

Final results of the CUPID-Mo $0\nu\beta\beta$ experiment

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Neutrinoless double beta decay

$2\nu\beta\beta$

- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$
- 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

$$(T_{1/2}^{0\nu})^{-1} = G_0 g_A^4 M^2 \left| \frac{m_{\beta\beta}}{m_e} \right|^2$$

Effective Majorana mass :

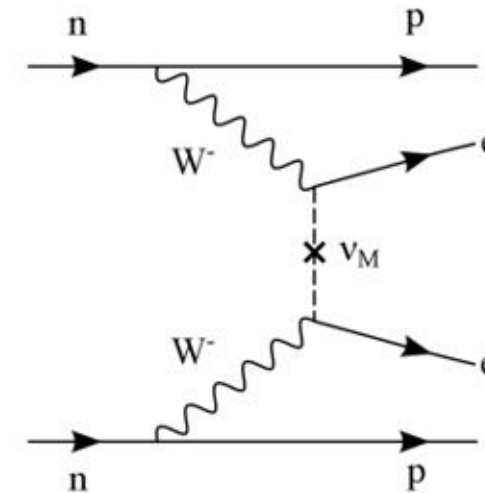
$$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$

Nuclear Matrix Element :

- Differences between different nuclear models

$0\nu\beta\beta$

- Hypothetical decay
- $2n \rightarrow 2p + 2e^-$
- **Lepton number violation $\Delta L = 2$**
- Majorana neutrino $\nu = \bar{\nu}$
- Majorana neutrino is needed in leptogenesis to explain the matter/antimatter asymmetry

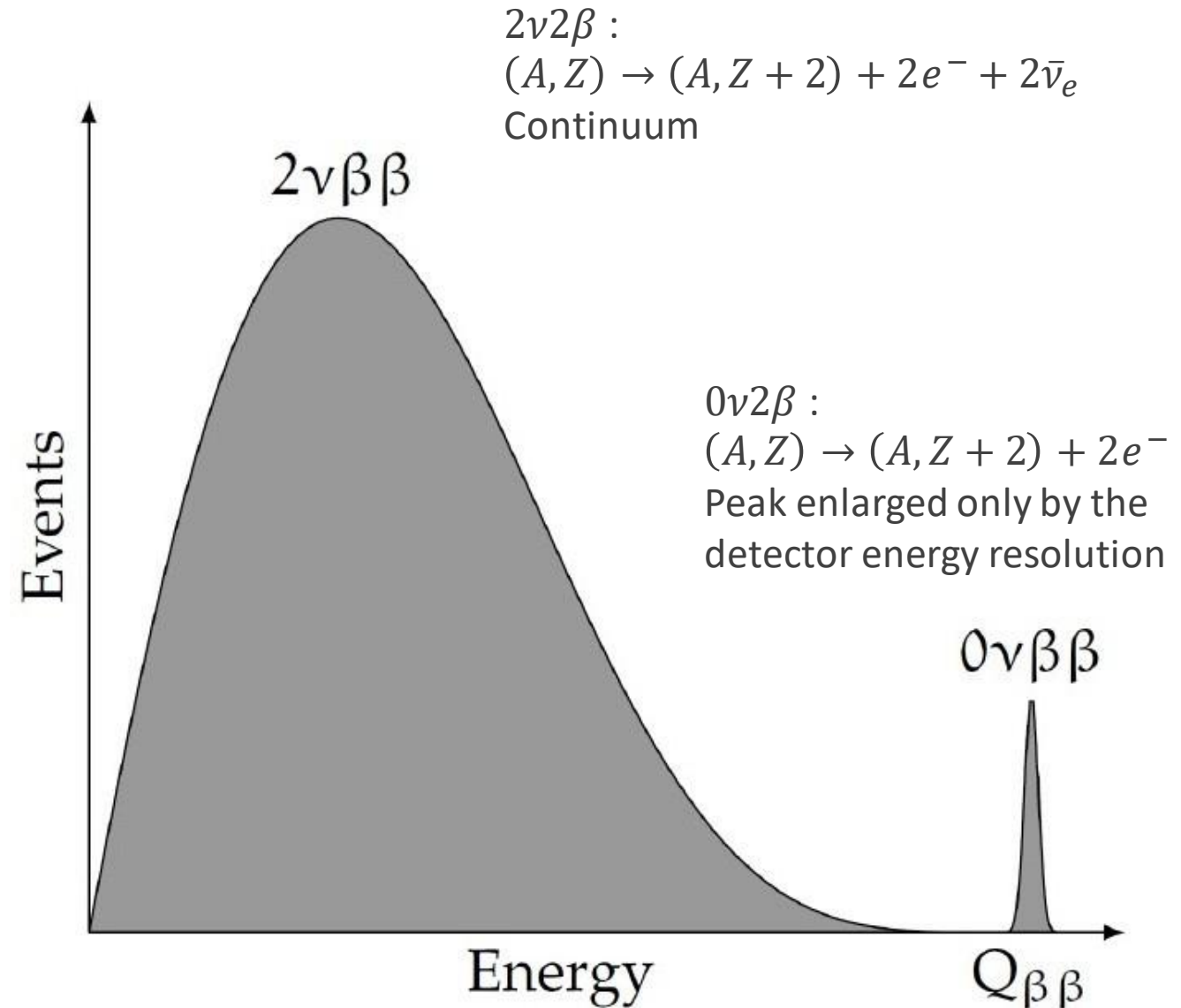


Searching for $0\nu2\beta$

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

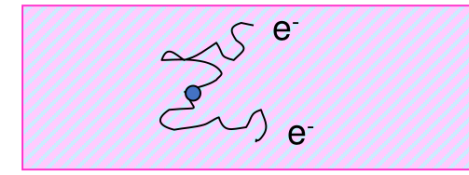
- Requires :

- Low background in the ROI (around the $Q_{\beta\beta}$)
- Good energy resolution
- High detection efficiency
- Large amount of the isotope of interest and long measurements

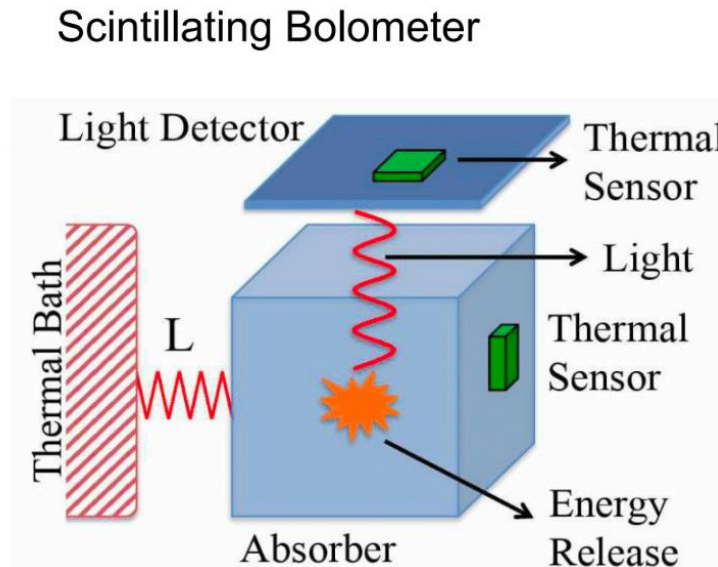


Bolometric technique

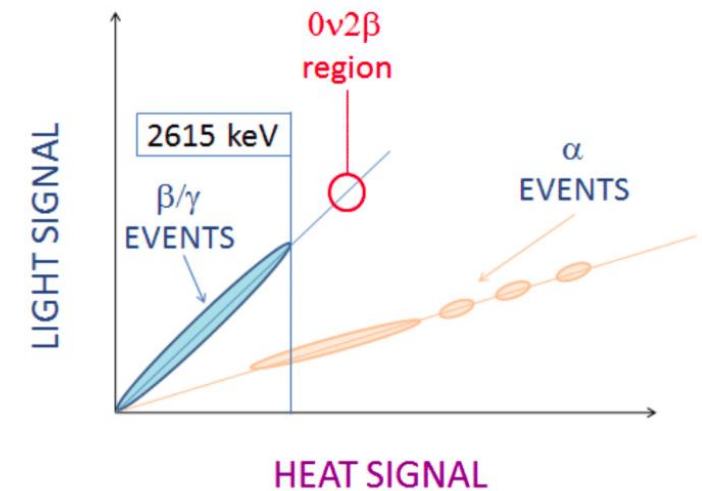
- Crystals cool down to $\sim 10\text{-}20\text{ mK}$
- Detector = source
 - High detection efficiency
- Good energy resolution
- Scintillating bolometers
 - Discriminations between β/γ and α particles
 - Heat and Light signals



Source \equiv Detector



Particle Identification



CUPID-Mo

Demonstrator for the next generation ton scale experiment CUPID

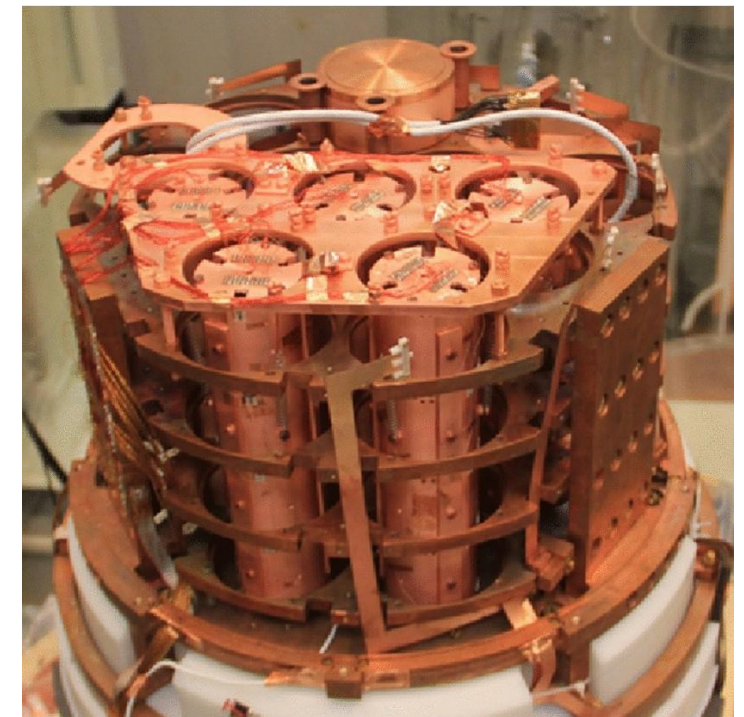
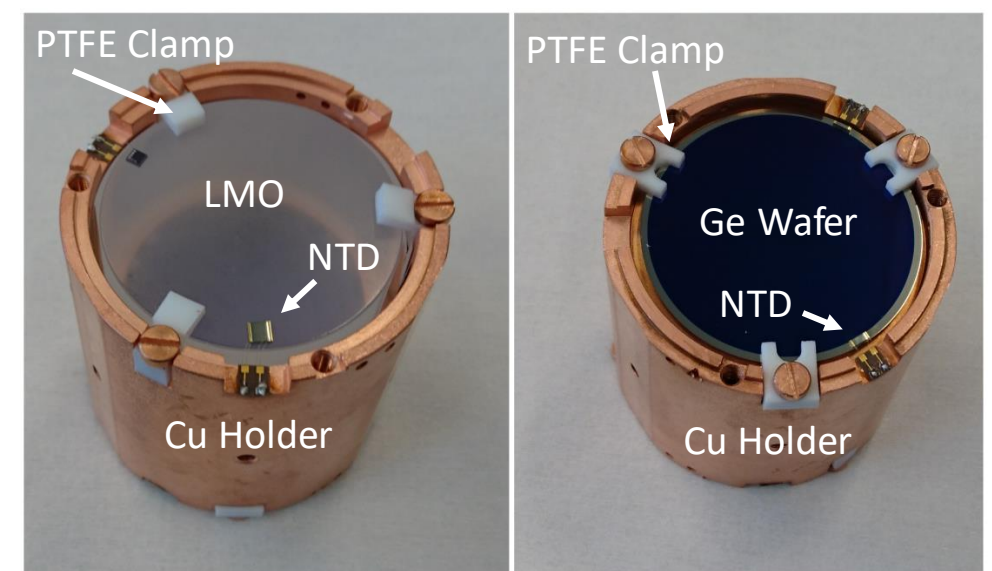
Installed at the Laboratoire Souterrain de Modane (LSM)

In the EDELWEISS cryostat

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

20 $\text{Li}_2^{100}\text{MoO}_4$ scintillating bolometers

- 0.2 kg $\text{Li}_2^{100}\text{MoO}_4$ cylindrical crystals ($\varnothing 44 \times 45$ mm)
- ^{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)



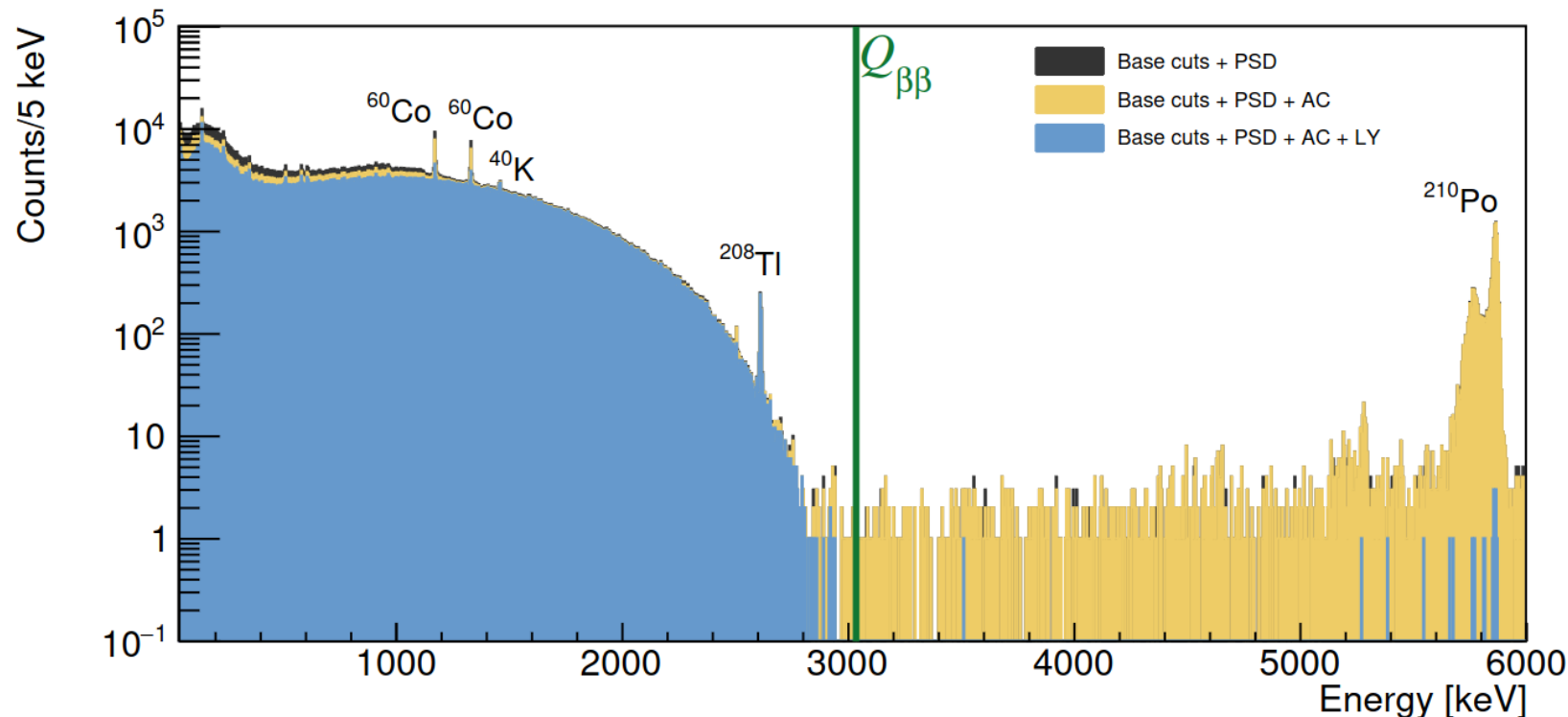
Coincidences cut (AC)

- 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 previous results

Performance close to the CUPID goals reached :

- Energy resolution: $\sim 7.4 \pm 0.4$ keV FWHM @ 3034 keV
- Crystal radiopurities: < 0.5 $\mu\text{Bq/kg}$ for ^{228}Th and ^{226}Ra
- α -particle rejection: $> 99.9\%$
- Selection efficiency: $\sim 90\%$

Limit on $0\nu\beta\beta$ half life:

- Blinded analysis on full exposure of 2.71 kg \times yr of data (1.47 kg \times yr for ^{100}Mo)

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

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

EPJC 82 (2022) 11, 1033

$2\nu\beta\beta$ and $0\nu\beta\beta$ decay to excited states analysis:

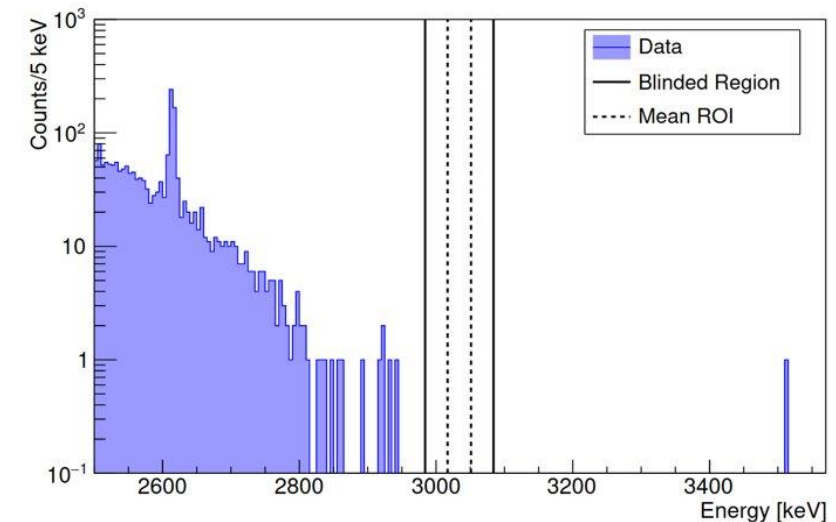
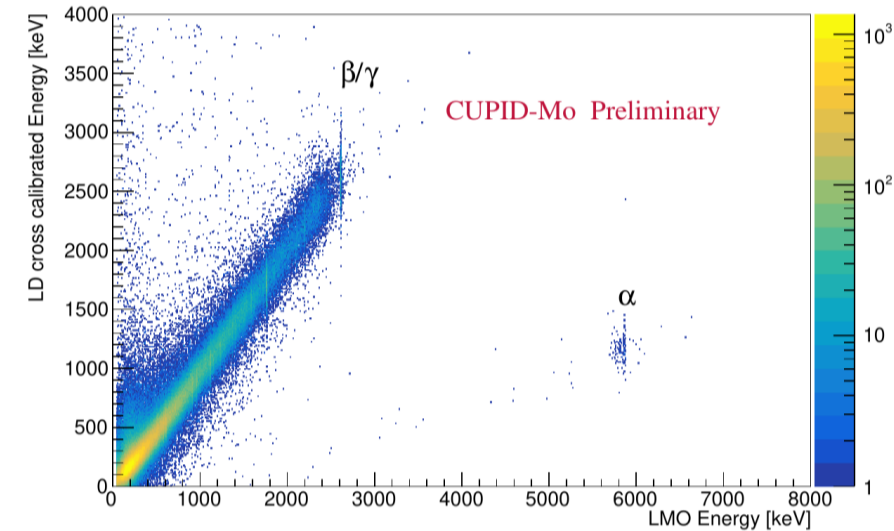
$$T_{1/2}(2\nu \rightarrow 0_1^+) = 7.5 \pm 0.8 \text{ (stat.)}_{-0.3}^{+0.4} \text{ (syst.)} \times 10^{20} \text{ yrs}$$

$$T_{1/2}(2\nu \rightarrow 2_1^+) > 4.4 \times 10^{21} \text{ yrs (90\% c.i.)}$$

$$T_{1/2}(0\nu \rightarrow 0_1^+) > 1.2 \times 10^{23} \text{ yrs (90\% c.i.)}$$

$$T_{1/2}(0\nu \rightarrow 2_1^+) > 2.1 \times 10^{23} \text{ yrs (90\% c.i.)}$$

Phys.Rev.C 107 (2023) 2, 025503

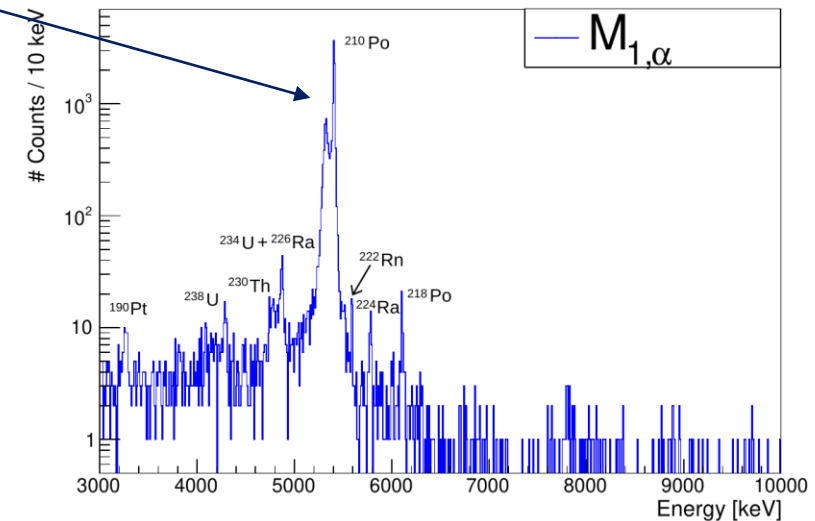
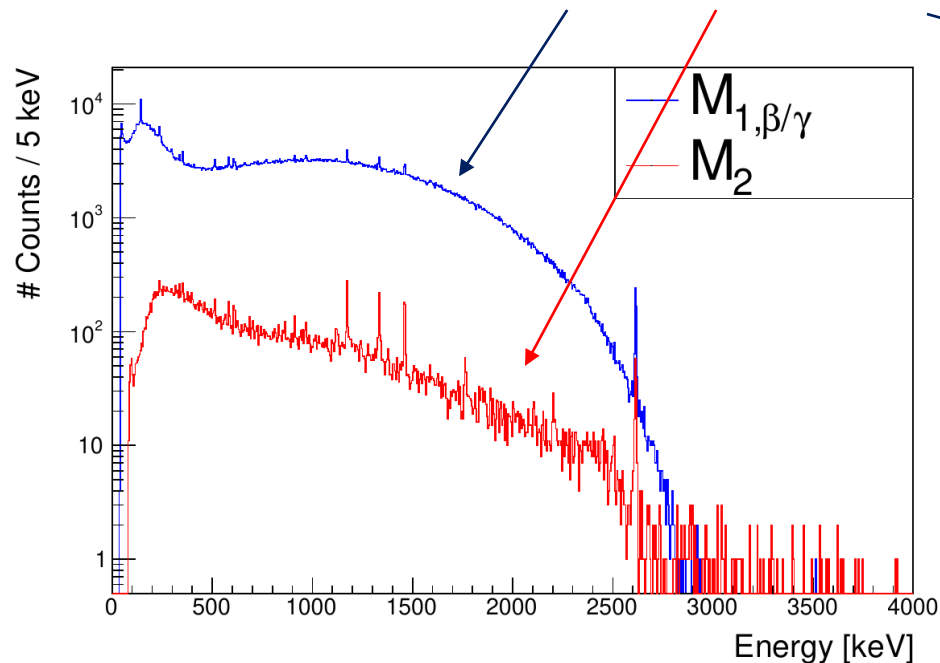
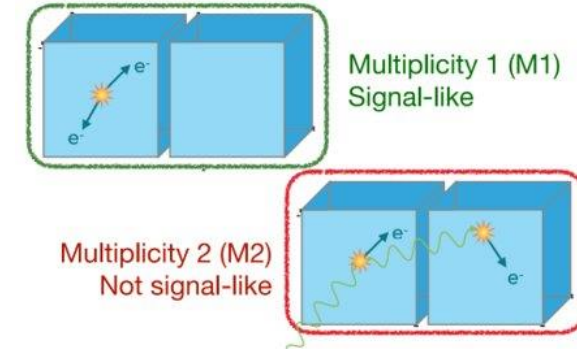


Background model

EPJC **83** (2023) 7, 675

Goal : Describe the experimental data by a linear combination of the Monte-Carlo 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

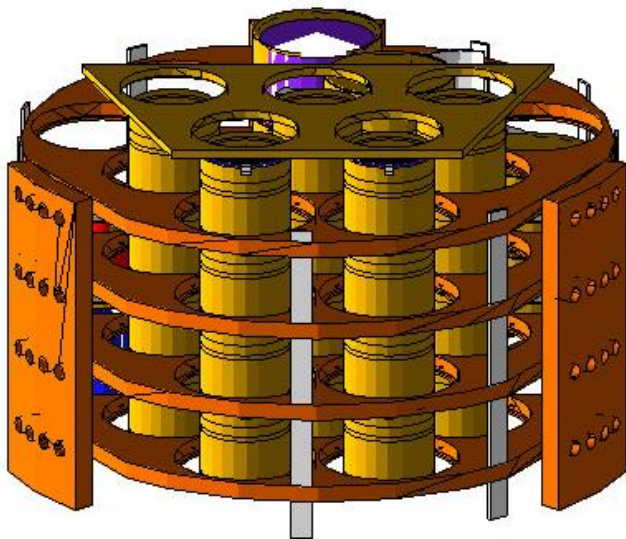
- Geant 4 based program
- Decays are generated in :

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

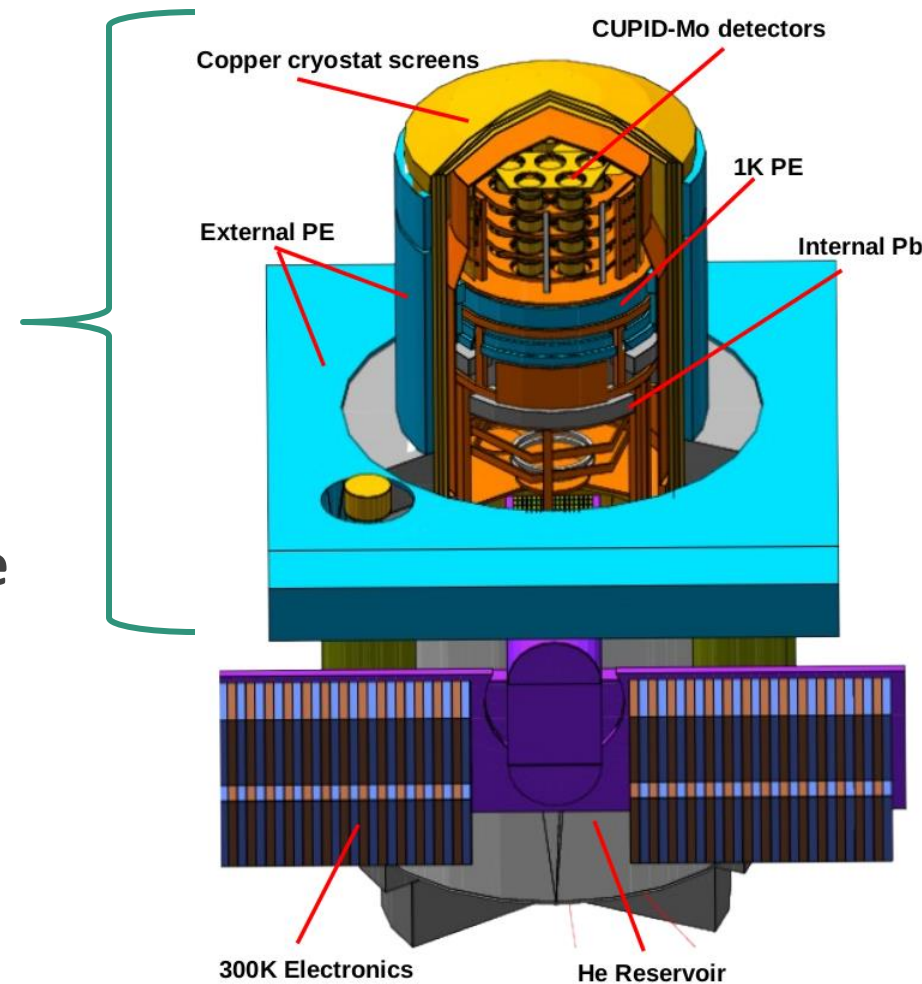
- Cryostat and shields

- Crystal bulk and surface
- Reflector bulk and surface

- Close sources

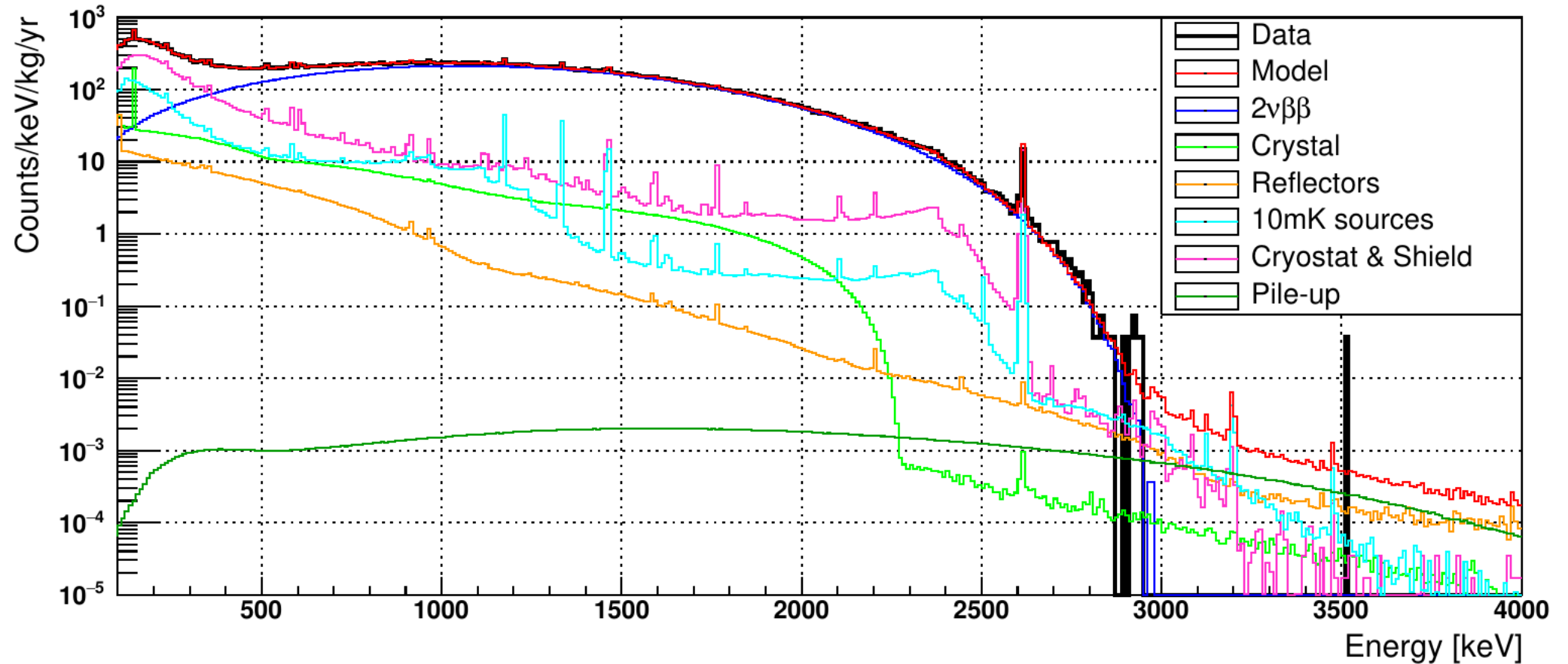


Geant4 Rendering of the CUPID-Mo detectors



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

Background Model : results

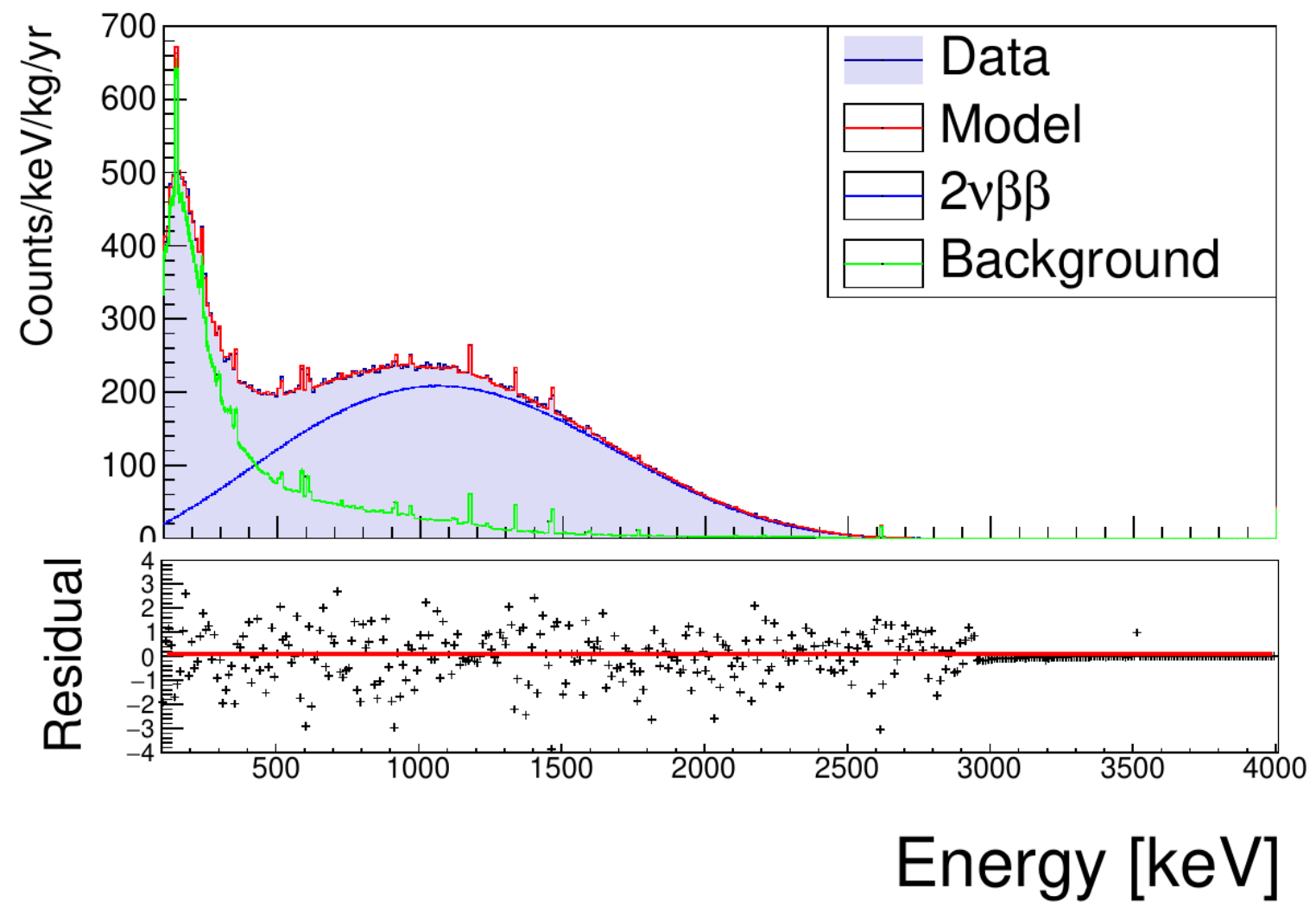


$$B = 3.7^{+1.7}_{-1.1} \times 10^{-3} \text{ cts/FWHM/mol}_{100\text{Mo}}/\text{yr} \quad \text{EPJC 83 (2023) 7, 675}$$

One of the lowest background index in a bolometric $0\nu\beta\beta$ experiment

$2\nu\beta\beta$ spectrum

NEW!



Excellent signal to background ratio

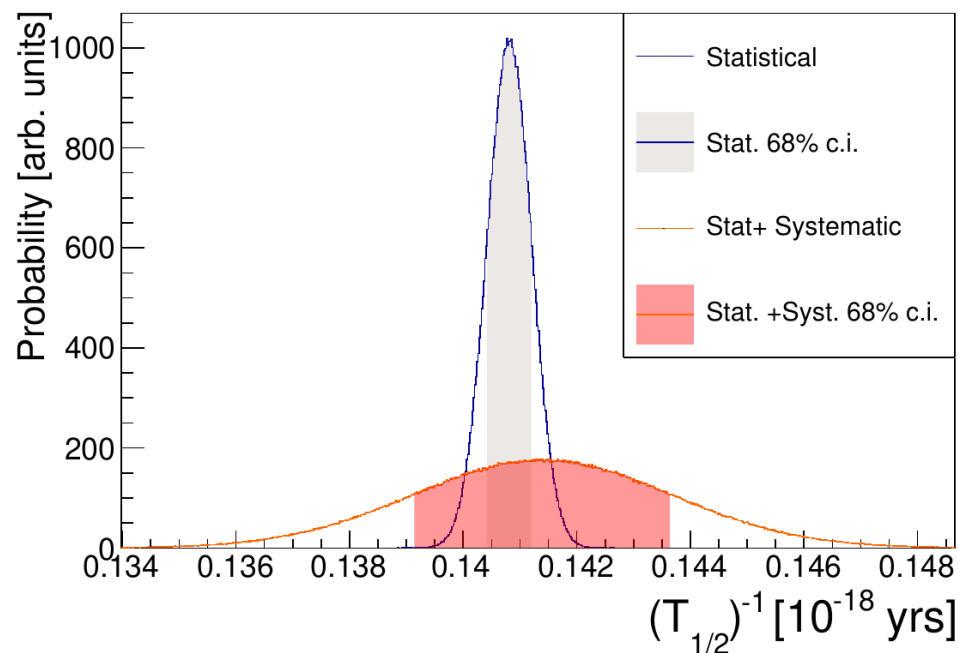
Allows for :

- Precise measurement of the $2\nu\beta\beta$ half life
- Studies of the spectral shape
- Limits on Beyond Standard Model processes

$2\nu\beta\beta$ half-life

NEW!

- The measurement comes directly from the background model fit
- Systematics based on tests varying the assumptions of the background model



Related to the background model

arXiv:2307.14086
Accepted by PRL

| Systematic test | Uncertainty $T_{1/2}$ [%] |
|---------------------------|-----------------------------|
| Binning | +/- 0.37 |
| Energy Bias | +0.11 -0.16 |
| Bremsstrahlung | +0.13 -0.22 |
| MC statistic | +/- 0.11 |
| Source location | +/- 0.83 |
| Minimal model | +/- 0.24 |
| $^{90}\text{Sr}+\text{Y}$ | +1.0 (uniform distribution) |
| Efficiency | +/- 1.2 |
| Isotope abundance | +/- 0.2 |

$$T_{1/2}^{2\nu\beta\beta} = 7.07 \pm 0.02 \text{ (stat.)} \pm 0.11 \text{ (syst.)} \times 10^{18} \text{ yr}$$

Most precise measurement
of $2\nu\beta\beta$ decay in ^{100}Mo

2νββ spectral shape measurement

- Measuring the 2νββ spectral shape constrains nuclear models for NME calculations that is important for the interpretation of the 0νββ
- We considered an improved description :

$$\frac{d\Gamma}{dE} = (g_A^{\text{eff}})^4 |M_{GT-1}^{2\nu}|^2 \left(\frac{dG_0^{2\nu}}{dE} + \xi_{31} \frac{dG_2^{2\nu}}{dE} + \frac{1}{3} \xi_{31}^2 \frac{dG_{22}^{2\nu}}{dE} + \left(\frac{1}{3} \xi_{31}^2 + \xi_{51} \right) \frac{dG_4^{2\nu}}{dE} \right)$$

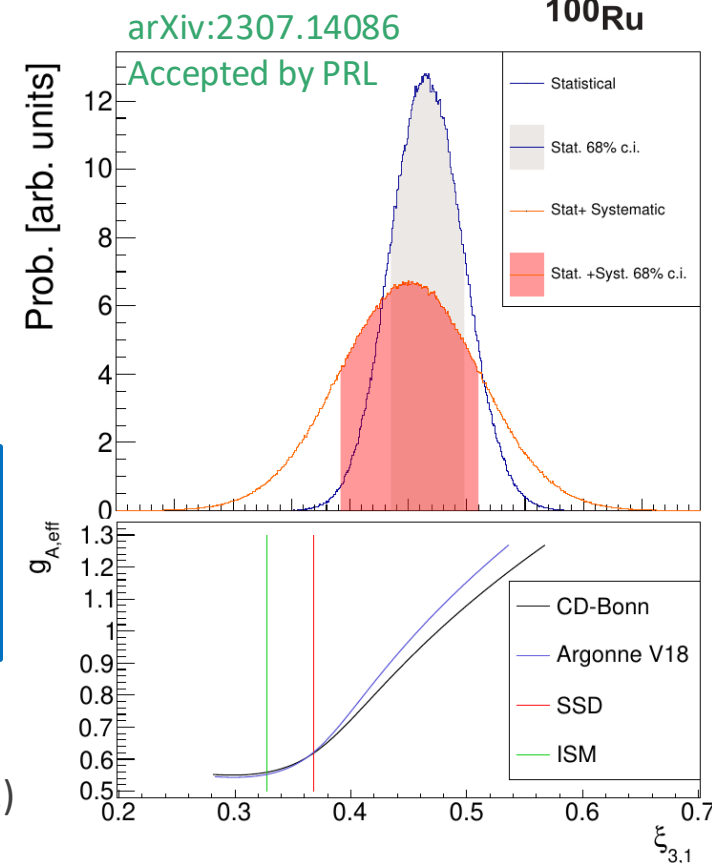
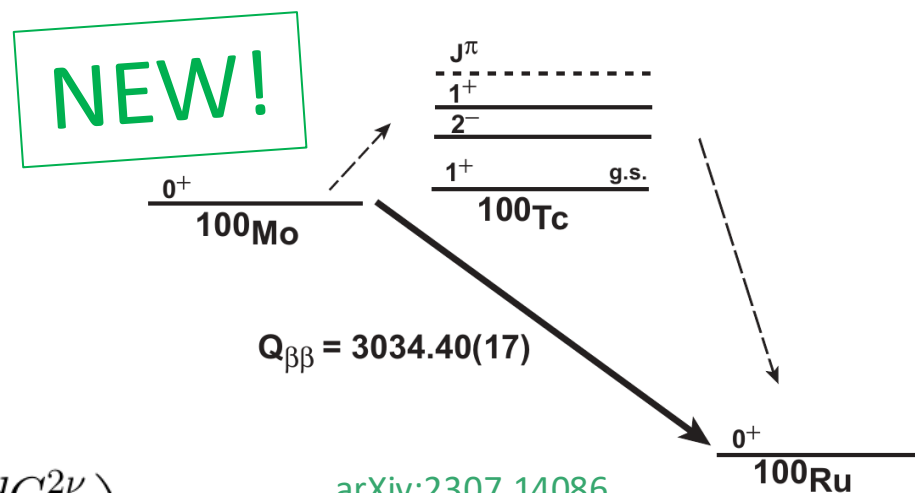
Phase space factors PRC 97 (2018) 034315

Spectral shape parameters

- We implemented this description in the fit, with a gaussian prior on $\xi_{5,1}/\xi_{3,1}$ that is well constrained by theory
- We obtained : $\xi_{3,1} = 0.45 \pm 0.03$ (stat.) ± 0.05 (syst.)
- By comparison with the theory we can measure the $g_{A,\text{eff}}$
- $g_{A,\text{eff}}(\text{pn-QRPA}) = 1.0 \pm 0.1$ (stat.) ± 0.2 (syst.)

First measurement of $\xi_{3,1}$ and first measurement of $g_{A,\text{eff}}$ based on a 2νββ spectral study

$$g_{A,\text{eff}}(\text{ISM}) = 1.11 \pm 0.03 \text{ (stat.) } \pm 0.05 \text{ (syst.)}$$



Conclusion

CUPID-Mo achieved performances close to the CUPID goals:

- Crystals radiopurities
- Energy resolution
- α discrimination

And also an excellent experiment on its own:

- Limit on the ^{100}Mo $0\nu\beta\beta$ half-life of $T_{1/2} > 1.8 \times 10^{24}$ yr
- One of the lowest background index in a bolometric $0\nu\beta\beta$ experiment
- 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
 - First measurement of $\xi_{3,1}$
 - First measurement of $g_{A,\text{eff}}$ within $2\nu\beta\beta$ spectral study

For more information:

- "*CUPID the next generation $0\nu\beta\beta$ bolometric experiment*" by Claudia Nones on Wednesday
- Posters by Pia Loaiza, Vladyslav Berest, Irene Nutini on session B

Leads to promising results for the future experiment CUPID

BACK-UP

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

