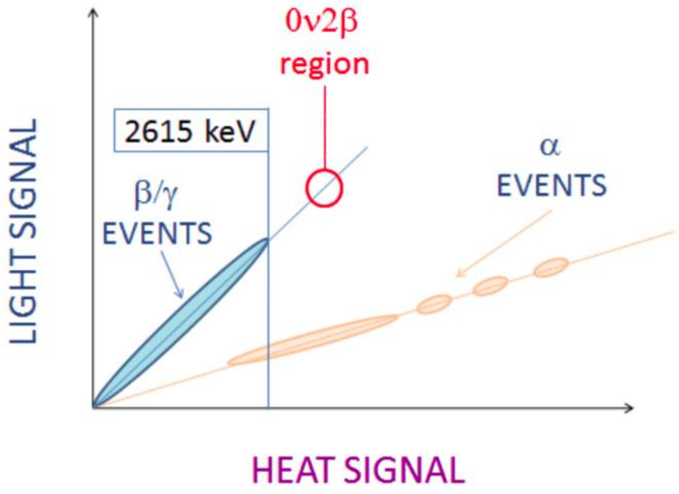
Source ≡ Detector

- 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)

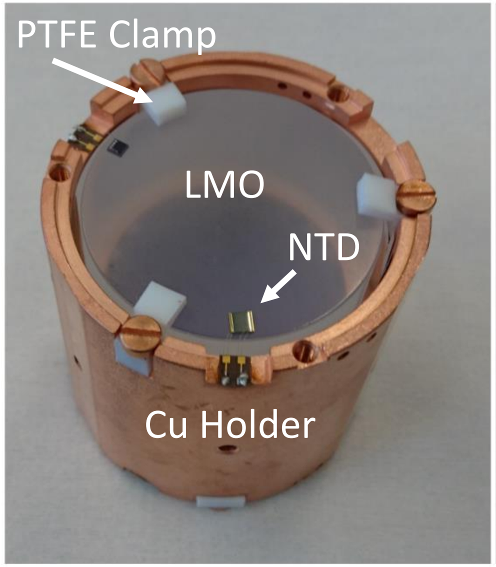
Installed in EDELWEISS cryostat

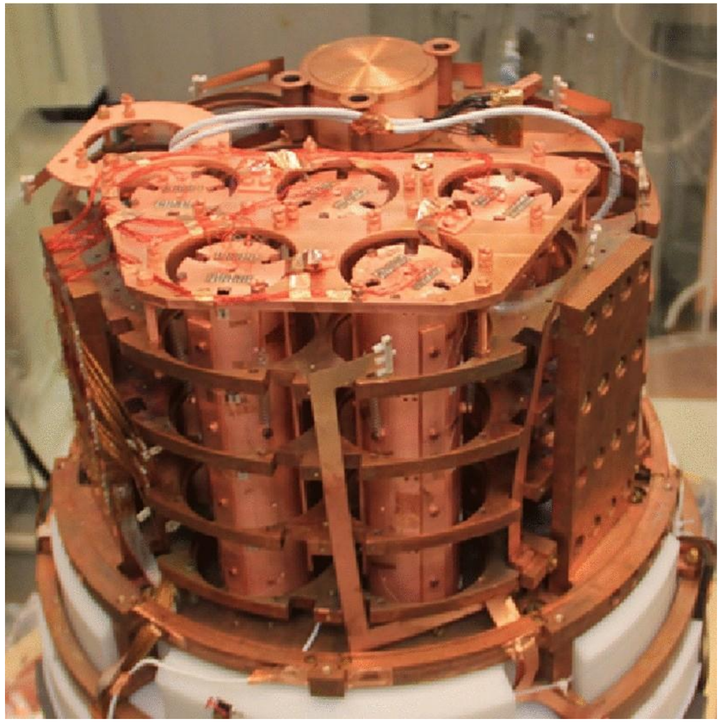
^{100}Mo $Q_{\beta\beta}$ = 3034 keV

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

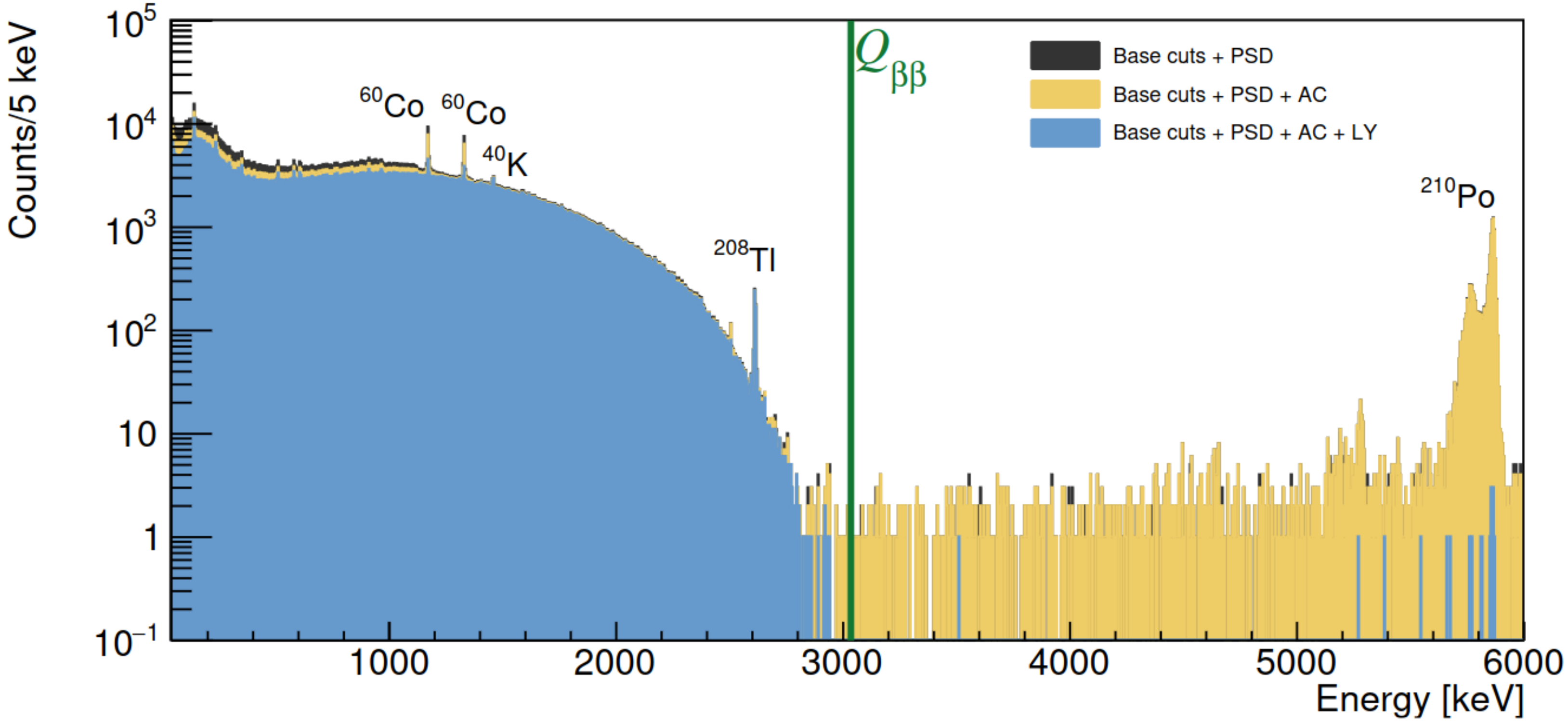
Trigger, Amplitude (Optimal Filter)[1]

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

→ Pulse shape cut (PSD)

↓ Coincidences cut (AC)
- Select events with energy deposition in only one crystal

↓ Light Detector cut (LY)
- Remove alpha particles

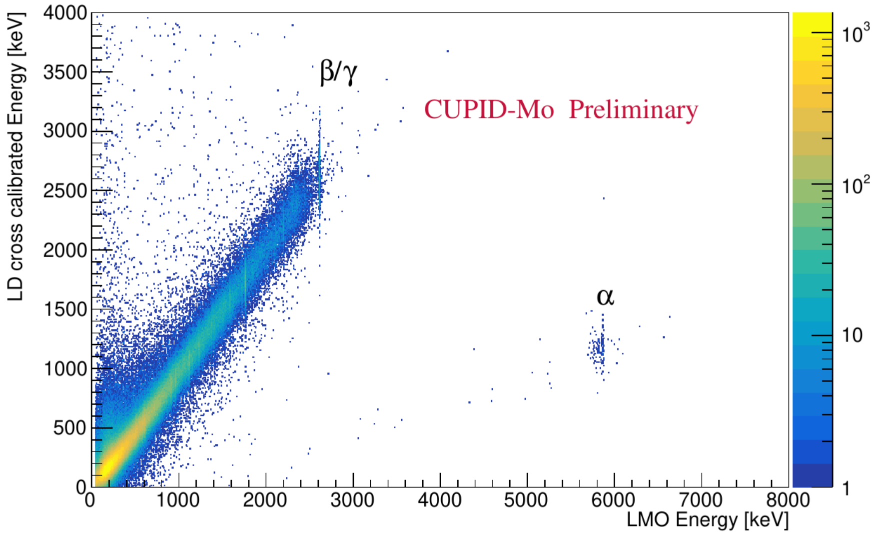


[1] : CUORE Phys. Rev. Lett. 124.122501

CUPID-Mo performances and 0νββ limit

Performance close to the CUPID goals reached :

- Energy resolution: ~ 7.4 +/- 0.4 keV FWHM @ 3034 keV
- Crystal radiopurities: < 0.5 μBq/kg for ^{228}Th and ^{226}Ra
- α-particle rejection: > 99.9 %
- Selection efficiency: ~ 90 %



Limit on 0νββ half life

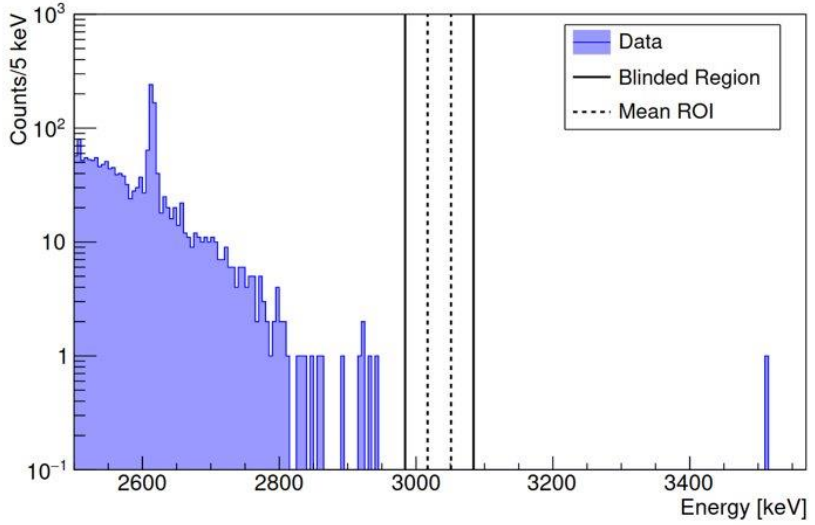
- Blinded analysis on full exposure of 2.71 kg×year of data (1.47 kg×year for ^{100}Mo)

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

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

Most stringent limit for ^{100}Mo

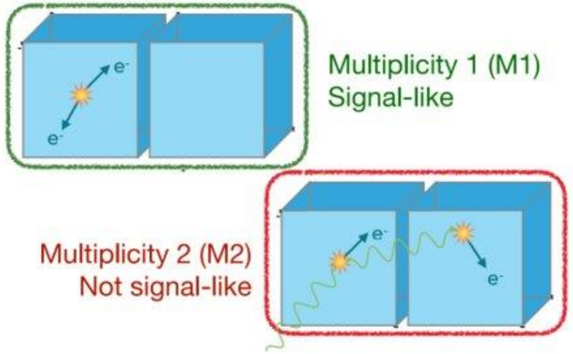
EPJC 82 (2022) 11, 1033



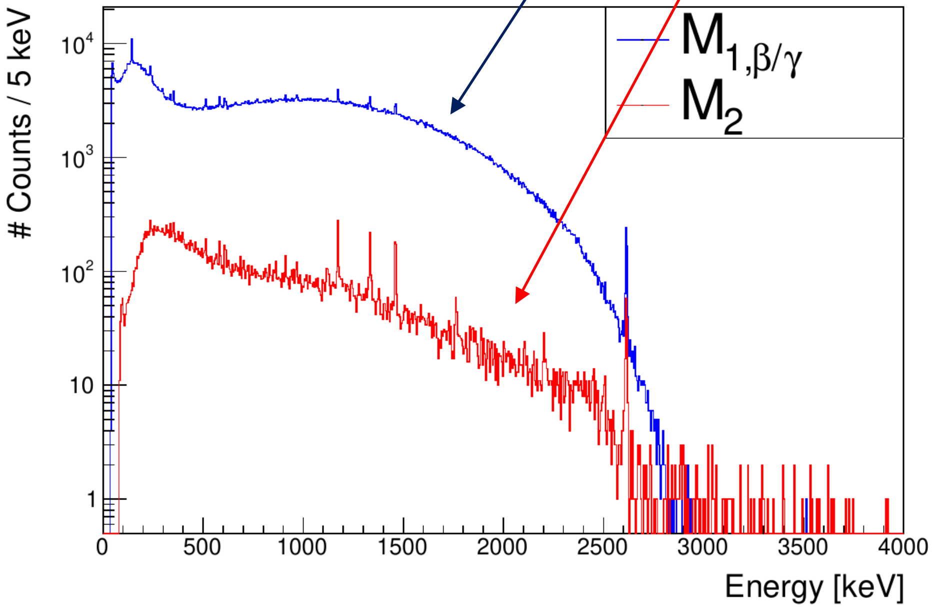
Background model

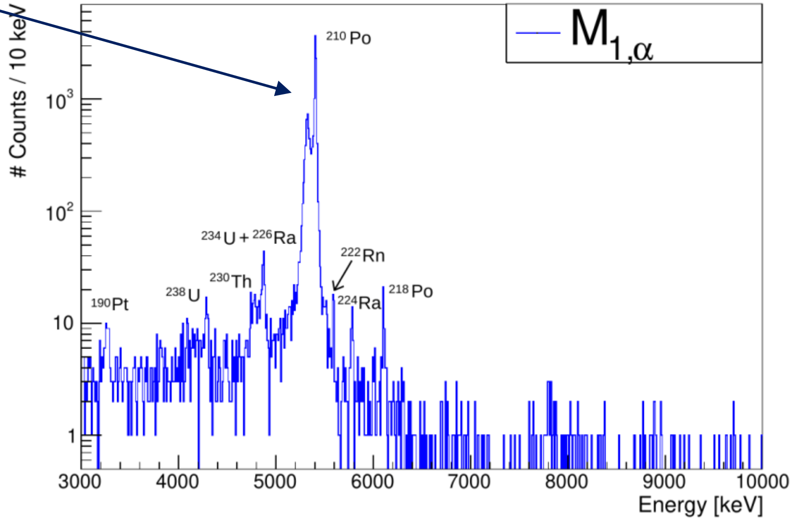
arXiv:2305.01402
Submitted to EPJC

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_2, $M_{1,\alpha}$ spectra



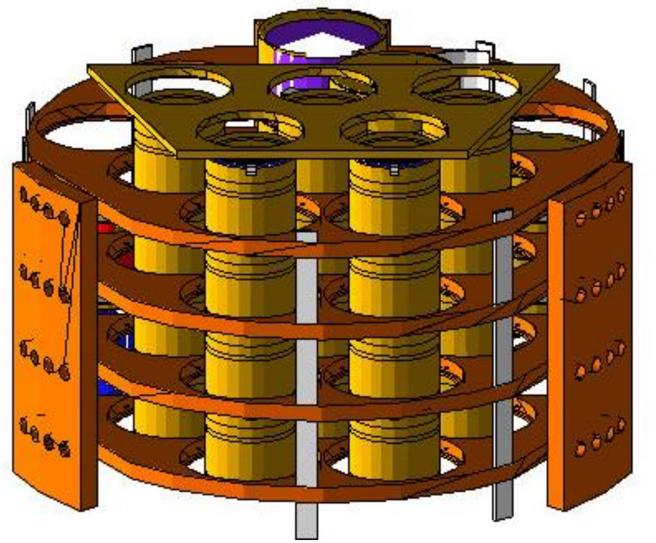


CUPID-Mo simulations

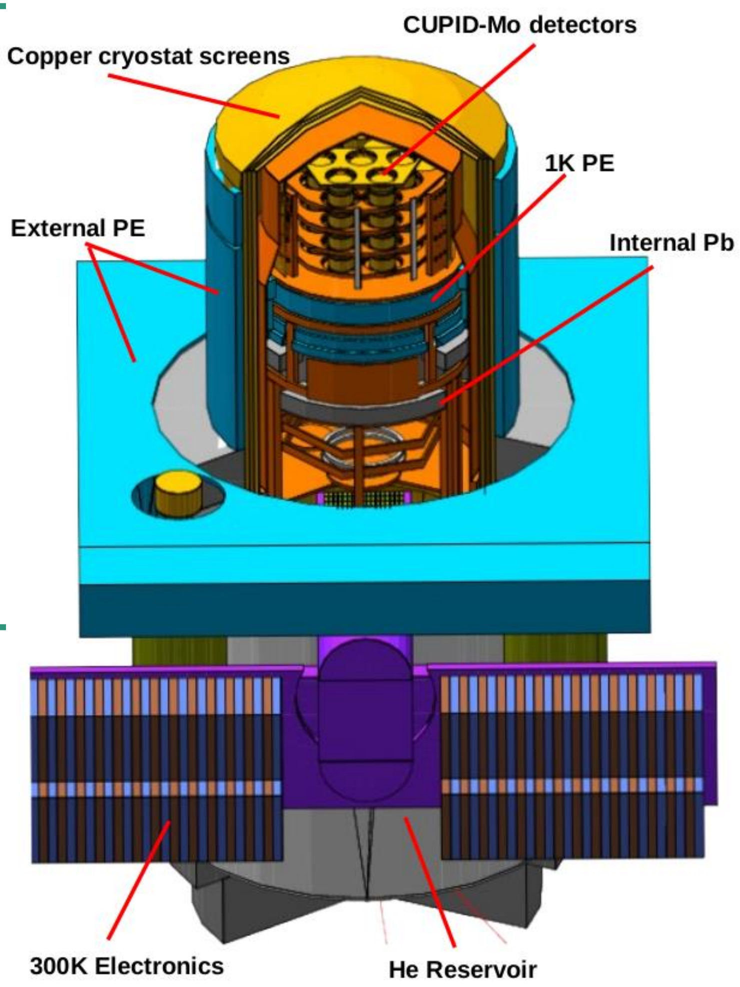
- Geant 4 based program
- Decays are generated in :

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

- **Cryostat and shields**
- **Crystal bulk and surface**
- **Reflector bulk and surface**
- **Close sources**

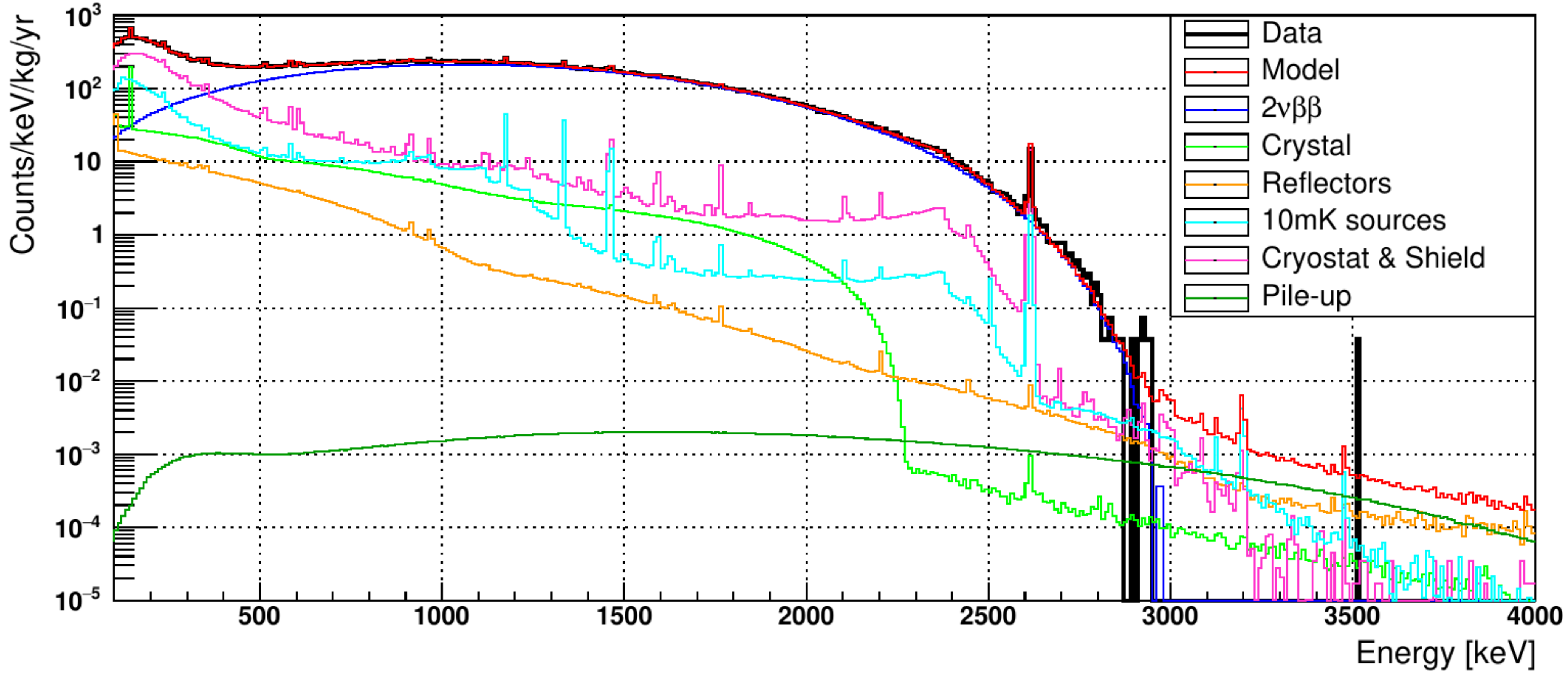


Geant4 Rendering of the CUPID-Mo detectors



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

Background Model : results



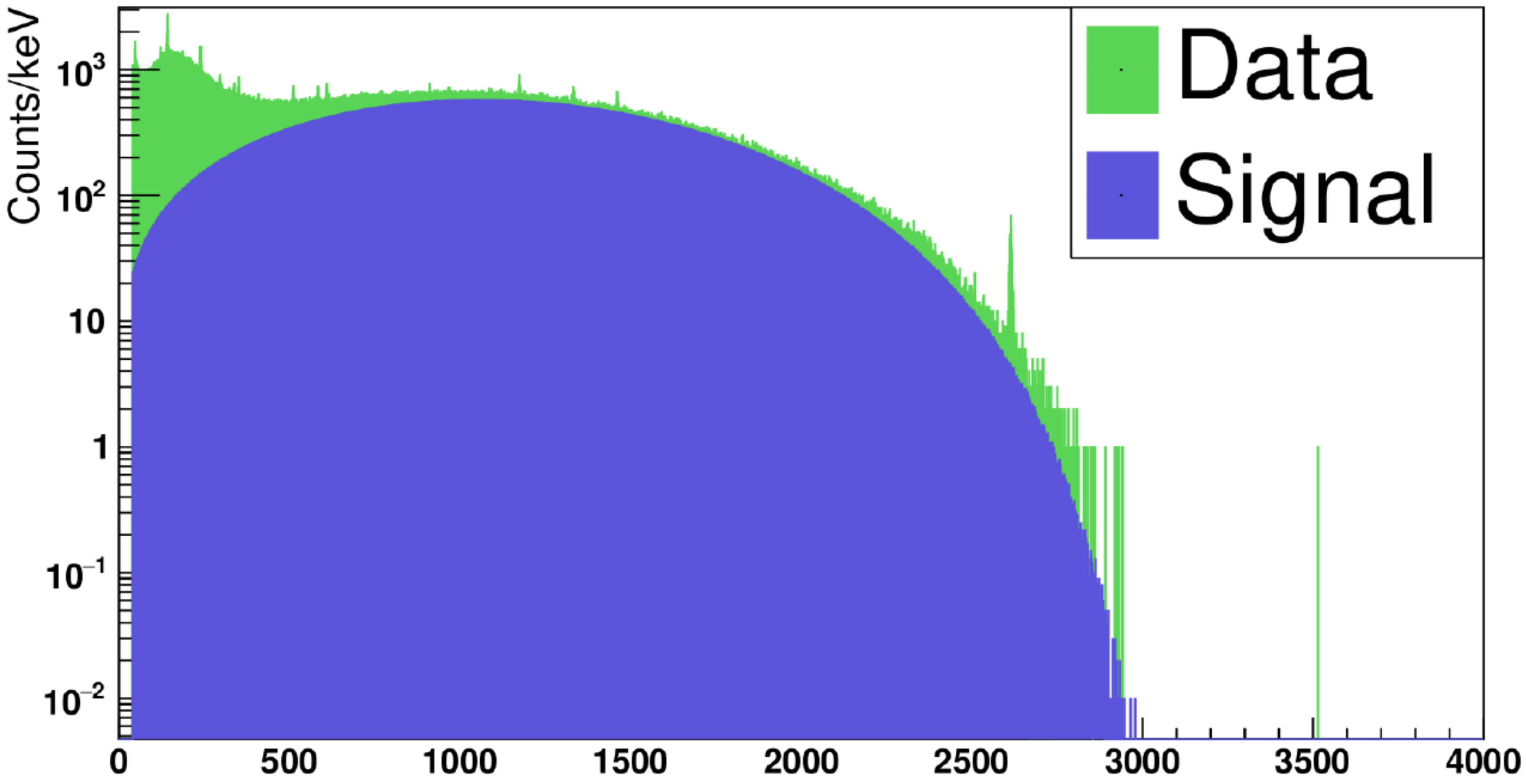
B = 3.7 $^{+1.7}_{-1.1}$ x 10^{-3} cts/FWHM/mol$_{iso}$/yr

arXiv:2305.01402
Submitted to EPJC

Lowest background index in a bolometric 0νββ experiment

2νββ spectrum

NEW!



Excellent signal to background ratio

Allows for :

- Precise measurement of the 2νββ half life
- Studies of the spectral shape
- Limits on BSM processes

2νββ half-life

NEW!

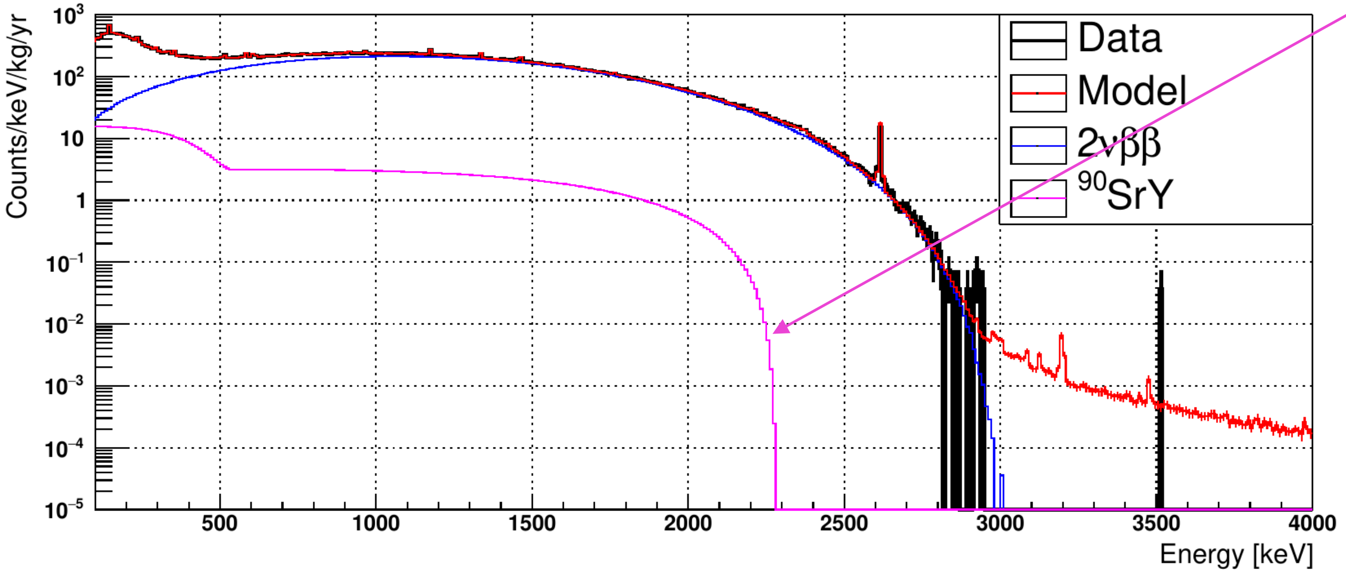
- The measurement comes directly from the background model fit
- $T_{1/2} = \ln(2) \times t \times \varepsilon \times N_{\beta\beta}/N_{obs}$

Number of ββ emitters

Number of observed ββ decays

Related to the background model

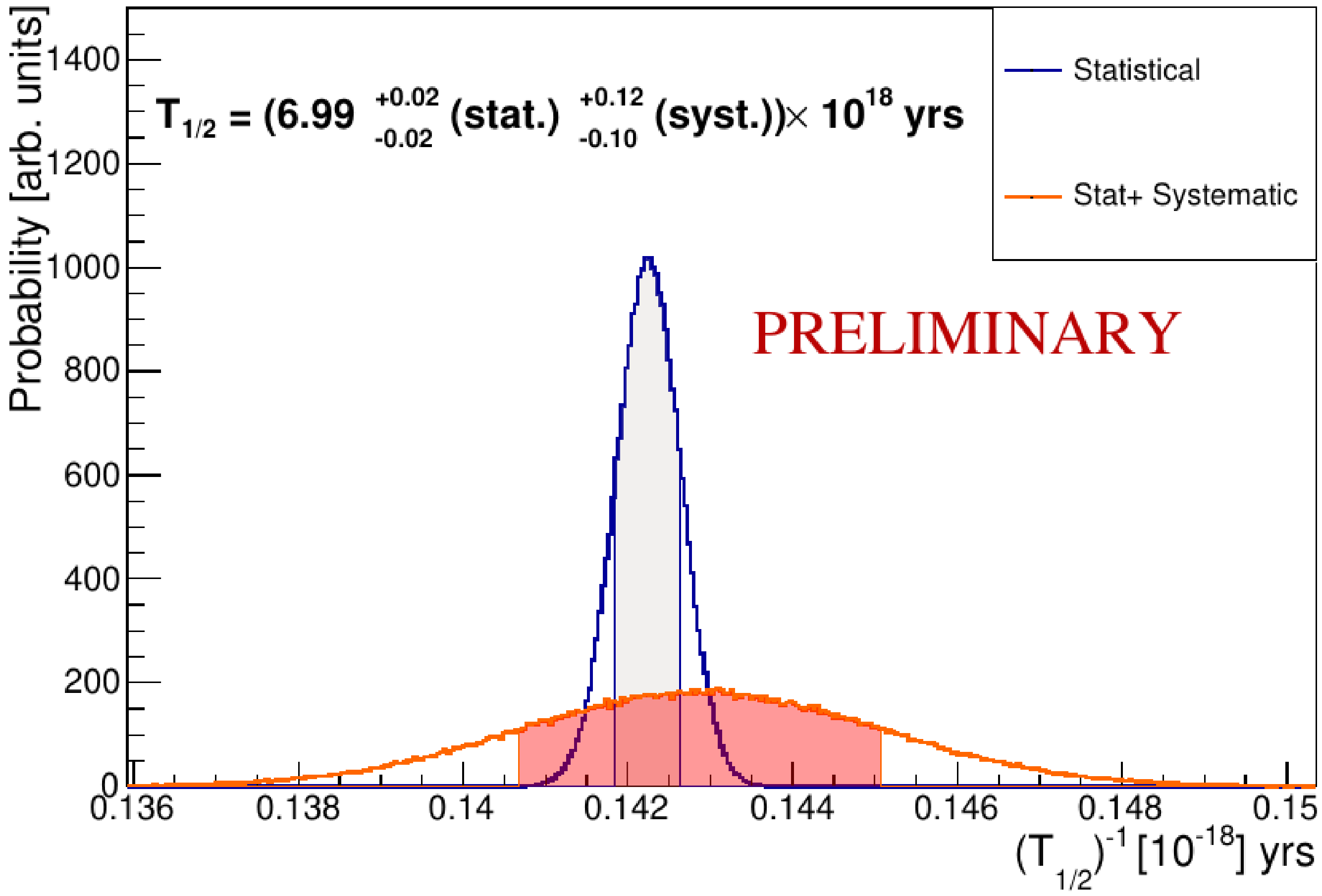
Systematic test	Error [%]
Binning	0.36
Energy Bias	0.08
Signal shape	0.20
MC statistic	0.07
Source location	0.80
Minimal model	0.20
^{90}Sr+Y	+0.94 (uniform distribution)
Efficiency	1.2
Isotope abundance	0.2



PRELIMINARY

2νββ half-life measurement

NEW!



Most precise measurement of 2νββ decay in any isotope

Work ongoing to consider theoretical uncertainties related to the spectral shape of the 2νββ

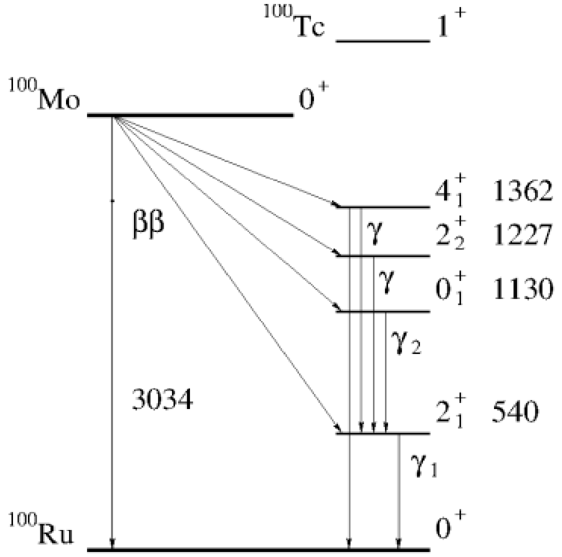
Decay process of ^{100}Mo $2\nu\beta\beta$

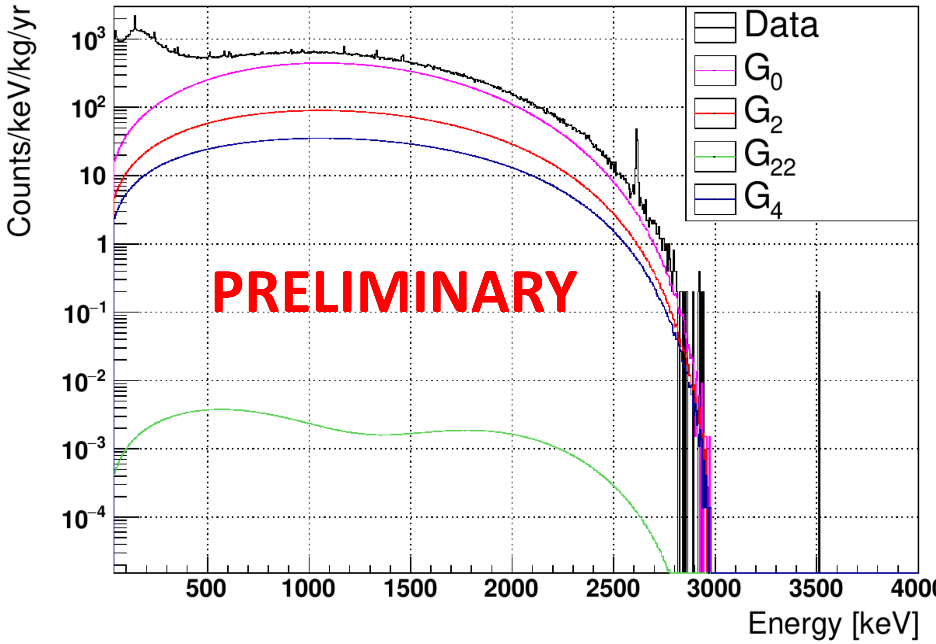
NEW!

Theoretical uncertainties related to the $2\nu\beta\beta$ spectral shape
Due to uncertainty of the intermediate virtual state

Commonly 2 hypothesis are considered:

- SSD : ← Favoured by the bkg model fit (p-value = 0.38)
  - Ground state of ^{100}Tc
- HSD : ← Disfavoured by the bkg model fit (p-value ~ 0)
  - Higher states of ^{100}Tc
  - Lepton energies are negligible compared to the ^{100}Tc energy level





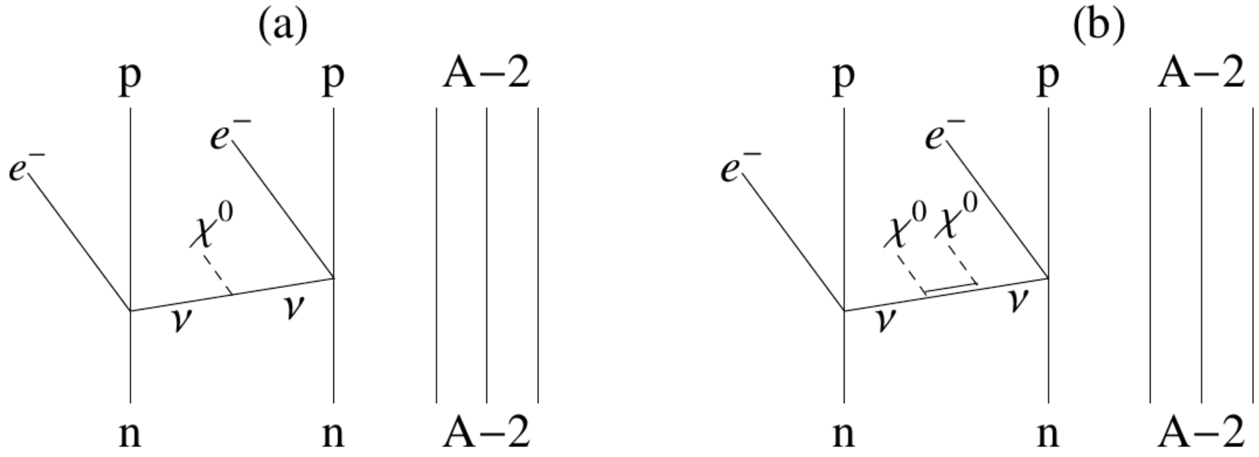
Work ongoing to use an improved theoretical model considering the lepton energies (from Fedor Simkovic)

This procedure allows the factorization of NMEs and phase-space factors

Permit to evaluate the values of the NMEs for the $2\nu\beta\beta$

BSM processes

NEW!



- Majoron bosons can explain 0νββ
  - Several models exists
  - Emission of 1 (a) or 2 (b) Majorons
  - Continuous electron sum energy spectrum
- Lorentz violation (2νββ)
  - Could be revealed by the neutrino momentum
  - $q \sim a_{of}^{(3)}$
  - $a_{of}^{(3)} = C \cdot \Gamma_{LV} / \Gamma_{SM}$
- Sterile neutrino (2νββ)
  - Affects the end point of the 2νββ

Experimentally these models produce a distortion of the 2νββ spectrum
Can be parametrized as : spectral shape ~ $(Q_{\beta\beta} - E)^n$

Emission of 1 Majoron : n=1, 2, 3
Emission of 2 Majorons : n=3, 7

Lorentz Violation : n = 4

2νββ: n=5

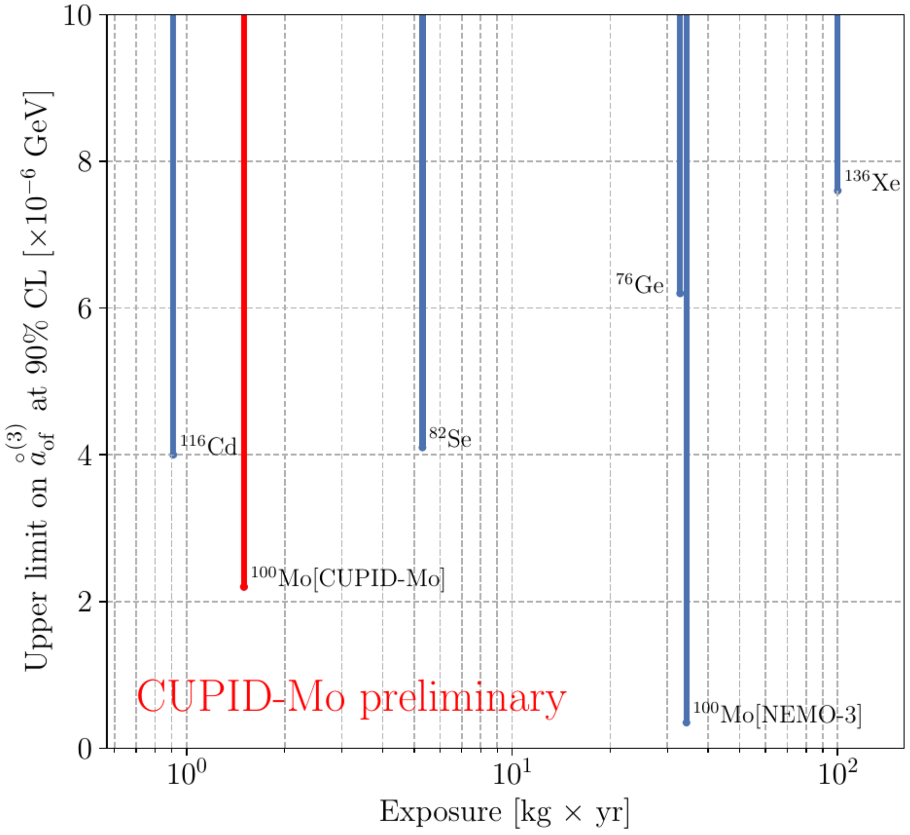
Spectral shape – BSM processes

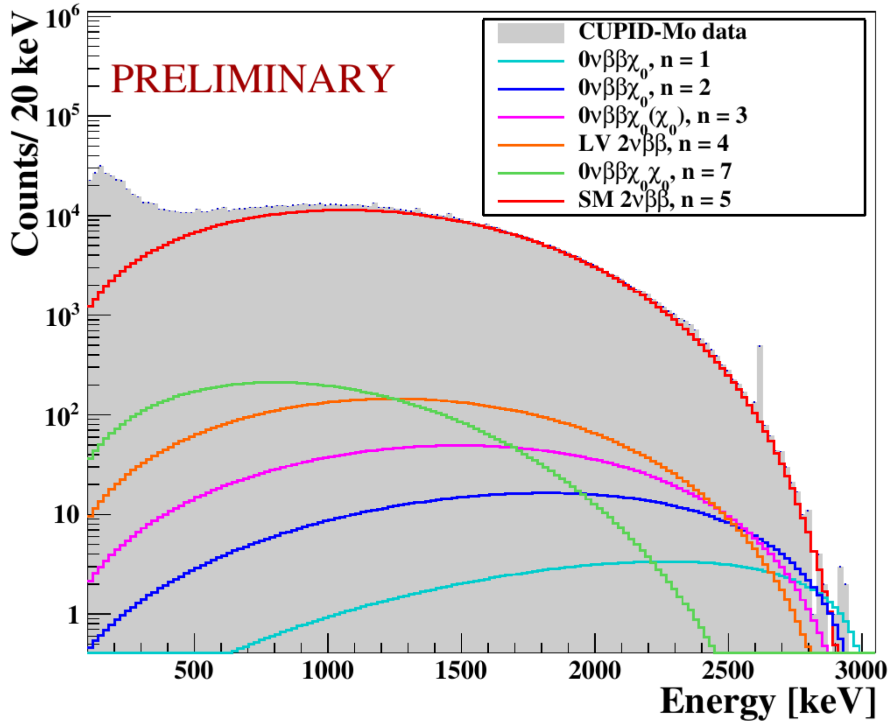
NEW! **PRELIMINARY**

- We performed a fit adding each possible contribution independently

Majoron process	Limit [10^{21} yr] (90% C.I.)
$\beta\beta\chi_0$ (n=1)	> 2.1
$\beta\beta\chi_0$ (n=2)	> 4.5
$\beta\beta\chi_0(\chi_0)$ (n=3)	> 1.4
$\beta\beta\chi_0\chi_0$ (n=7)	> 0.5

- Lorentz Violation





Evaluation of the systematics is ongoing

Measurement of $Q_{\beta\beta}$

NEW!

- Possible shift between γ and ββ events in calibration
- Some theoretical works suggested a value different from the accepted one (3034.40(17) keV)

- Decay rate is parameterized by :

$$d\Gamma/dE = A(E) \times (Q_{\beta\beta} - E)^5$$

- The data are fitted in a Bayesian approach with background coming from the background model fit

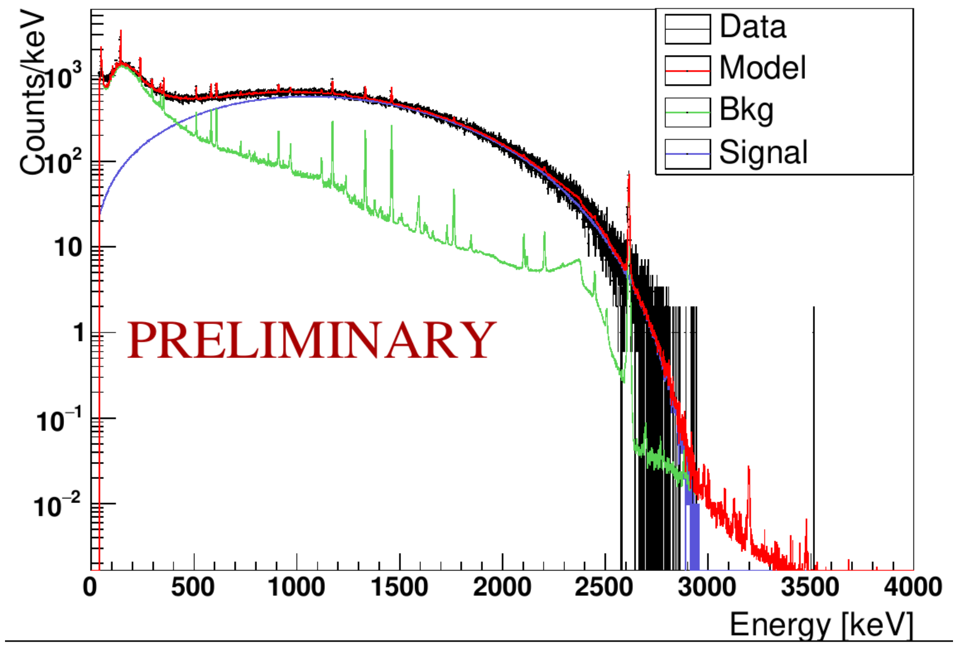
- Can be visualized by a Kurie plot (commonely used for single beta decay)

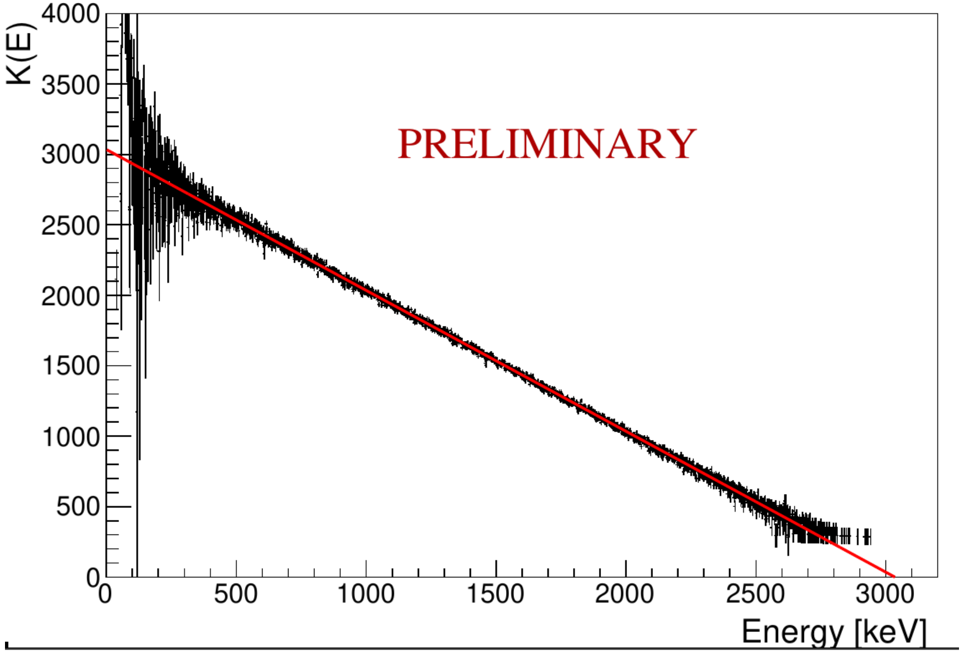
$$K_i(E) = (n_i - f_B(E_i)/A(E_i))^{1/5} = Q_{\beta\beta} - E$$

n_i : number of counts in bin i
f_b : background shape

- $Q_{\beta\beta}$ = 3038.4 +/- 1.5 (stat.) +/- 7 (syst.) keV

PRELIMINARY





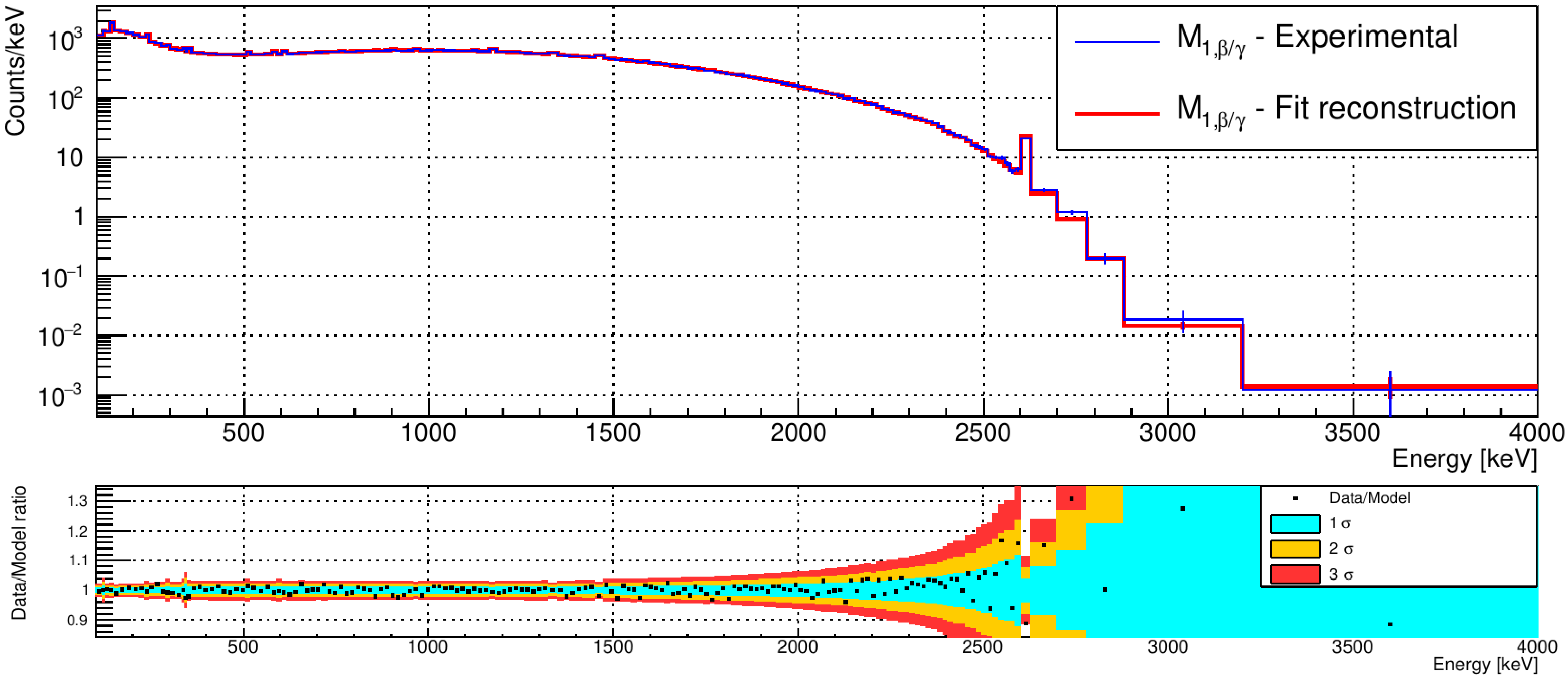
Conclusion

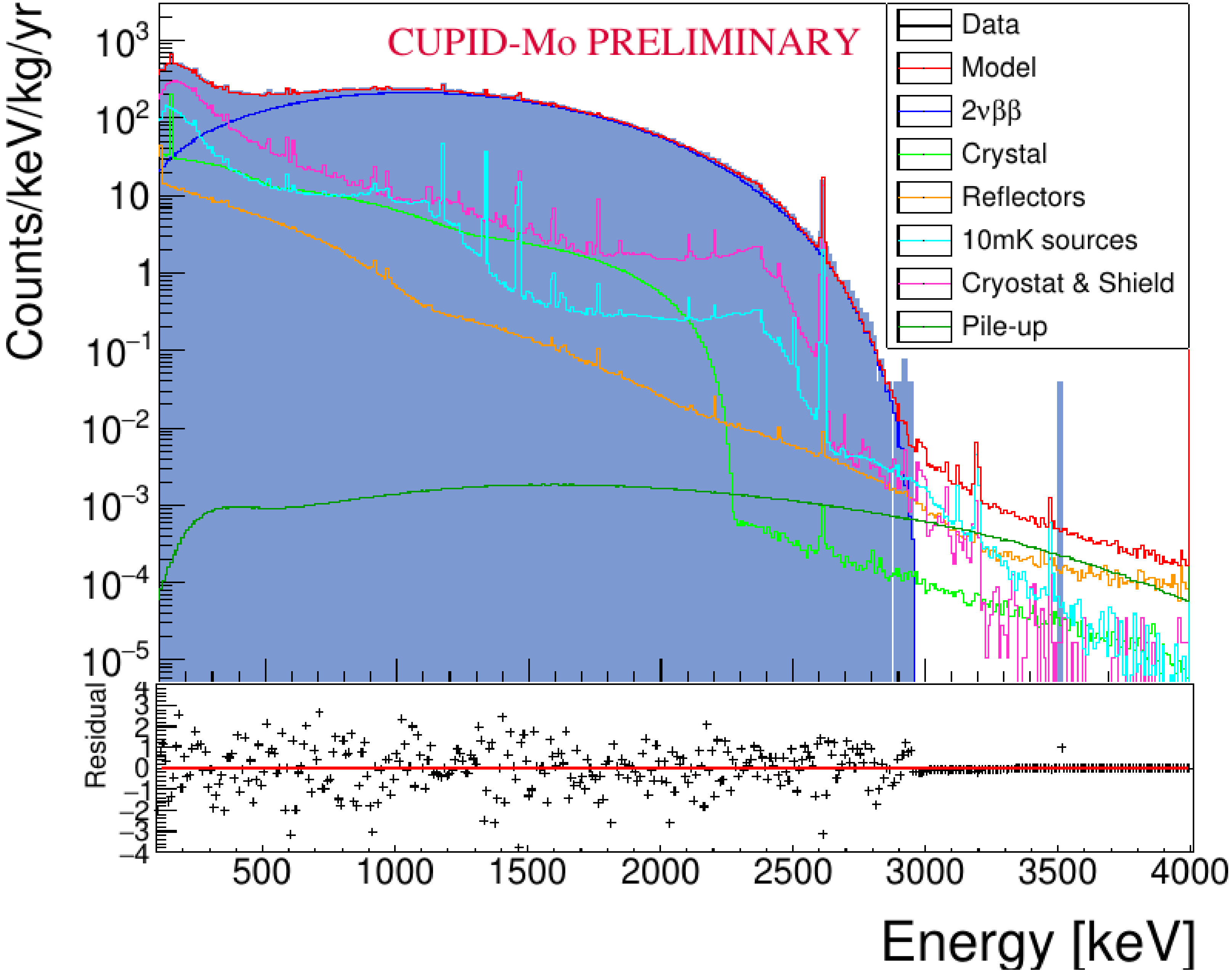
Thanks to the background model we can obtain new physics results:

- Most precise measurement of the ^{100}Mo $2\nu\beta\beta$ half-life
- Spectral shape analysis of the ^{100}Mo $2\nu\beta\beta$ spectrum
- Limits on BSM processes
- Measurement of the ^{100}Mo $Q_{\beta\beta}$

BACK-UP

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




CUPID-Mo PRELIMINARY
Data
Model
2νββ
Crystal
Reflectors
10mK sources
Cryostat & Shield
Pile-up
Counts/keV/kg/yr
Residual
Energy [keV]