Searching for new physics in $2\nu\beta\beta$ with scintillating cryogenic calorimeters

Ph.D. thesis defence XXXV cycle — 16/05/2024

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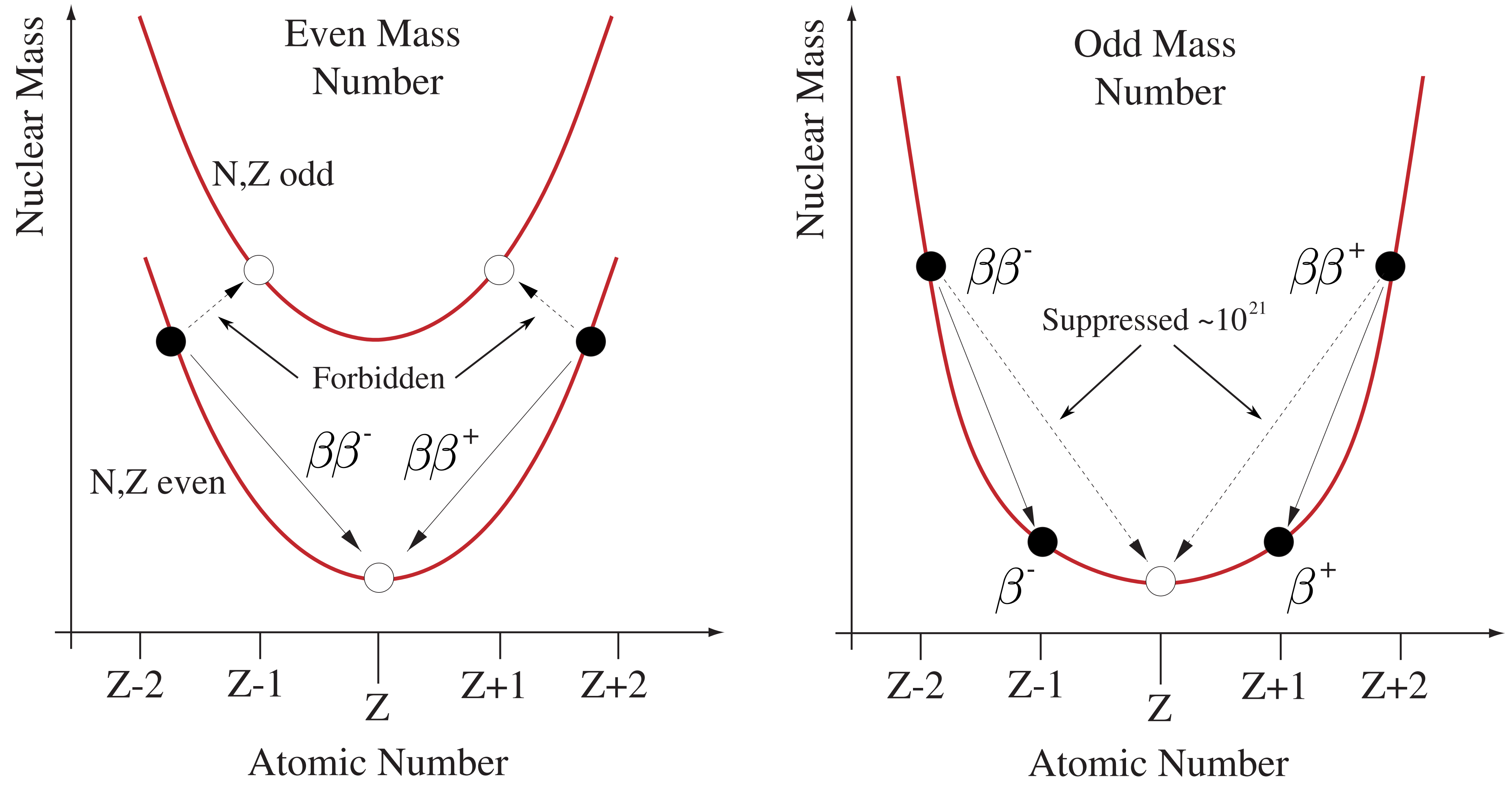
Outline

Double-β decays

In nature, only a subset of even-even nuclei could decay through double-β decay.

This can happen when the attractive nuclear pairing interaction adds binding energy to nuclei with even numbers of protons and neutrons.

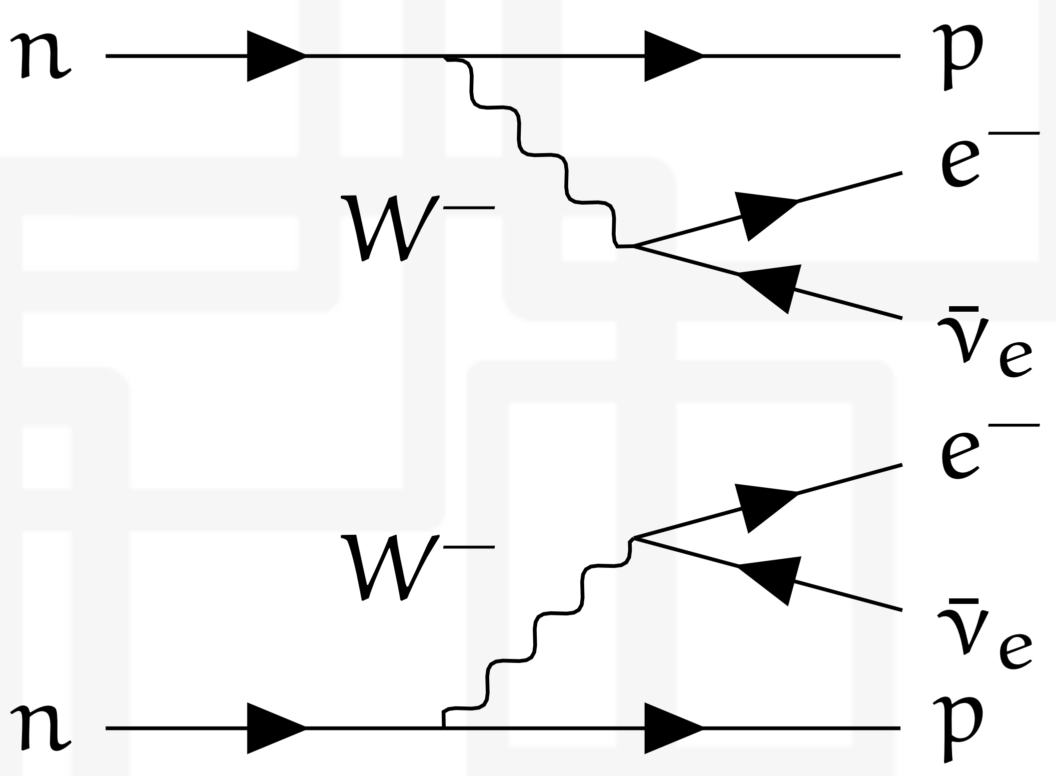
Isotope	Isotopic abundance (%)	Enrichment (%)
^{48}Ca	0.187	16
^{76}Ge	7.8	92
^{82}Se	8.7	96
^{96}Zr	2.8	86
^{100}Mo	9.8	99
^{116}Cd	7.5	82
^{130}Te	34.08	92
^{136}Xe	8.9	90
^{150}Nd	5.6	91

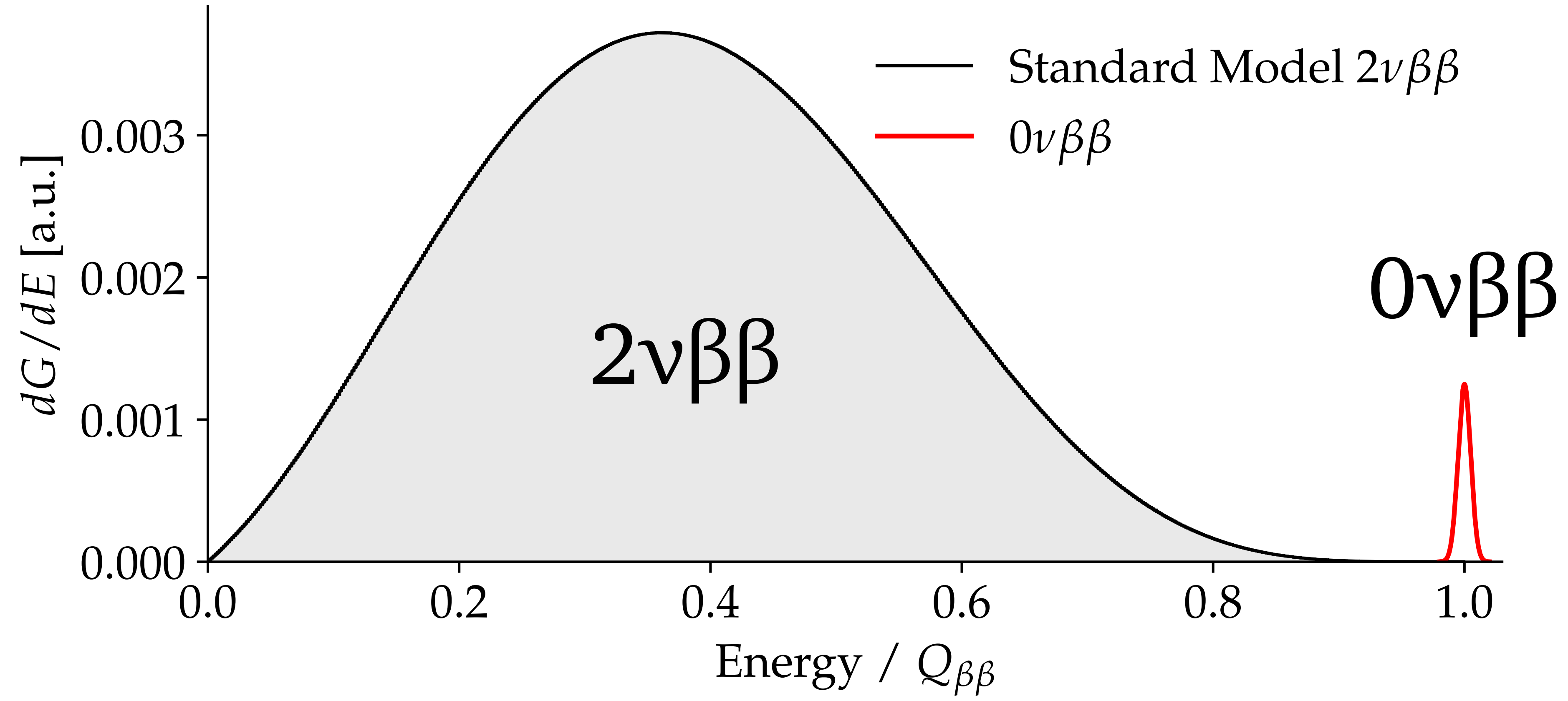


Double-β decays

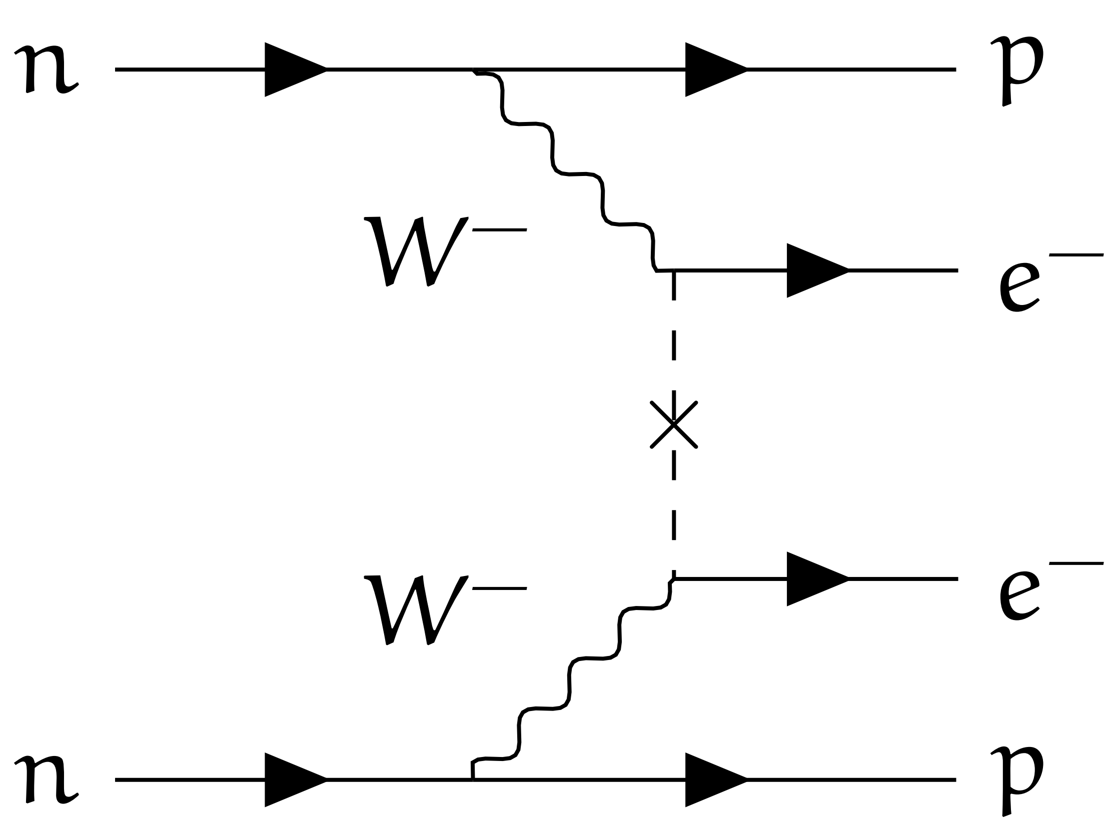
$$Q_{\beta\beta} = m_f - m_i$$

$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}$





$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$



Half-life from 10^{18} — 10^{21} yr

Isotope	$Q_{\beta\beta}$ [MeV]	$T^{2\nu}_{1/2}$ [yr]
^{48}Ca	4.263	$6.4^{+0.7}_{-0.6}$ (stat.)$^{+1.2}_{-0.9}$ (syst.) $\times 10^{19}$
^{76}Ge	2.039	2.022 ± 0.018 (stat.) ± 0.038 (syst.) $\times 10^{21}$
^{82}Se	2.998	8.69 ± 0.05 (stat.)$^{+0.09}_{-0.06}$ (syst.) $\times 10^{19}$
^{96}Zr	3.348	2.35 ± 0.14 (stat.) ± 0.16 (syst.) $\times 10^{19}$
^{100}Mo	3.035	7.07 ± 0.02 (stat.) ± 0.11 (syst.) $\times 10^{18}$
^{116}Cd	2.813	2.63 ± 0.01 (stat.)$^{+0.11}_{-0.13}$ (syst.) $\times 10^{19}$
^{130}Te	2.527	$8.76^{+0.09}_{-0.07}$ (stat.)$^{+0.14}_{-0.17}$ (syst.) $\times 10^{20}$
^{136}Xe	2.459	2.165 ± 0.016 (stat.) ± 0.059 (syst.) $\times 10^{21}$
^{150}Nd	3.371	9.34 ± 0.22 (stat.)$^{+0.62}_{-0.60}$ (syst.) $\times 10^{18}$

- Lepton number violating process not conserving the B-L symmetry of the SM
- Only practical way to probe that neutrinos are Majorana particles, validating the so called “see-saw” mechanism

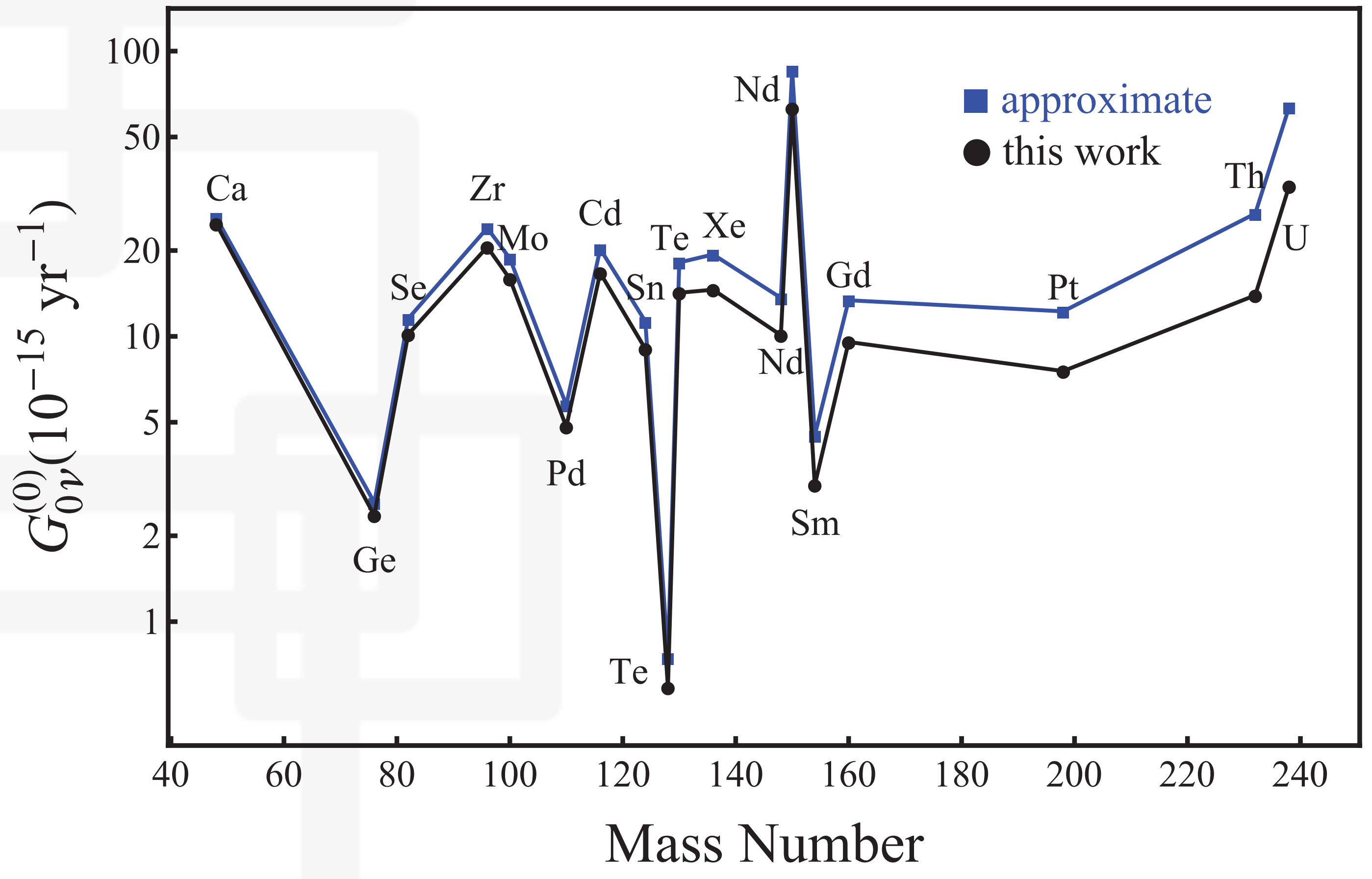
Isotope	$T^{0\nu}_{1/2}$ [y]
^{76}Ge	$> 1.8 \times 10^{26}$
^{82}Se	$> 4.6 \times 10^{24}$
^{100}Mo	$> 1.8 \times 10^{24}$
^{116}Cd	$> 2.2 \times 10^{23}$
^{130}Te	$> 2.2 \times 10^{25}$
^{136}Xe	$> 2.3 \times 10^{26}$

0νββ inverse half-life

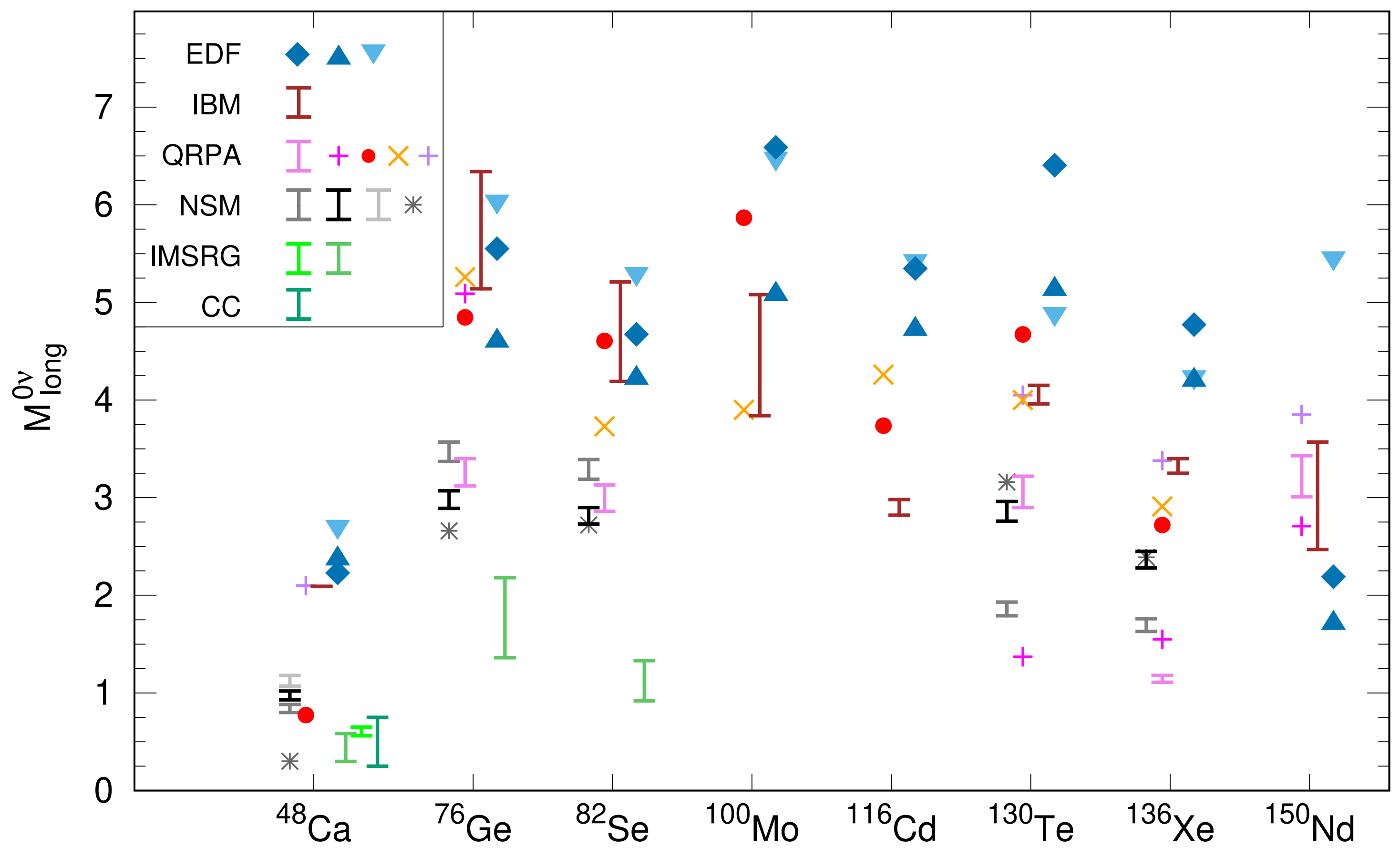
$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

Phase Space Factor

$$G_{0\nu} \propto Q^5_{\beta\beta}$$



Nuclear Matrix Element depends on nuclear models. Still a source of uncertainty



Effective Majorana Mass, the parameter of interest

$$m_{\beta\beta} = \left| \sum_{j=1}^{3} U^2_{ej} m_j \right| = \left| U^2_{e1} m_1 + U^2_{e2} e^{i\beta_1} m_2 + U^2_{e3} e^{i\beta_2} m_3 \right|$$

Isotope	$T^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [eV]
^{76}Ge	$> 1.8 \times 10^{26}$	$< (0.079 - 0.180)$
^{82}Se	$> 4.6 \times 10^{24}$	$< (0.263 - 0.545)$
^{100}Mo	$> 1.8 \times 10^{24}$	$< (0.280 - 0.490)$
^{116}Cd	$> 2.2 \times 10^{23}$	$< (1.0 - 1.7)$
^{130}Te	$> 2.2 \times 10^{25}$	$< (0.090 - 0.305)$
^{136}Xe	$> 2.3 \times 10^{26}$	$< (0.036 - 0.156)$

What about $2\nu\beta\beta$?

Can we use it to search for new physics?

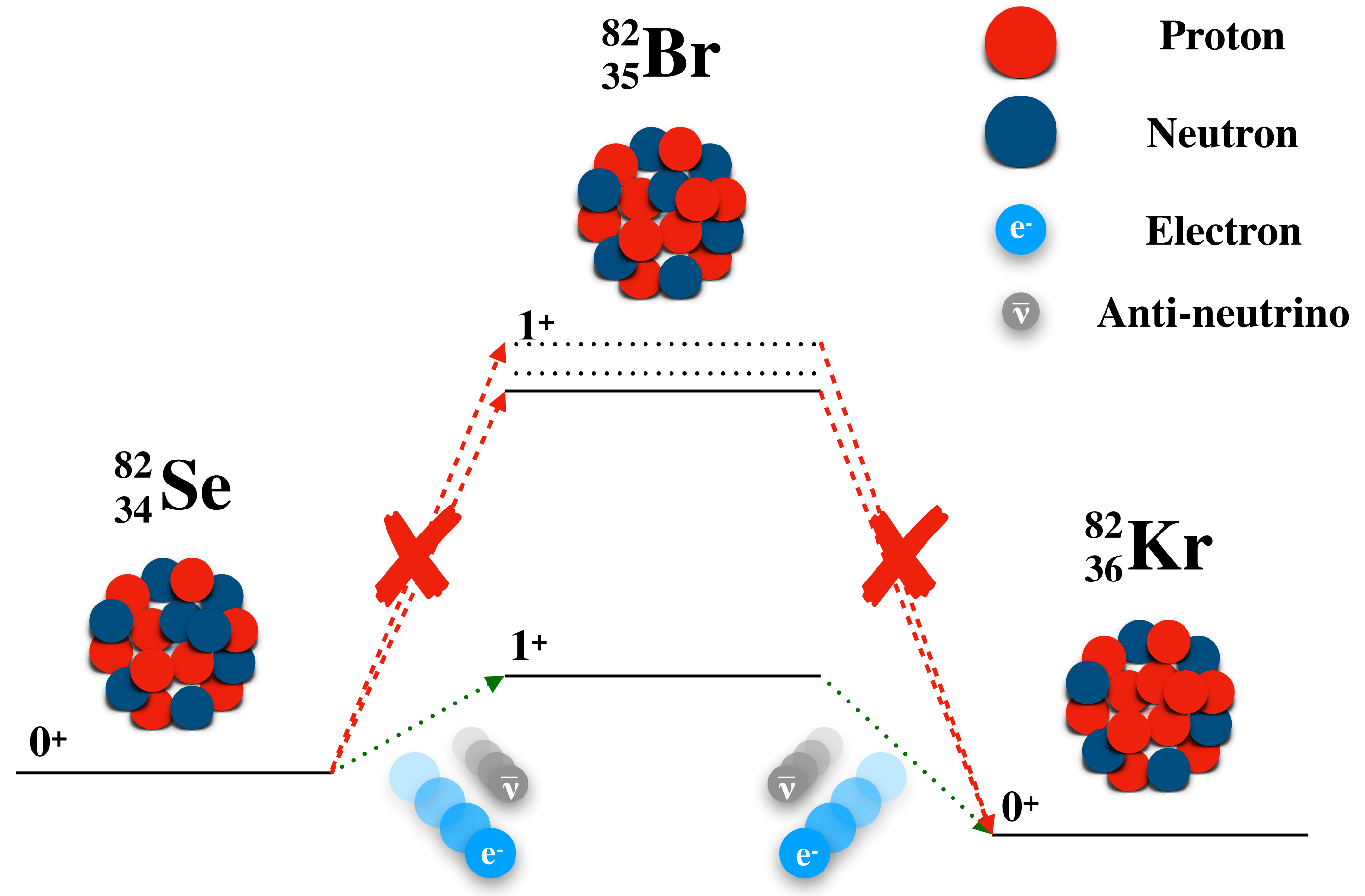
2νββ spectrum: HSD vs. SSD

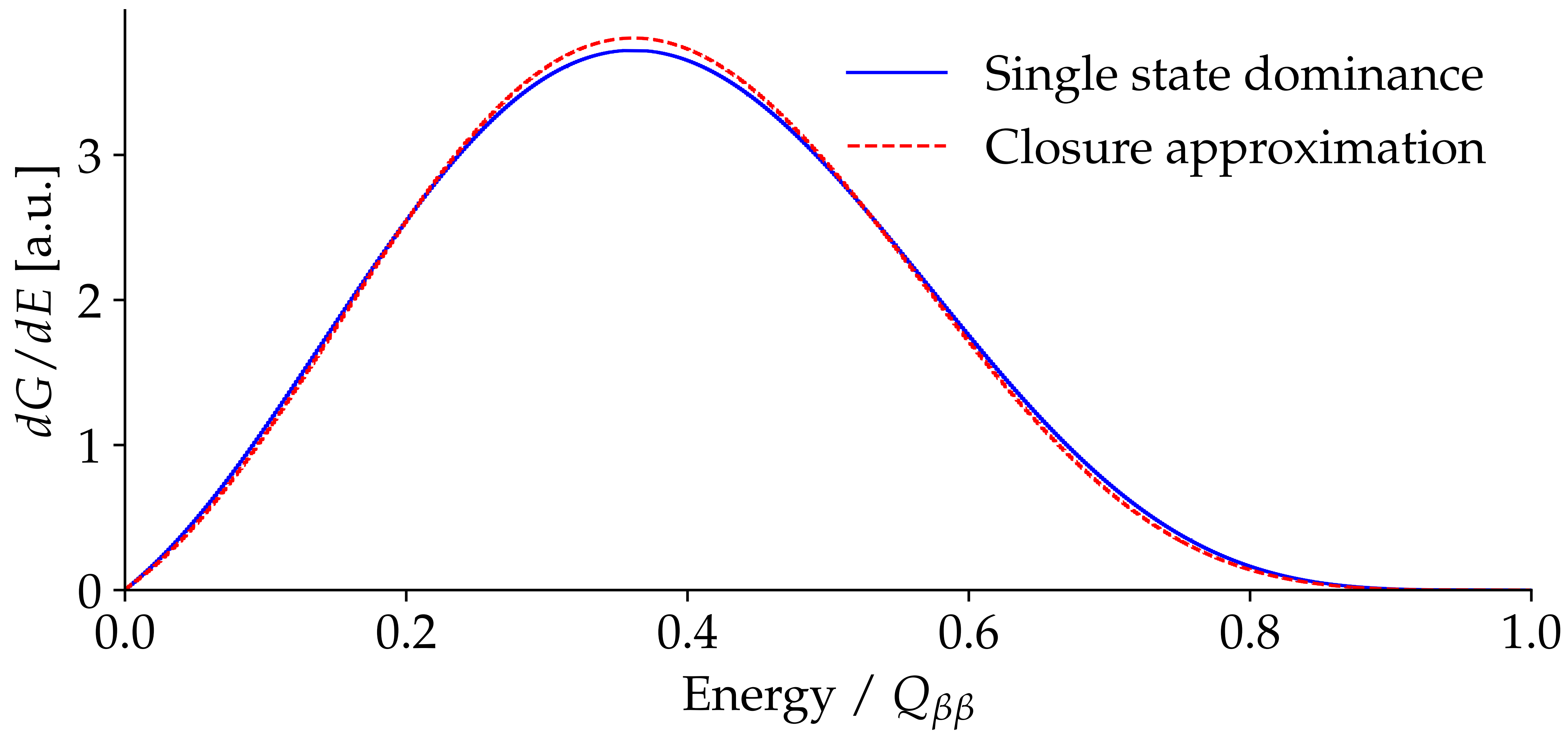
$$\frac{\Gamma_{2\nu}}{\ln 2} = [T_{1/2}^{2\nu}]^{-1} = G_{2\nu}|M_{2\nu}|^2$$

- $G_{2\nu}$ is the Phase Space Factor (PSF)
- $M_{2\nu}$ is the Nuclear Matrix Element (NME)

Assumptions on the energy of the intermediate nuclear state:

- Single-state dominance (SSD)→ ^{100}Mo and ^{82}Se
- Higher-state dominance (HSD) or Closure approximation (CA)





2νββ improved description

Instead of approximating SSD or HSD, the 2νββ PSF is written as a sum of components representing a Taylor expansion in terms of the lepton energies:

$$\Gamma_{2\nu} = \left|M_1^{2\nu}\right|^2 \left\{ G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu} + \frac{1}{3}\left(\xi_{31}^{2\nu}\right)^2 G_{22}^{2\nu} + \left[\frac{1}{3}\left(\xi_{31}^{2\nu}\right)^2 + \xi_{51}^{2\nu}\right] G_4^{2\nu} \right\}$$

$\xi_{31}^{2\nu}$ and $\xi_{51}^{2\nu}$ determine the shape of the spectrum

When $\xi_{31}^{2\nu}, \xi_{51}^{2\nu} = 0 \rightarrow$ HSD

Or $\xi_{31}^{2\nu}, \xi_{51}^{2\nu} \neq 0 \rightarrow$ SSD (the values depend on the nucleus)

Instead of making assumptions, the values of $\xi_{31}^{2\nu}, \xi_{51}^{2\nu}$ can be measured

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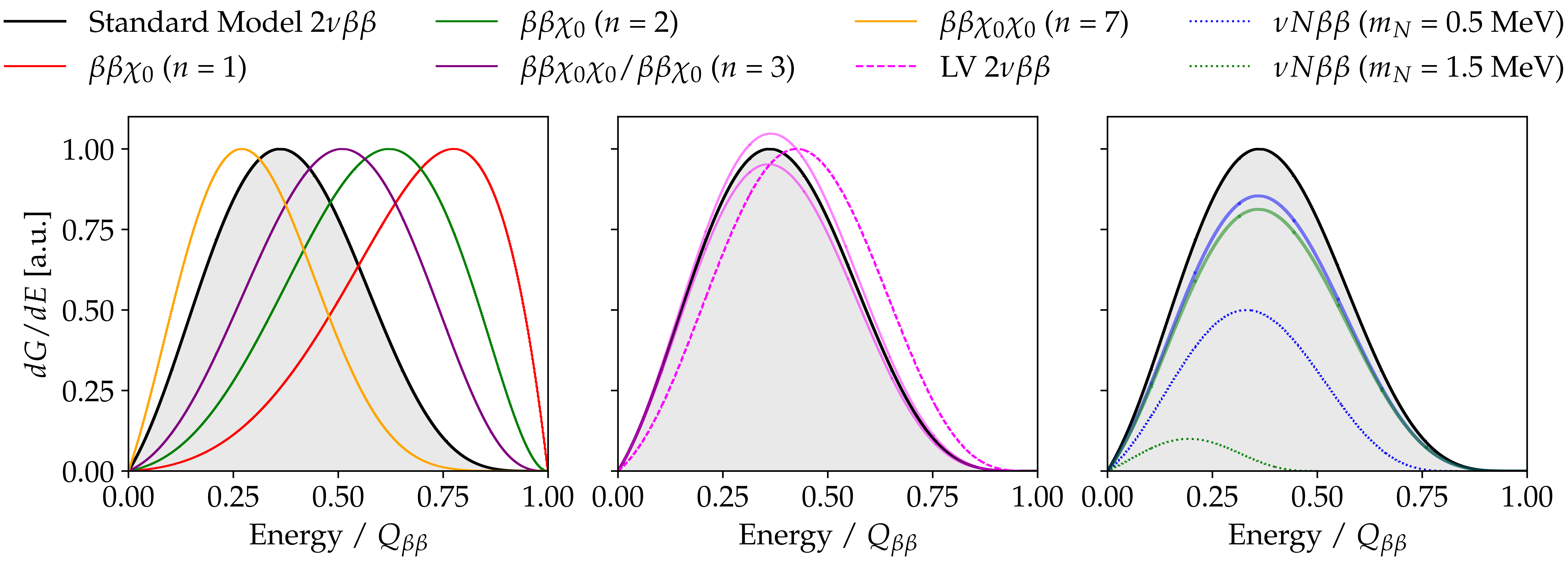
Exotic double-β decays



Majoron emitting modes

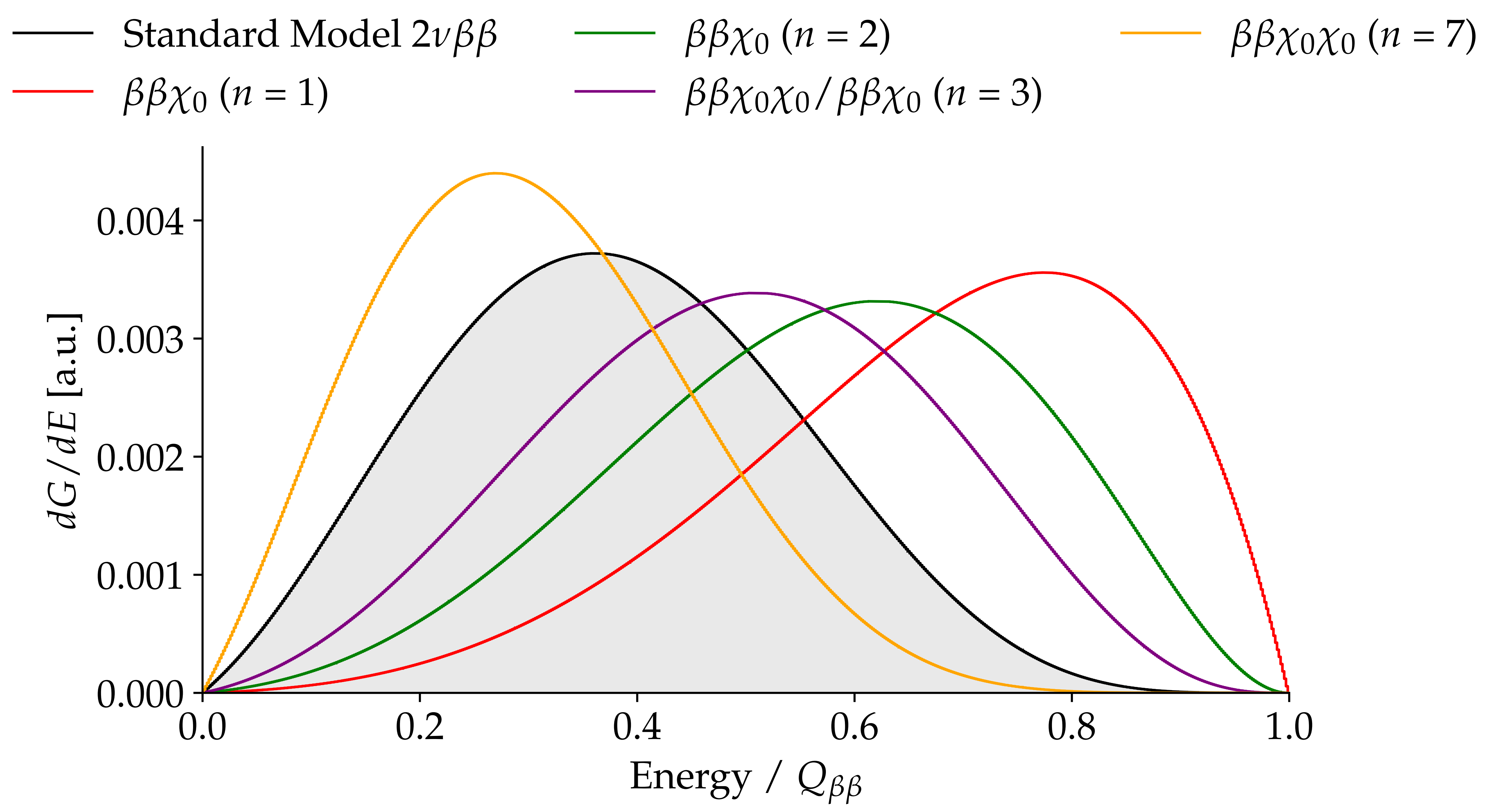
Majorons are massless bosons resulting from the spontaneous B−L symmetry breaking in the low-energy regime.

One (**ββχ₀**) or two (**ββχ₀χ₀**) Majorons can be emitted according to the different models

The parameter of interest is the neutrino-Majoron coupling:

$$[T^{1/2}_{0\nu M}]^{-1} = G_{0\nu M} \left| \left\langle g^{M}_{ee} \right\rangle \right|^{2m} \left| M_{0\nu M} \right|^{2}$$

$$\frac{d\Gamma}{dT} \propto \left(Q_{\beta\beta} - T \right)^{n}$$



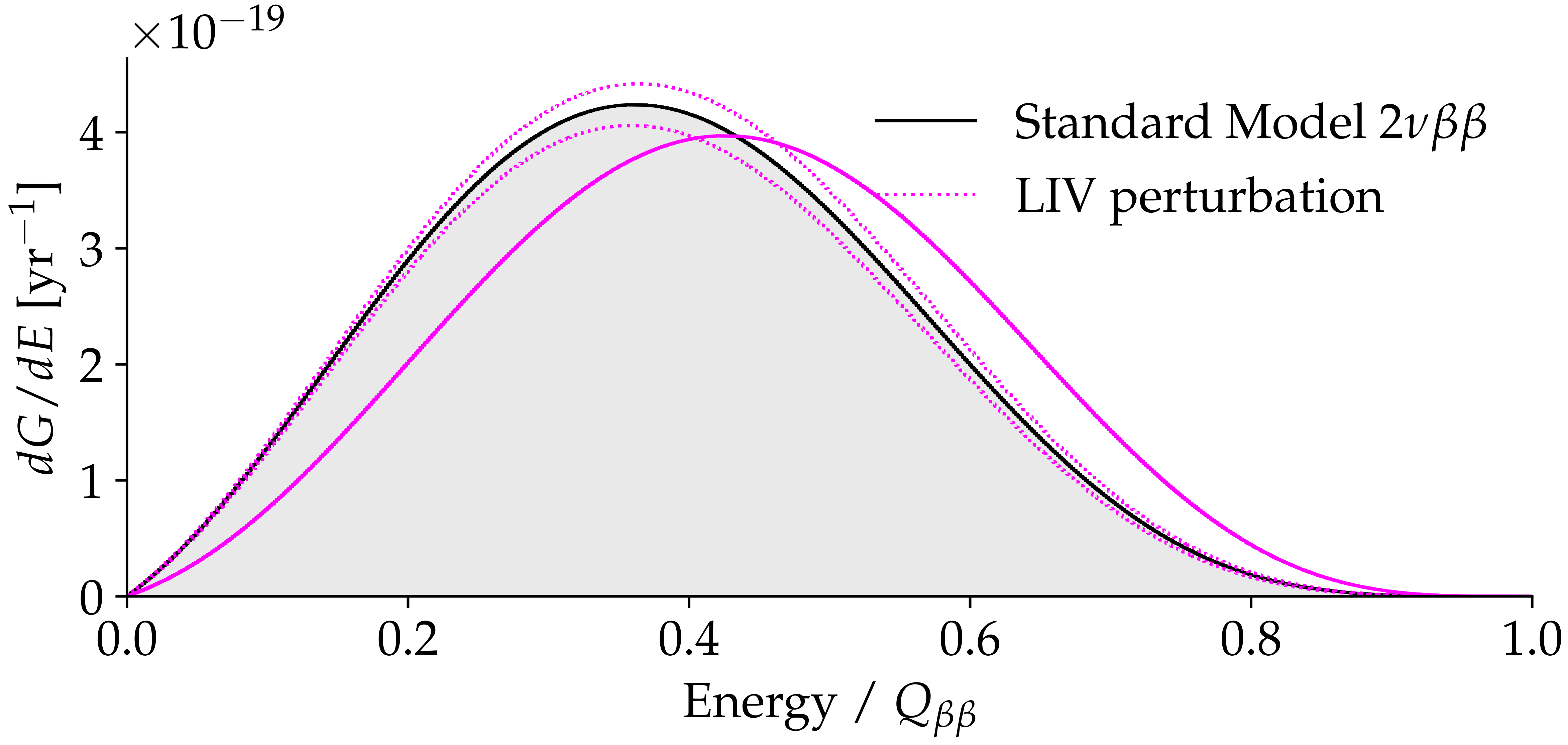
Lorentz violating 2νββ

The Standard Model Extension predict the existence of Lorentz Violating (LV) fields.

In the neutrino sector it can modify the decay rate of 2νββ

$$\Gamma = \Gamma_{SM} + 10 \cdot \dot{a}_{of}^{(3)} \cdot \Gamma_{LV}$$

$\dot{a}_{of}^{(3)}$ is the *countershaded operator* and determines the strength of the Lorentz violating effect.



Isotope	Limit on $\dot{a}_{of}^{(3)}$ [GeV]
^{76}Ge	$(-2.7 < \dot{a}_{of}^{(3)} < 6.2) \cdot 10^{-6}$
^{82}Se	$\dot{a}_{of}^{(3)} < 4.1 \cdot 10^{-6}$
^{136}Xe	$-2.65 \cdot 10^{-5} < \dot{a}_{of}^{(3)} < 7.6 \cdot 10^{-6}$
^{116}Cd	$\dot{a}_{of}^{(3)} < 4.0 \cdot 10^{-6}$
^{100}Mo	$(-4.2 < \dot{a}_{of}^{(3)} < 3.5) \cdot 10^{-7}$
^{3}H	$\lvert\dot{a}_{of}^{(3)}\rvert < 3.0 \cdot 10^{-8}$

Sterile neutrino emission

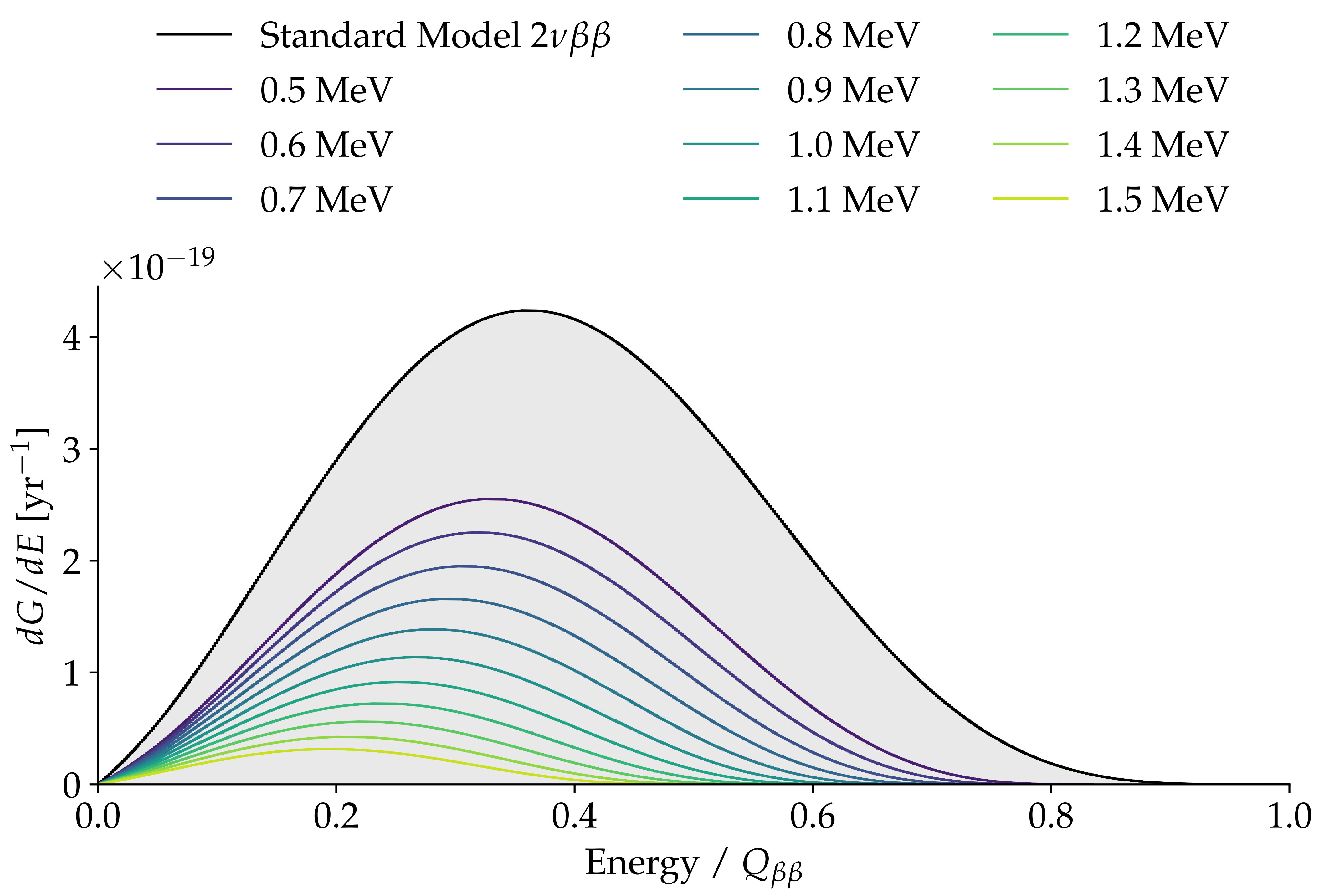
If the sterile neutrino N has a mass $m_N < Q_{\beta\beta}$, it can be emitted instead of an antineutrinos in the 2νββ (νNββ):

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \bar{\nu} + N$$

The effect on the total decay rate is:

$$\Gamma = \cos^4\theta\Gamma_{SM} + 2\cos^2\theta\sin^2\theta\Gamma_{\nu N}$$

Where $\sin^2\theta$ is called active-sterile mixing strength



Outline

1. Double-β decays
2. Scintillating cryogenic calorimeters
3. CUPID-0 combined background model
4. CUPID-Mo BSM studies
5. CUPID sensitivity
6. Conclusion and outlook

Plenty of experimental techniques

Xenon time projection chambers
^{136}Xe
[EXO-200, nEXO, NEXT]

HPGe semiconductor detectors
^{76}Ge
[GERDA, Majorana Demonstrator, LEGEND]

Large liquide scintillators
^{136}Xe
[KamLAND-Zen, SNO+]

$0\nu\beta\beta$

Cryogenic calorimeters
^{130}Te, ^{100}Mo, ^{82}Se
[CUORE, CUPID, AMoRE]

Tracking calorimeters
^{100}Mo, ^{82}Se + others
[NEMO-3, SuperNEMO]

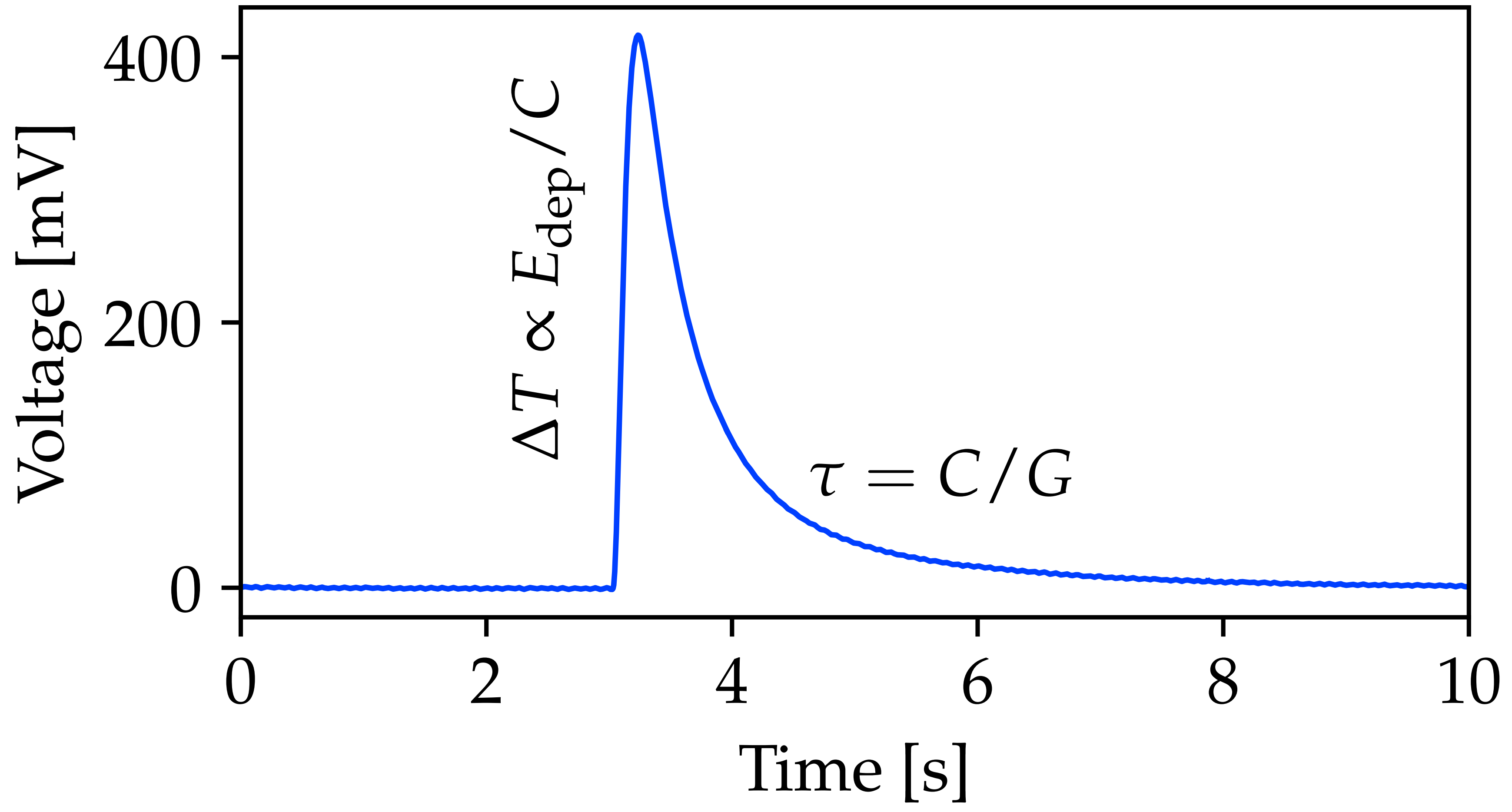
+ many others

Cryogenic calorimeters for 0νββ searches

Highly sensitive calorimeters operated at cryogenic temperature (∼10 mK)

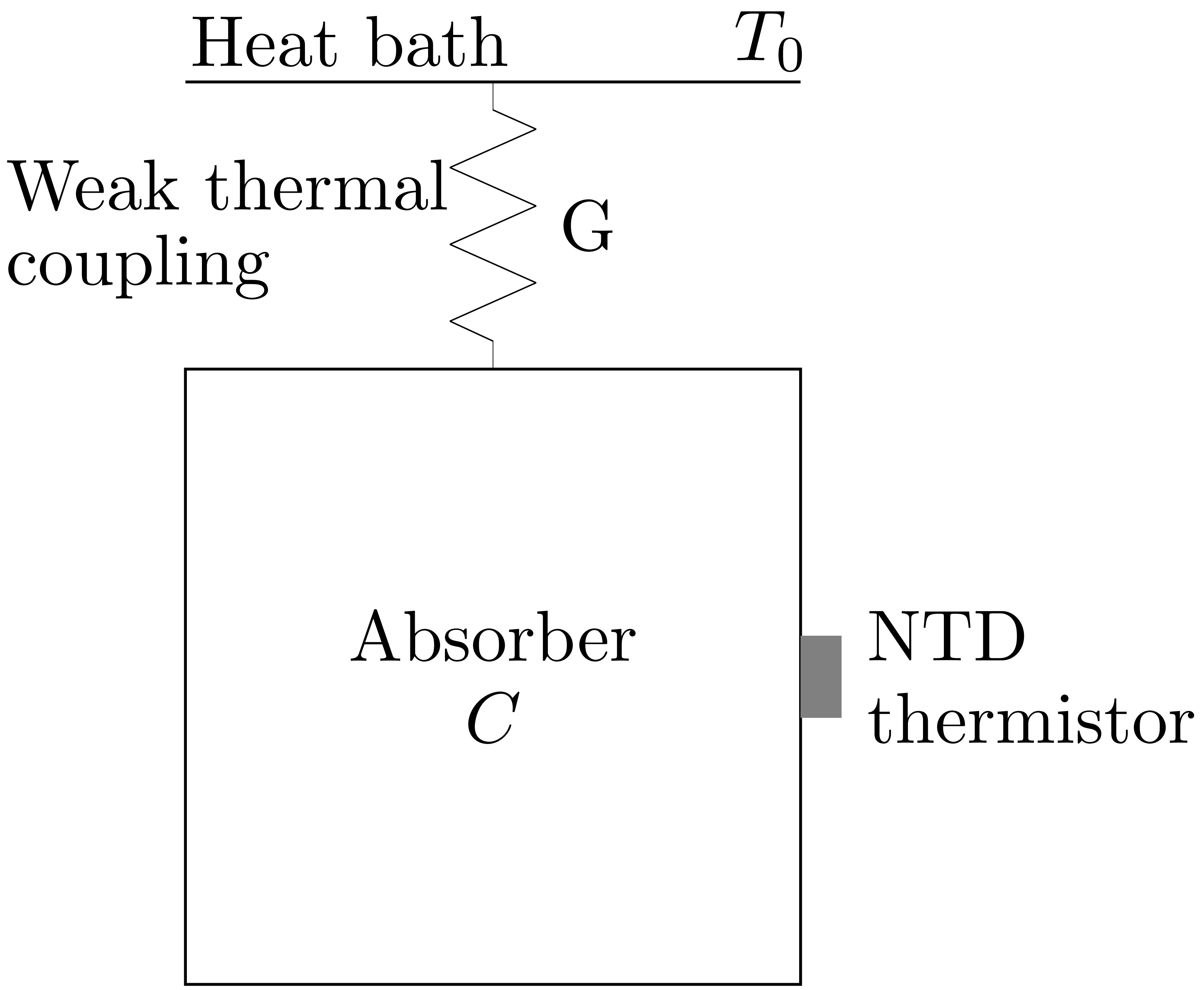
$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau}\right) \quad \text{where} \quad \tau = \frac{C}{G}$$

From Debye law $C \propto T^3$



$C = 10^{-9} J/K$

$\Delta T = 0.1 \frac{\text{mK}}{\text{MeV}}$ at 10mK



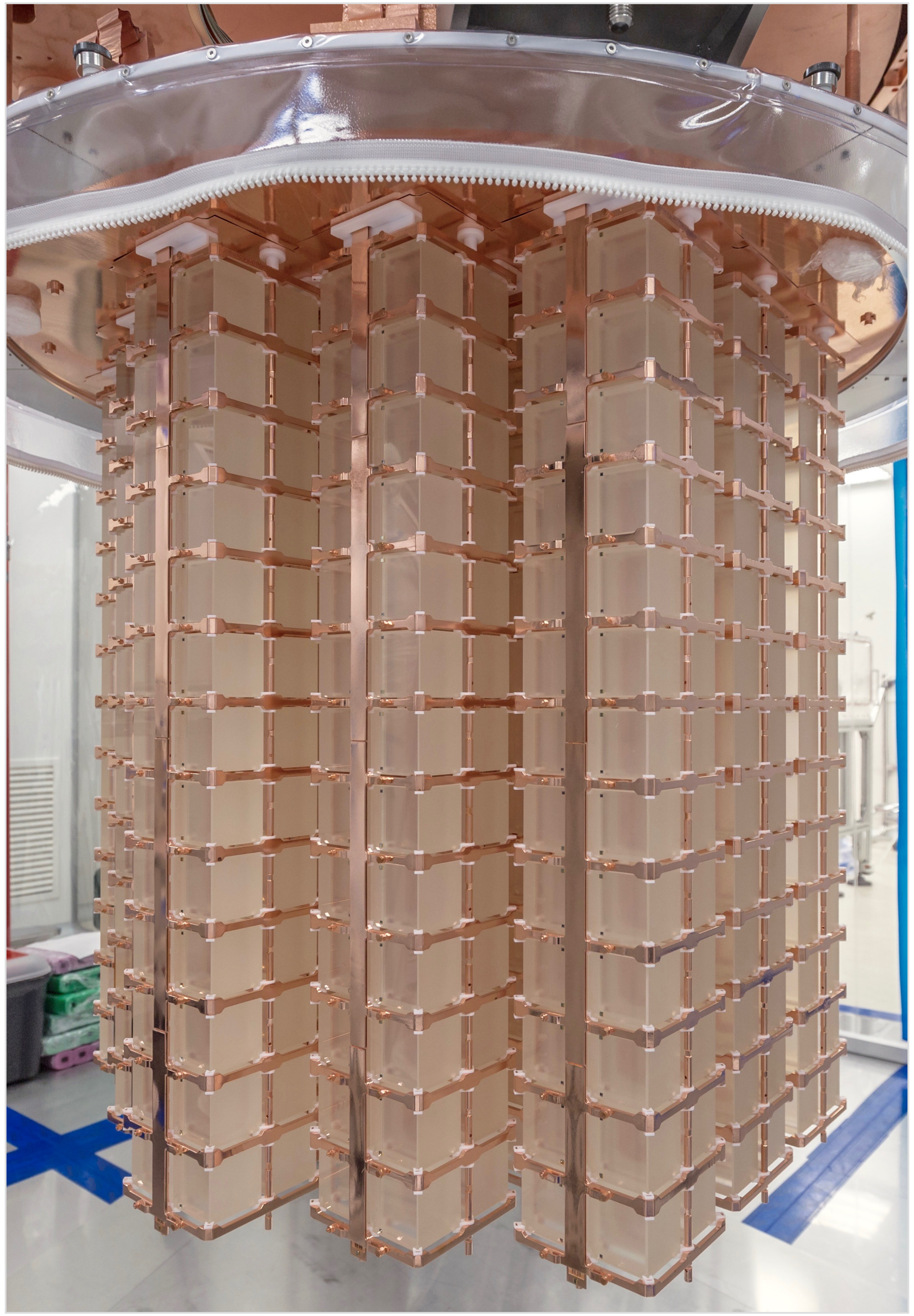
C = heat capacity

G = thermal conductance

Performances

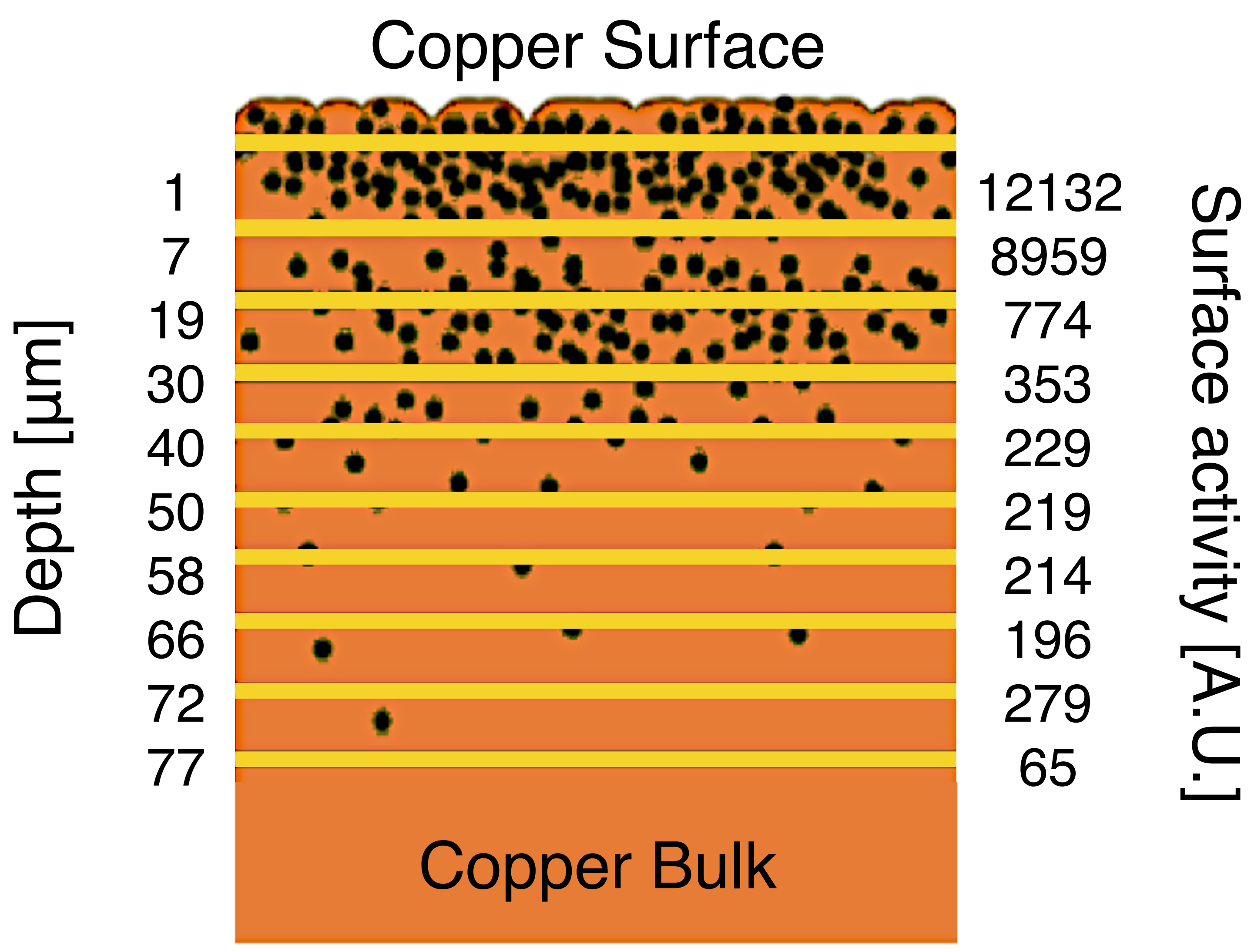
- **Excellent energy resolution** (<1% at 3 MeV)
- **High detection efficiency**, the emitting isotope is embedded in the detector
- Possibility to study **different ββ emitters** (and take those with higher $Q_{\beta\beta}$)
- Radio-pure materials
- Mass scalability

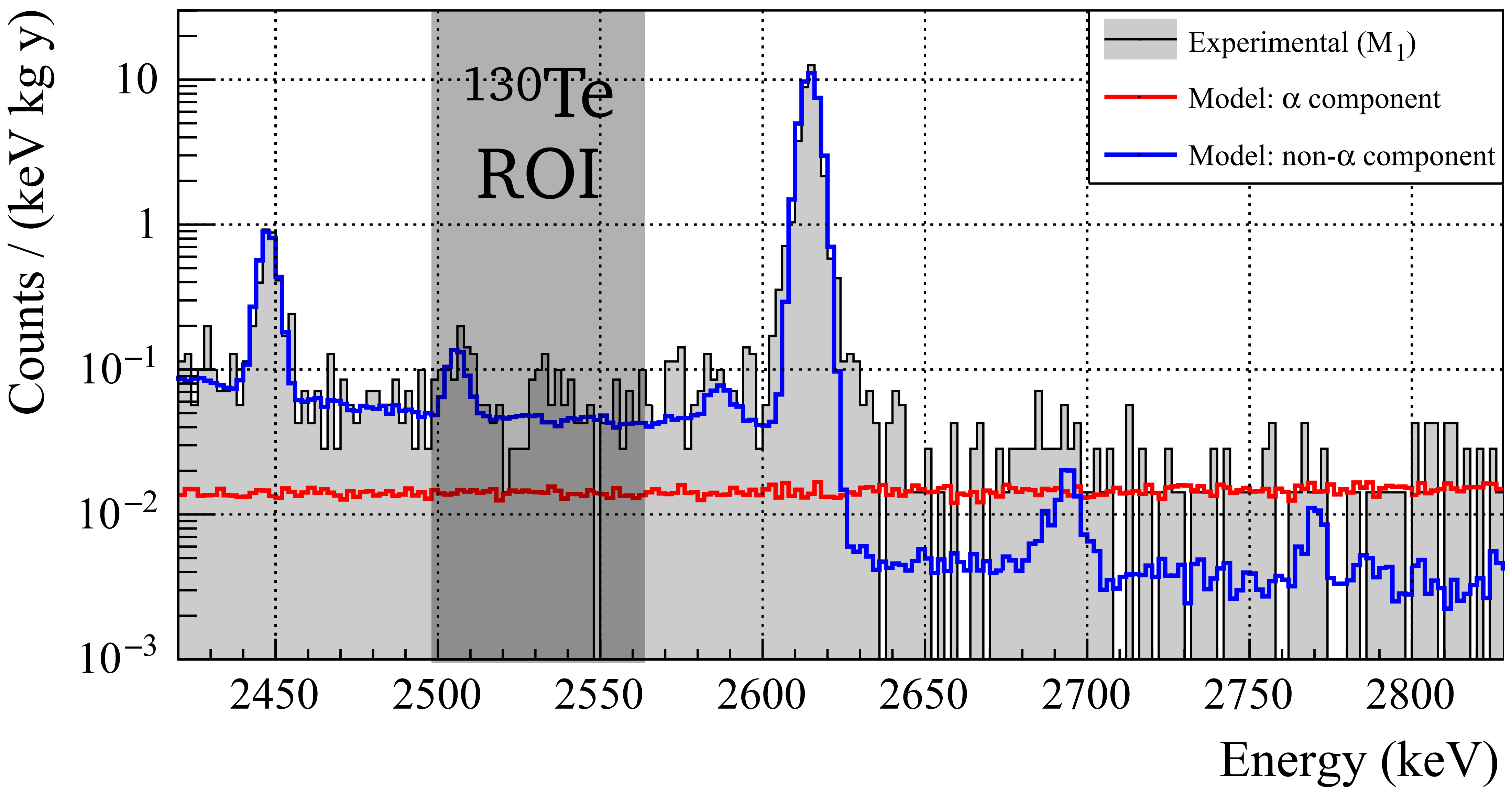
CUORE experiment



Degraded α-particles

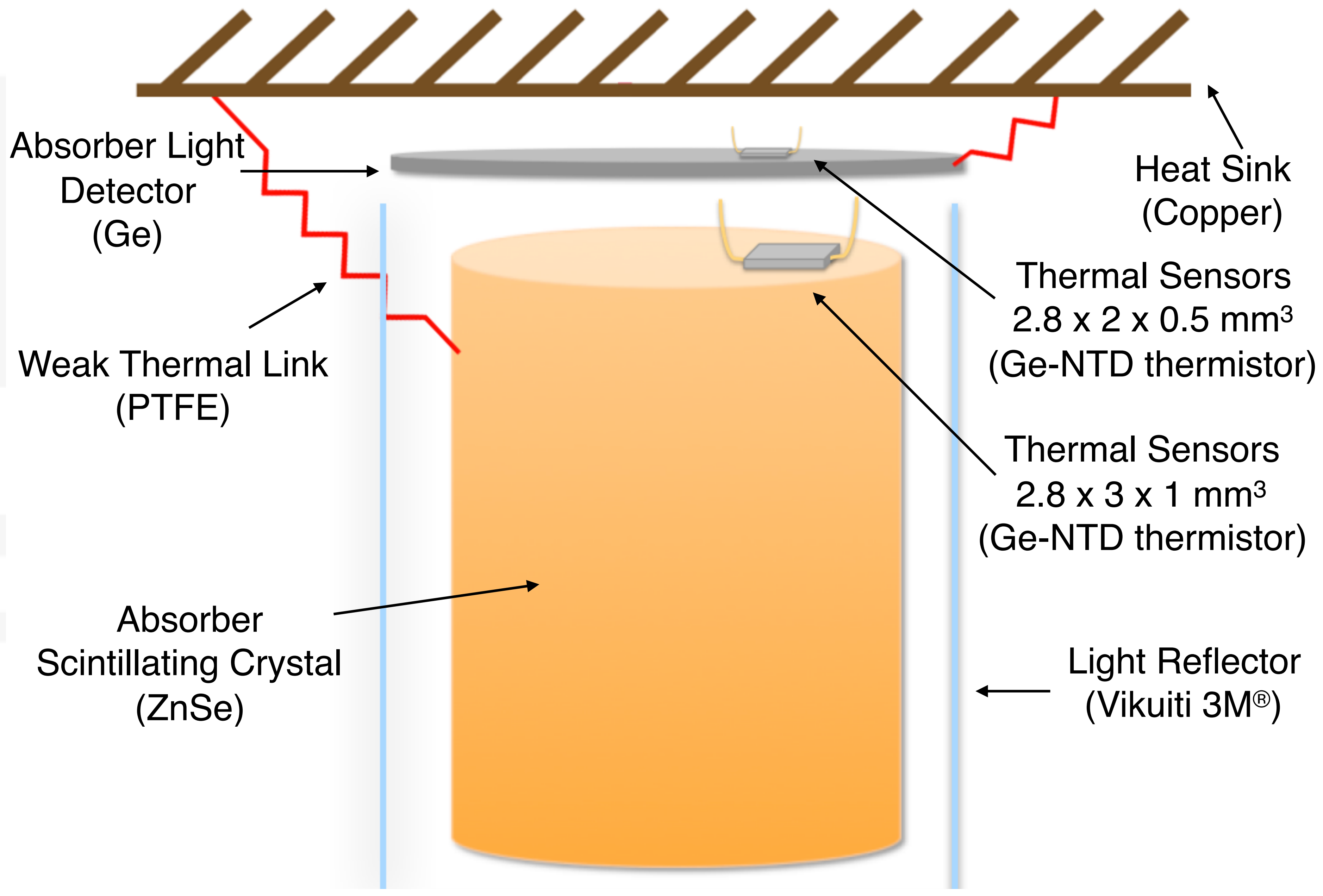
- A significant background come from degraded α-particles from contamination in passive material
- Needs for a technique able to **distinguish α-particles from β/γ radiation**
- Further background reduction with high Q-value isotopes

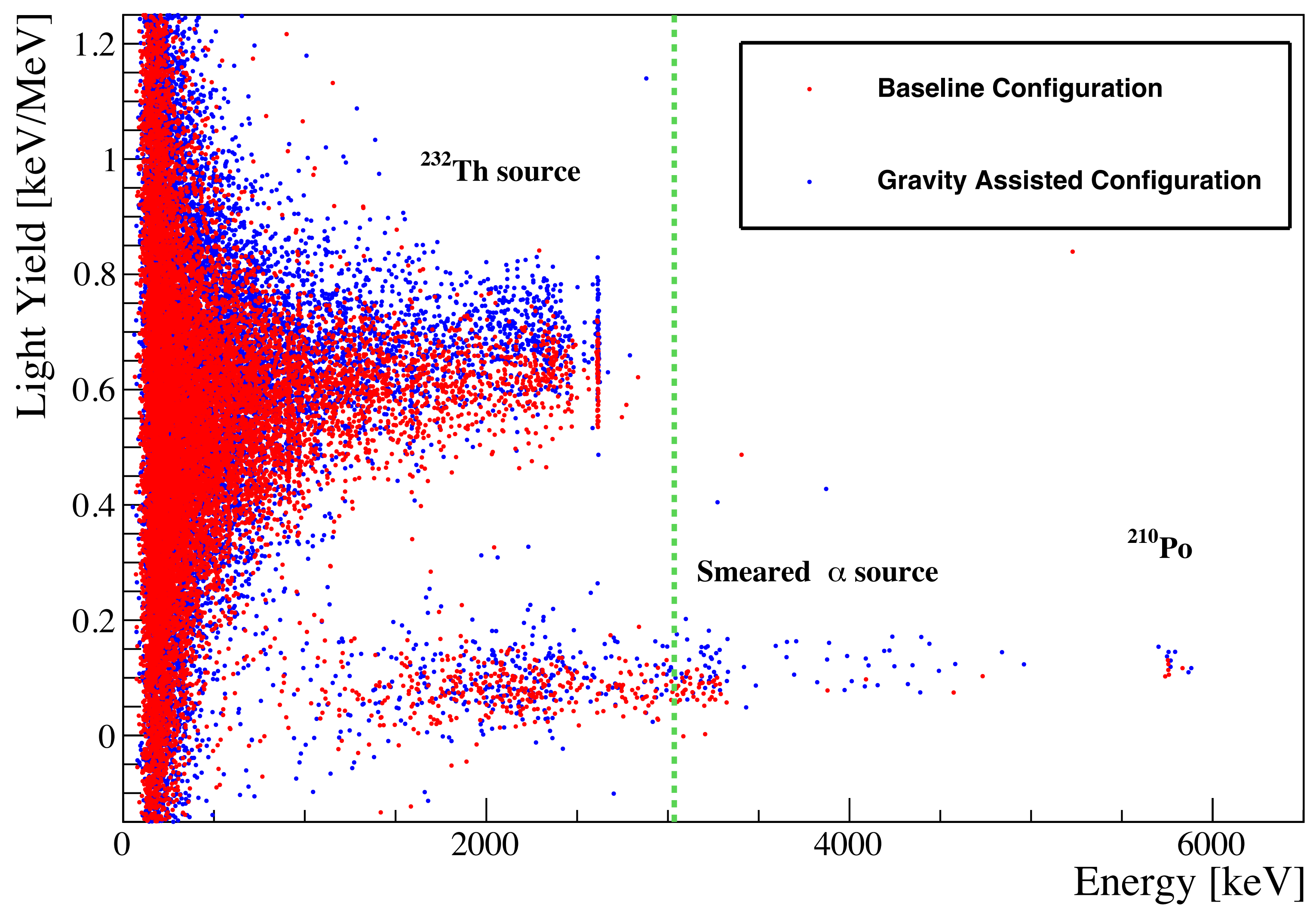


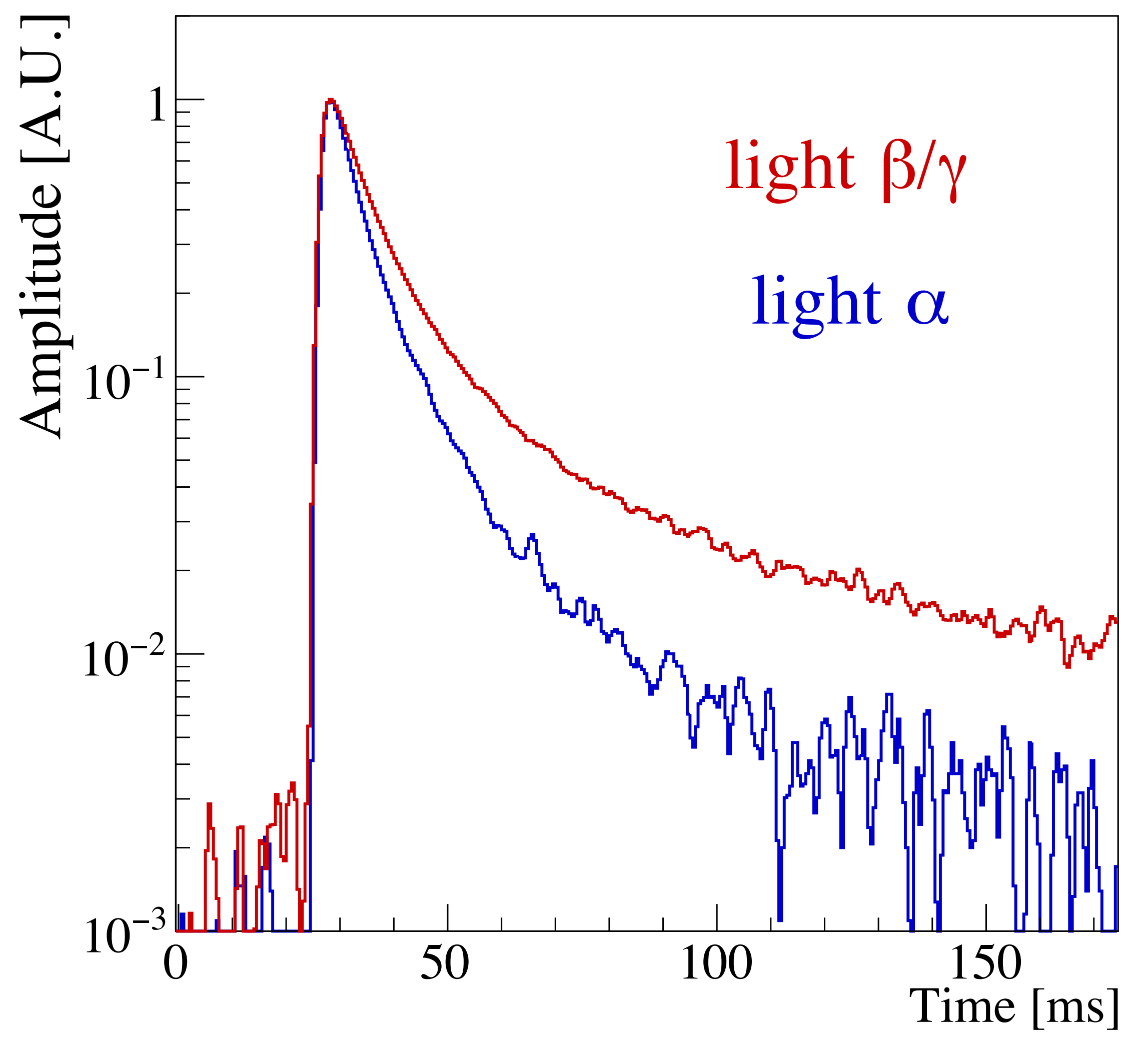


Scintillating cryogenic calorimeters

- Absorber: scintillating crystals at cryogenic temperatures (ZnSe, Li_2MoO_4, etc…)
- Light Detector: thin Germanium wafer coupled to the absorber working as a cryogenic calorimeter
- The particle identification can be done with by detecting the amount of light emitted (Light Yield) or the pulse shape of light signals

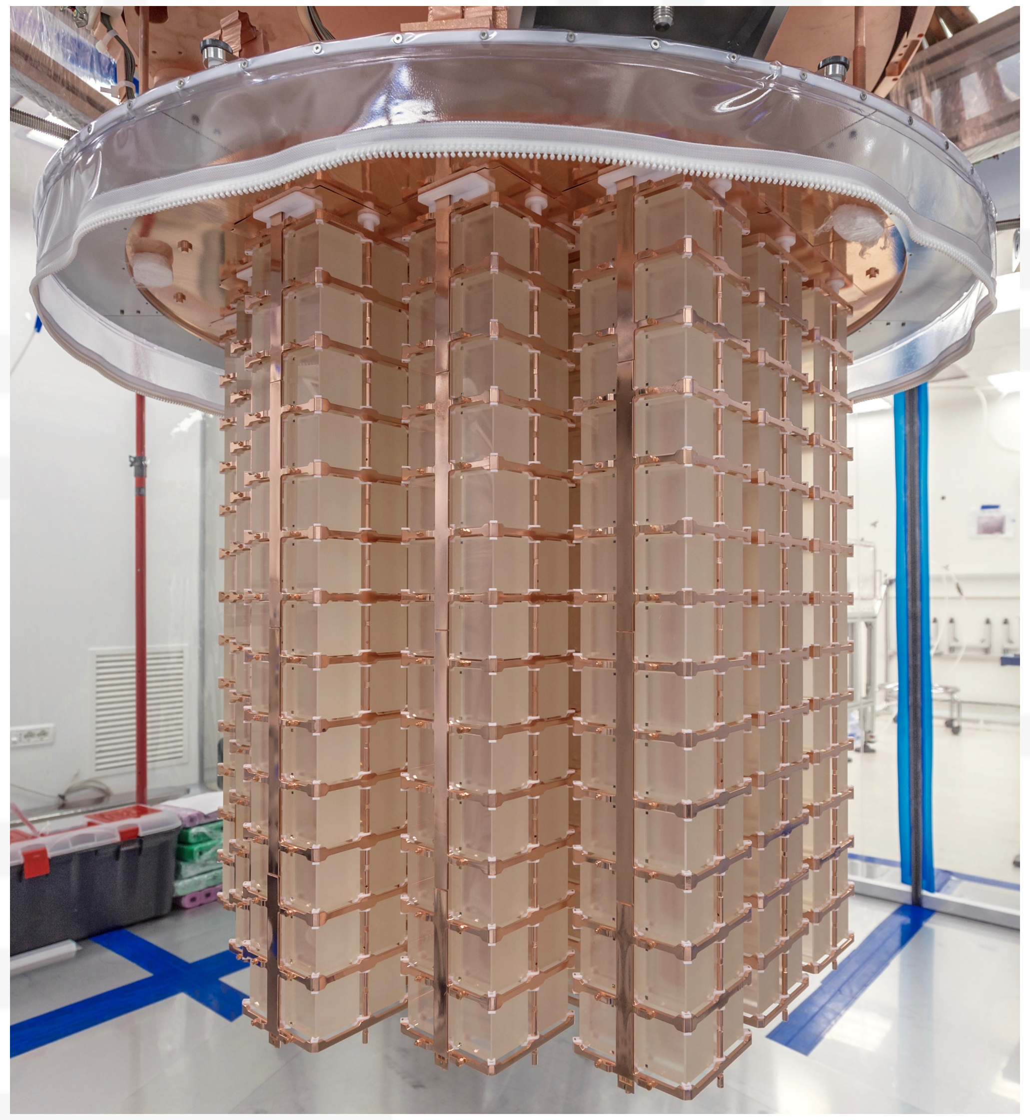




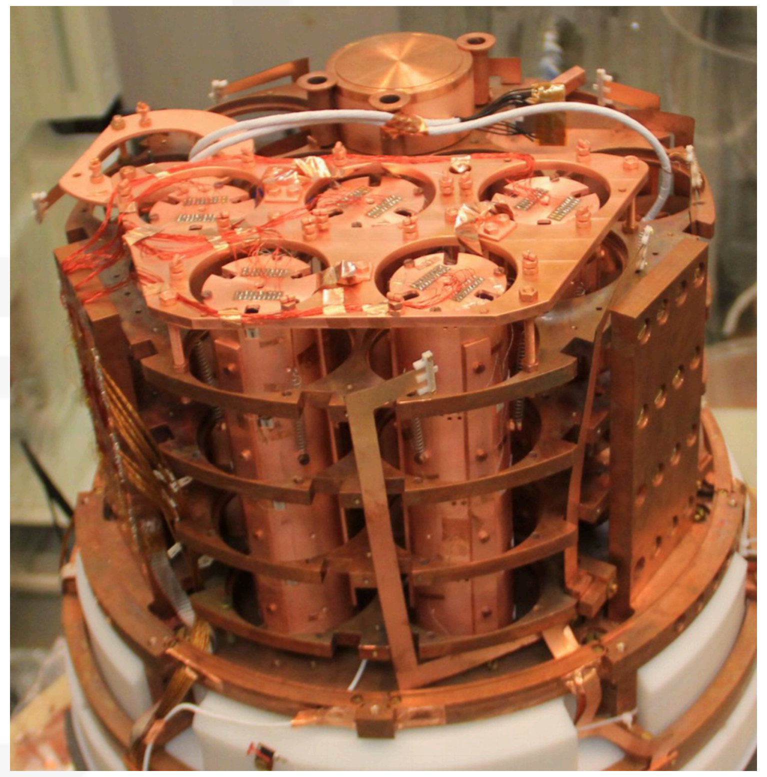


From CUORE to CUPID

CUORE



- 988 TeO_2 crystals
- 206 kg of ^{130}Te
- Largest cryogenic facility in the world
- **BI ~ 1.5 × 10^{-2} ckky**
- No particle identification



CUPID-Mo

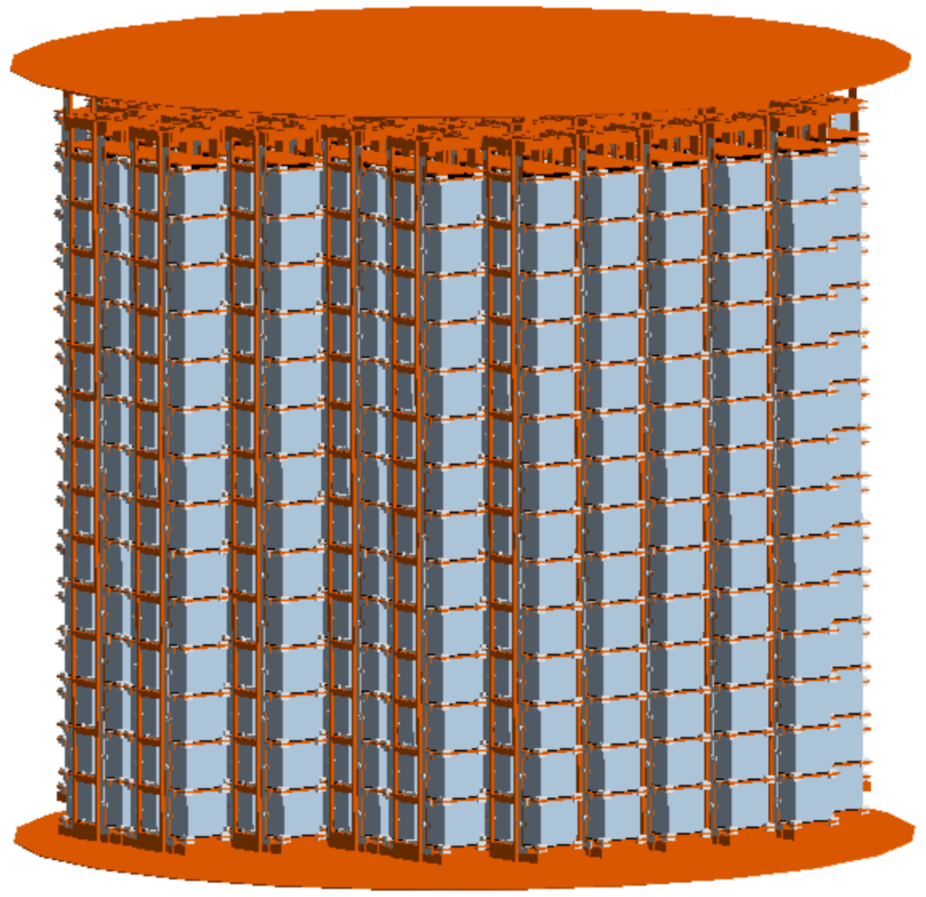
- 20 Li_2MoO_4 crystals
- 20 Ge light detectors
- 2.3 kg of ^{100}Mo
- **BI ~ 3.9×10^{-3} ckky**

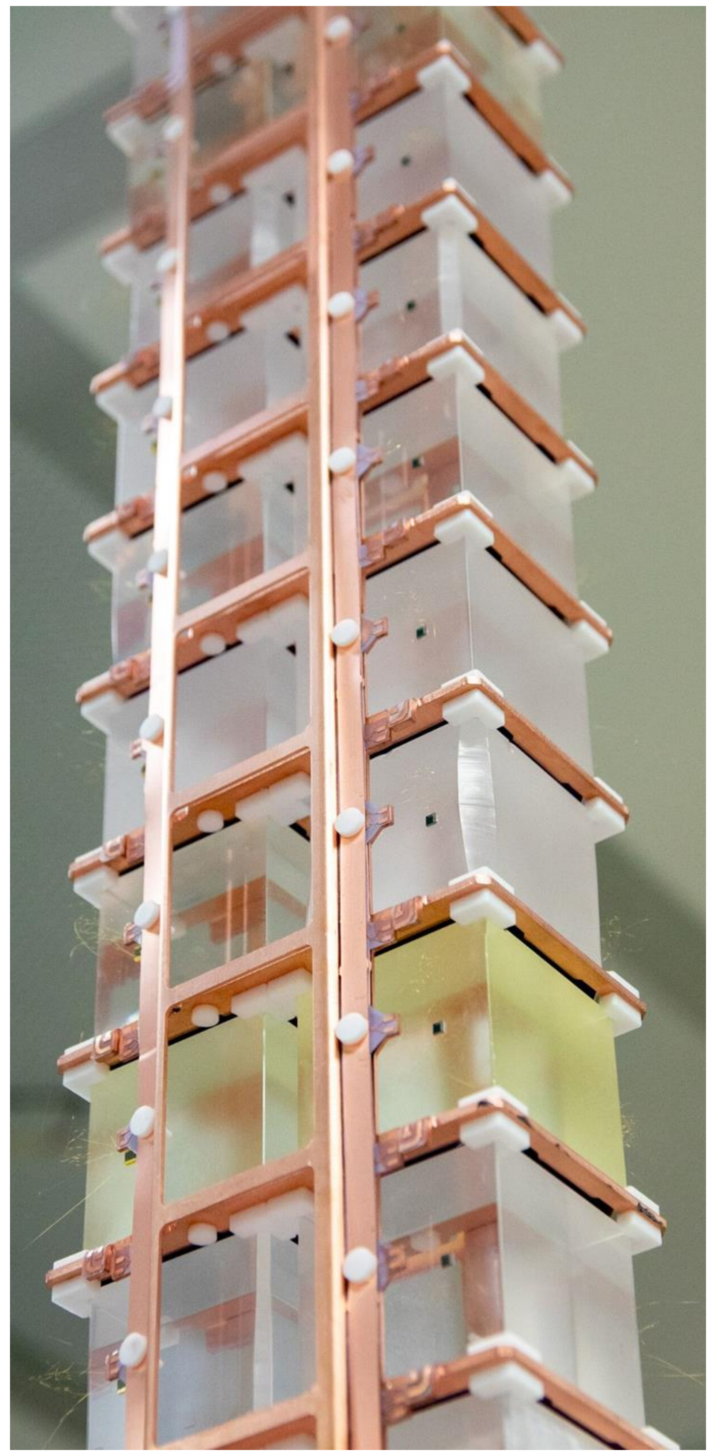
CUPID-0

- 26 ZnSe crystals
- 31 Ge light detectors
- 5.2 kg of ^{82}Se
- **BI ~ 4.0×10^{-3} ckky**

CUPID - next generation

- 1596 Li_2MoO_4 crystals
- 1710 Ge light detectors
- 240 kg of ^{100}Mo
- **Target BI ~ 10^{-4} ckky**
- Re-use of CUORE cryogenic facility





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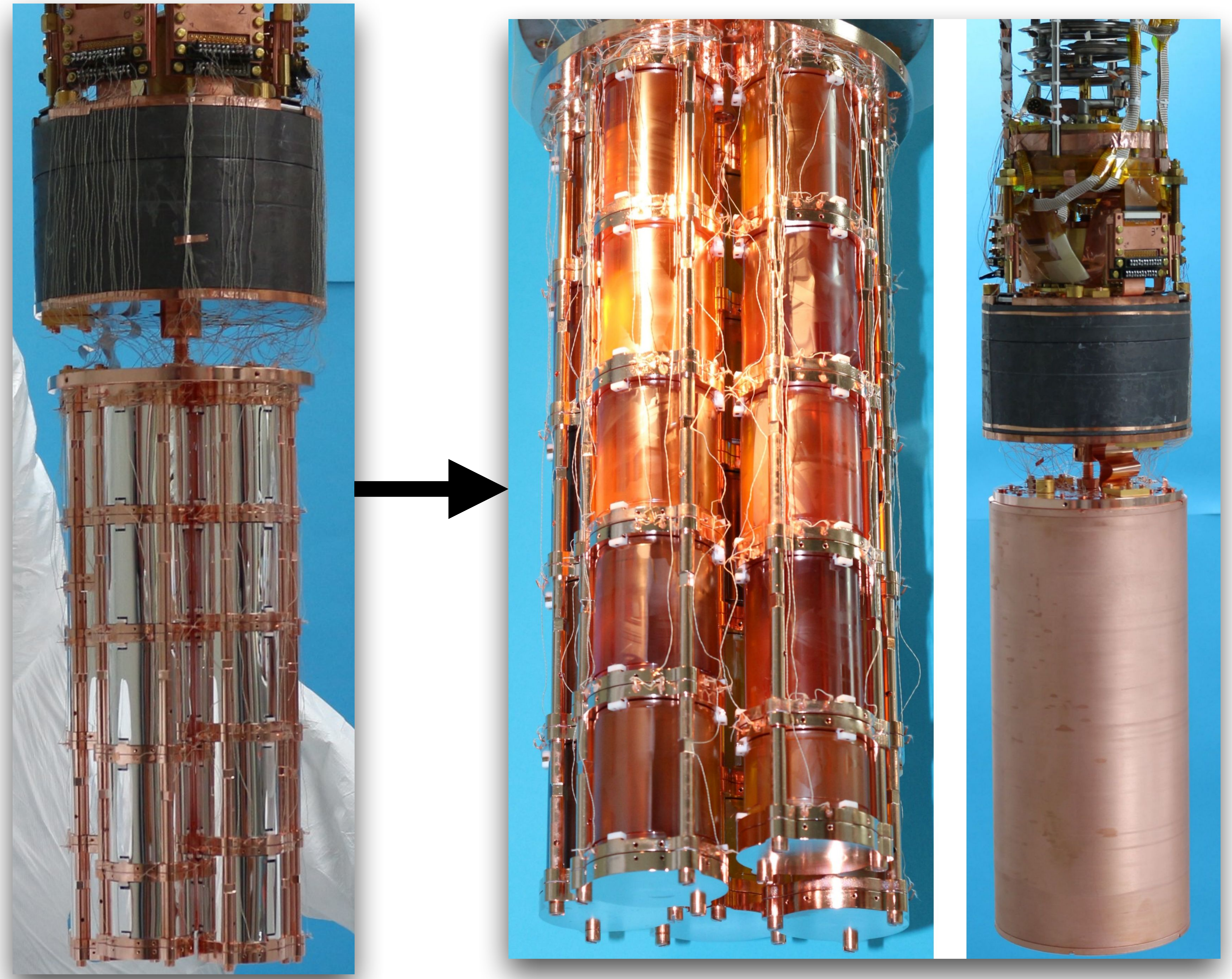
The CUPID-0 detector

- 24 ZnSe crystals enriched at >95% of ^{82}Se + two natural ones + 31 Ge Light detectors
- Located at LNGS
- $Q_{\beta\beta}(^{82}Se)$ = ~2998 keV → low background region
- NTD-Ge thermistors as temperature sensors
- Total mass: 10.5 kg ZnSe

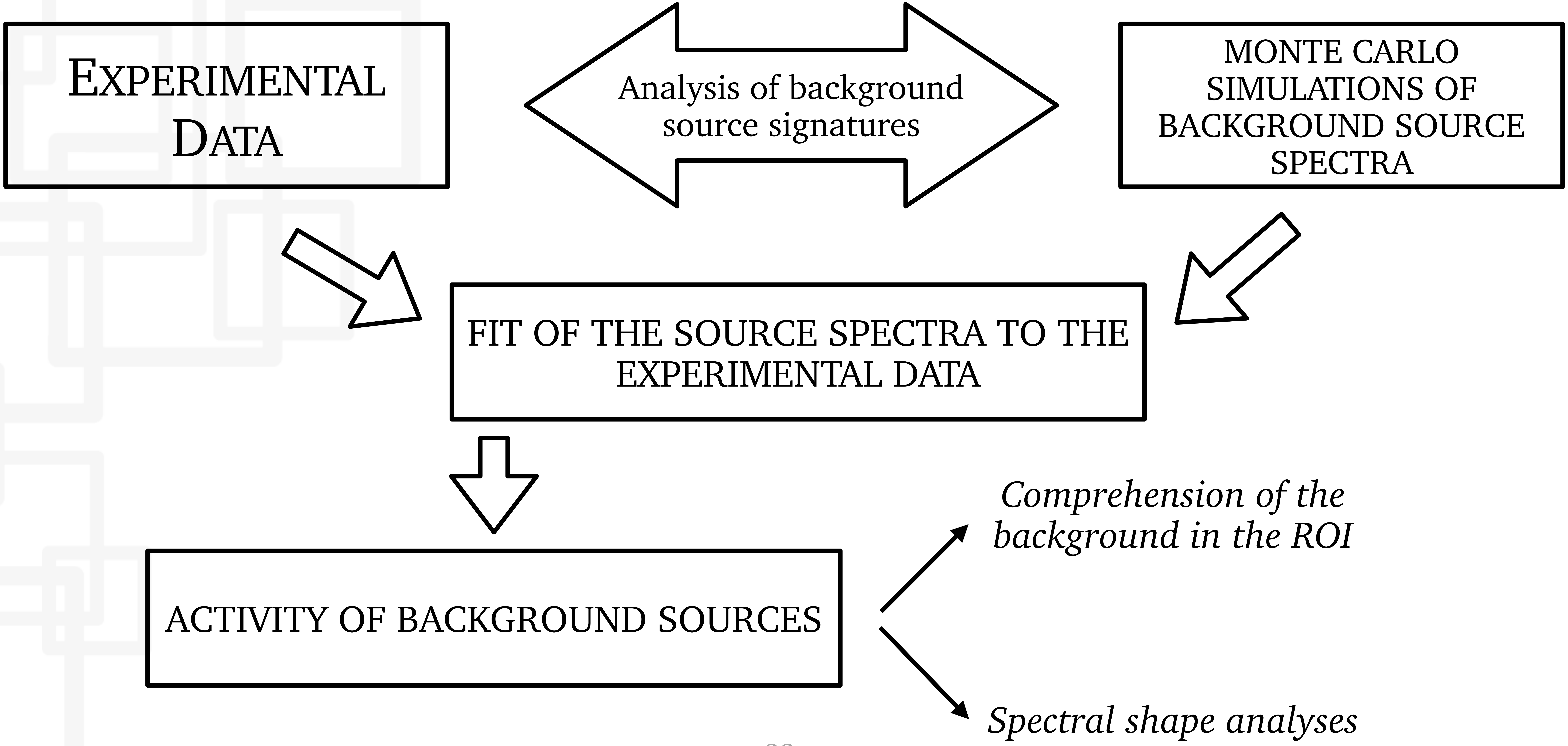
In Jan 2019 the CUPID-0 collaboration has made an upgrade of the detector, starting the so-called "Phase II" of the experiment.

Phase I
9.99 kg×y

Phase II
5.74 kg×y

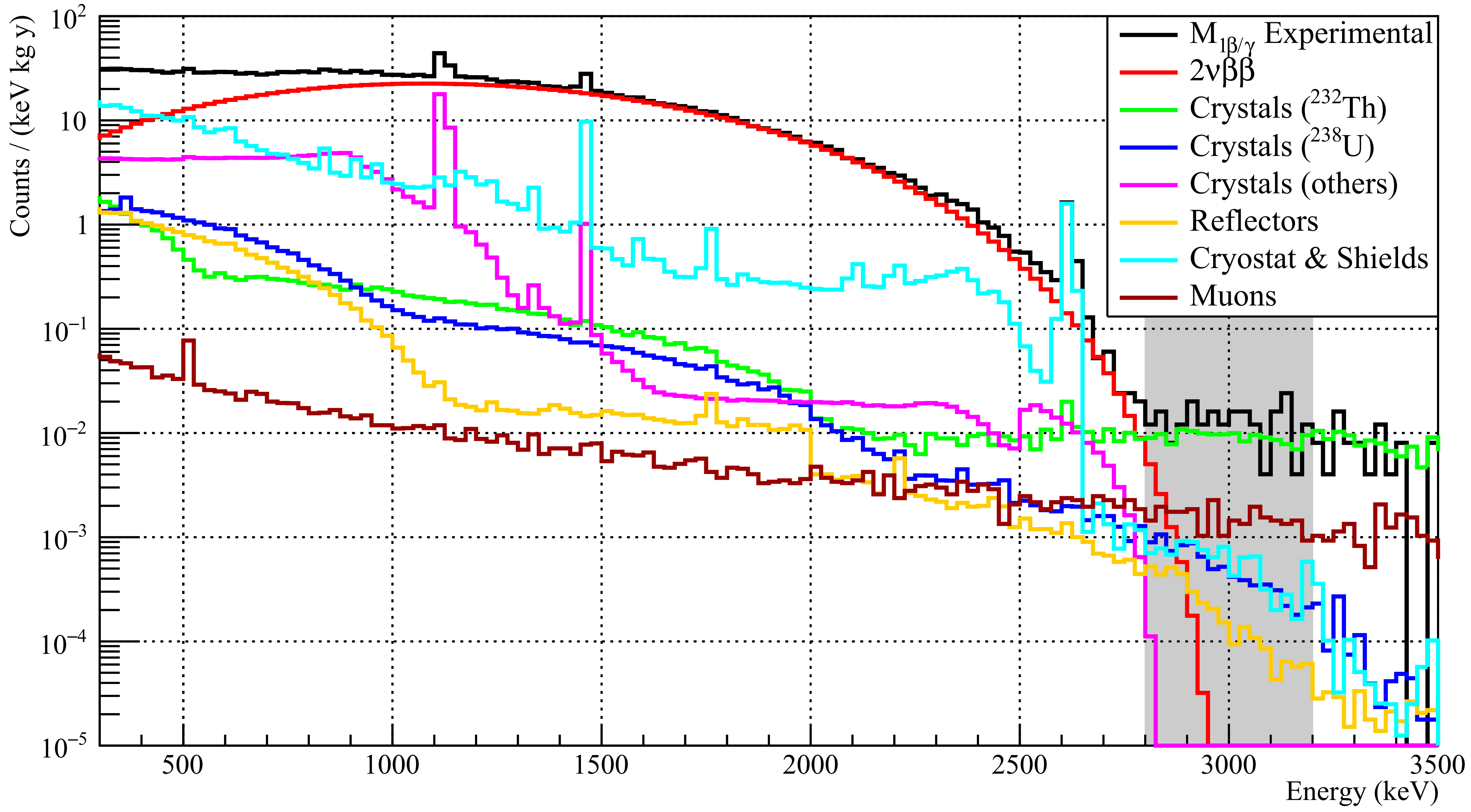


Background model



Phase I background model

- Fundamental for the spectral shape reconstruction and identify dominant background sources
- Further precision with the integration of Phase II data



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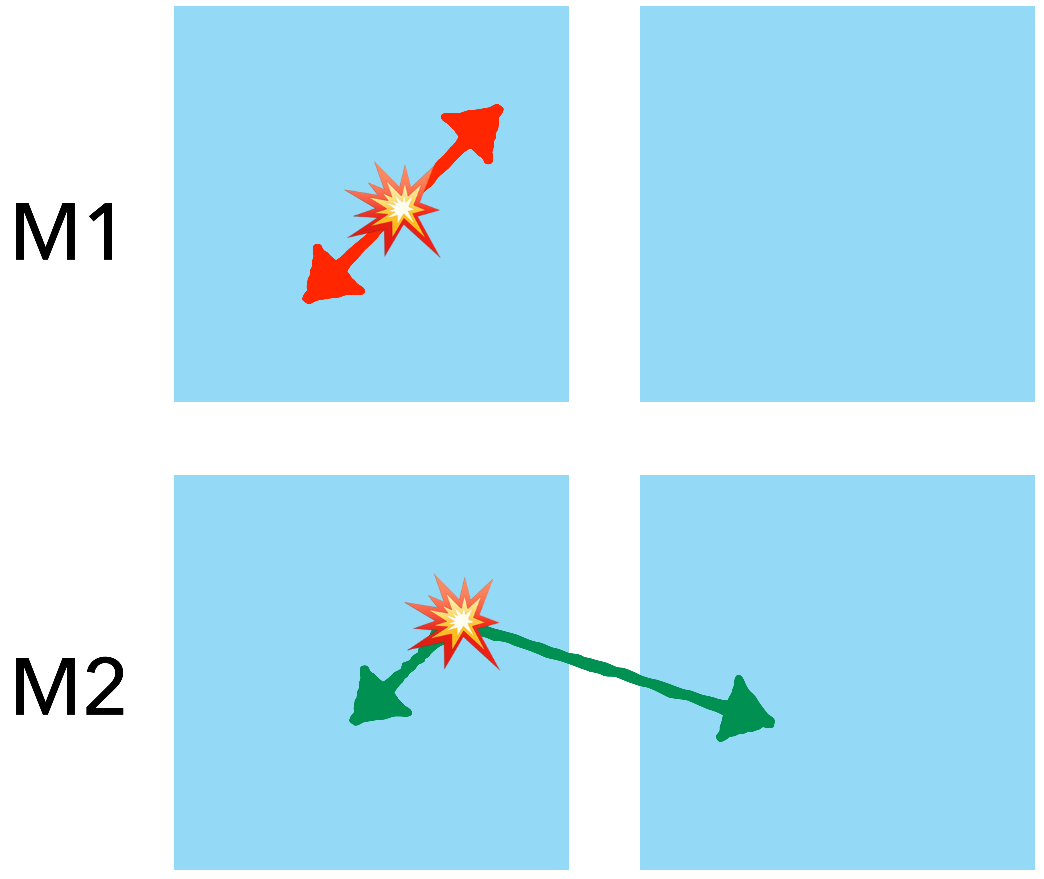
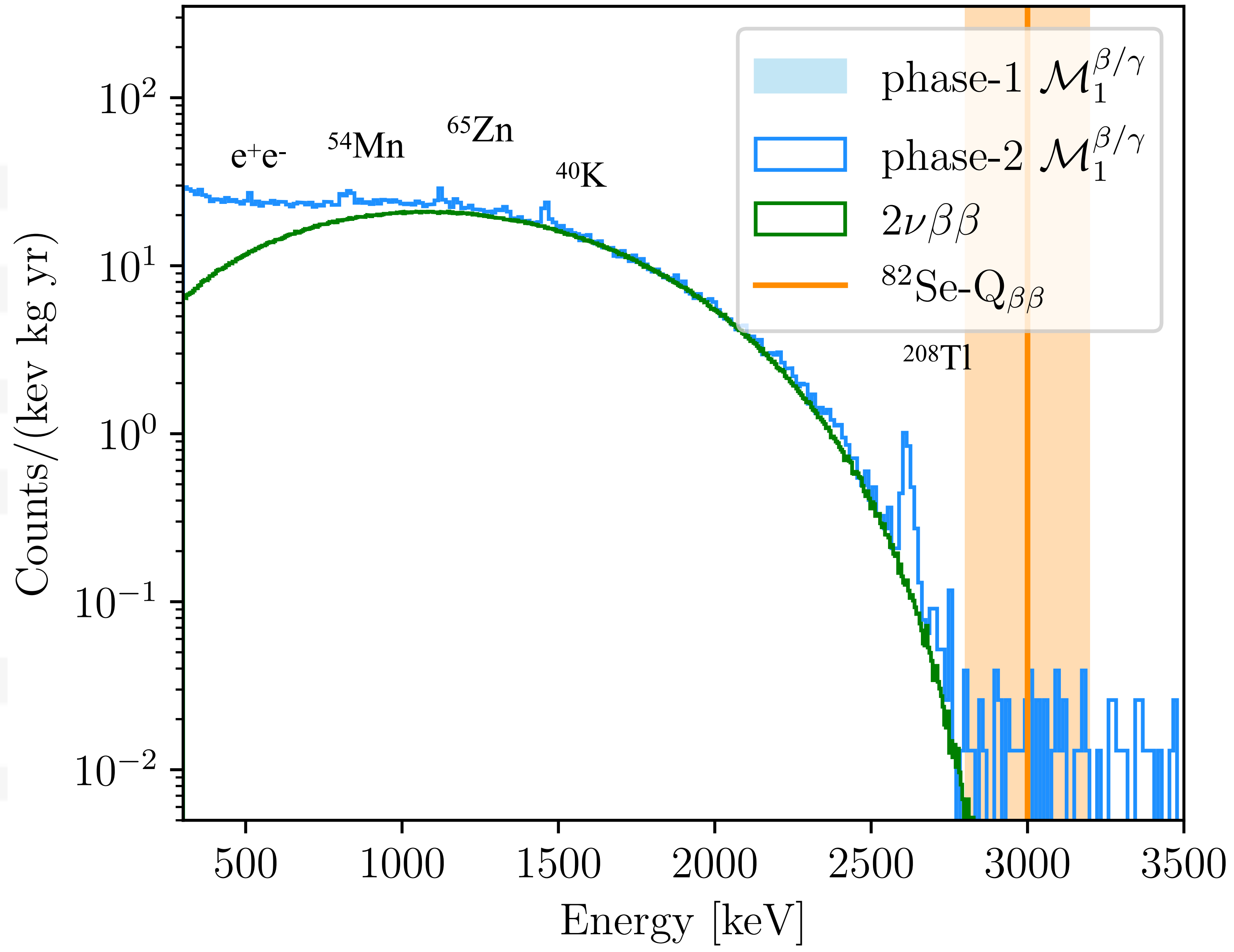
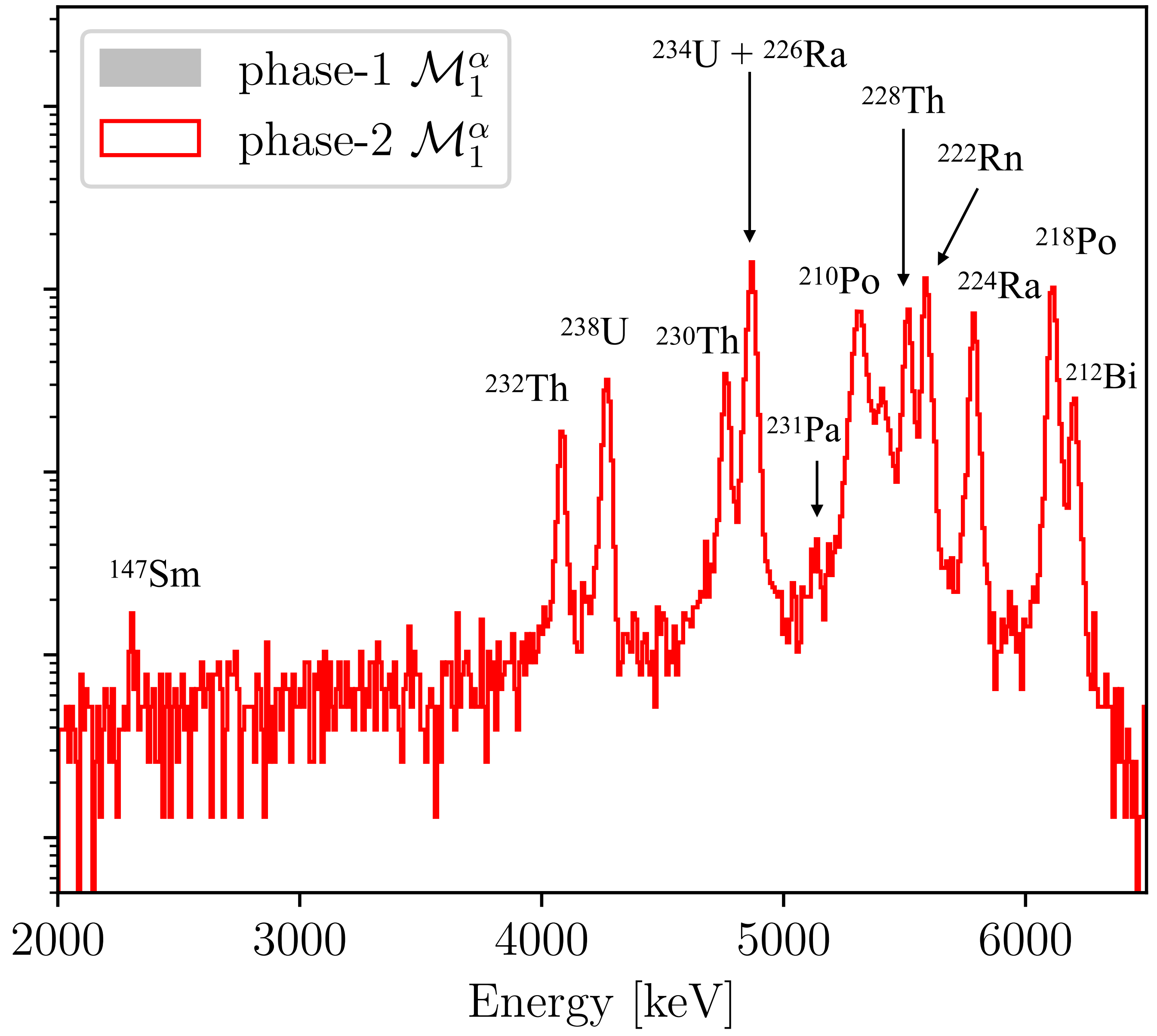
Experimental spectra

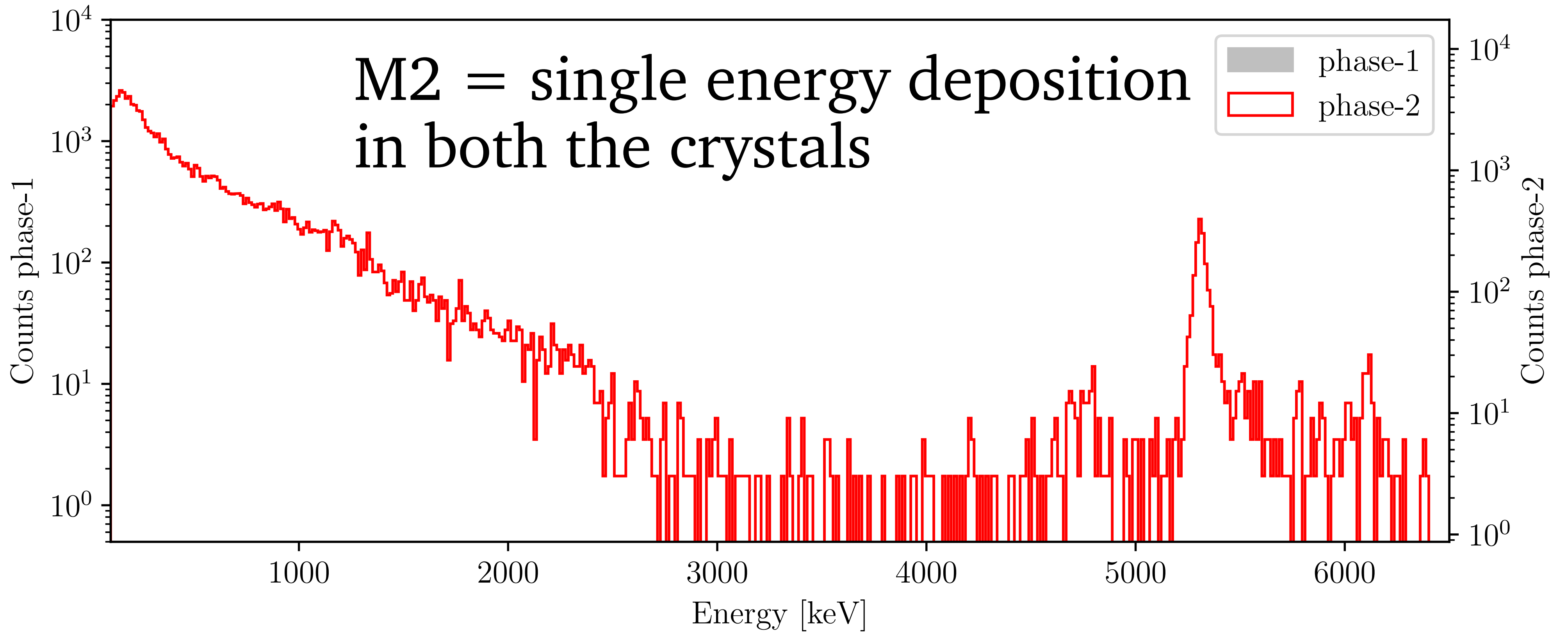
Data selection based on time coincidences and particle identification.

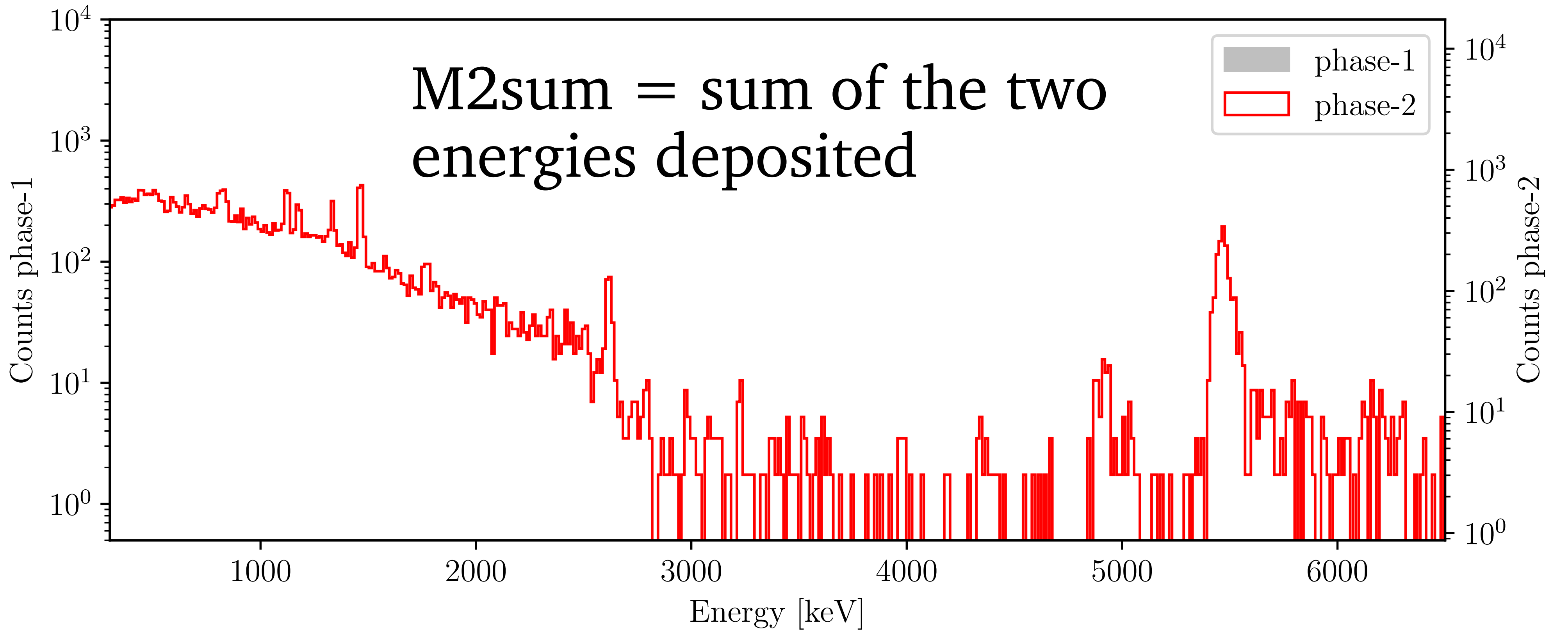
- α-contaminations have the same activity in phase-I and phase-II
- Higher alpha continuum from close component contaminations (10 mK)
- 2νββ is dominant up to 3 MeV







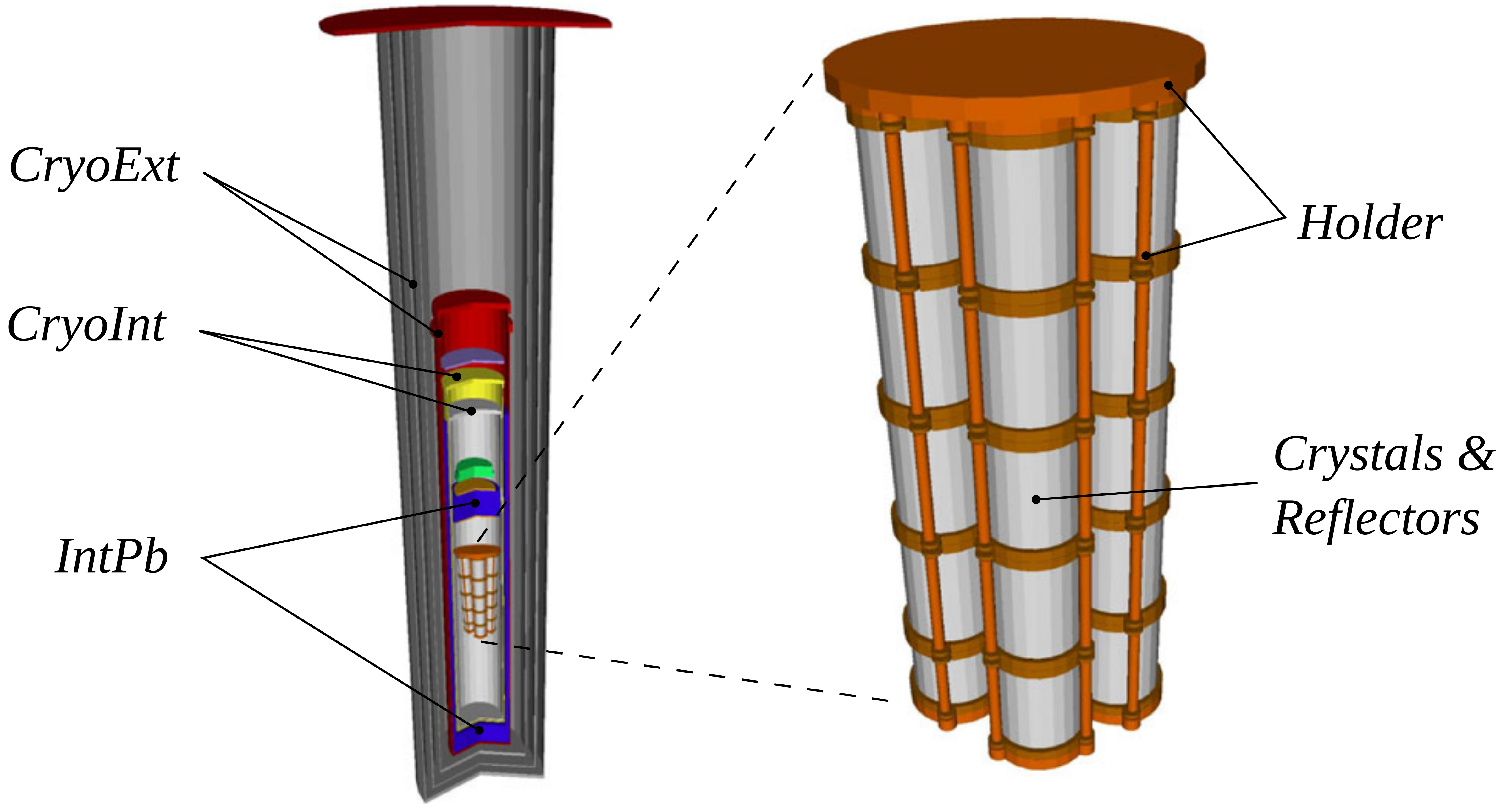




Background model - simulations

- A GEANT4 based software taking into account the detector geometry generates a **series on Monte Carlo spectra**
- The simulations are processed with a **custom software to implement experimental features** on simulated data (energy and time resolution, coincidences, particle identification…)

The background sources included follows the material components and the geometry. Degenerate spectra are grouped together in a single simulation



+ PbExt

Phase-I → Reflectors + Holders

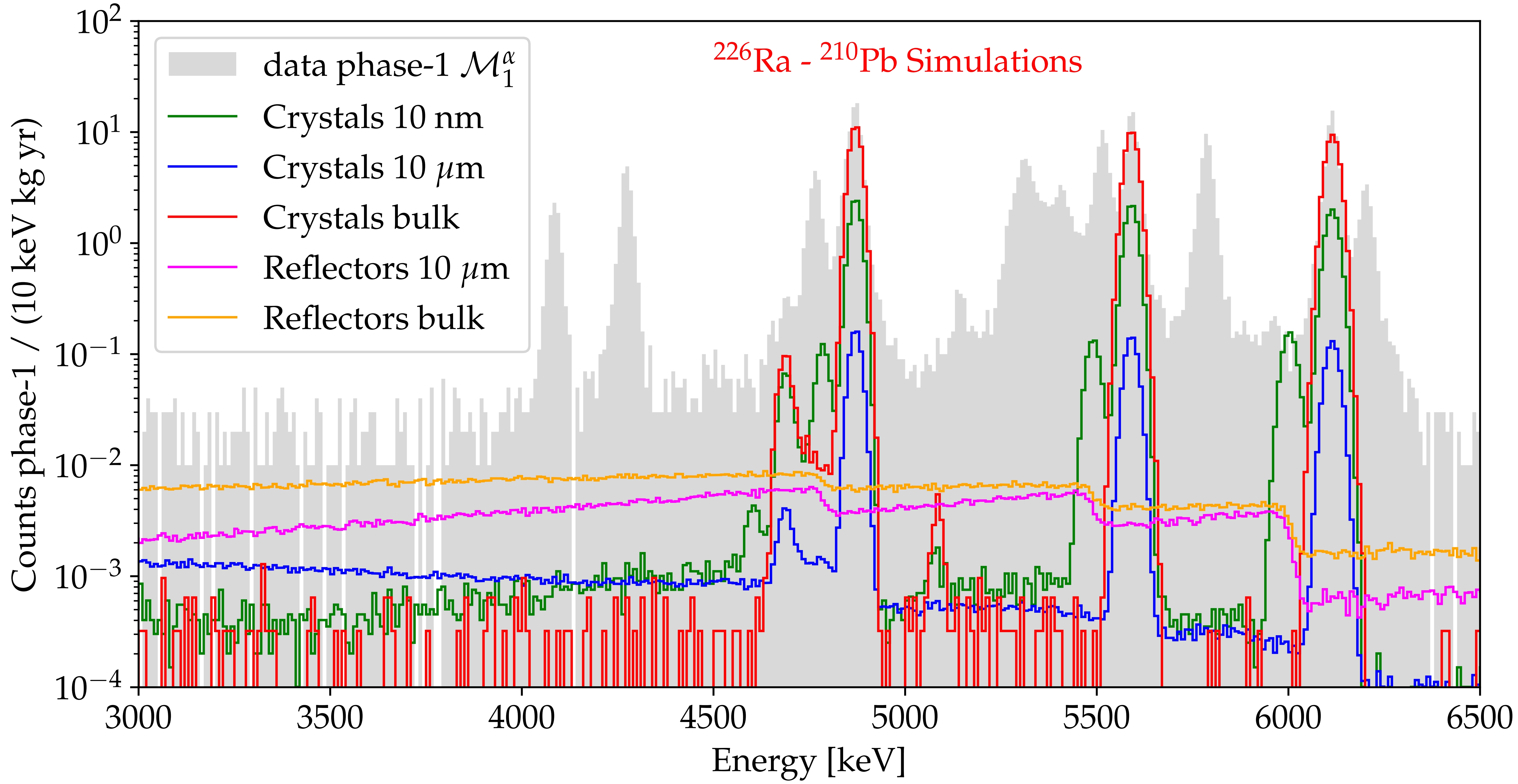
Phase-II → Holders + 10mK

Background model - sources

- Long-living radioisotope (^{232}Th, ^{238}U, ^{235}U, ^{40}K) with the possible breaks of the chains → Crystals, Holders and Cryostat
- Cosmogenic activation products of Copper and ZnSe (^{65}Zn, ^{60}Co, ^{54}Mn) → Crystals and Holders
- Muons → Environment
- 2νββ using SSD approximation

Crystal contaminants are modeled with different depth profiles $e^{-x/\lambda}$

λ = depth parameter assumed to be 10nm or 10μm

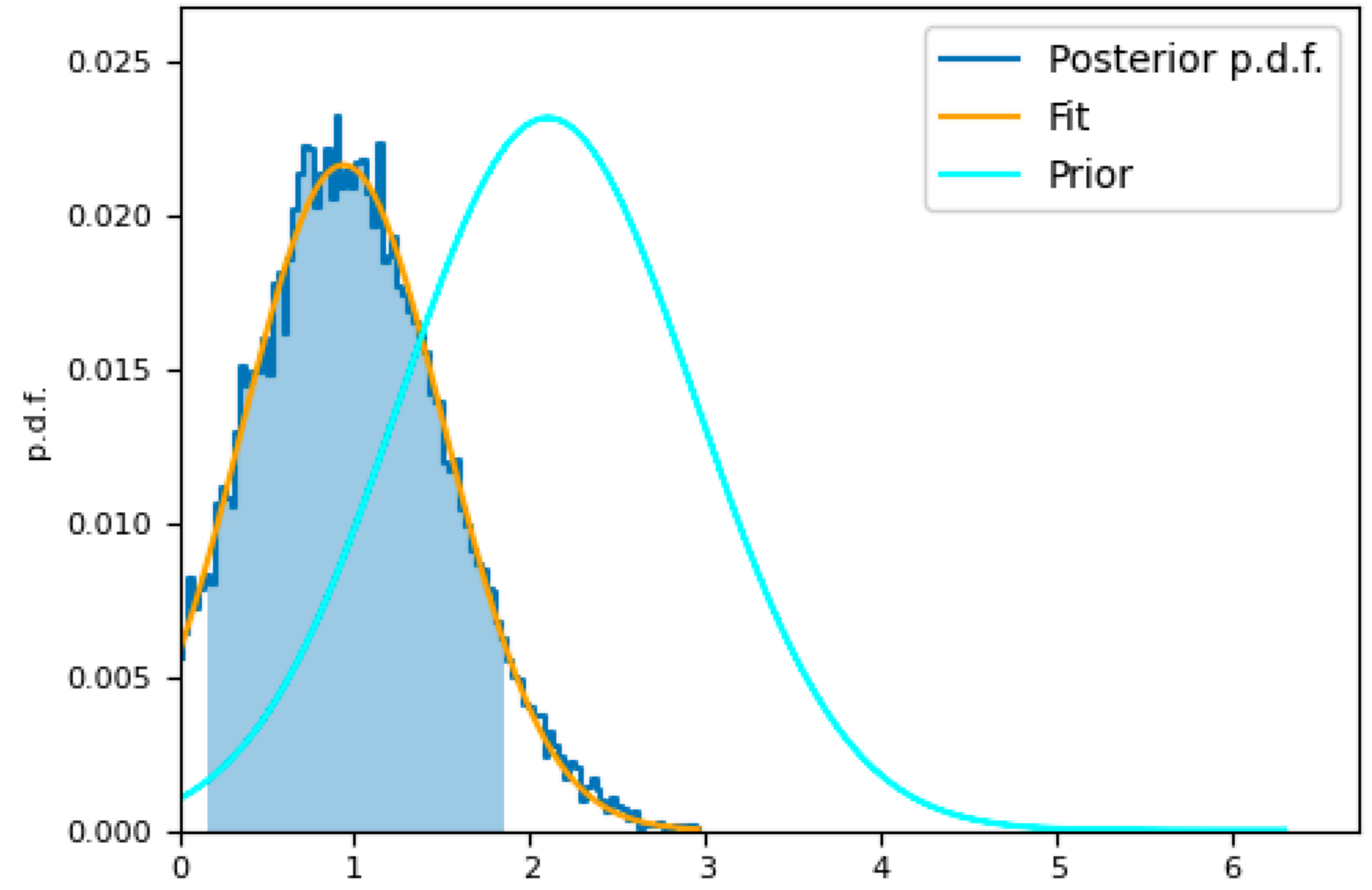


Background model - Fit

Binned simultaneous Maximum Likelihood fit using a Bayesian framework with a Markov Chain Monte Carlo (MCMC) approach.

We model the spectra i and energy bin b as $f_i\left(E_b;\vec{N}\right) = \sum_{j=1}^{N_s} N_j \cdot f_{j,i}\left(E_b\right)$

$$\text{Activity}\left[\frac{\text{Bq}}{\text{kg}}\right] = \frac{N_j \cdot N^{MC}}{\text{Mass[kg]} \times \text{livetime[s]}}$$



From the Bayes theorem the *joint posterior pdf* is

$$\text{Posterior}\left(\vec{N} \mid \text{data}\right) \propto \prod_{i,b} \text{Pois}\left(n_{i,b} \mid f_i\left(E_b;\vec{N}\right)\right) \times \text{Prior}\left(\vec{N}\right)$$

Background model - Fit

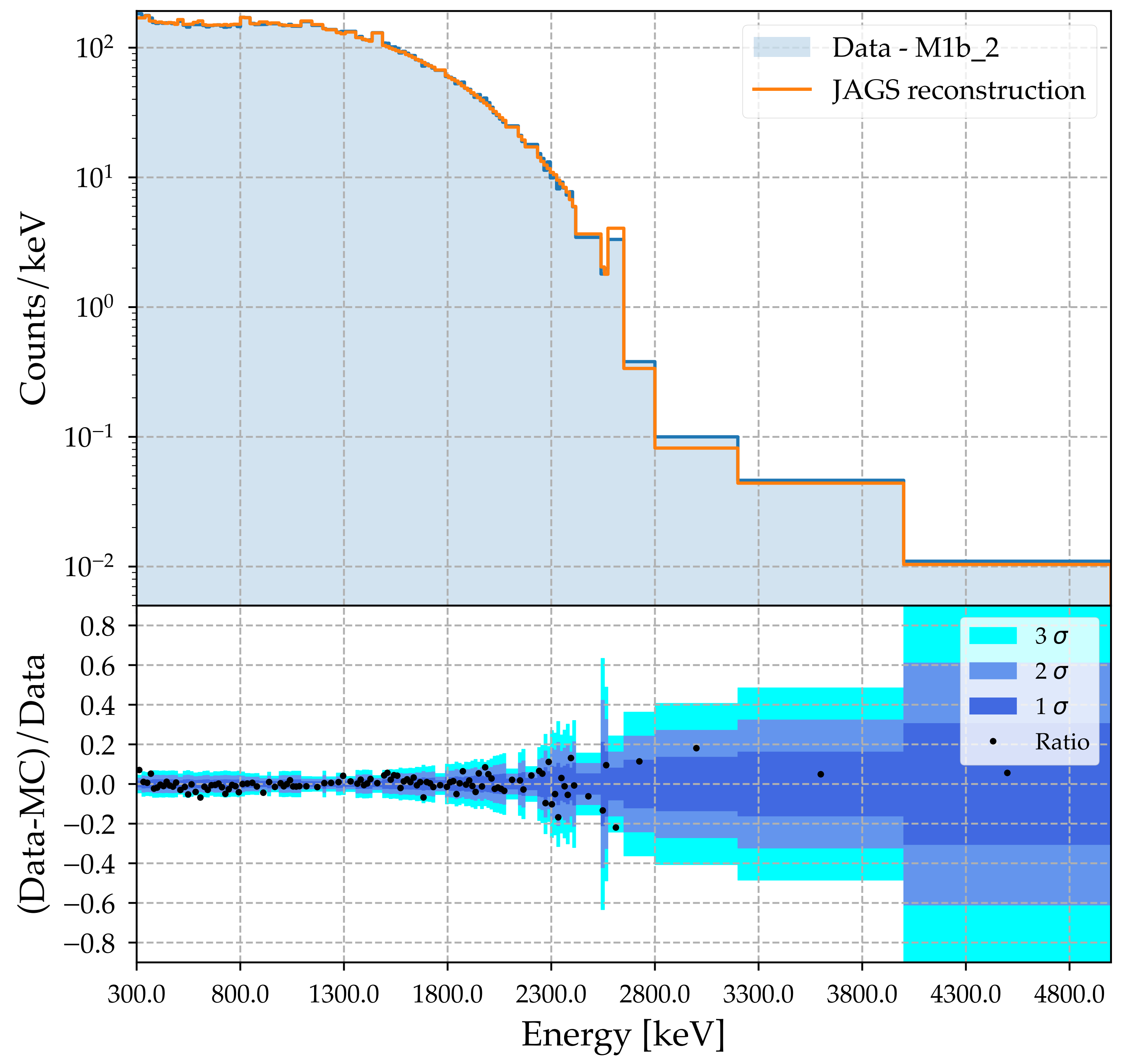
Variable binning for low counts regions and peaks

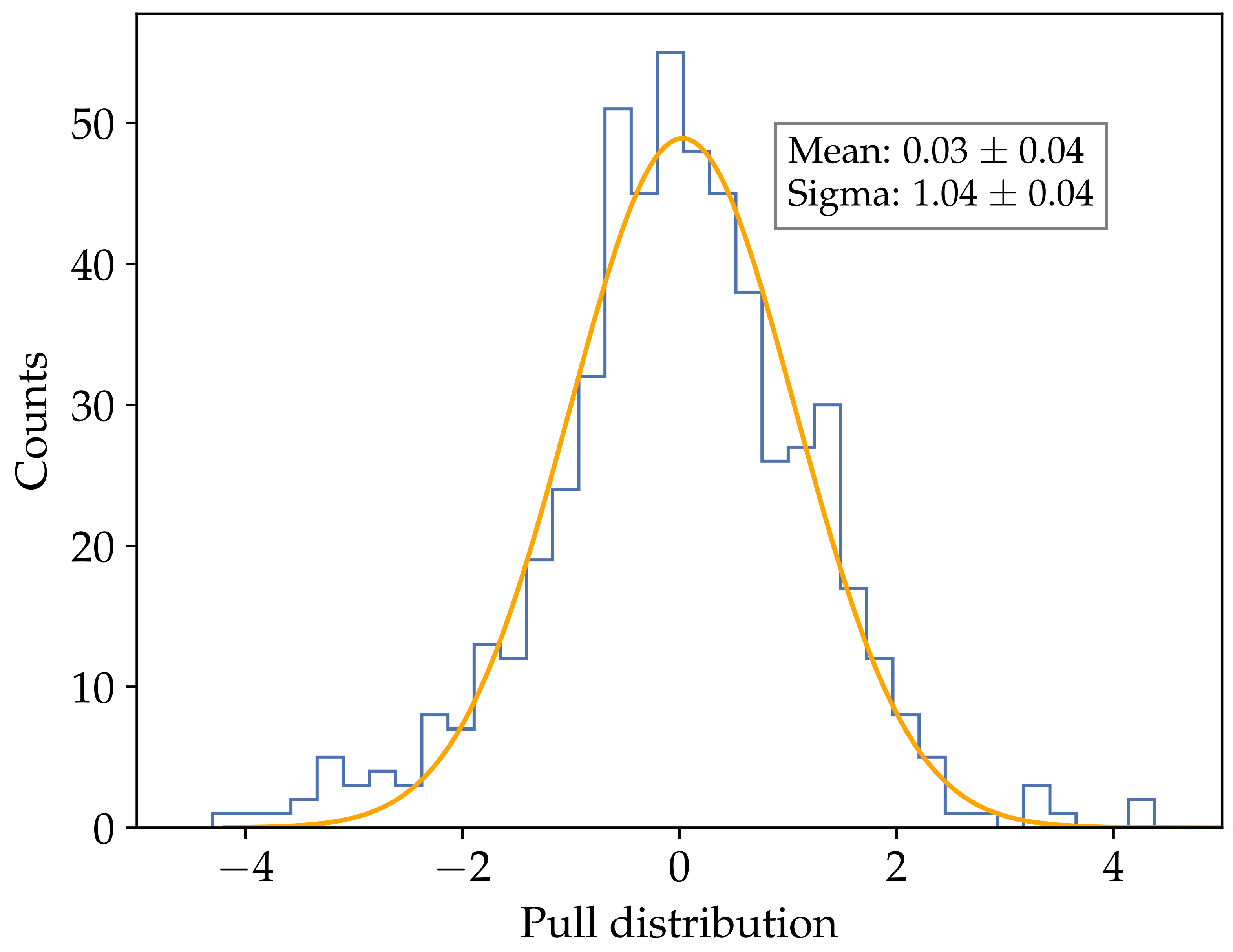
Constraints on all the long living isotopes to have the same activity between phase-I and phase-II

+ priors based on previous experiments results and measured muon flux

Simultaneous fit on 8 experimental experimental spectra using **JAGS,** 78 simulations, with 17 couples of them constrained

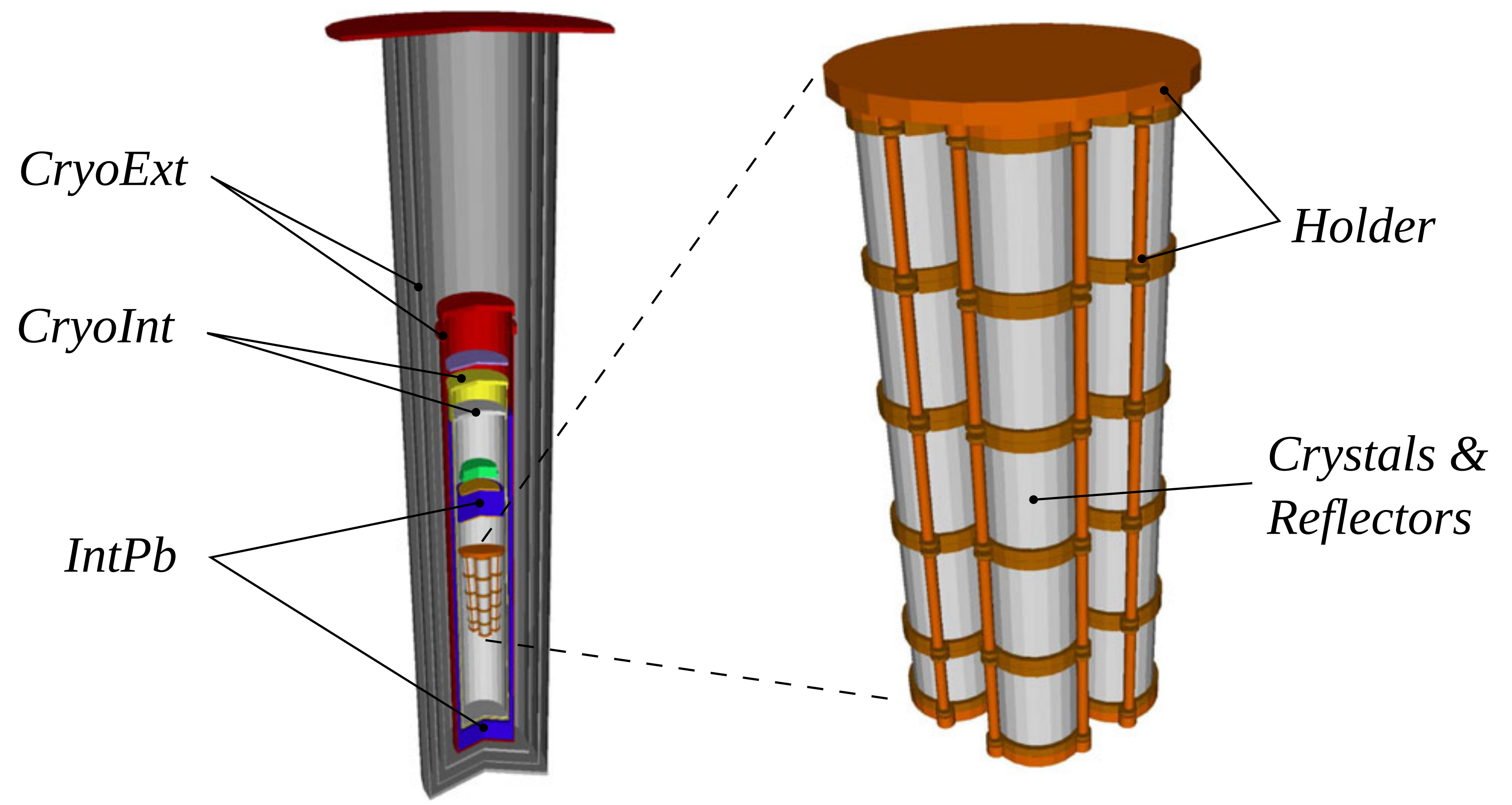
This list of sources and this configuration of the parameters define the *Reference* fit

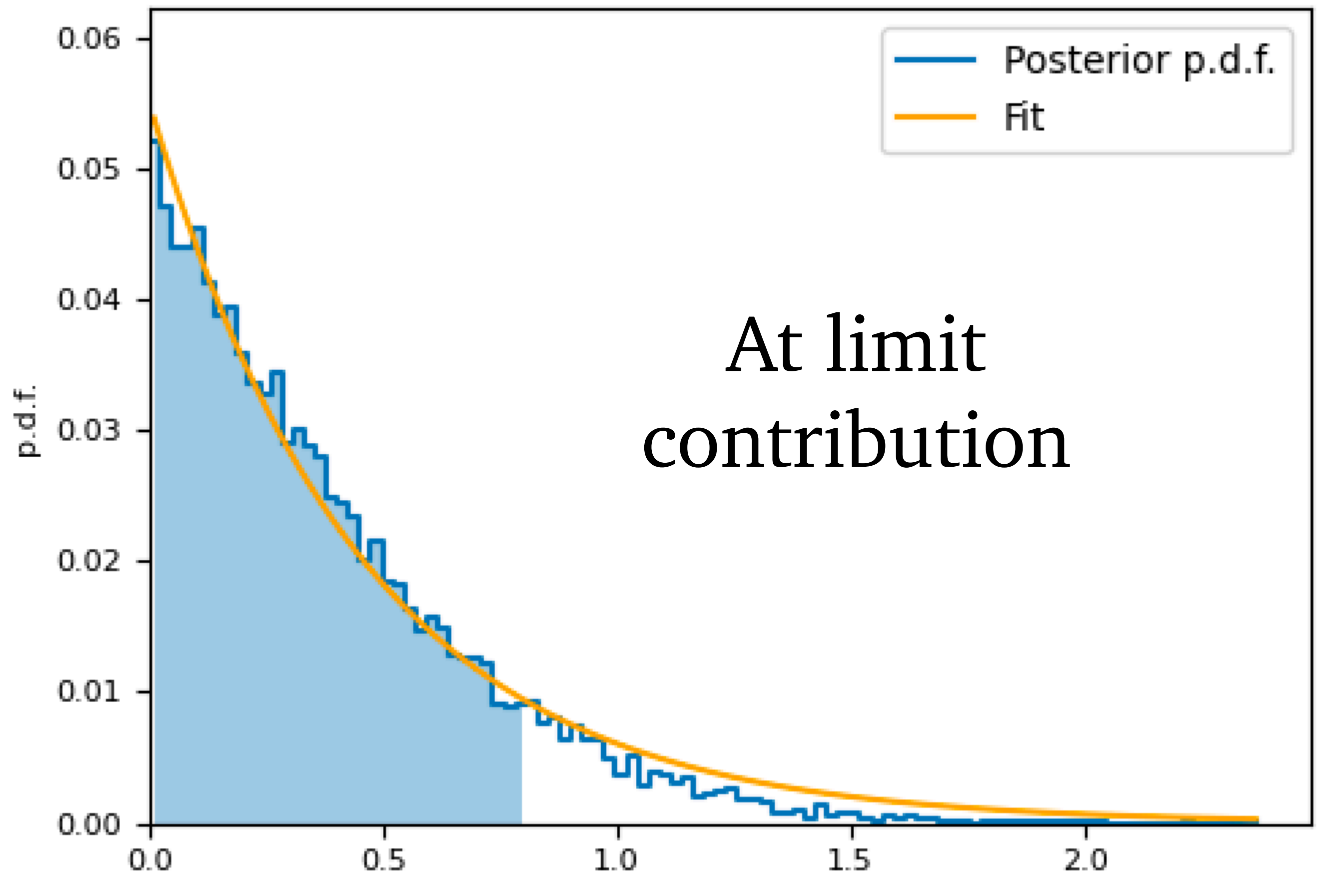


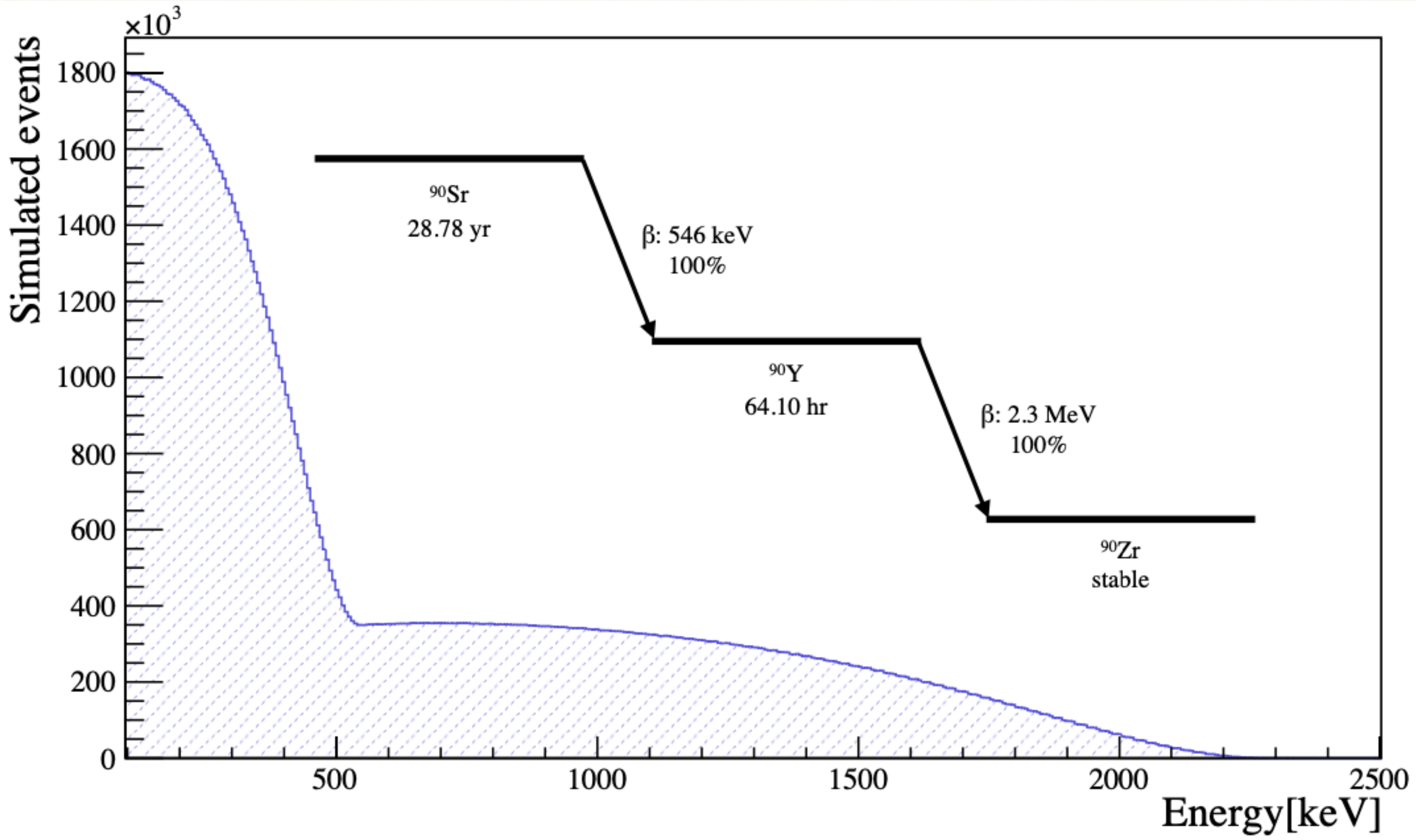


Fit systematics

- Energy **calibration**: alternative energy scale corrected for the ^{56}Co calibration residuals
- **^{90}Sr/^{90}Y**
- **Source location** effects
- **Reduced list** of sources: remove sources which posterior p.d.f. is compatible with 0
- Others…



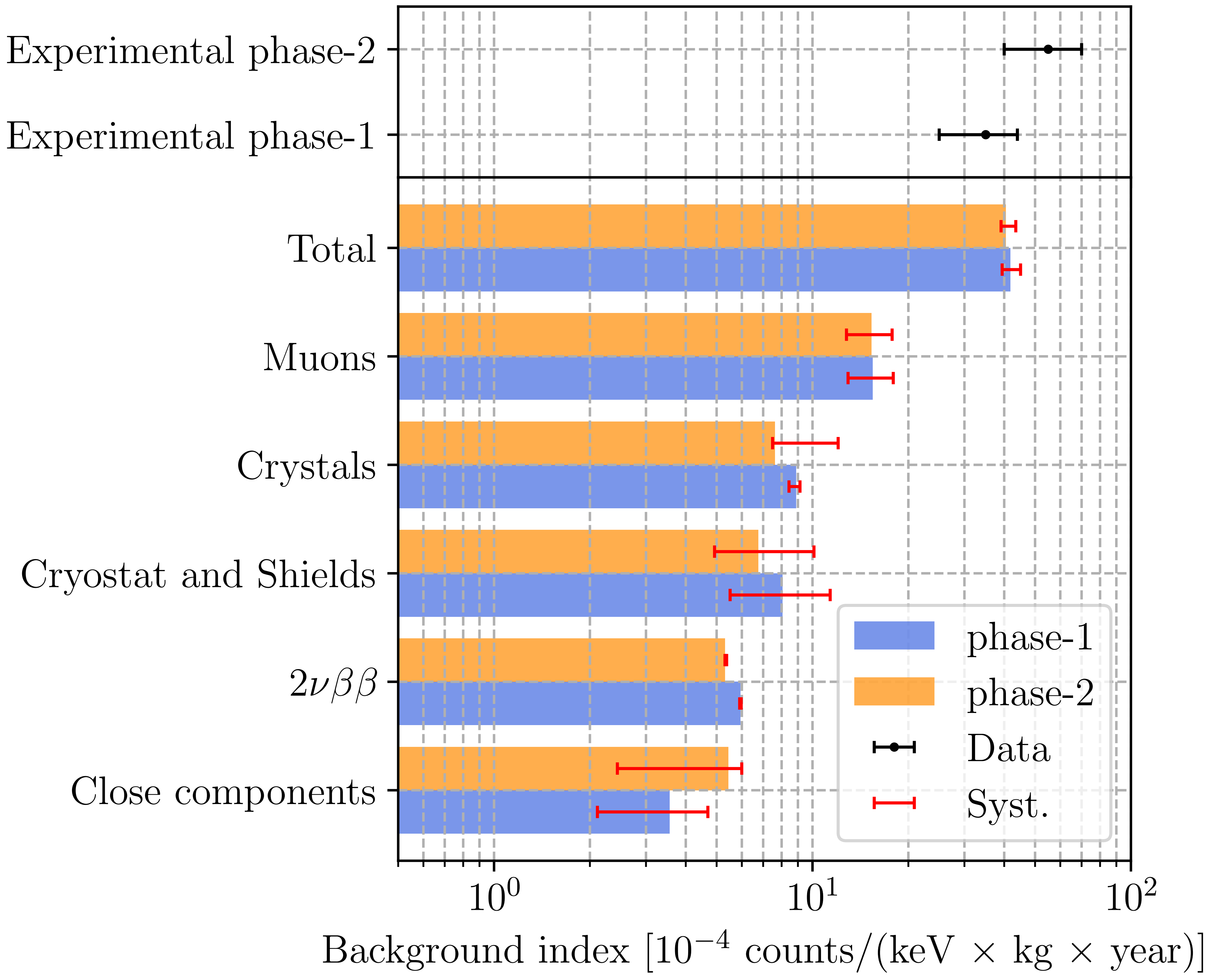




Background in the ROI

- Simulations can reproduce the background in the 0νββ ROI applying the same cuts used in experimental data
- The higher background in phase II is explained as an over-fluctuation

Component	ROI$_{bkg}$ rate [10^{-4} counts/keV/kg/yr]		
	phase-I (only)	phase-I (comb.)	phase-II (comb.)
Crystals	$11.7 \pm 0.6\ ^{+1.6}_{-0.8}$	$8.9 \pm 0.5\ ^{+0.3}_{-0.4}$	$7.6 \pm 0.4\ ^{+4.4}_{-0.1}$
Near Components	$2.1 \pm 0.3\ ^{+2.2}_{-1.0}$	$3.6 \pm 0.3\ ^{+1.1}_{-1.4}$	$5.4 \pm 0.9\ ^{+0.6}_{-3.0}$
Cryostat & Shields	$5.9 \pm 1.3\ ^{+7.2}_{-2.9}$	$8.0 \pm 1.5\ ^{+3.3}_{-2.5}$	$6.8 \pm 1.0\ ^{+3.3}_{-1.8}$
Muons	$15.3 \pm 1.3 \pm 2.5$	$15.4 \pm 0.7 \pm 2.5$	$15.3 \pm 0.7 \pm 2.5$
$2\nu\beta\beta$	$6.0 \pm 0.02\ ^{+0.13}_{-0.09}$	$5.93 \pm 0.03\ ^{+0.04}_{-0.02}$	$5.31 \pm 0.03\ ^{+0.06}_{-0.04}$
Total	$41 \pm 2\ ^{+9}_{-4}$	$42 \pm 2\ ^{+4}_{-4}$	$40 \pm 2\ ^{+4}_{-2}$
Experimental	$35\ ^{+10}_{-9}$	$35\ ^{+10}_{-9}$	$55\ ^{+15}_{-15}$



2νββ half-life measurement

Fit systematics combined with the 68% difference between the *Reference*

+Fit systematics (+1.0%)(−0.7%)
+Stat. uncertainty (±0.6%) (including efficiency and enrichment uncertainty)
+Theoretical uncertainty (±0.3%) (SSD vs. HSD)
= (+1.2%)(−0.9%)

Final result:

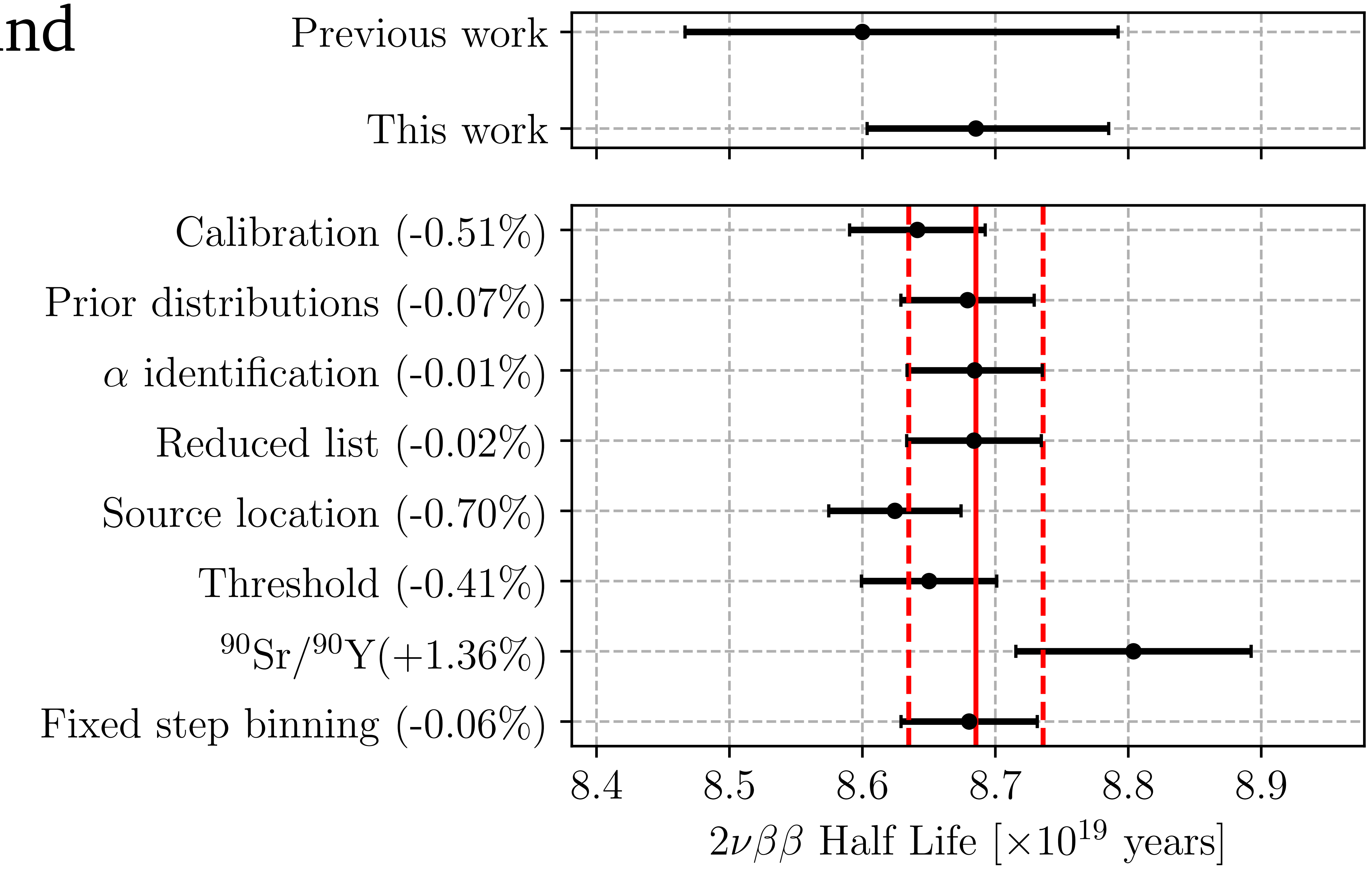
$$T_{1/2}^{2\nu} = \left[8.69 \pm 0.05(\text{stat.})^{+0.06}_{-0.09}(\text{syst.})\right] \times 10^{19}\text{yr}$$

In terms of NME:

$$\mathscr{M}_{2\nu}^{eff} = 0.0760 \begin{array}{l} + \ 0.0006 \\ - \ 0.0007 \end{array}$$

Published on PRL

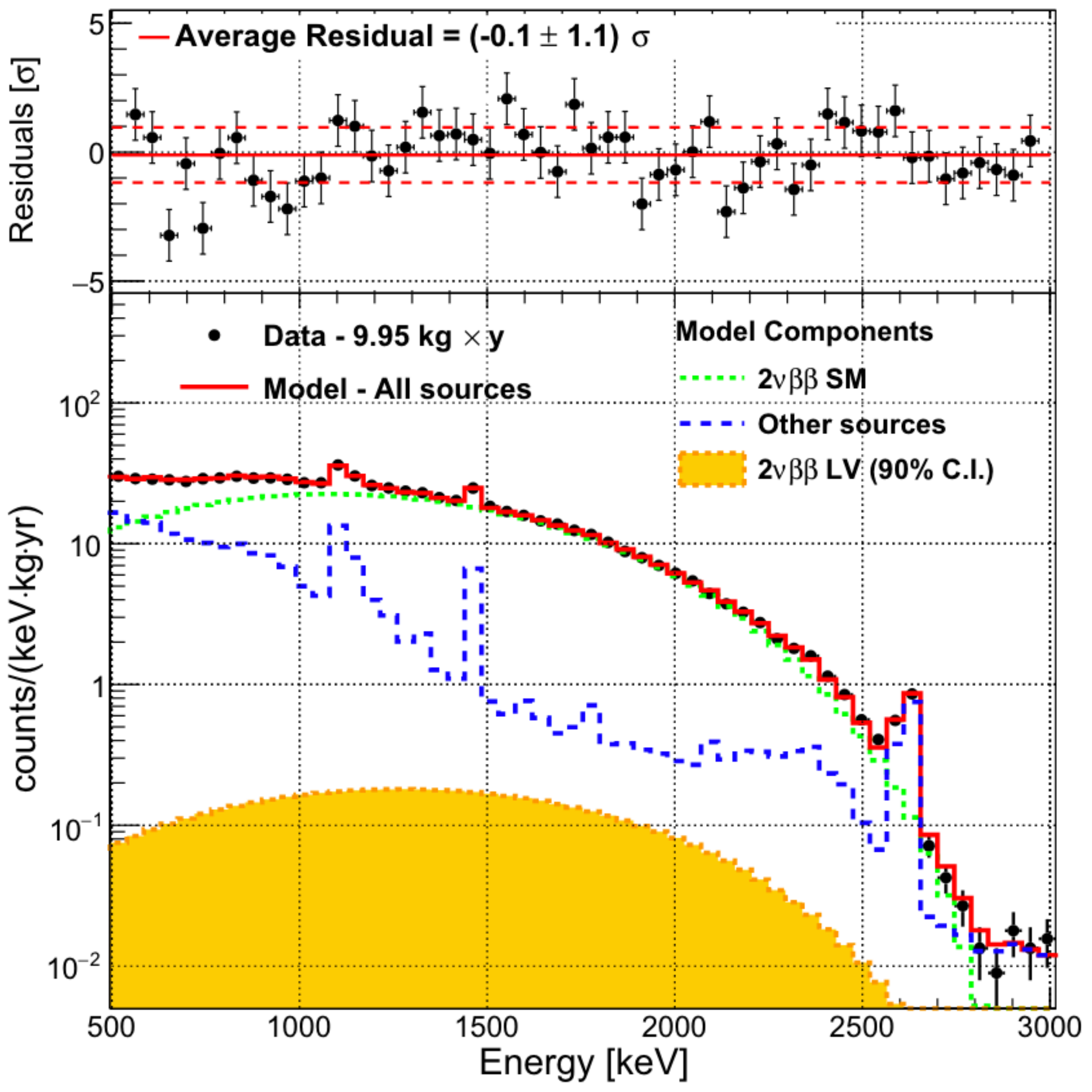
Phys.Rev.Lett. 131 (2023) 22



From BM to BSM studies

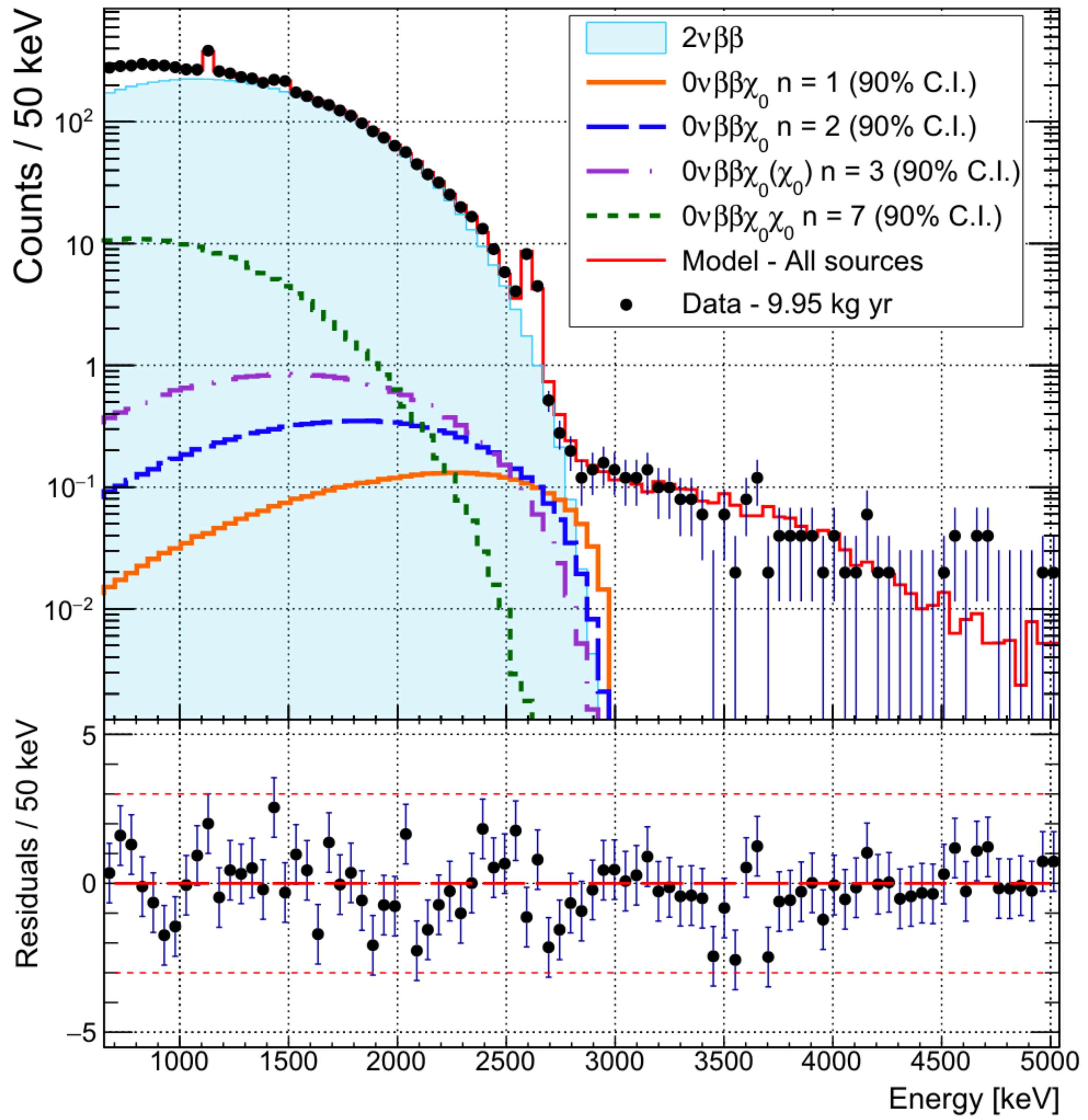
The background model serves as a starting point in the search for exotic double-β decays

LV 2νββ in CUPID-0 phase I



Phys. Rev. D **100**, 092002 (2019)

Majoron emitting modes in CUPID-0 phase I



Phys. Rev. D **107**, 032006 (2023)

Outline

1. Double-β decays
2. Scintillating cryogenic calorimeters
3. CUPID-0 combined background model
4. CUPID-Mo BSM studies
5. CUPID sensitivity
6. Conclusion and outlook

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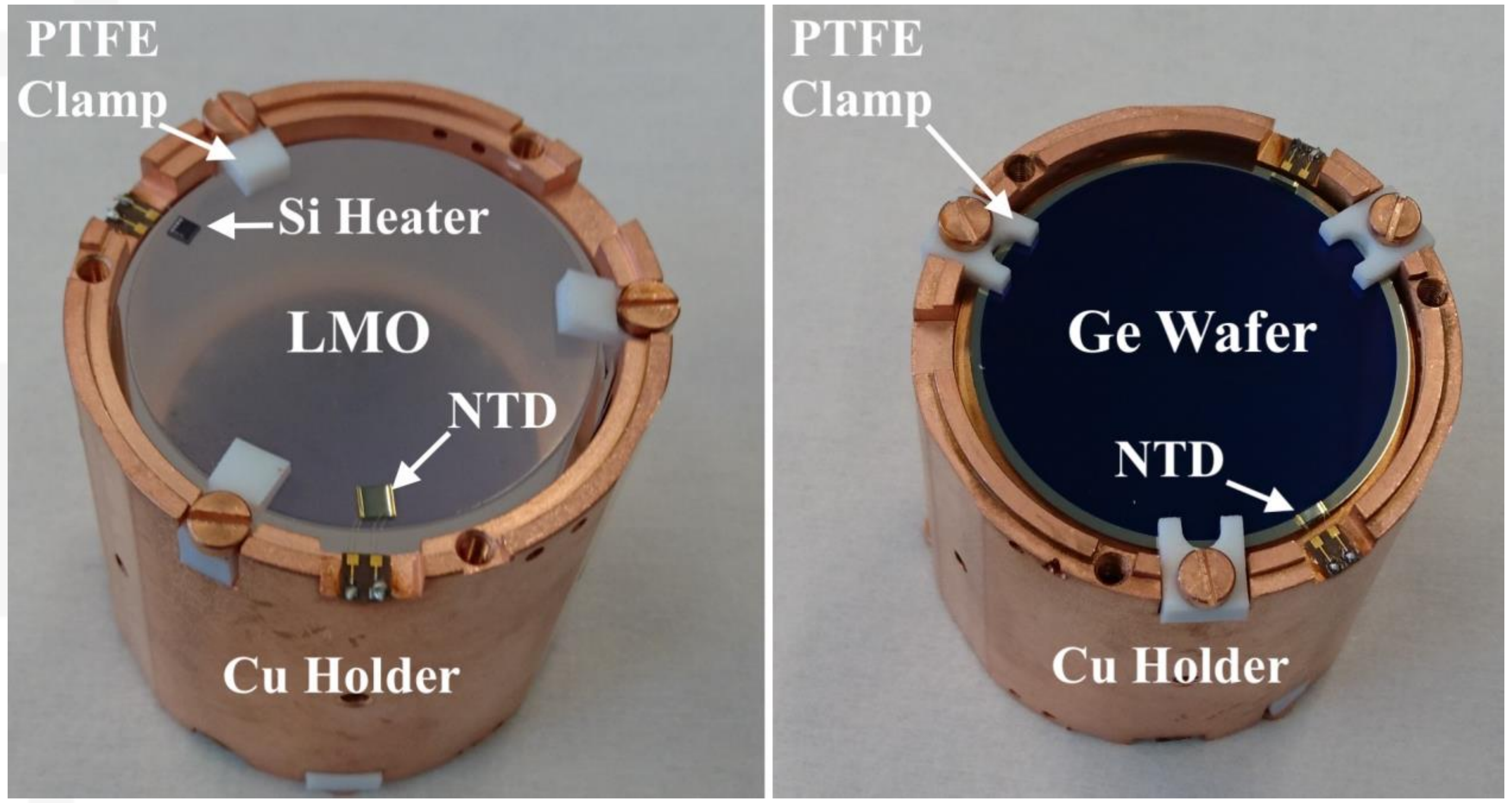
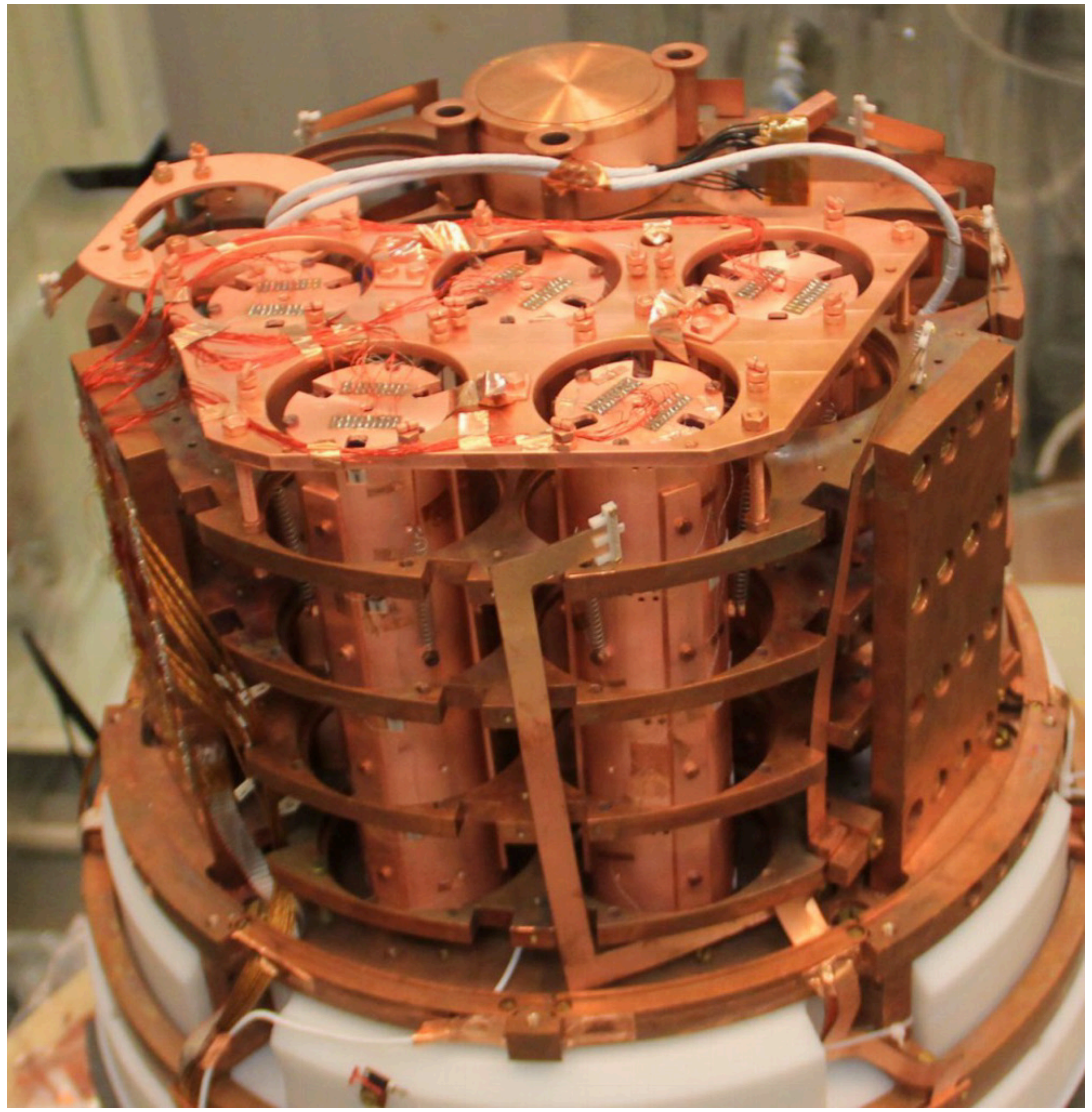
The CUPID-Mo experiment

- 20 Li_2MoO_4 crystals enriched at >95% of ^{100}Mo + 20 Ge Light detectors
- Located at MODANE in EDELWEISS cryostat
- $Q_{\beta\beta}(^{100}Mo) \sim 3034$ keV
- NTD-Ge thermistors as temperature sensors
- Total exposure: 2.71 kg × yr

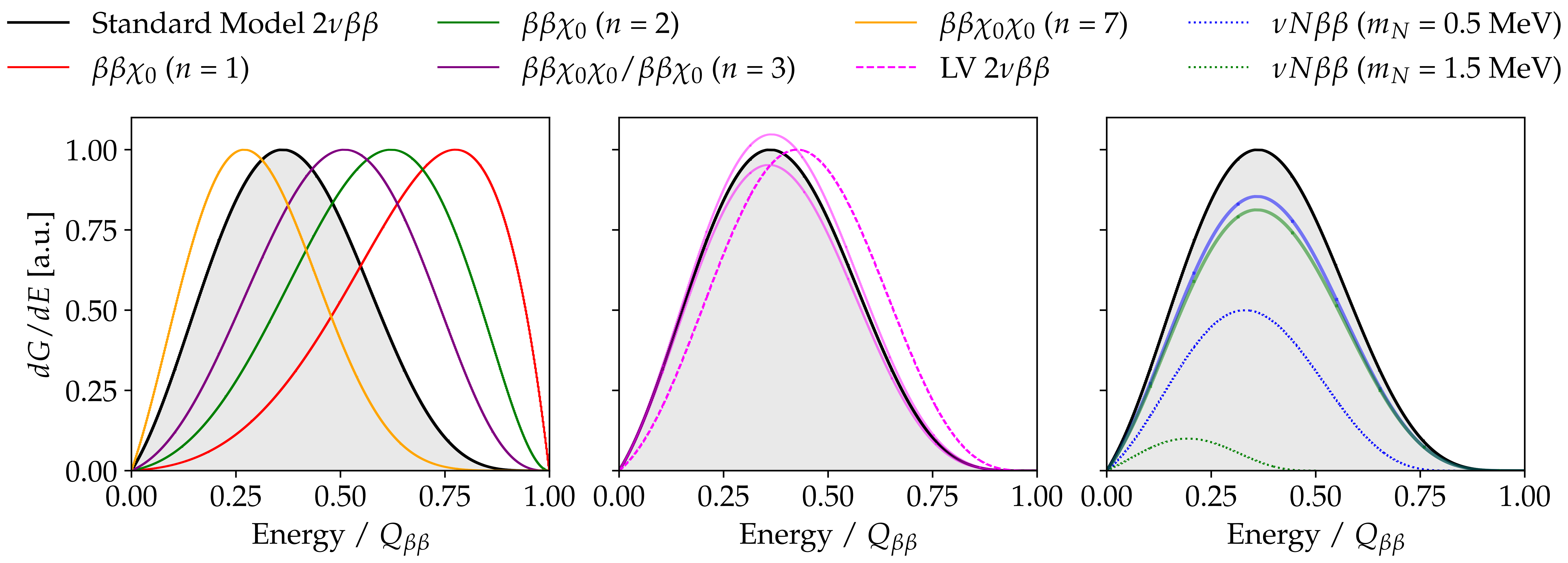




Spectral shape studies - introduction

Type I: e.g. Majoron decays, where the BSM decay is completely unrelated to the SM $2\nu\beta\beta$ → **the lower the $2\nu\beta\beta$ decay rate, the higher the sensitivity (^{136}Xe)**

Type II: e.g. Lorentz violation and Sterile neutrino emissions, where the BSM process is in competition with the SM $2\nu\beta\beta$ and tends to decrease the decay rate → **the higher the $2\nu\beta\beta$ decay rate, the higher the sensitivity (^{100}Mo)**



Spectral shape studies - analysis

1. Simulate the BSM spectra with GEANT4

2. Add the BSM spectrum into the background model fit

3. Extract from the fit the marginalised posterior p.d.f. over the parameter of interest for each BSM process and integrate it to get the limit

4. Systematics: Binning, source location, $2\nu\beta\beta$ bremsstrahlung (±10%), Energy scale (±1 keV), Minimal model, $^{90}Sr/^{90}Y$

^{100}Mo $2\nu\beta\beta$ half-life

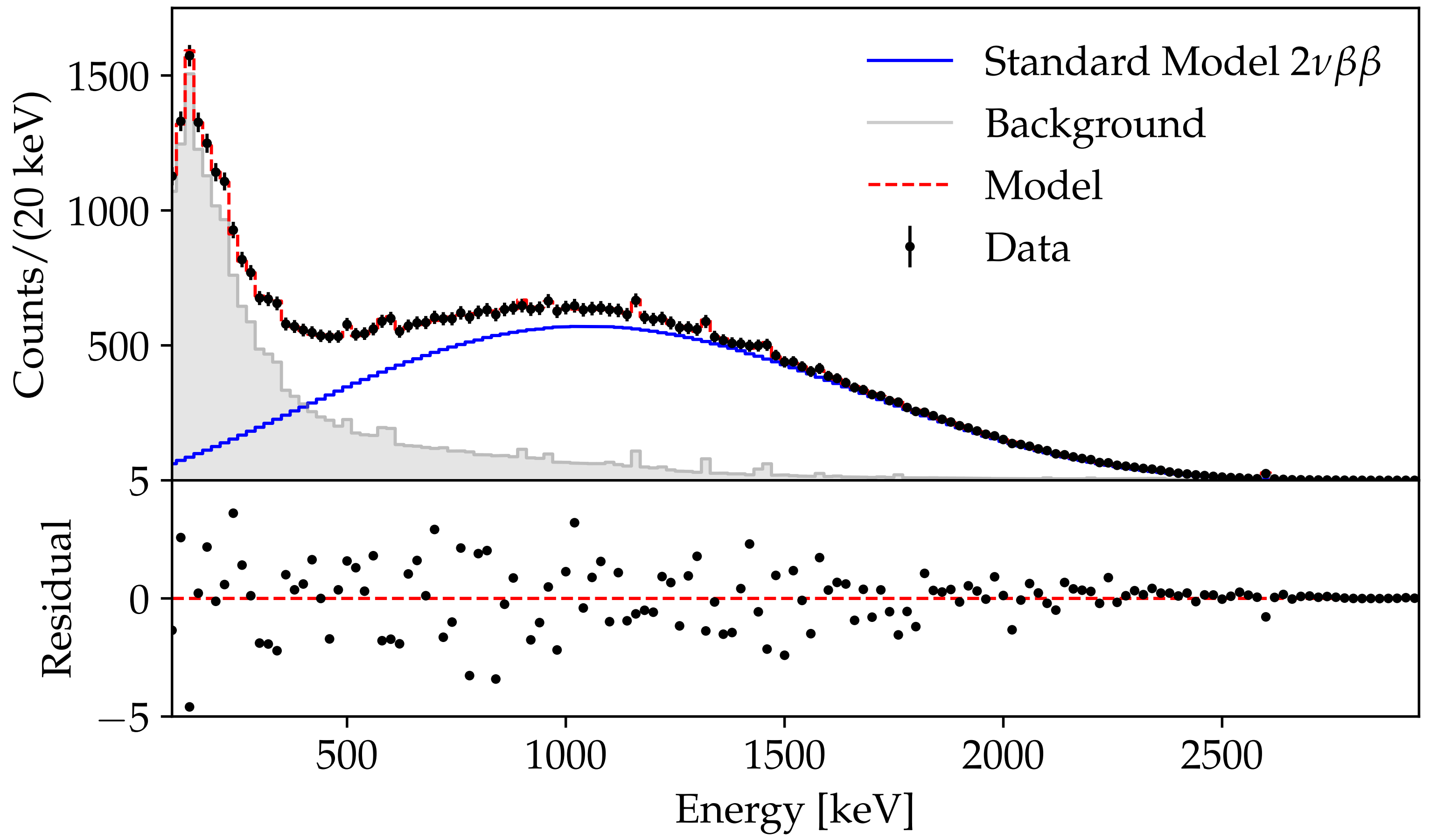
$$7.07 \pm 0.02(\text{stat.}) \pm 0.1(\text{syst.}) \times 10^{18}$$

Fixed $2\nu\beta\beta$ spectral shape under the SSD assumption

The result can be compared with the other experiments

Fluctuating $2\nu\beta\beta$ spectral shape according to the improved description

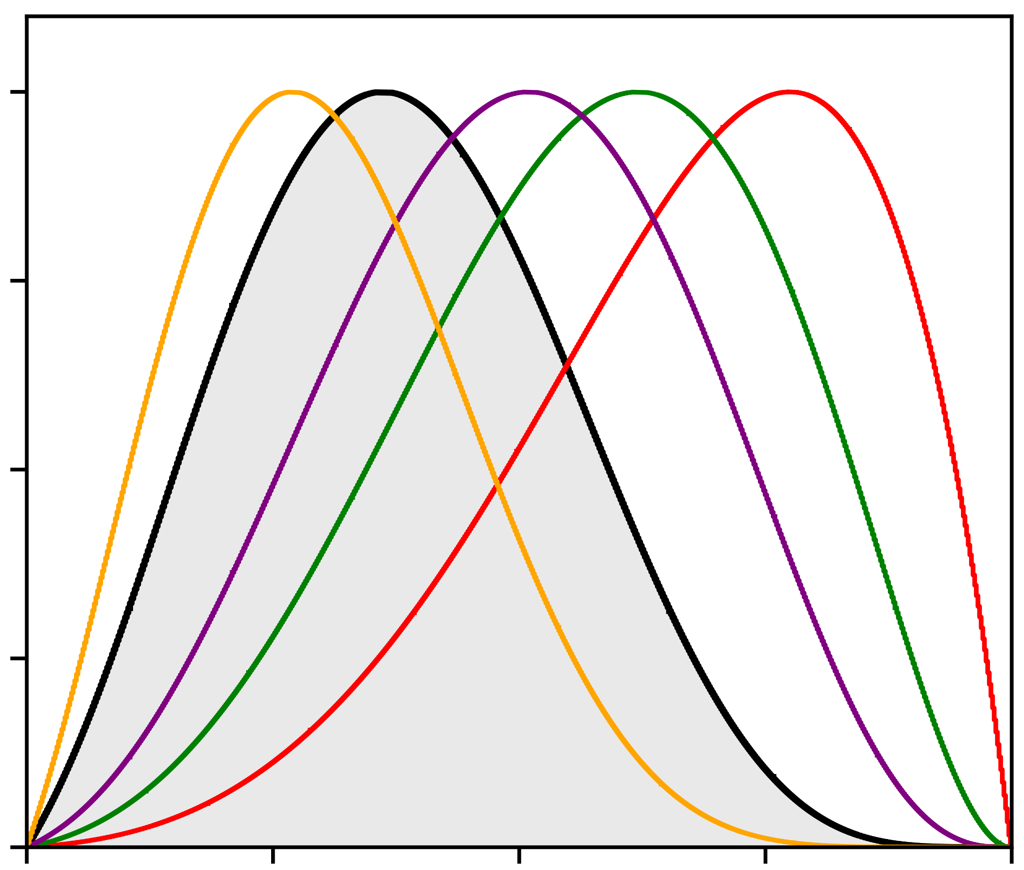
Systematic effect never considered by any experiment before

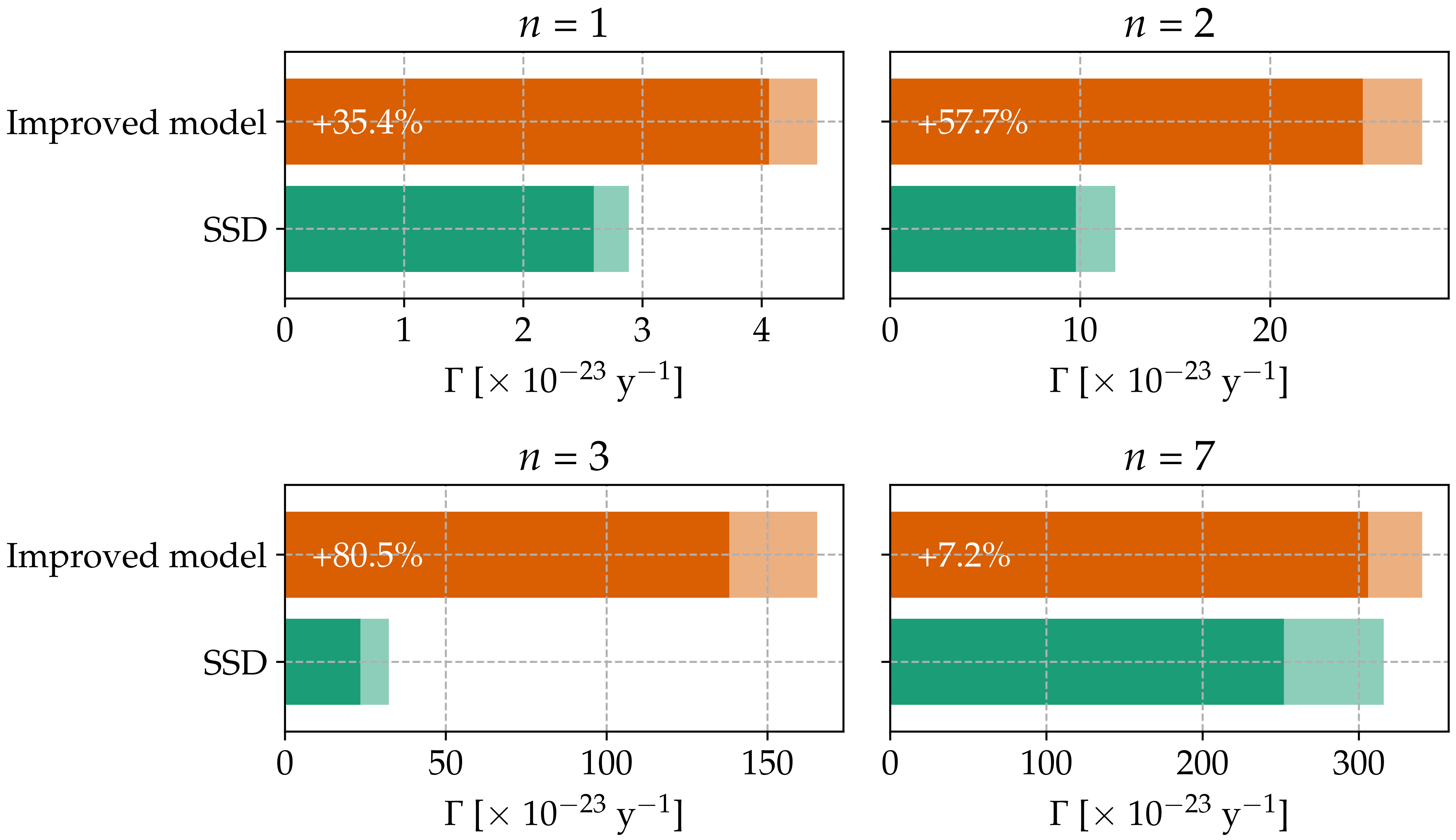


Phys.Rev.Lett. 131 (2023) 16, 162501

Results: Majoron emitting decays

- The improved model has a large impact on the final limit
- SSD limits are a factor 2 − 5 less stringent than NEMO-3, despite its exposure is 22 times higher than CUPID-Mo



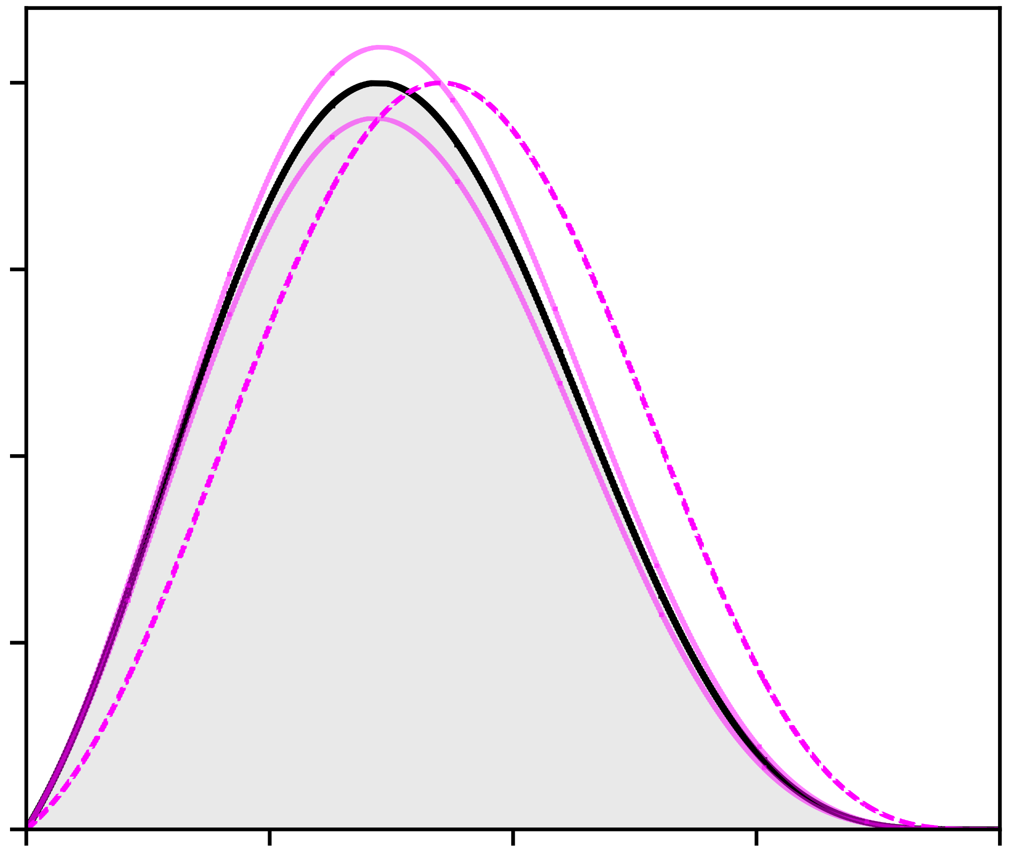


Decay mode	$T_{1/2}$ limit SSD [y]	$T_{1/2}$ limit IM [y]	g_{ee}^{M} limit SSD	g_{ee}^{M} limit IM
	this work			
$\beta\beta\chi_0$ ($n=1$)	2.4×10^{22}	1.6×10^{22}	$(4.0 - 6.9)\times 10^{-5}$	$(5.0 - 8.5)\times 10^{-5}$
$\beta\beta\chi_0$ ($n=2$)	5.8×10^{21}	2.7×10^{21}	-	-
$\beta\beta\chi_0$ ($n=3$)	2.2×10^{21}	0.5×10^{21}	0.053	0.112
$\beta\beta\chi_0\chi_0$ ($n=3$)	2.2×10^{21}	0.5×10^{21}	2.1	3.1
$\beta\beta\chi_0\chi_0$ ($n=7$)	2.2×10^{20}	2.0×10^{20}	2.2	2.3
	NEMO-3 [57, 60]			
$\beta\beta\chi_0$ ($n=1$)	4.4×10^{22}		$(3.0 - 5.1)\times 10^{-5}$	
$\beta\beta\chi_0$ ($n=2$)	9.9×10^{21}		-	
$\beta\beta\chi_0$ ($n=3$)	4.4×10^{21}		0.023	
$\beta\beta\chi_0\chi_0$ ($n=3$)	4.4×10^{21}		1.42	
$\beta\beta\chi_0\chi_0$ ($n=7$)	1.2×10^{21}		1.15	

Results: Lorentz violating 2νββ

- The countershaded operator can assume negative values → negative fluctuations are allowed in the fit
- Strong anti correlation between the SM and LV components, it get worse with the improved model
- Double-sided limit at 90% C.I.

$$\dot{a}^{(3)}_{of} = 10 \cdot \frac{G_{SM}}{\delta G_{LV}} \cdot \frac{\Gamma^m_{LV}}{\Gamma^m_{SM}}$$



NEMO-3 limit

$$-4.2 \cdot 10^{-7} < \dot{a}^{(3)}_{of} < 3.5 \cdot 10^{-7}$$

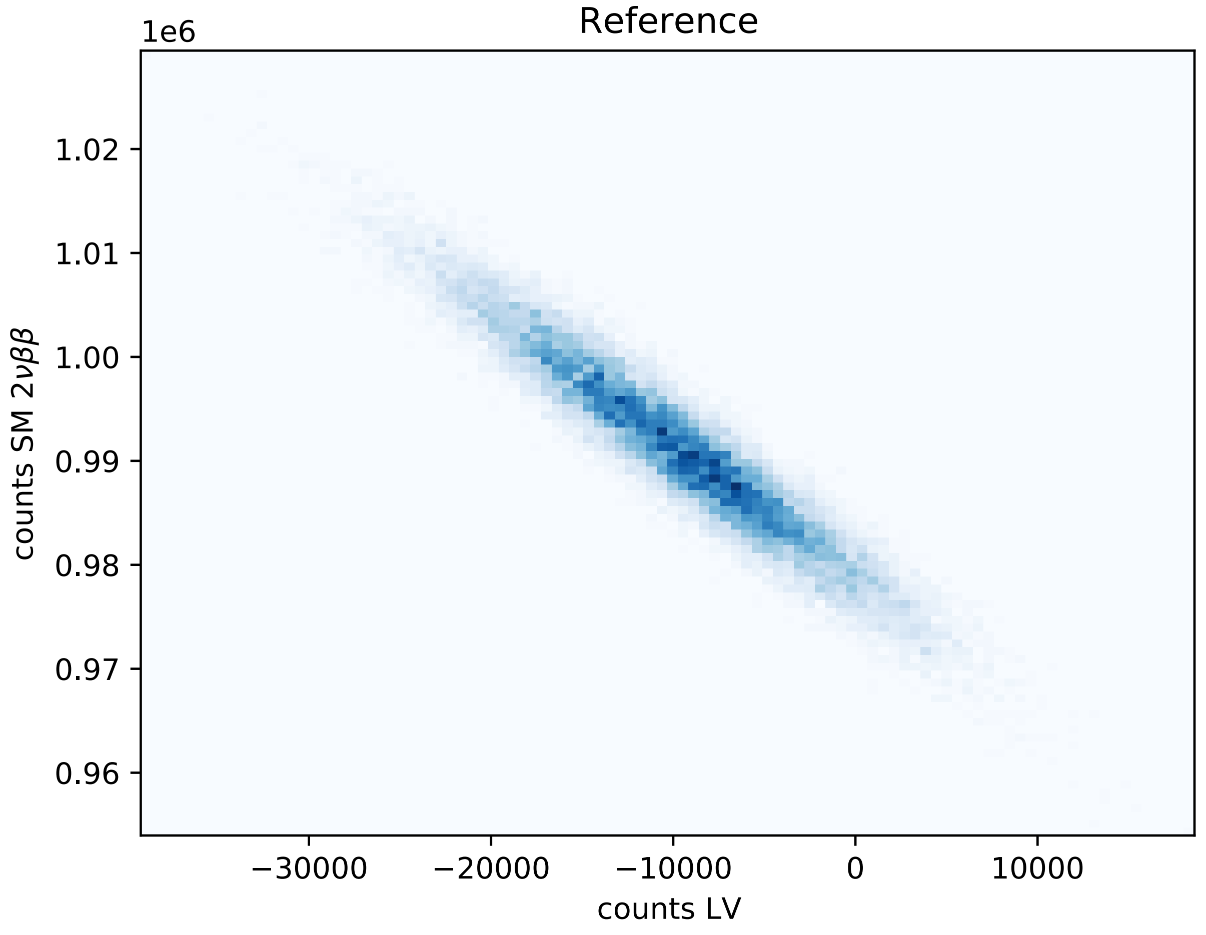
CUPID-Mo SSD limit

$$-8.1 \cdot 10^{-6} < \dot{a}^{(3)}_{of} < 2.2 \cdot 10^{-6}$$

CUPID-Mo improved model limit

$$-6.5 \cdot 10^{-6} < \dot{a}^{(3)}_{of} < 2.5 \cdot 10^{-5}$$

SSD



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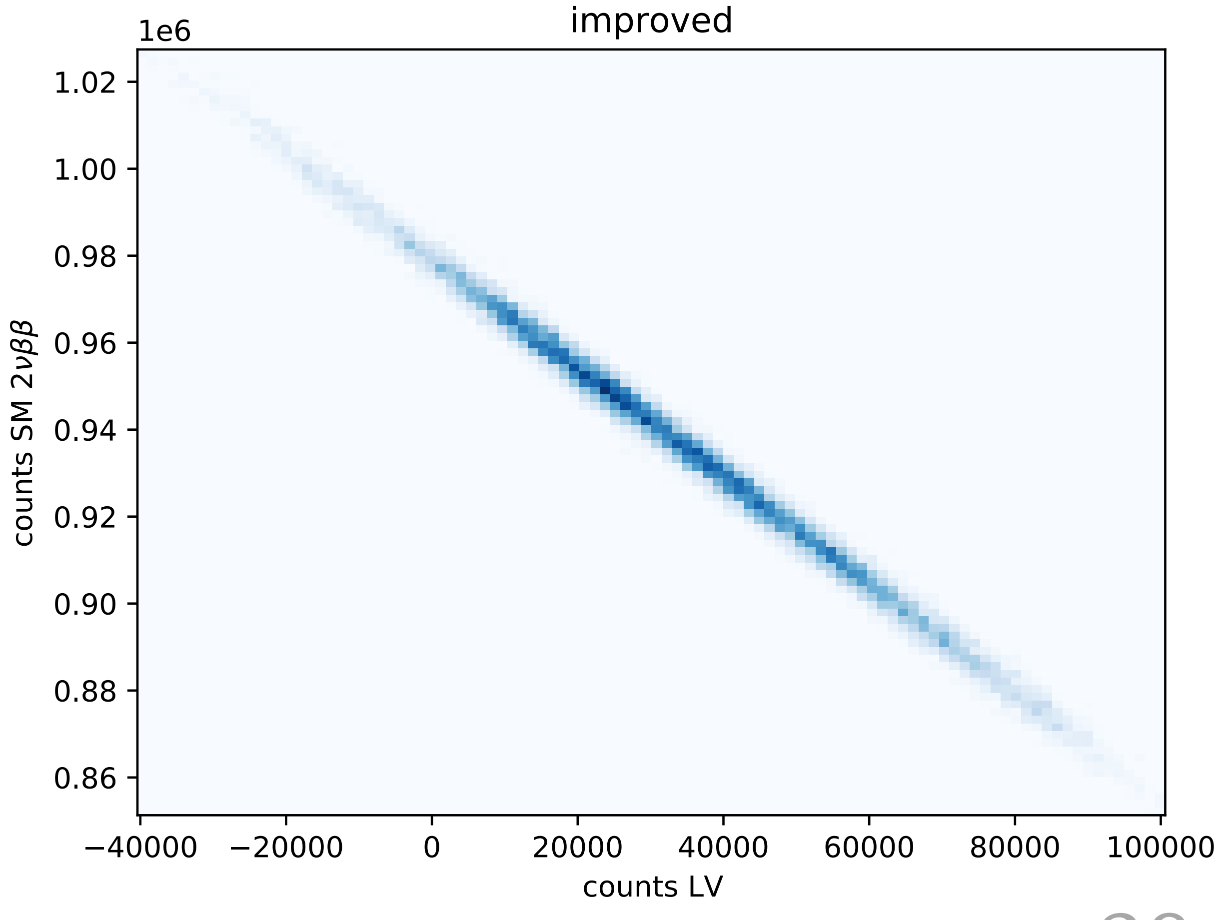
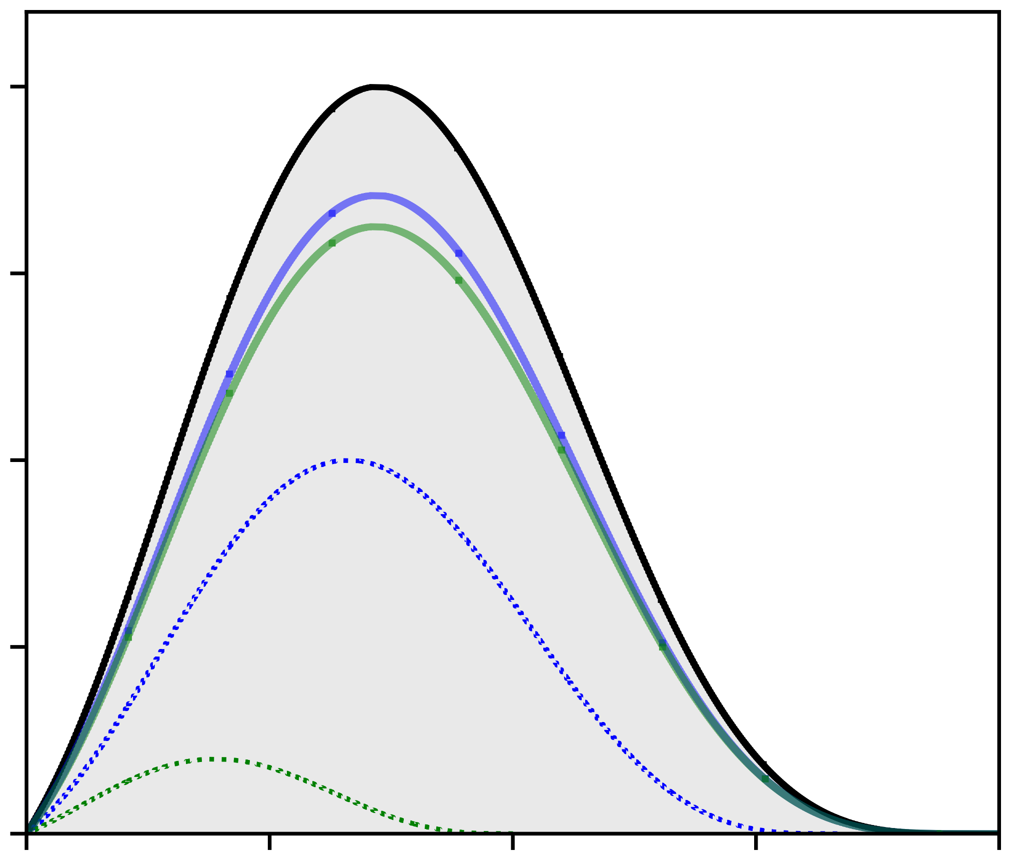
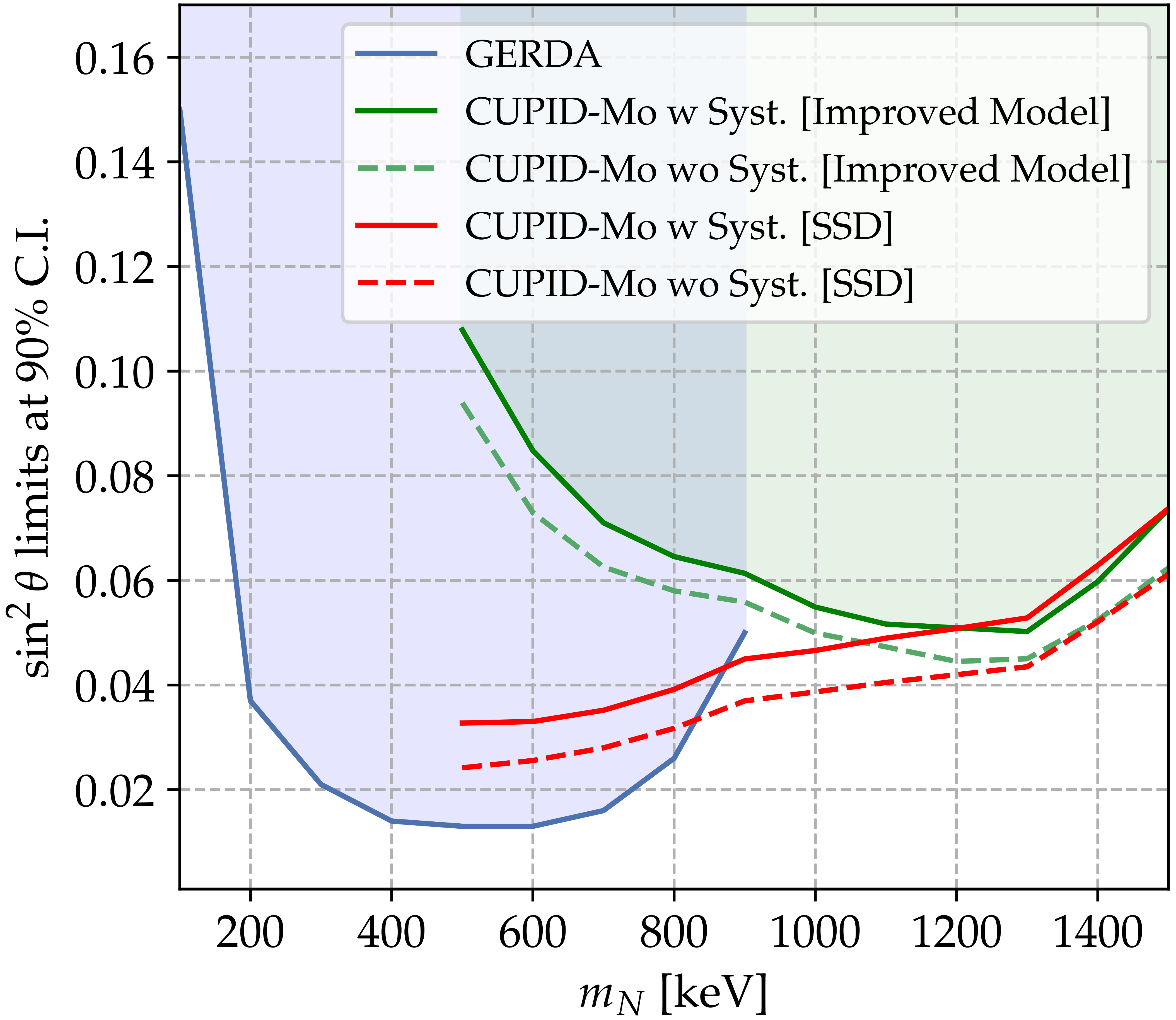


Results: Sterile neutrino emission

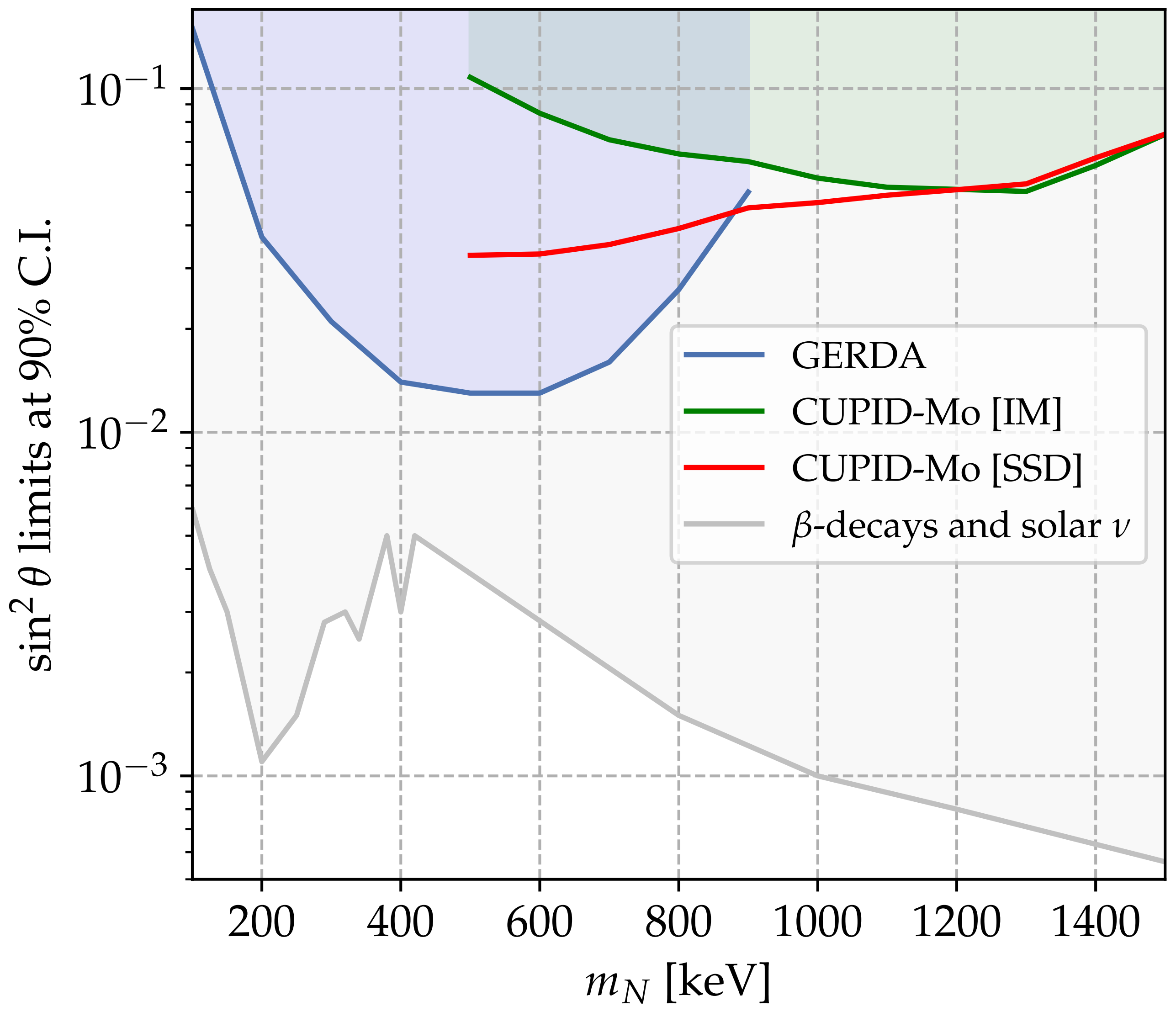
- First limit on sterile neutrino mixing angles from a bolometric experiment
- The large $Q_{\beta\beta}$ of ^{100}Mo allows to investigate a larger range
- The uncertainties on the $2\nu\beta\beta$ shape affects mostly the low values of m_N

$$\sin^2\theta = \frac{G_{SM}}{2G_{\nu N}} \cdot \frac{\Gamma^m_{\nu N}}{\Gamma^m_{SM}}$$





Still far from exploring the not-excluded region



Outline

CUPID will be the experiment with the largest amount of $2\nu\beta\beta$ events ever collected

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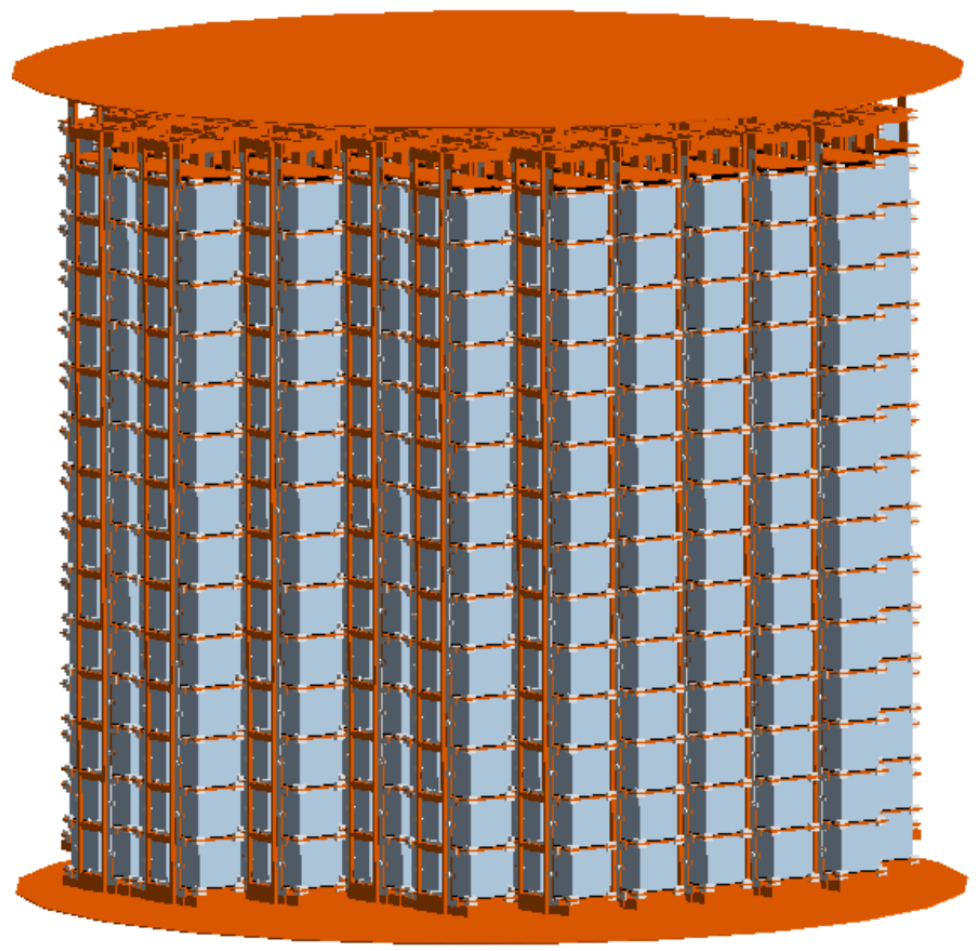
CUPID sensitivity studies

Construction of the CUPID Background Budget

Project the CUPID background on toy spectra



Knowledge of radioactive contaminants

Multivariate bayesian fit with new physics hypotheses

CUPID-0,CUPID-Mo and CUORE background model

Sensitivity estimation

Preliminary background projection

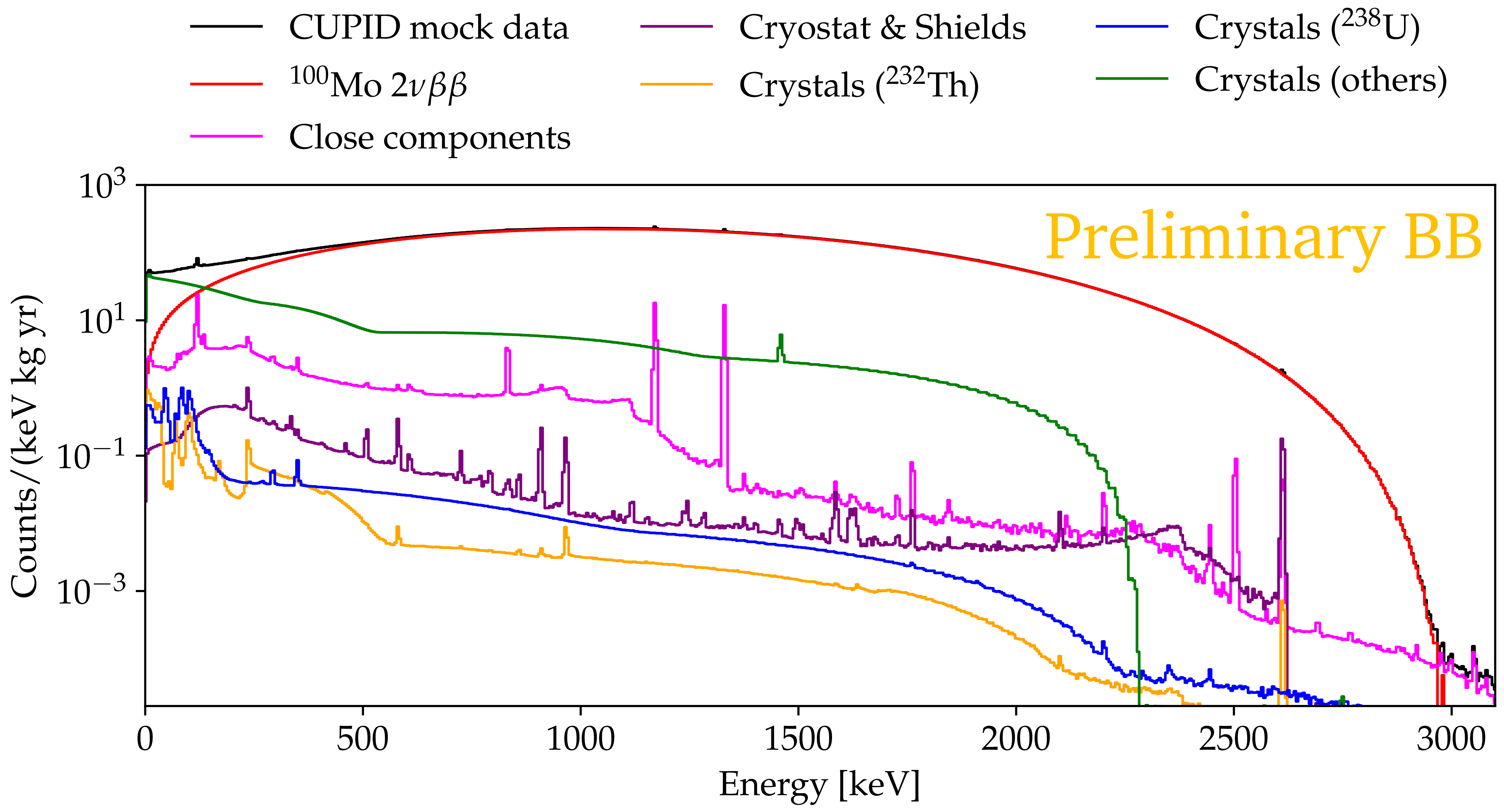
Most common radioactive sources:

- Long-living radioactive nuclei: ^{232}Th, ^{238}U and ^{40}K
- Anthropogenic radioactive isotopes such as ^{87}Rb and ^{90}Sr
- Cosmogenic activation products in holders and crystals

Only the SSD assumption for 2νββ was considered

Reference activities:

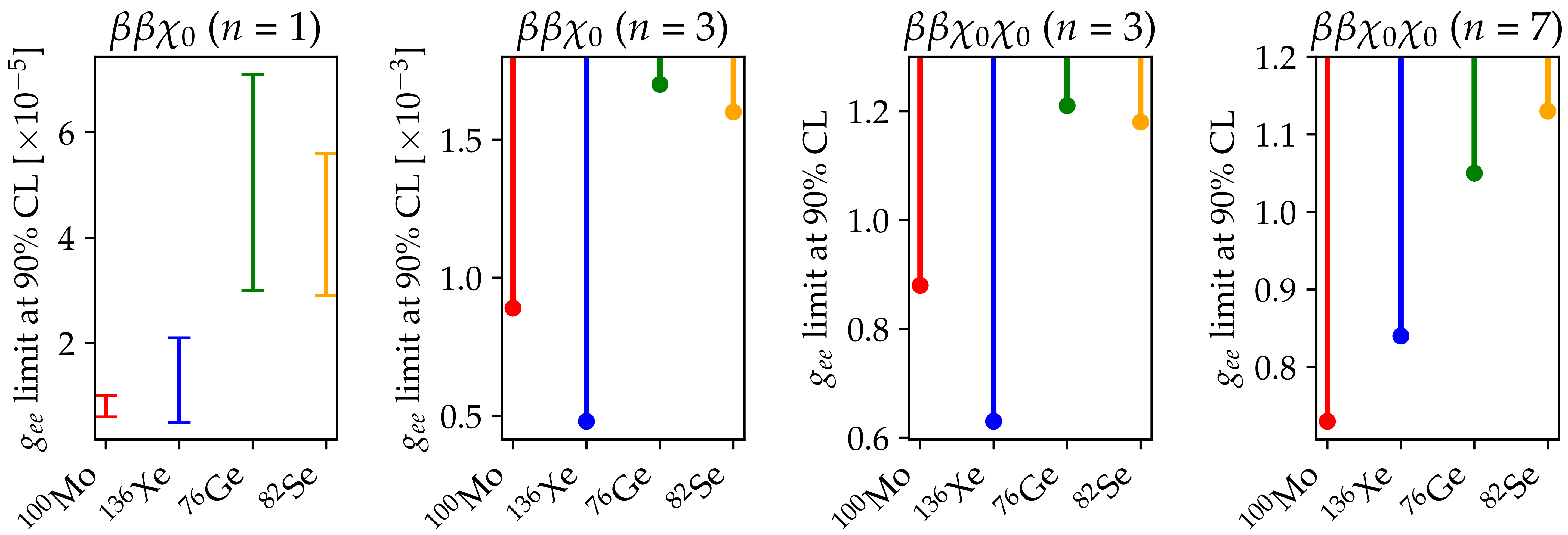
- Preliminary CUORE background model for cryostat and holders contaminants
- Preliminary CUPID-Mo background model for crystal contaminants
- ACTIVIA



Sensitivity: Majoron decays

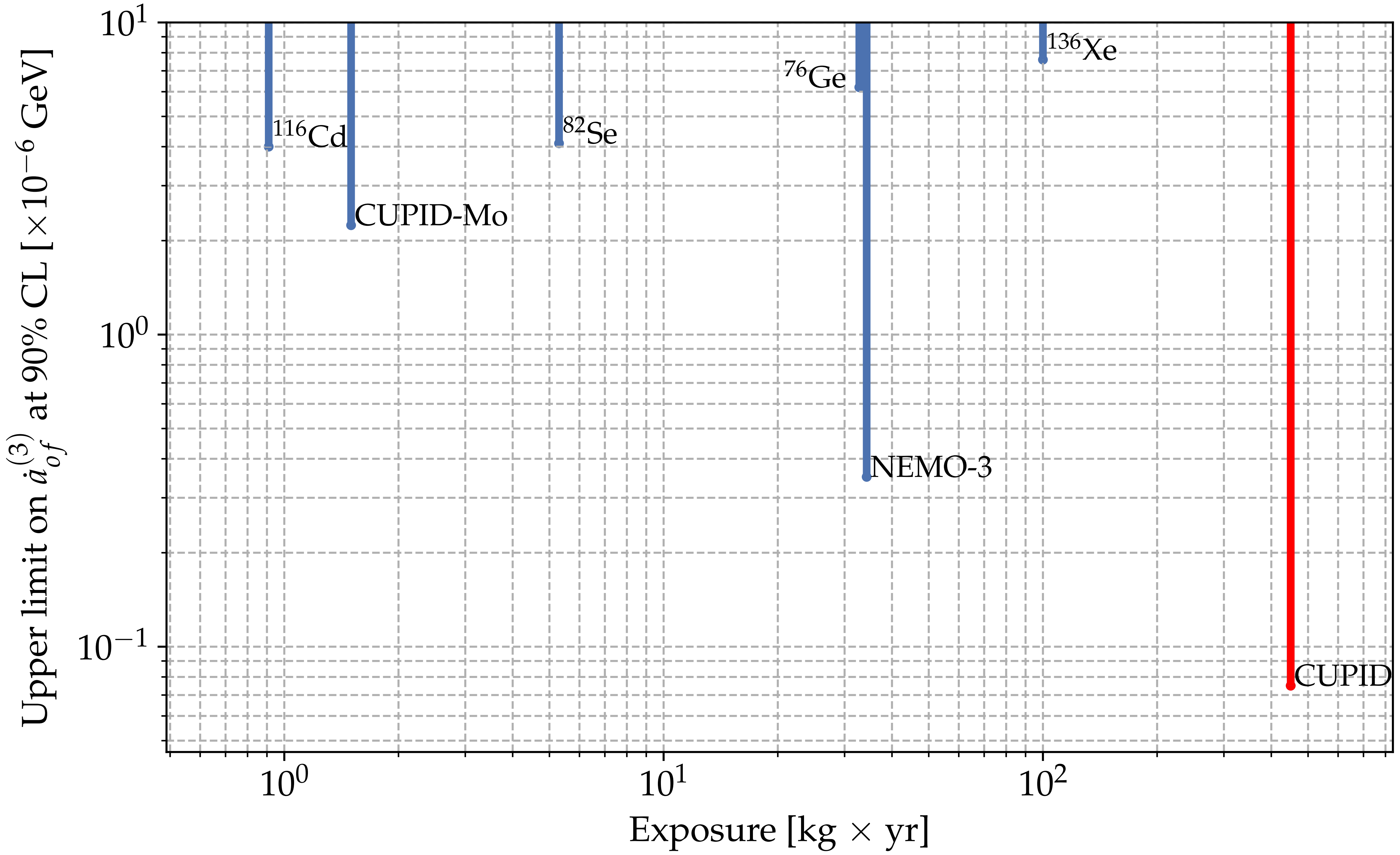
- 450 kg·yr of ^{100}Mo exposure (~2 years of CUPID data taking)
- With 450 kg·yr of ^{100}Mo the CUPID median exclusion sensitivity on the neutrino-Majoron coupling will be competitive with the limits set with ^{136}Xe

Decay mode	CUPID exclusion sensitivity		NEMO-3 [46, 135]	
	$T_{1/2}$ [yr]	g_{ee}^{M}	$T_{1/2}$ [yr]	g_{ee}^{M}
$\beta\beta\chi_0$ $(n=1)$	1.2×10^{24}	$(0.6 - 1.0)\times10^{-5}$	4.4×10^{22}	$(3.0-5.1)\times10^{-5}$
$\beta\beta\chi_0$ $(n=2)$	2.0×10^{23}	-	9.9×10^{21}	-
$\beta\beta\chi_0$ $(n=3)$	7.5×10^{22}	0.0089	4.4×10^{21}	0.023
$\beta\beta\chi_0\chi_0$ $(n=3)$	7.5×10^{22}	0.88	4.4×10^{21}	1.42
$\beta\beta\chi_0\chi_0$ $(n=7)$	1.9×10^{22}	0.73	1.2×10^{21}	1.15



Sensitivity: Lorentz violating 2νββ

With 450 kg·yr of ^{100}Mo we expect to reach the most stringent limit on the *countershaded* operator among 0νββ experiments



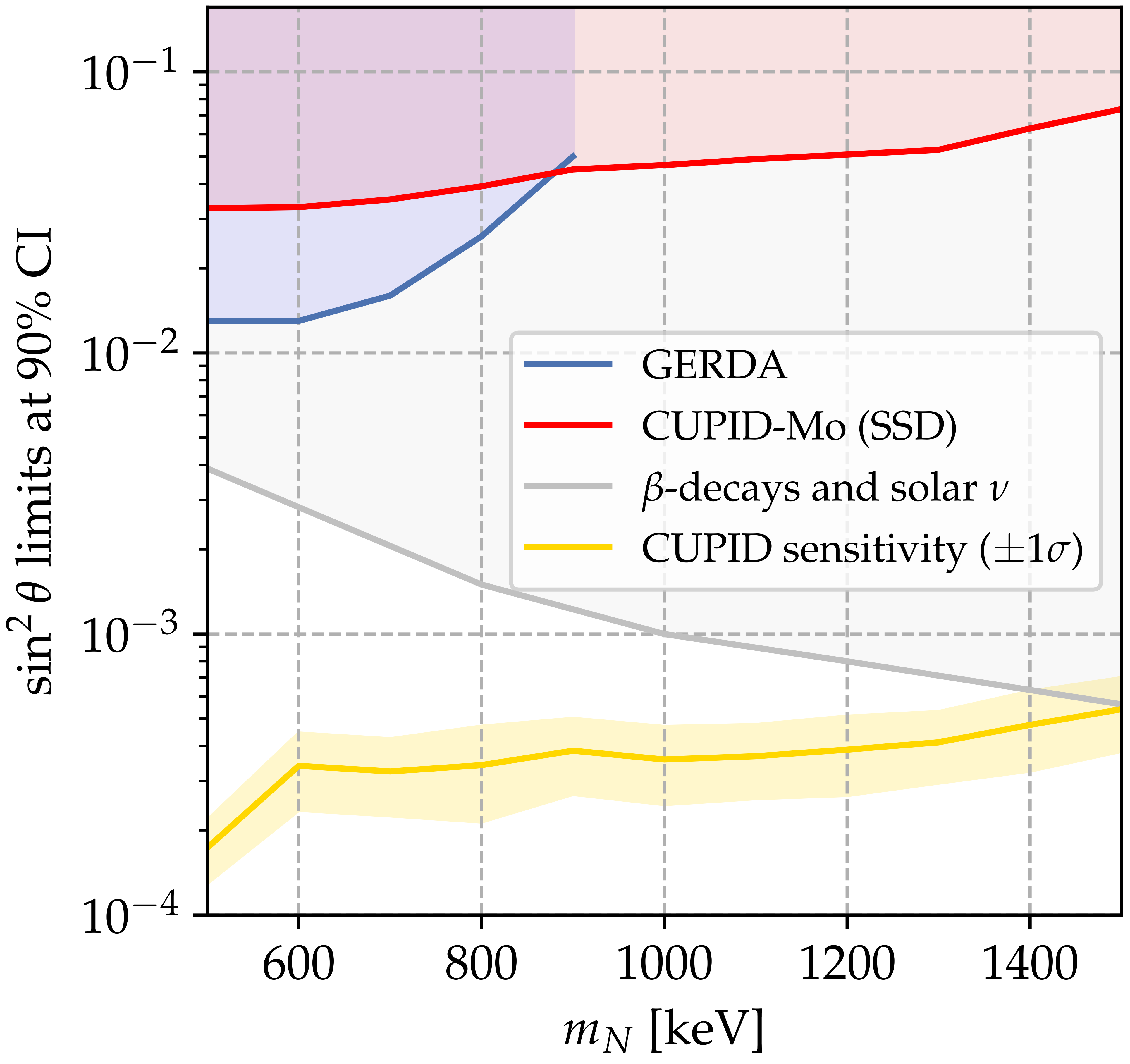
CUPID

$$-2.2 \cdot 10^{-7} < \dot{a}^{(3)}_{of} < 7.5 \cdot 10^{-8}$$

Isotope	Limit on $\dot{a}^{(3)}_{of}$ [GeV]
^{76}Ge	$(-2.7 < \dot{a}^{(3)}_{of} < 6.2) \cdot 10^{-6}$
^{82}Se	$\dot{a}^{(3)}_{of} < 4.1 \cdot 10^{-6}$
^{136}Xe	$-2.65 \cdot 10^{-5} < \dot{a}^{(3)}_{of} < 7.6 \cdot 10^{-6}$
^{116}Cd	$\dot{a}^{(3)}_{of} < 4.0 \cdot 10^{-6}$
^{100}Mo	$(-4.2 < \dot{a}^{(3)}_{of} < 3.5) \cdot 10^{-7}$
^{3}H	$\lvert\dot{a}^{(3)}_{of}\rvert < 3.0 \cdot 10^{-8}$

Sensitivity: Sterile neutrino emission

CUPID median exclusion sensitivity with 450 kg·yr of ^{100}Mo



Outline

1. Double-β decays
2. Scintillating cryogenic calorimeters
3. CUPID-0 combined background model
4. CUPID-Mo BSM studies
5. CUPID sensitivity
6. Conclusion and outlook

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Conclusions

- The increasing interest in the search for 0νββ leads experiments to reach higher and higher exposures
- The large statistic of 2νββ events collected by these experiments can be used to study the nuclear properties of 2νββ and to search for exotic double-β decays
- On this purpose, scintillating cryogenic calorimeters is a promising technology due to its excellent resolution, high detection efficiency and particle identification that allow the accurate background reconstruction
- In CUPID-0 we measured the unprecedented sensitivity the half-life of ^{82}Se 2νββ thanks to the excellent data reconstruction provided by the combined background model
- In CUPID-Mo we demonstrated the potential of Li_2MoO_4 based detectors in the search for exotic double-β decays, considering a systematic effect never considered before and paving the way for the future experiments
- The CUPID exclusion sensitivity demonstrates that we expect to set competitive limits on the exotic double-β decays parameters

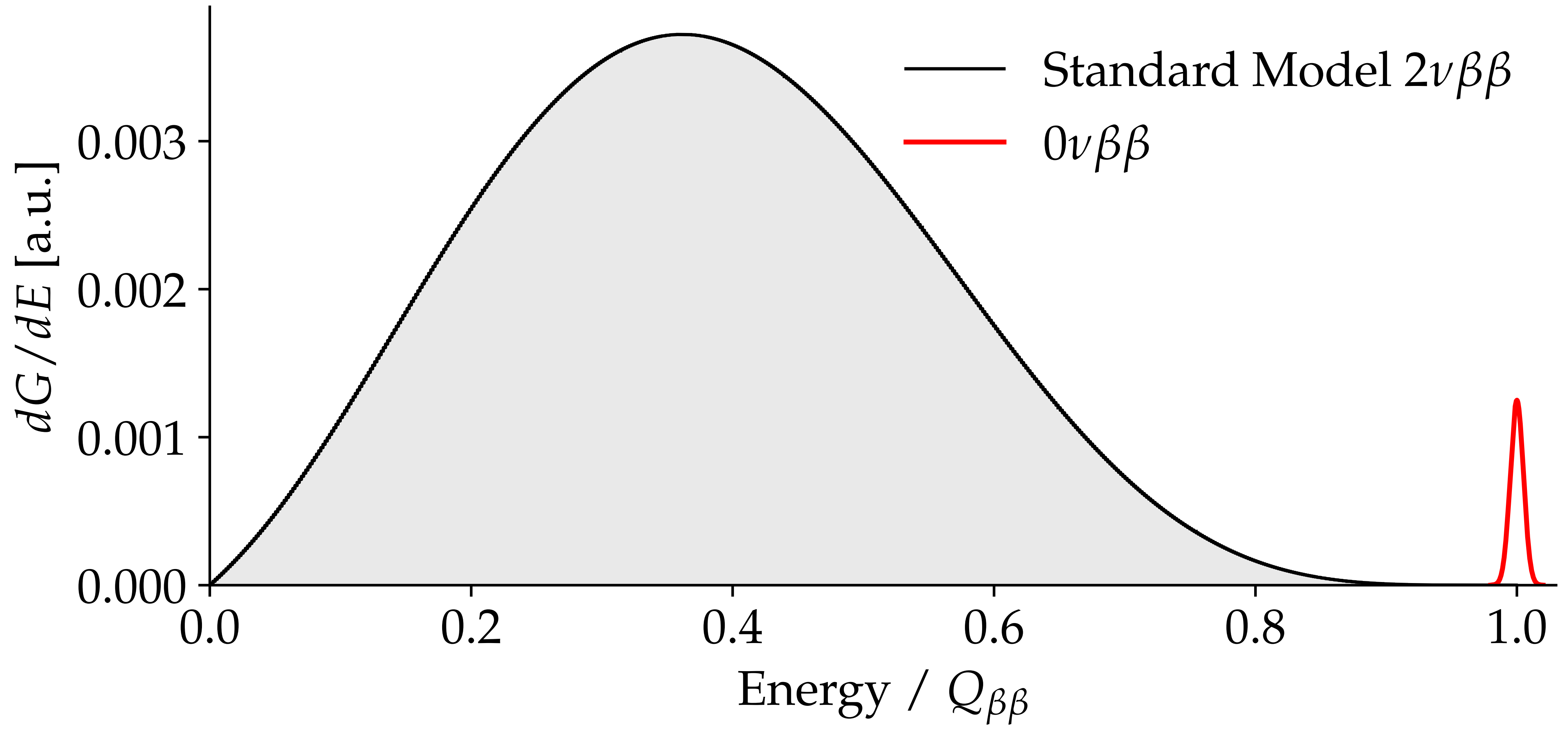
Thanks for the attention

Backup slides

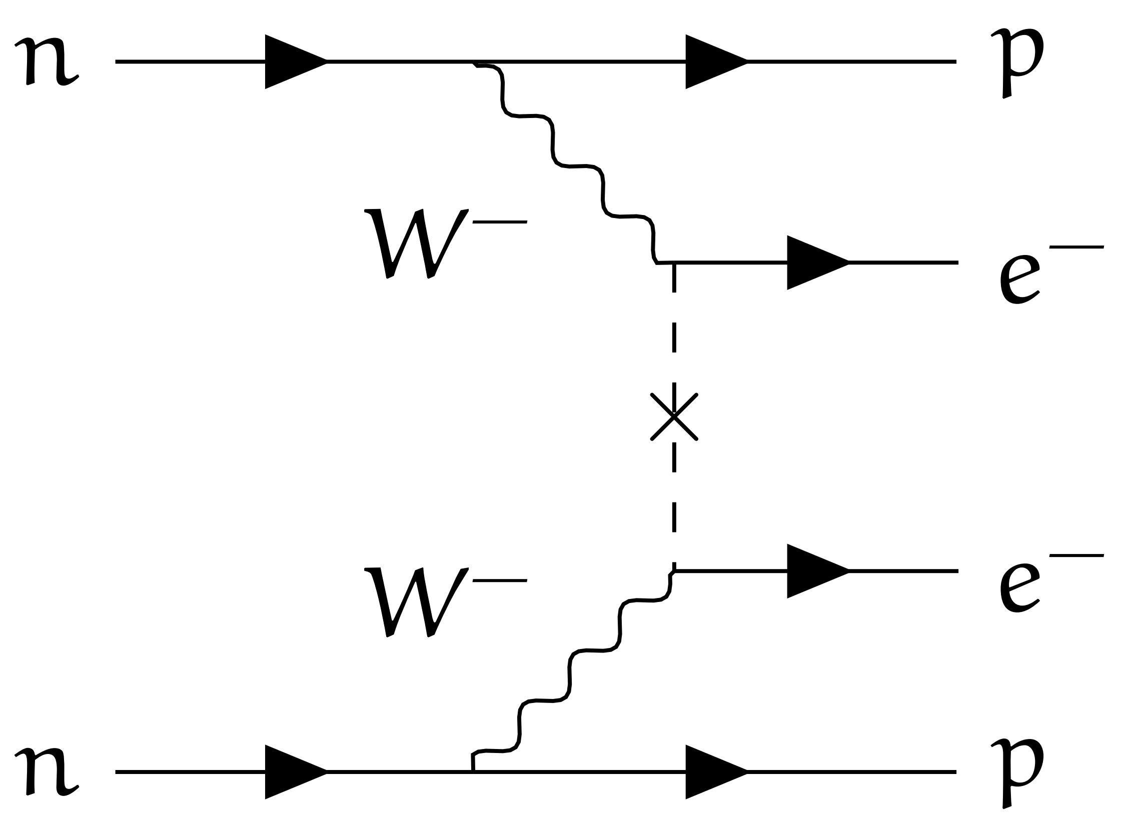
Neutrinoless double-β decay (0νββ)

0νββ is a nuclear process implying the decay of two neutrons into protons and electrons without the emission of antineutrinos.

- It would establish a total lepton number violation (ΔL = 2) not conserving the B-L symmetry of the SM
- Only practical way to probe that neutrinos are Majorana particles, validating the so called “see-saw” mechanism
- Its signature is a sharp peak at the Q-value of the decay



$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

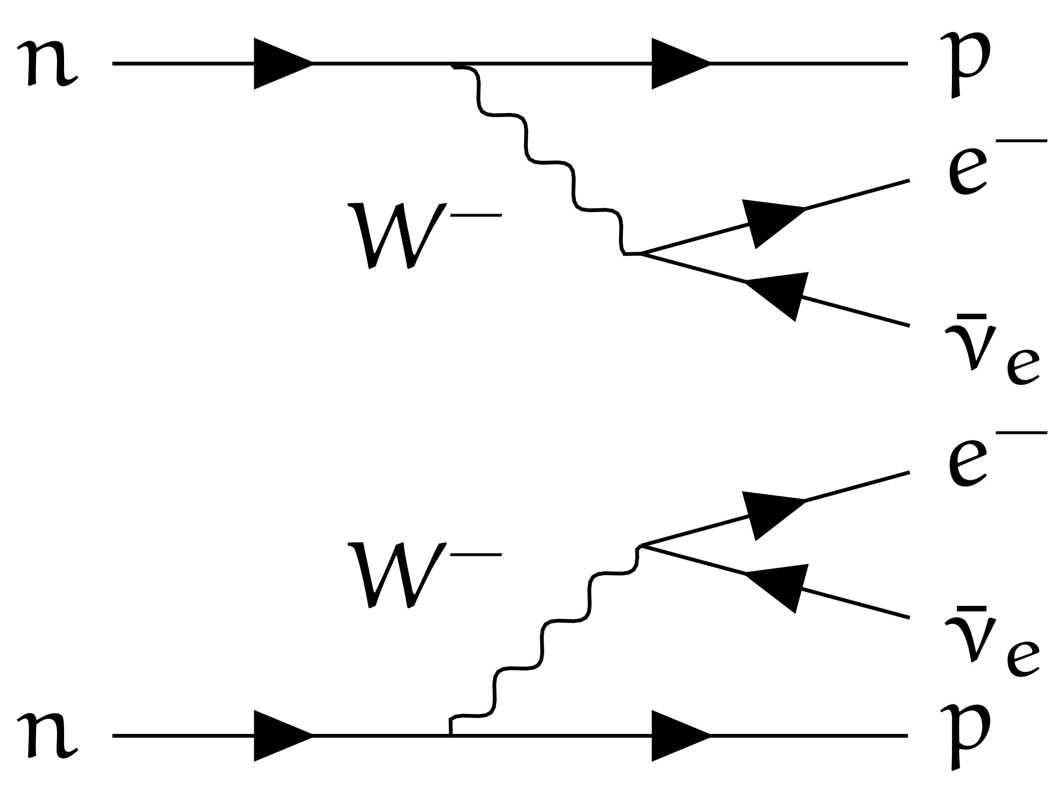


Isotope	$T^{0\nu}_{1/2}$ [y]
^{76}Ge	$> 1.8 \times 10^{26}$
^{82}Se	$> 4.6 \times 10^{24}$
^{100}Mo	$> 1.8 \times 10^{24}$
^{116}Cd	$> 2.2 \times 10^{23}$
^{130}Te	$> 2.2 \times 10^{25}$
^{136}Xe	$> 2.3 \times 10^{26}$

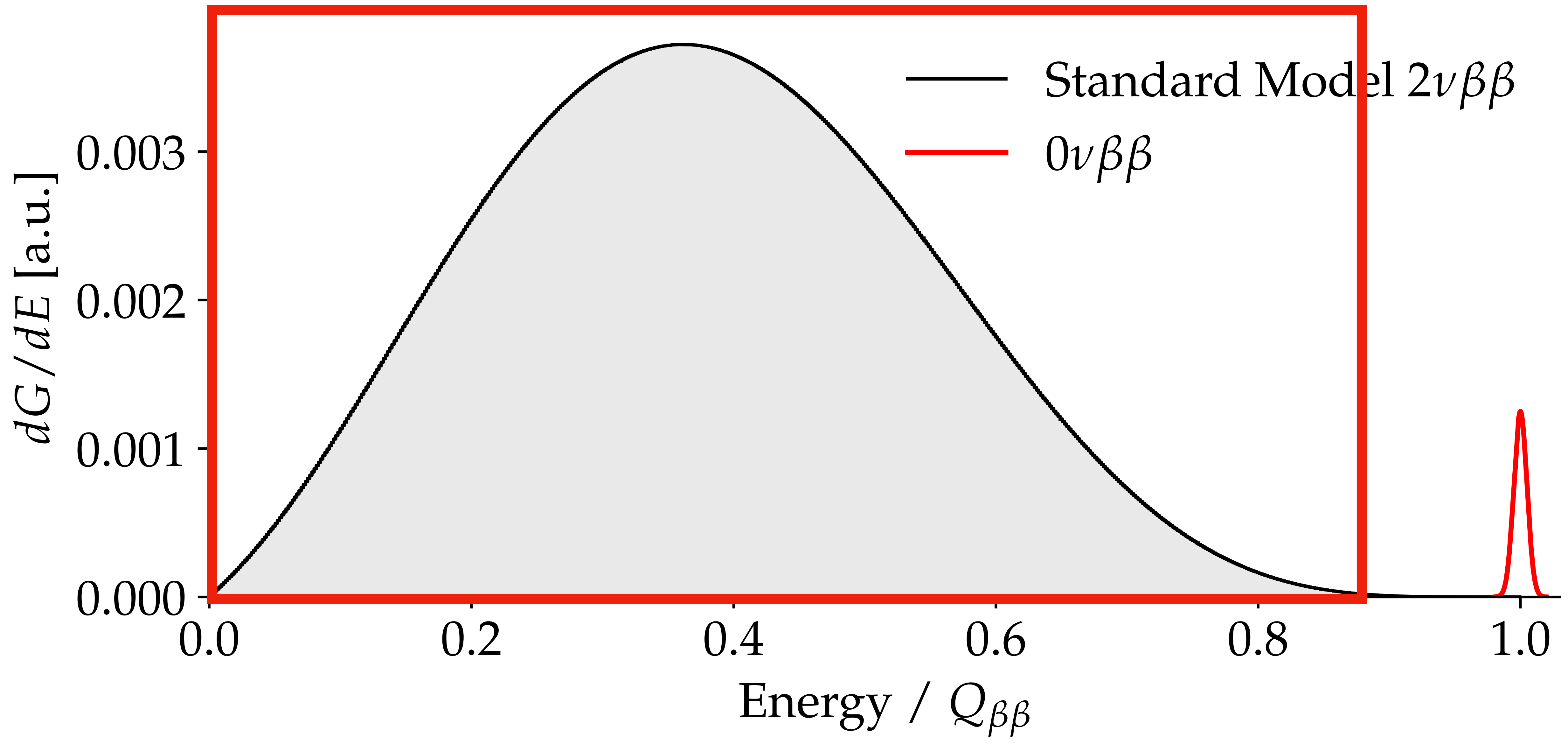
Two-neutrinos double-β decay (2νββ)

0νββ is a nuclear process implying the decay of two neutrons into protons, electrons and antineutrinos.

- SM allowed second order weak process which half-life spans the range 10^{18}-10^{21} years
- It has been observed for several nuclei



$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}$$

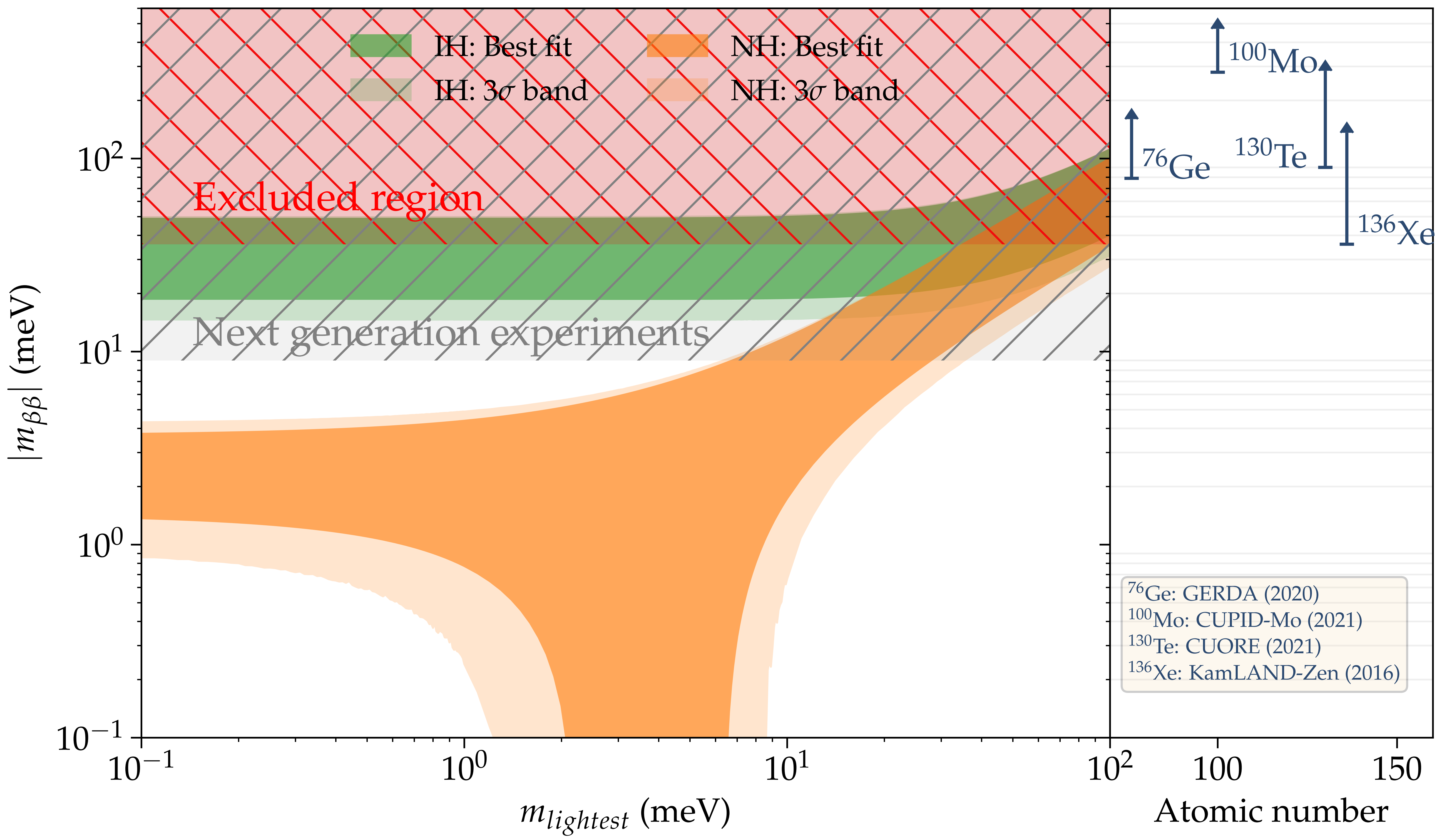


Isotope	$Q_{\beta\beta}$ [MeV]	$T^{2\nu}_{1/2}$ [yr]
^{48}Ca	4.263	$6.4^{+0.7}_{-0.6}$ (stat.)$^{+1.2}_{-0.9}$ (syst.) $\times 10^{19}$
^{76}Ge	2.039	2.022 ± 0.018 (stat.) ± 0.038 (syst.) $\times 10^{21}$
^{82}Se	2.998	8.69 ± 0.05 (stat.)$^{+0.09}_{-0.06}$ (syst.) $\times 10^{19}$
^{96}Zr	3.348	2.35 ± 0.14 (stat.) ± 0.16 (syst.) $\times 10^{19}$
^{100}Mo	3.035	7.07 ± 0.02 (stat.) ± 0.11 (syst.) $\times 10^{18}$
^{116}Cd	2.813	2.63 ± 0.01 (stat.)$^{+0.11}_{-0.13}$ (syst.) $\times 10^{19}$
^{130}Te	2.527	$8.76^{+0.09}_{-0.07}$ (stat.)$^{+0.14}_{-0.17}$ (syst.) $\times 10^{20}$
^{136}Xe	2.459	2.165 ± 0.016 (stat.) ± 0.059 (syst.) $\times 10^{21}$
^{150}Nd	3.371	9.34 ± 0.22 (stat.)$^{+0.62}_{-0.60}$ (syst.) $\times 10^{18}$

0νββ experimental limits

- The uncertainties on the nuclear matrix elements affects the limits on the effective Majorana mass
- The lobster plot shows which regions are favoured assuming Inverted Hierarchy and Normal Hierarchy

Isotope	$T^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [eV]
^{76}Ge	$> 1.8 \times 10^{26}$	$< (0.079 - 0.180)$
^{82}Se	$> 4.6 \times 10^{24}$	$< (0.263 - 0.545)$
^{100}Mo	$> 1.8 \times 10^{24}$	$< (0.280 - 0.490)$
^{116}Cd	$> 2.2 \times 10^{23}$	$< (1.0 - 1.7)$
^{130}Te	$> 2.2 \times 10^{25}$	$< (0.090 - 0.305)$
^{136}Xe	$> 2.3 \times 10^{26}$	$< (0.036 - 0.156)$



$$m_{\beta\beta} = \left| \sum_{j=1}^{3} U_{ej}^2 m_j \right| = \left| U_{e1}^2 m_1 + U_{e2}^2 e^{i\beta_1} m_2 + U_{e3}^2 e^{i\beta_2} m_3 \right|$$

Experimental sensitivity

We are looking for an extremely rare decay whose signature is a sharp peak, the sensitivity is half-life corresponding to the maximum signal that can be hidden by a background fluctuation:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{\ln 2}{n_\sigma}\frac{N_A i \epsilon}{A}\sqrt{\frac{Mt}{(BI)\Delta E}}$$

Where it assumes Poissonian background fluctuations in the region of interest (ROI). The dependence of the square root of the exposure (Mt) is the main limiting factor.

Nevertheless, if we assume zero-background in the ROI:

$$T_{0\nu} > \ln 2 \frac{x\eta\epsilon N_A}{A}\frac{Mt}{n_L}$$

Zero background is the key ingredient to boost the sensitivity!

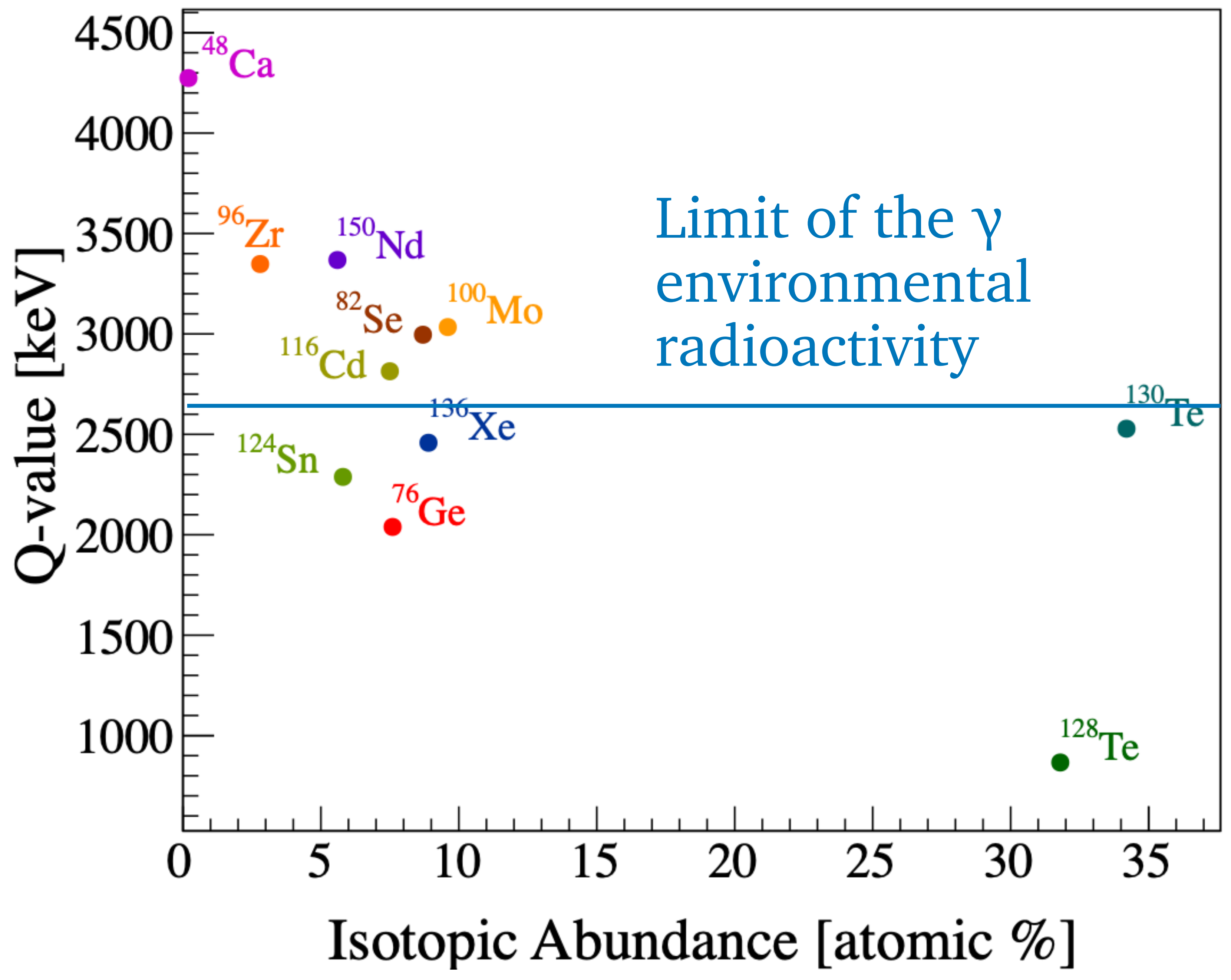
Experimental sensitivity

- **Large exposure** (Mt) necessary to reach high sensitivities (enrichment required for most of the candidate isotopes)

- **High Q-value**, for larger PSF and reject most of the environmental radioactivity

- **High detection efficiency** (ϵ)

- **High energy resolution** (ΔE)



- (BI) = background index

Formula with background:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{\ln 2}{n_\sigma} \frac{N_A i \epsilon}{A} \sqrt{\frac{Mt}{(BI)\Delta E}}$$

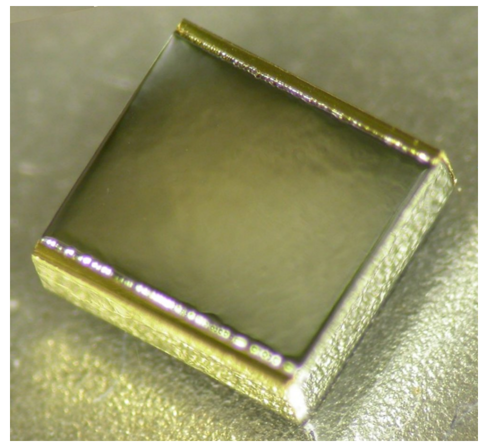
Formula without background:

$$T_{0\nu} > \ln 2 \frac{x\eta\epsilon N_A}{A} \frac{Mt}{n_L}$$

NTD-Ge thermistors

- For macro-calorimeters the best temperature sensor is the Neutrons Transmutation Doped Ge thermistor, Small Ge crystals with a extremely high and uniform distribution of impurities, obtained exposing the the Ge-wafer to a neutron beam

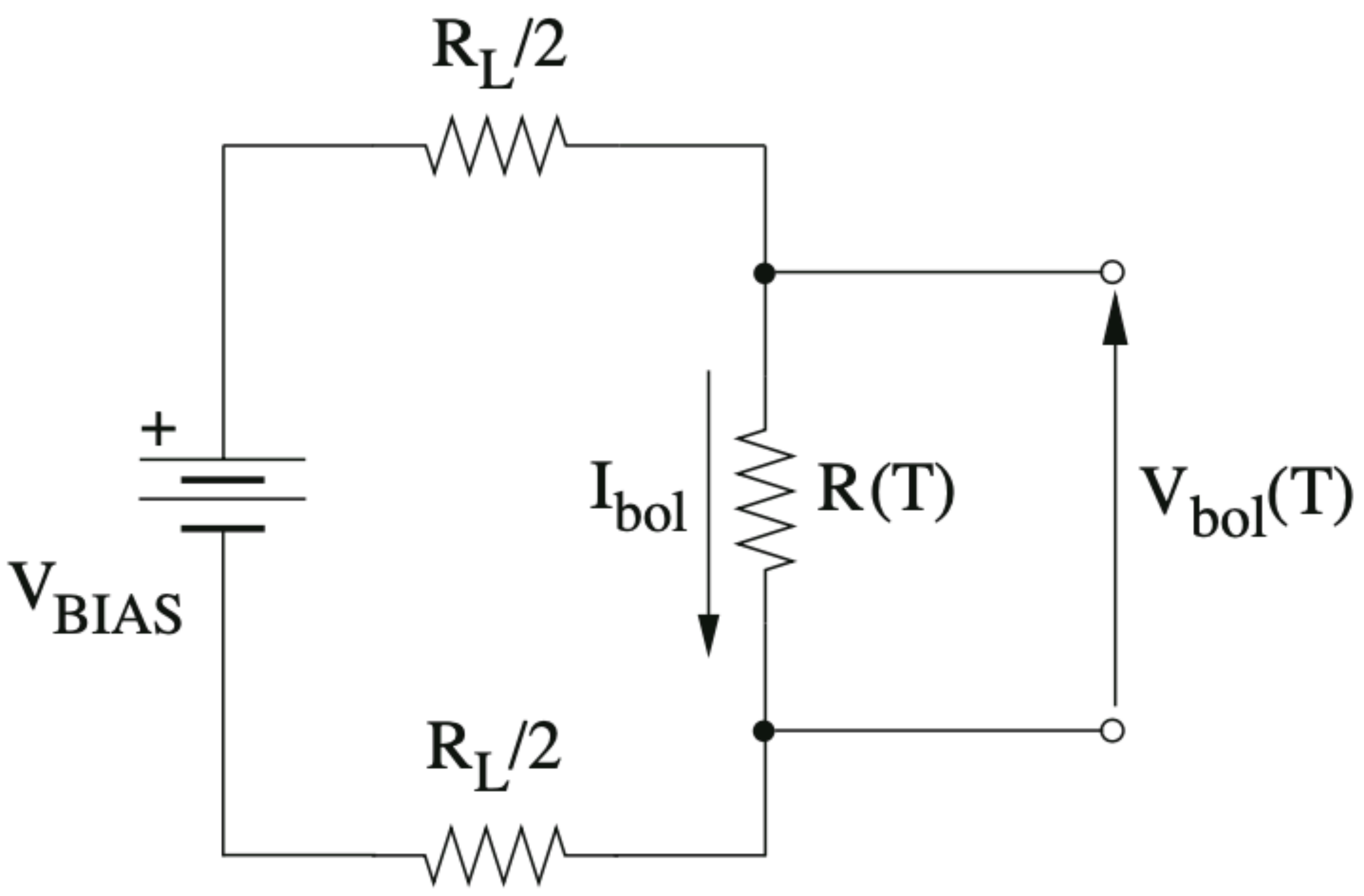
$$R(T) = R_0 \exp \left(T_0 / T \right)^{\gamma}$$

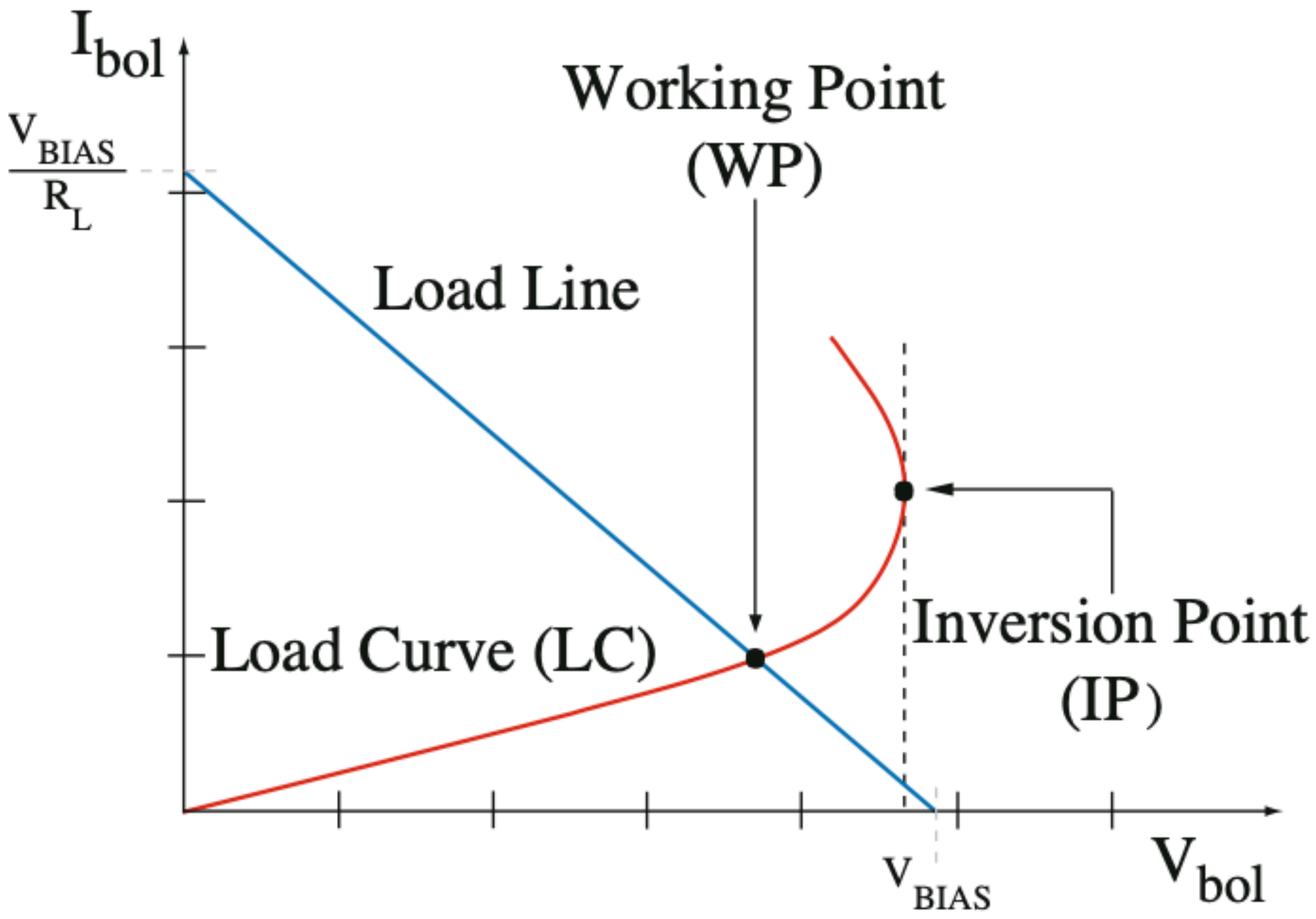


- Each crystal is equipped with one NTD and one heater, used to inject artificial pulses to characterize the sensor performances and stabilize drifts in temperature

- Thermal and electric contact made with 50 μm gold wires thermally coupled to the thermal bath

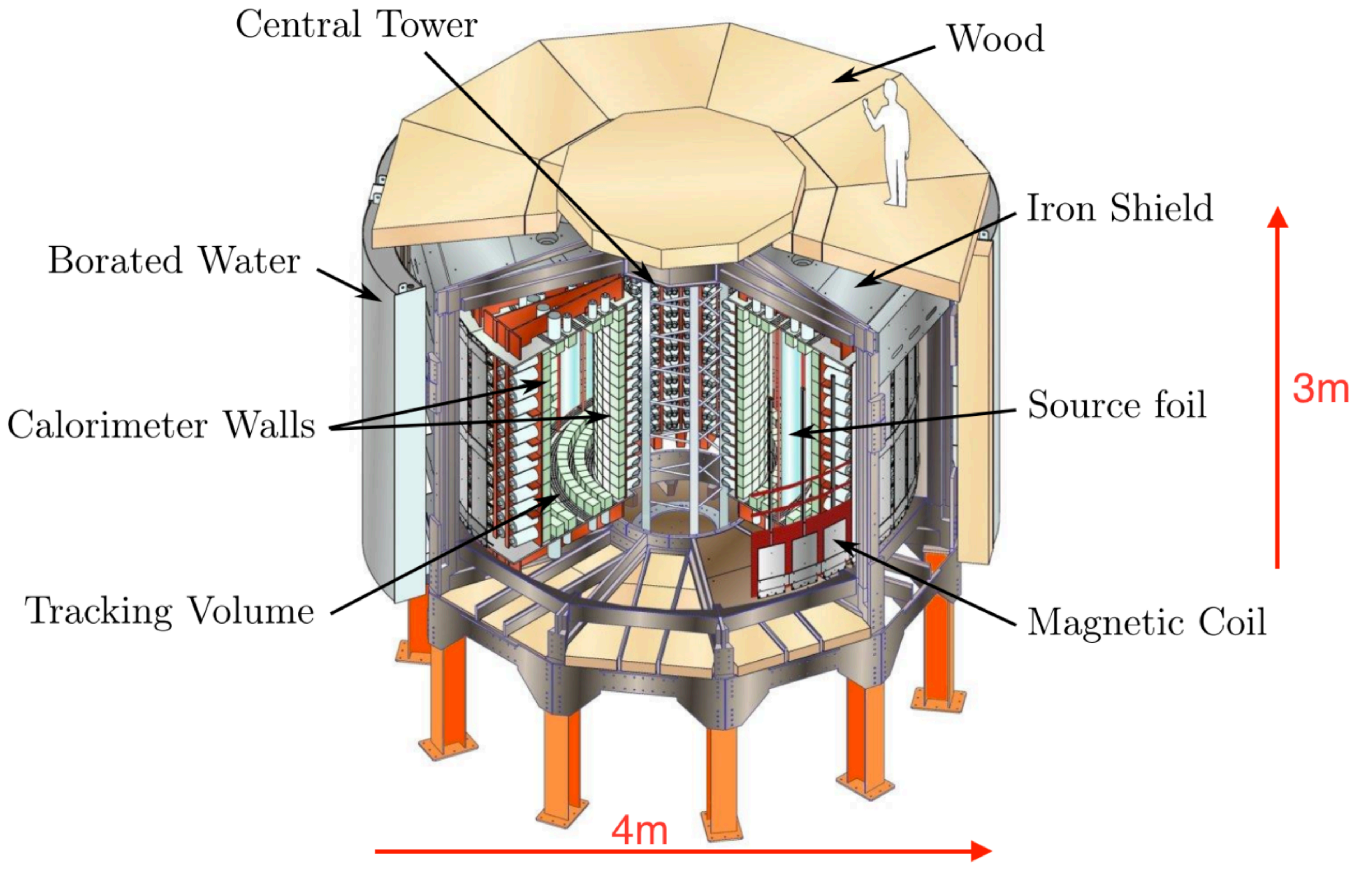
NTD-Ge thermistors: read-out

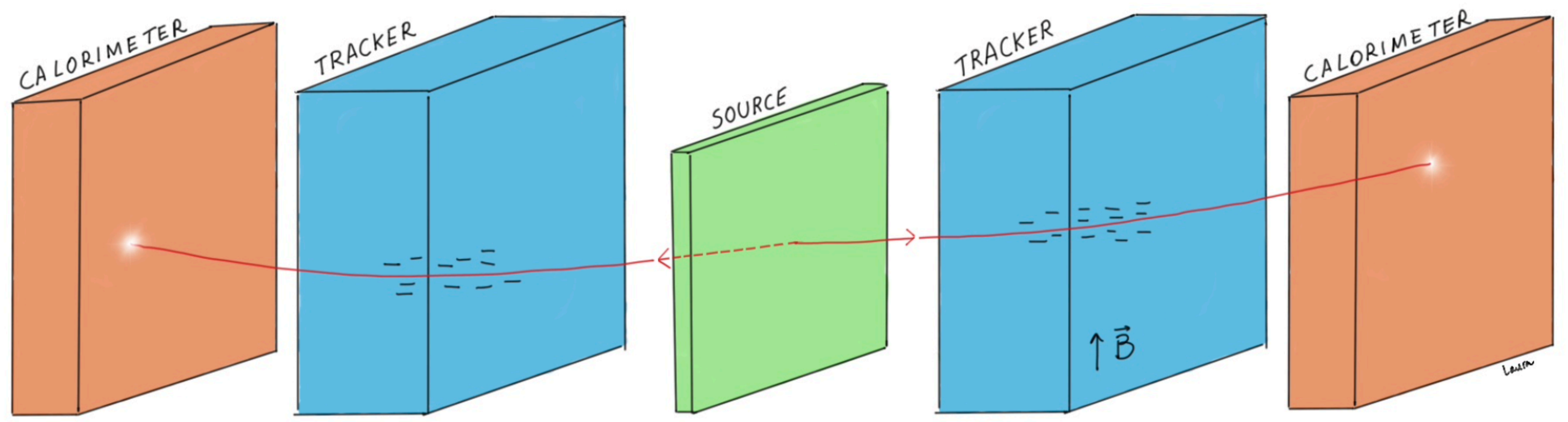


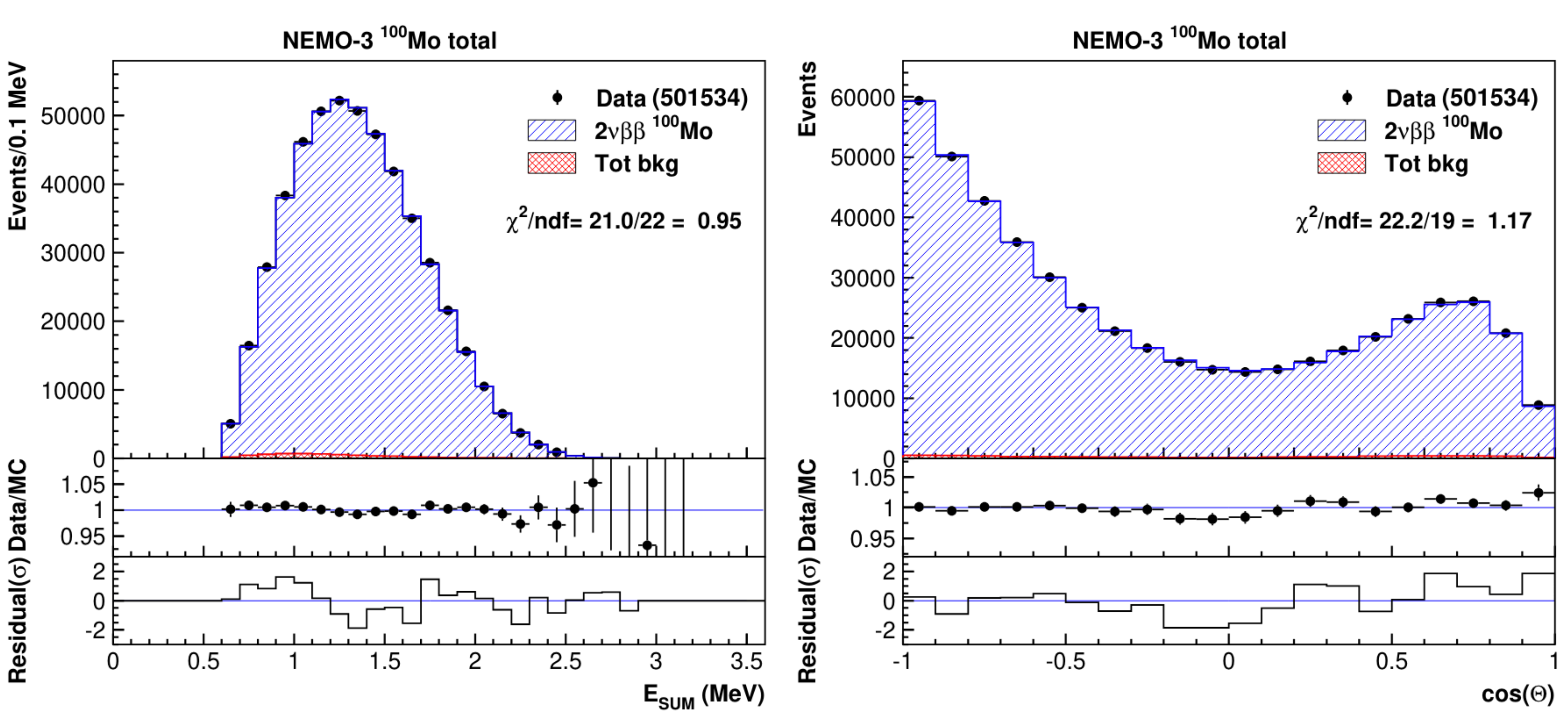


NEMO-3 experiment

- Tracking calorimeters
- Detection of both electrons emitted separately → possibility to measure the angle between the two electrons emitted
- energy resolution of a single calorimeter σ ~100 keV
- Detector acceptance and selection efficiency ε = (2.356 ± 0.002)%







Majoron emitting modes

One (ββχ₀) or two (ββχ₀χ₀) Majorons can be emitted according to the different models

The parameter of interest is the neutrino-Majoron coupling:

$$[T^{1/2}_{0\nu M}]^{-1} = G_{0\nu M} \left| \langle g^M_{ee} \rangle \right|^{2m} \left| M_{0\nu M} \right|^2$$

model	spectral index	Decay mode	NG boson	ΔL	Ref.
IB IC IIB	1	$\beta\beta\chi_0$	No Yes No	0 0 -2	[121]
"bulk"	2	$\beta\beta\chi_0$	bulk field	0	[123]
IIF IIC	3	$\beta\beta\chi_0$	Gauge boson Yes	-2 -2	[122] [121]
ID IE IID	3	$\beta\beta\chi_0\chi_0$	No Yes No	0 0 -1	[121]
IIE	7	$\beta\beta\chi_0\chi_0$	Yes	-2	[124]

decay mode	$T_{1/2}$ [yr]	G [$\times 10^{-18}$yr^{-1}]	NME	g_{ee} lower limit
^{76}Ge [133]				
$\beta\beta\chi_0$ ($n=1$)	$> 6.4 \times 10^{23}$	44.2	(2.66 - 6.34)	$(3.0 - 7.1) \times 10^{-5}$
$\beta\beta\chi_0$ ($n=2$)	$> 2.9 \times 10^{23}$	-	-	-
$\beta\beta\chi_0$ ($n=3$)	$> 1.2 \times 10^{23}$	0.073	0.381	1.7×10^{-2}
$\beta\beta\chi_0\chi_0$ ($n=3$)	$> 1.2 \times 10^{23}$	0.22	0.0026	1.21
$\beta\beta\chi_0\chi_0$ ($n=7$)	$> 1.1 \times 10^{23}$	0.420	0.0026	1.05
^{82}Se [134]				
$\beta\beta\chi_0$ ($n=1$)	$> 1.2 \times 10^{23}$	361	(2.72 - 5.30)	$(2.9 - 5.6) \times 10^{-5}$
$\beta\beta\chi_0$ ($n=2$)	$> 3.8 \times 10^{22}$	-	-	-
$\beta\beta\chi_0$ ($n=3$)	$> 1.4 \times 10^{22}$	1.22	0.305	1.6×10^{-2}
$\beta\beta\chi_0\chi_0$ ($n=3$)	$> 1.4 \times 10^{22}$	3.54	0.002	1.18
$\beta\beta\chi_0\chi_0$ ($n=7$)	$> 2.2 \times 10^{21}$	26.9	0.002	1.13
^{100}Mo [46, 135]				
$\beta\beta\chi_0$ ($n=1$)	$> 4.4 \times 10^{22}$	598	(3.84 - 6.59)	$(3.0 - 5.1) \times 10^{-5}$
$\beta\beta\chi_0$ ($n=2$)	$> 9.9 \times 10^{21}$	-	-	-
$\beta\beta\chi_0$ ($n=3$)	$> 4.4 \times 10^{21}$	2.42	0.263	2.3×10^{-2}
$\beta\beta\chi_0\chi_0$ ($n=3$)	$> 4.4 \times 10^{21}$	6.15	0.0019	1.42
$\beta\beta\chi_0\chi_0$ ($n=7$)	$> 1.2 \times 10^{21}$	50.8	0.0019	1.15
^{116}Cd [57]				
$\beta\beta\chi_0$ ($n=1$)	$> 8.2 \times 10^{21}$	569	(3.105 - 5.43)	$(8.5 - 15) \times 10^{-5}$
$\beta\beta\chi_0$ ($n=2$)	$> 4.1 \times 10^{21}$	-	-	-
$\beta\beta\chi_0$ ($n=3$)	$> 2.6 \times 10^{21}$	2.28	0.144	5.6×10^{-2}
$\beta\beta\chi_0\chi_0$ ($n=3$)	$> 2.6 \times 10^{21}$	5.23	0.0009	2.37
$\beta\beta\chi_0\chi_0$ ($n=7$)	$> 8.9 \times 10^{20}$	33.9	0.0009	1.94
^{136}Xe [131, 132]				
$\beta\beta\chi_0$ ($n=1$)	$> 2.6 \times 10^{24}$ $> 4.3 \times 10^{24}$	409	(1.11 - 4.77)	$(0.6 - 2.8) \times 10^{-5}$ $(0.5 - 2.1) \times 10^{-5}$
$\beta\beta\chi_0$ ($n=2$)	$> 1.0 \times 10^{24}$ $> 9.8 \times 10^{23}$	-	-	- -
$\beta\beta\chi_0$ ($n=3$)	$> 4.5 \times 10^{23}$ $> 6.3 \times 10^{23}$	1.47	0.160	4.8×10^{-3} 4.0×10^{-3}
$\beta\beta\chi_0\chi_0$ ($n=3$)	$> 4.5 \times 10^{23}$ $> 6.3 \times 10^{23}$	3.05	0.0011	0.69 0.63
$\beta\beta\chi_0\chi_0$ ($n=7$)	$> 1.1 \times 10^{22}$ $> 5.1 \times 10^{22}$	12.5	0.0011	1.23 0.84

Lorentz violating 2νββ

SM is an effective quantum field theory that includes all possible operators that can be constructed with the SM fields and that introduce Lorentz violation but preserve the SM gauge invariance. Experimental searches for Lorentz violation are done in different sectors of physics, including **matter, photon, neutrino, and gravity**. Four operators, called *countershaded*, equally change all neutrino energies and have no impact on oscillations, therefore they are labeled as “oscillation free” (of) and can be studied only through weak decays.

$$p = (E, \mathbf{p}) \longrightarrow p = (E, \mathbf{p} + \mathbf{a}^{(3)}_{of} - \mathring{a}^{(3)}_{\text{of}} \hat{\mathbf{p}})$$

Lorentz violation does not affect the NME but appears as a kinematic effect modifying the phase space factor, thus the summed electron energy distribution:

$$\frac{d\Gamma^{2\nu}_{SME}}{dK} = |\mathcal{M}_{2\nu}|^2 \left(\frac{d\mathcal{G}_{SM}}{dK} + \frac{d(\delta\mathcal{G}_{LV})}{dK} \right)$$

Isotope	Limit on $\mathring{a}^{(3)}_{of}$ [GeV]
^{76}Ge	$(-2.7 < \mathring{a}^{(3)}_{of} < 6.2) \cdot 10^{-6}$
^{82}Se	$\mathring{a}^{(3)}_{of} < 4.1 \cdot 10^{-6}$
^{136}Xe	$-2.65 \cdot 10^{-5} < \mathring{a}^{(3)}_{of} < 7.6 \cdot 10^{-6}$
^{116}Cd	$\mathring{a}^{(3)}_{of} < 4.0 \cdot 10^{-6}$
^{100}Mo	$(-4.2 < \mathring{a}^{(3)}_{of} < 3.5) \cdot 10^{-7}$
^{3}H	$\lvert\mathring{a}^{(3)}_{of}\rvert < 3.0 \cdot 10^{-8}$

Sterile neutrino emissions

If the sterile neutrino N has a mass $m_N < Q_{\beta\beta}$, it can be emitted instead of an antineutrinos in the 2νββ (νNββ):

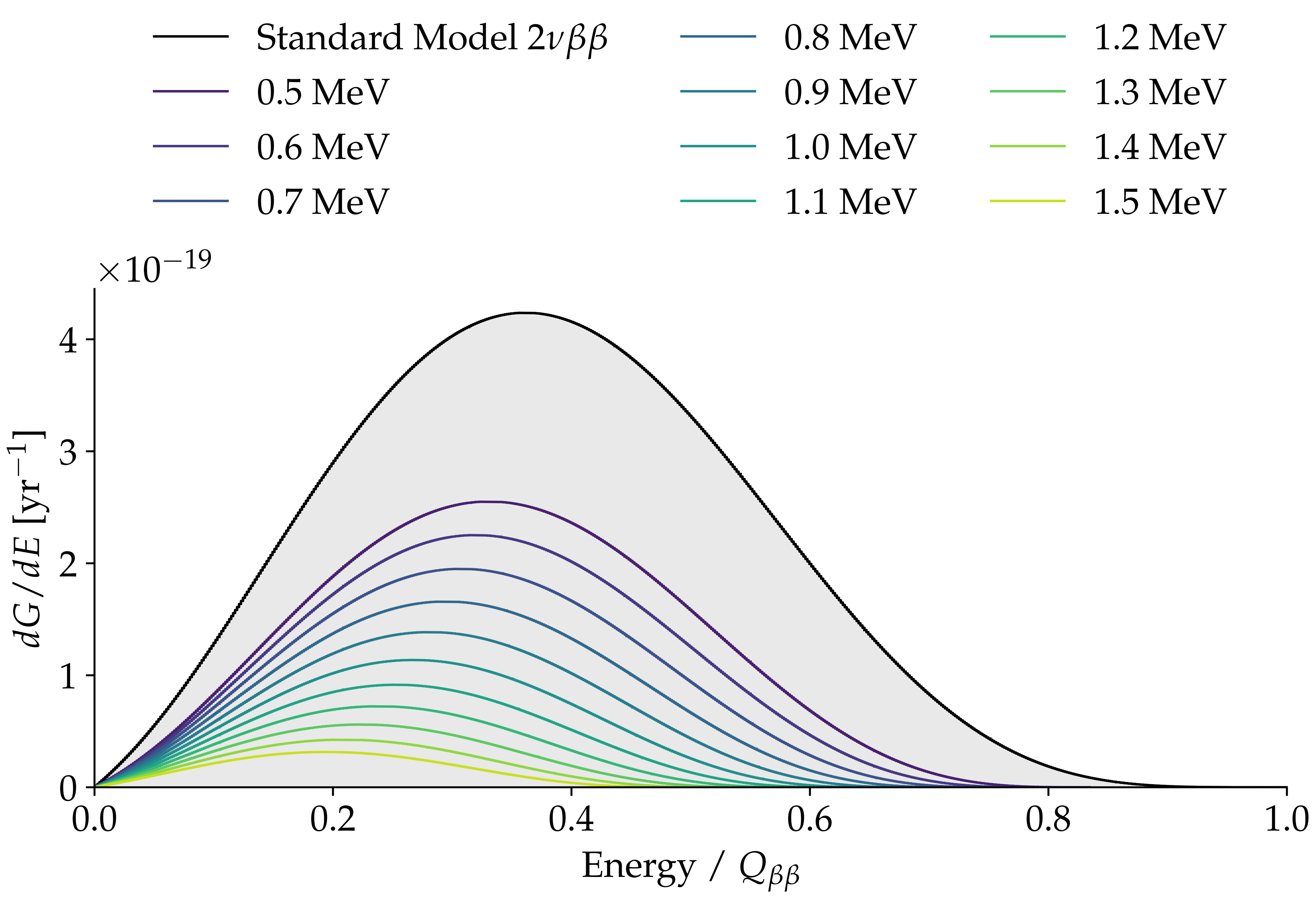
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \bar{\nu} + N$$

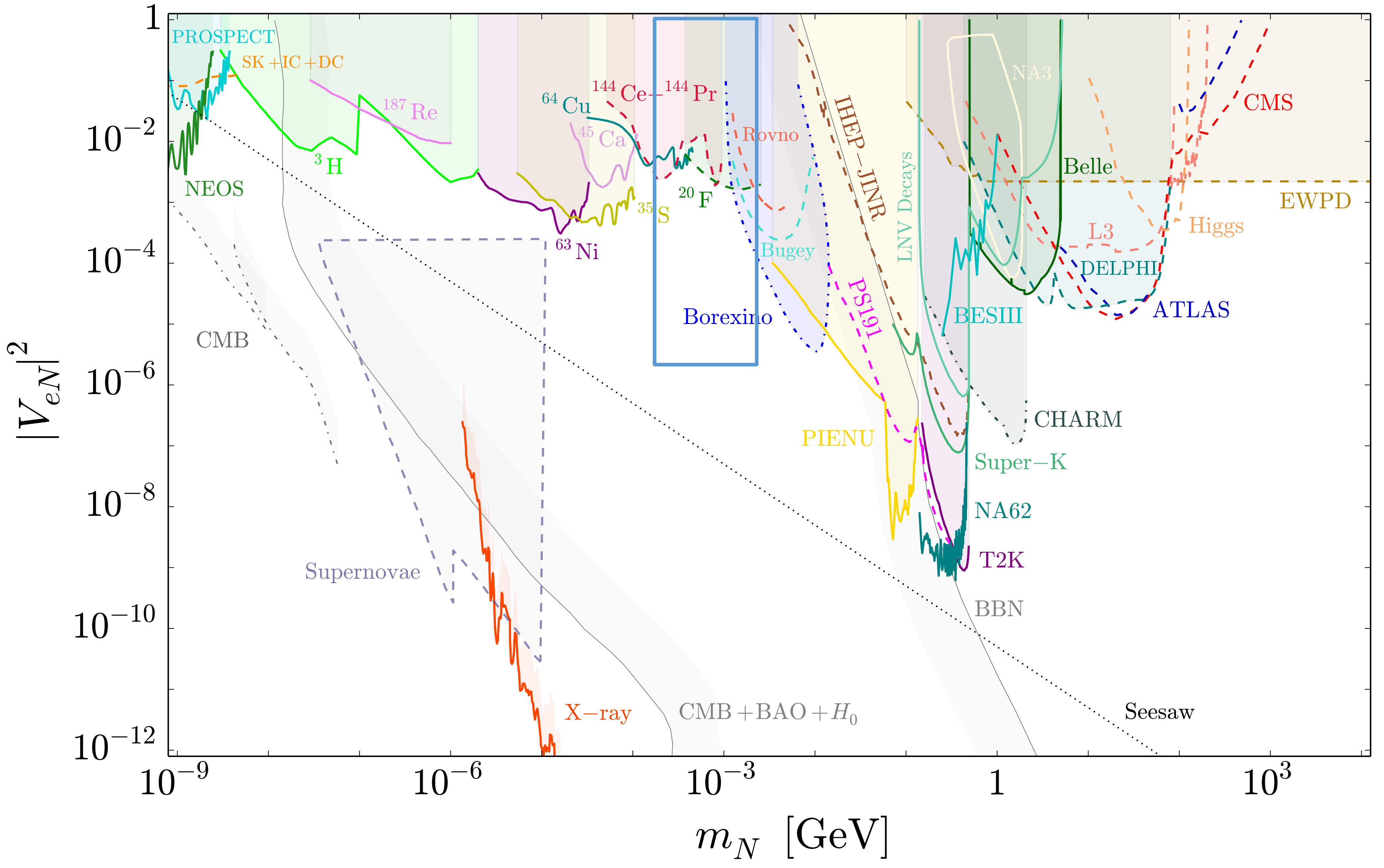
The effect on the total decay rate is:

$$\Gamma = \cos^4\theta\Gamma_{SM} + 2\cos^2\theta\sin^2\theta\Gamma_{\nu N}$$

Where $\sin^2\theta$ is called active-sterile mixing strength

We can set limits where the actual boundaries are relatively weak



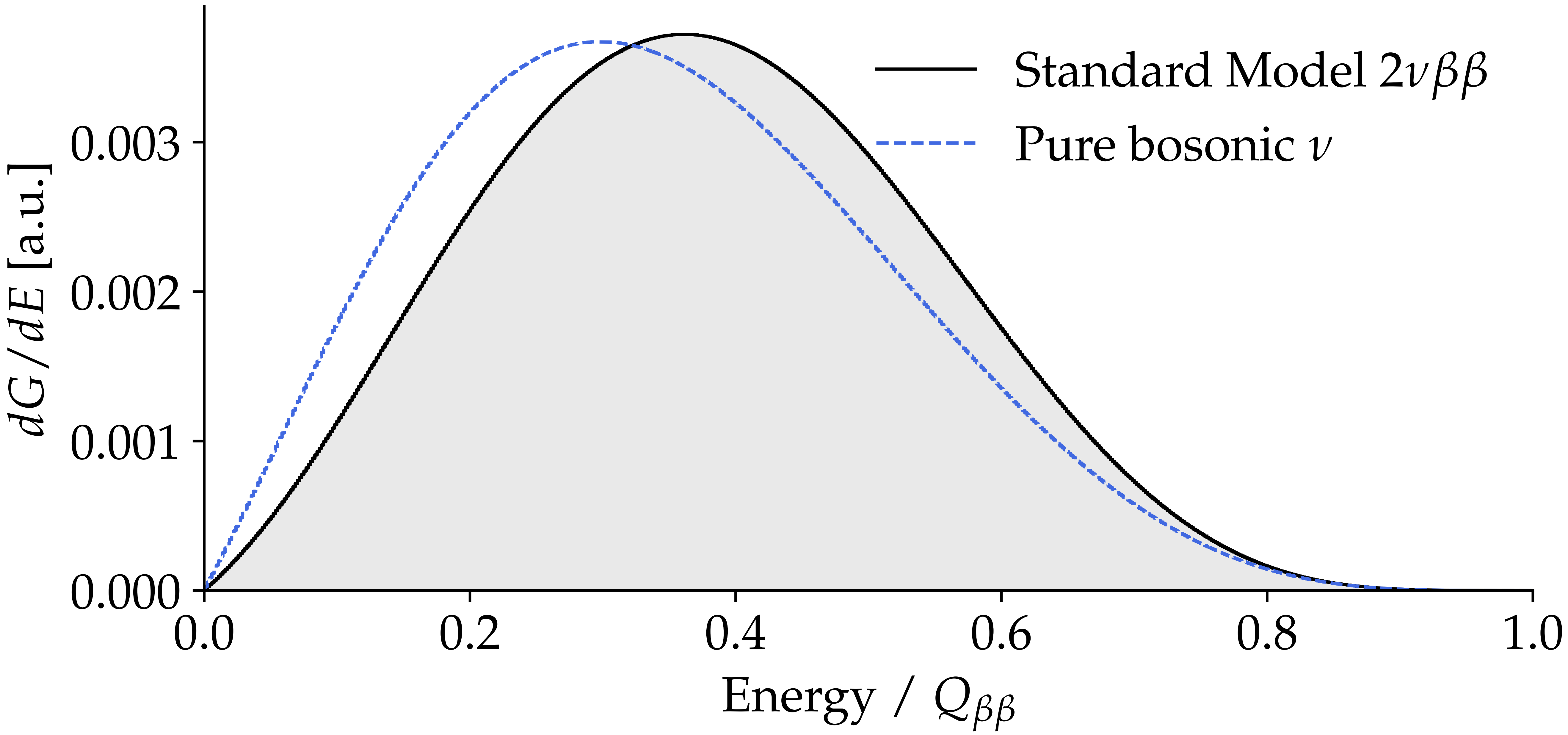


Bosonic neutrinos

In the hypothesis in which neutrinos partly obey to the Bose-Einstein statistic, the emission of two identical neutrinos in $2\nu\beta\beta$ offers the opportunity to investigate the Pauli's exclusion principle.

$$\Gamma_{2\nu\beta\beta} = \cos^4\chi\Gamma_f + \sin^4\chi\Gamma_b$$

Where $\sin^4\chi$ represents the bosonic fraction of the neutrino wave function, while Γ_f and Γ_b are the decay rates for the pure fermionic and pure bosonic neutrinos.

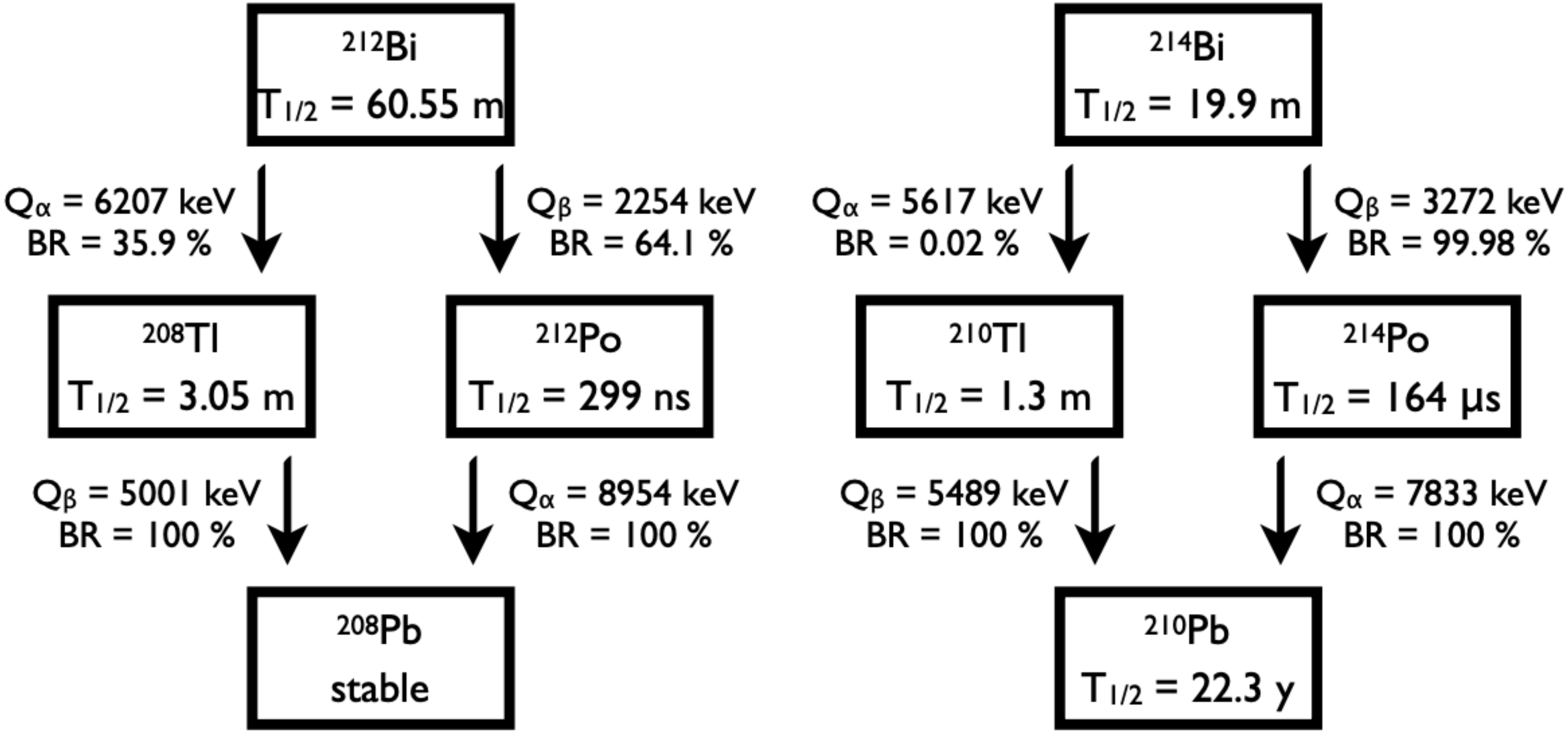


$$r_0 = \Gamma_b/\Gamma_f$$ $\longrightarrow$ Has to be calculated from the theory and it depends on the nuclear model adopted

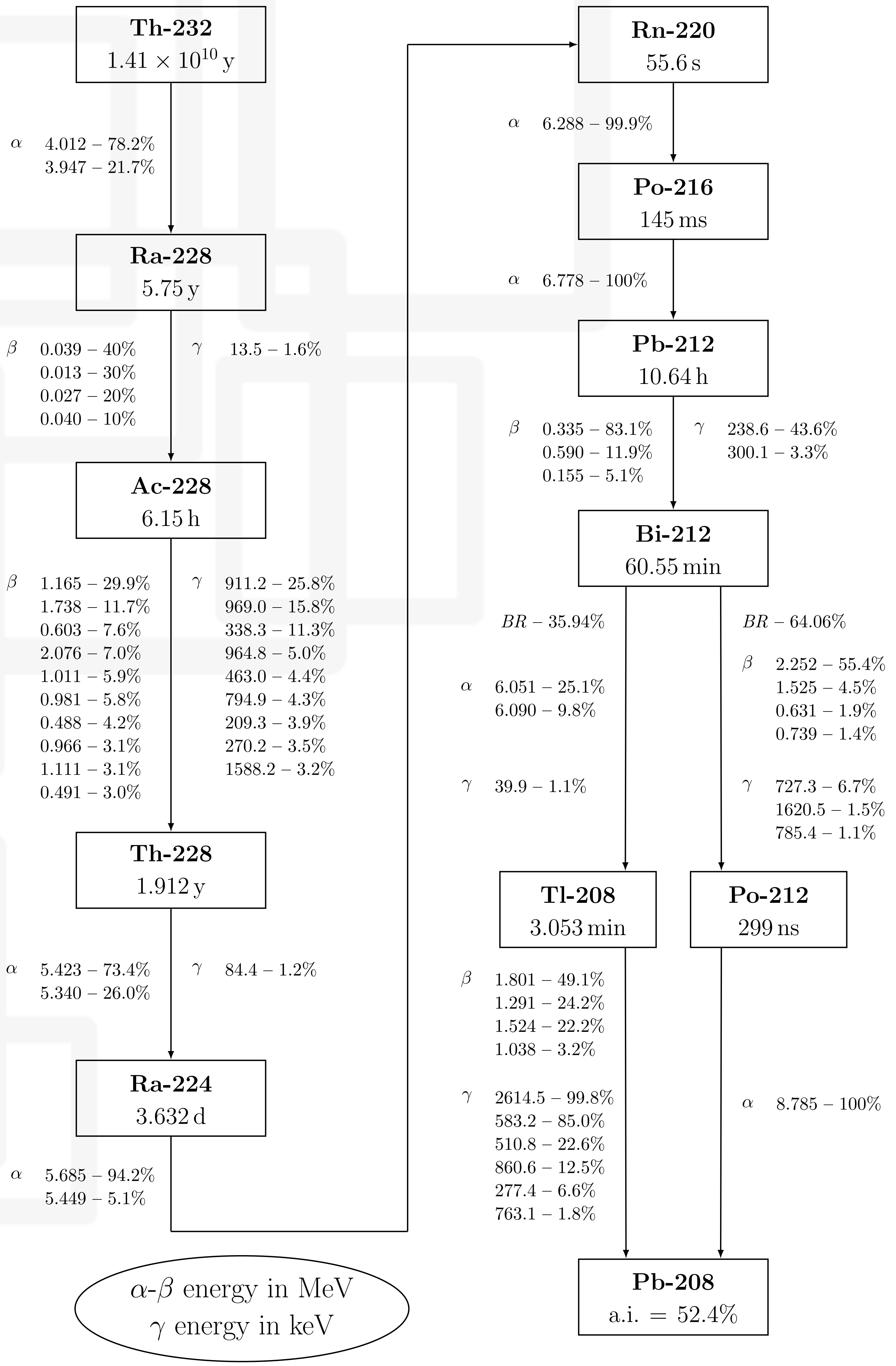
$r_0(^{100}Mo) = 0.076$

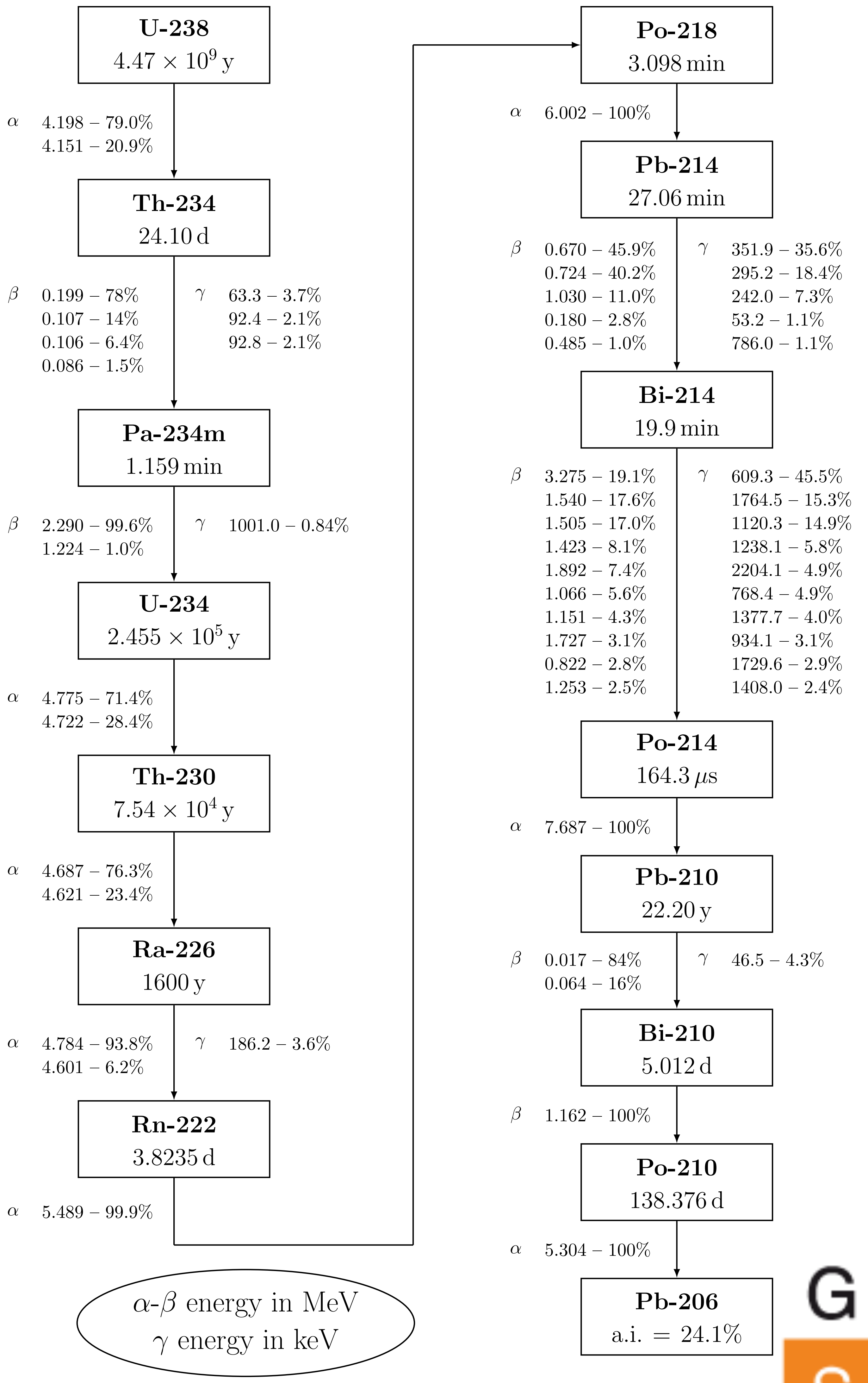
$r_0(^{76}Ge) = 0.0014$

Background in the ROI

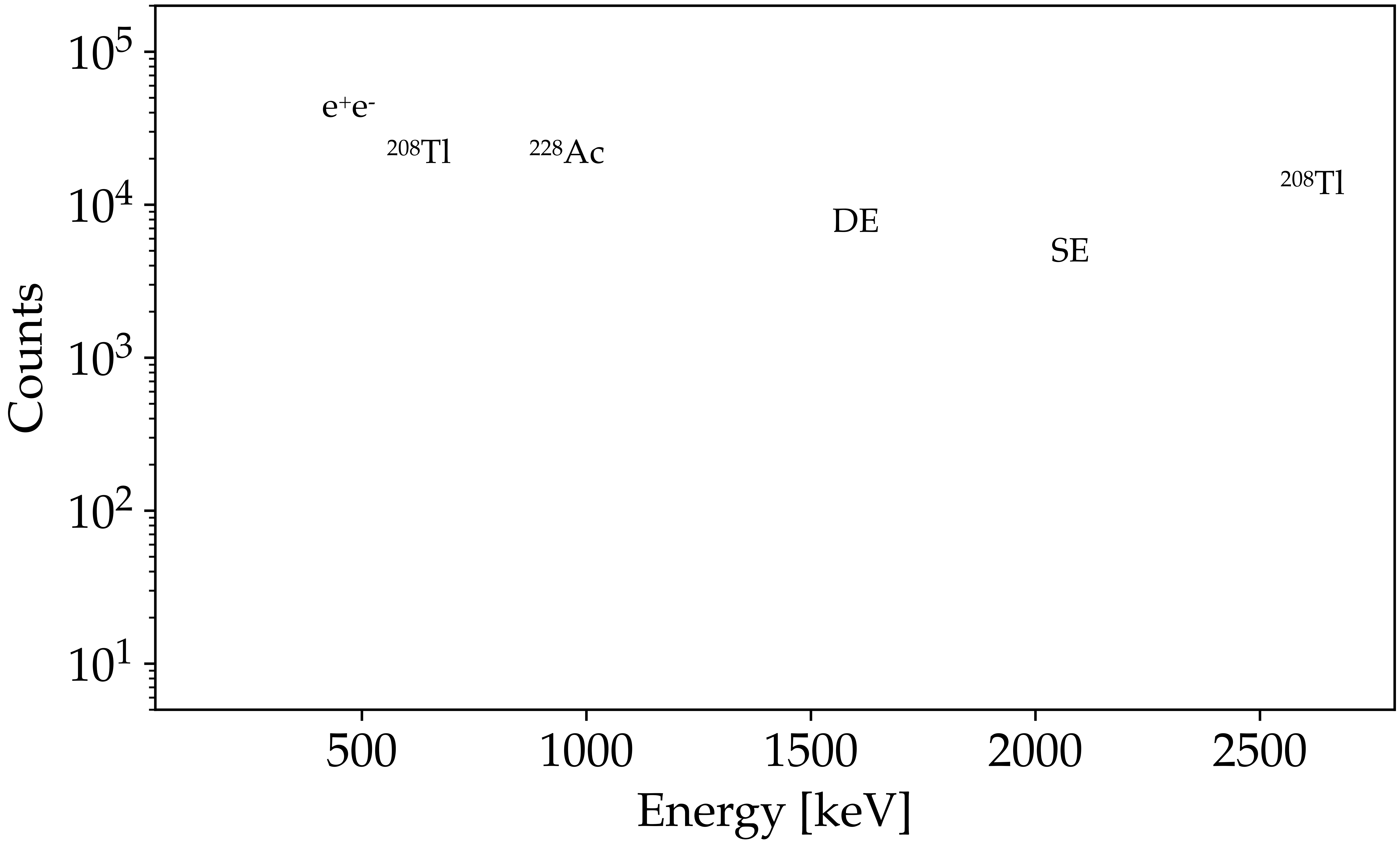


Radioactive chains

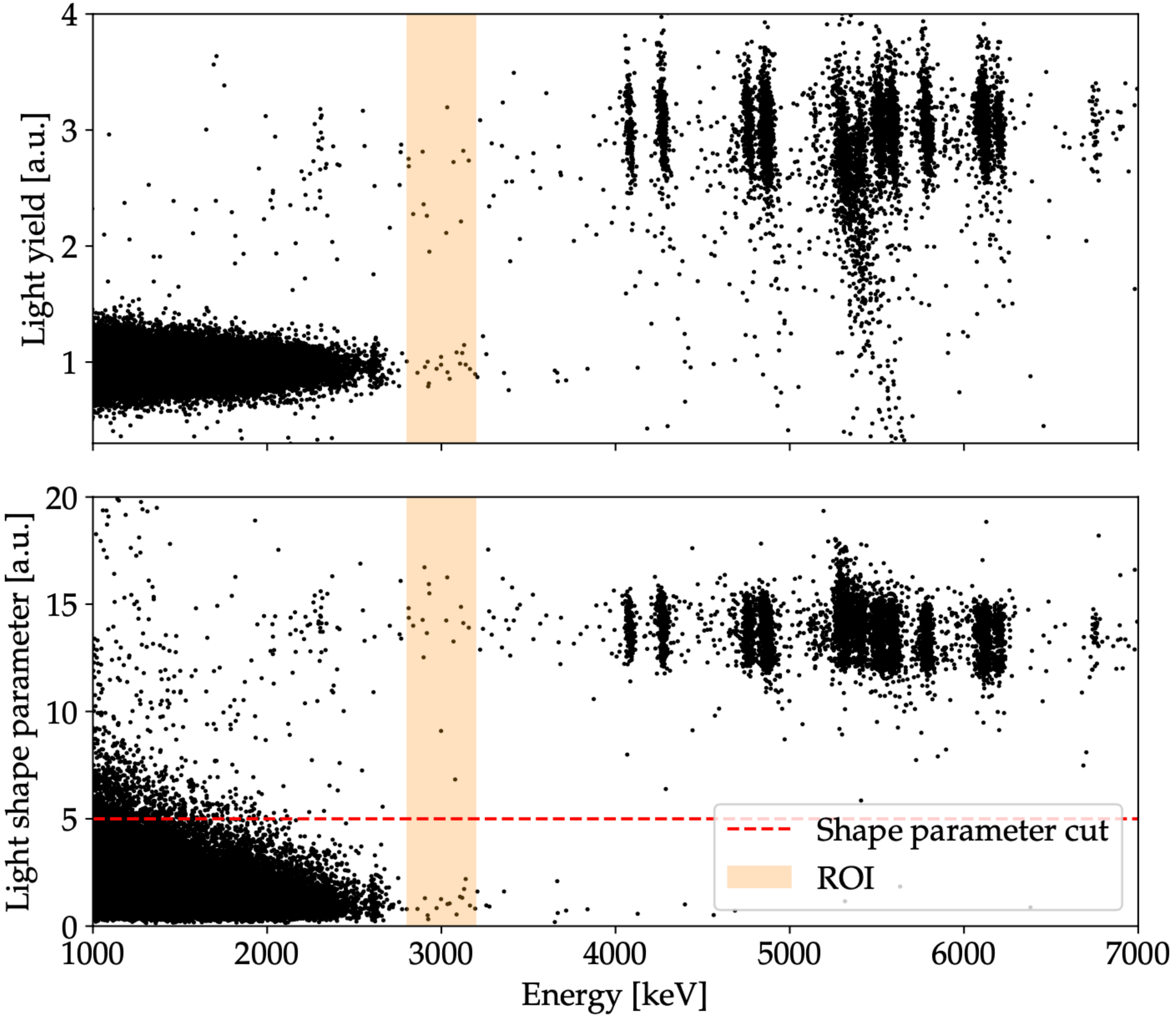




CUPID-0 calibration spectrum

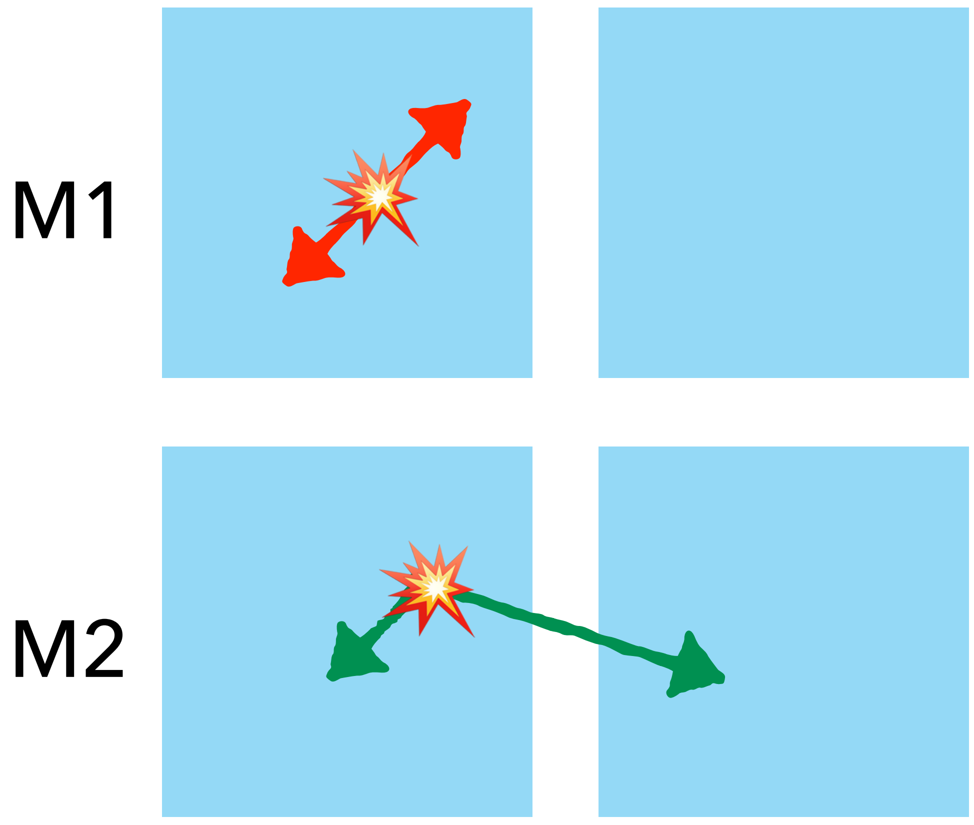


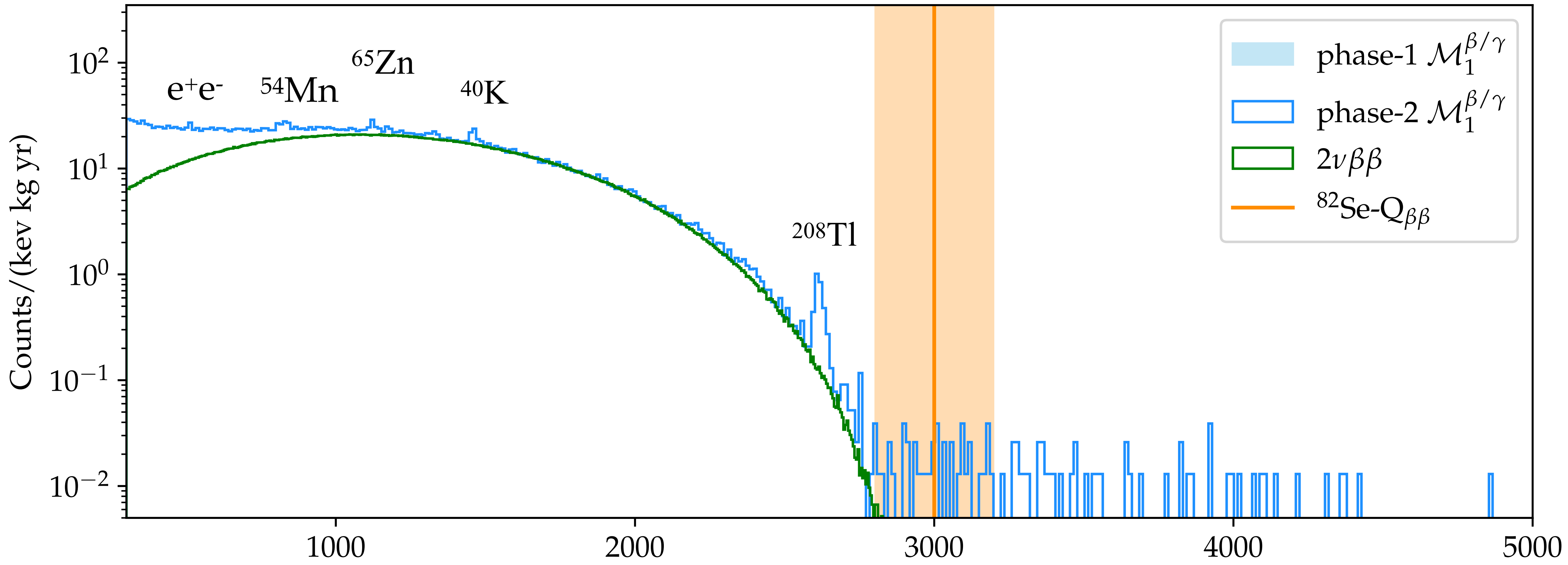
CUPID-0 particle identification

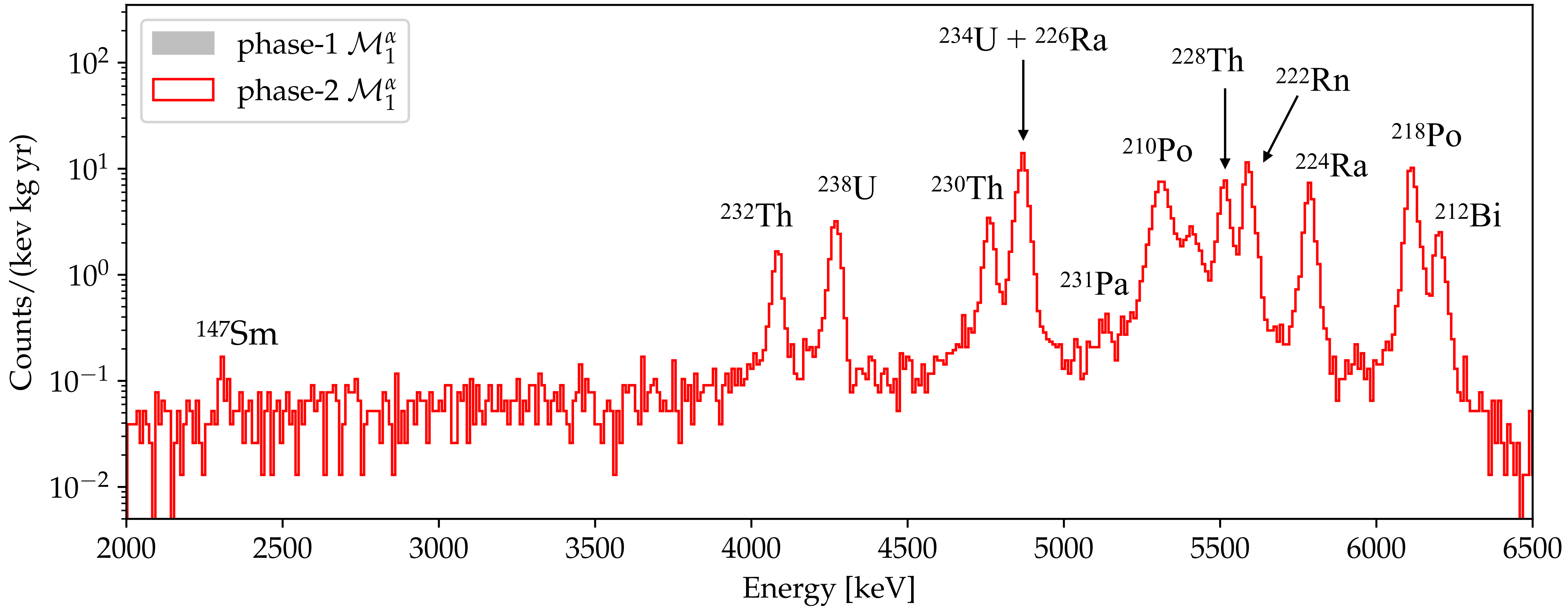


From phase-I to phase-II - M1

- Almost all the α-peaks have the same intensity in phase-I and phase-II
- ^{65}Zn decayed in phase-II, while other peaks appeared (from cosmogenic activation of copper)
- Higher α continuum from close component contaminations (10 mK)
- 2νββ is dominant up to 3 MeV





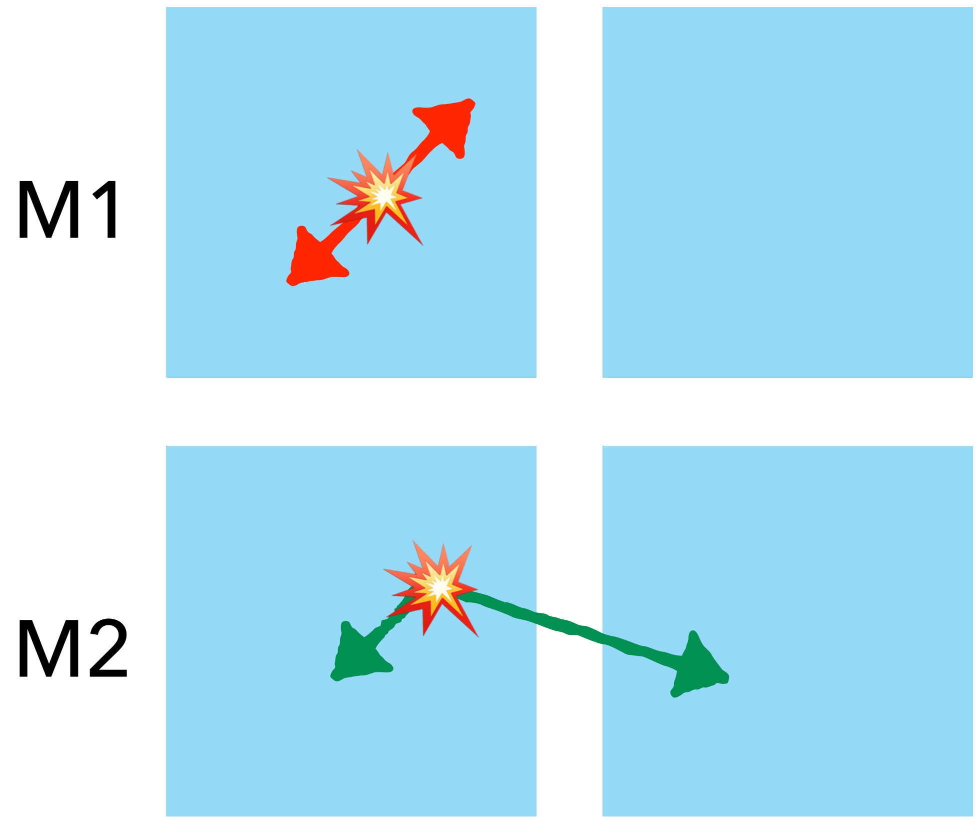


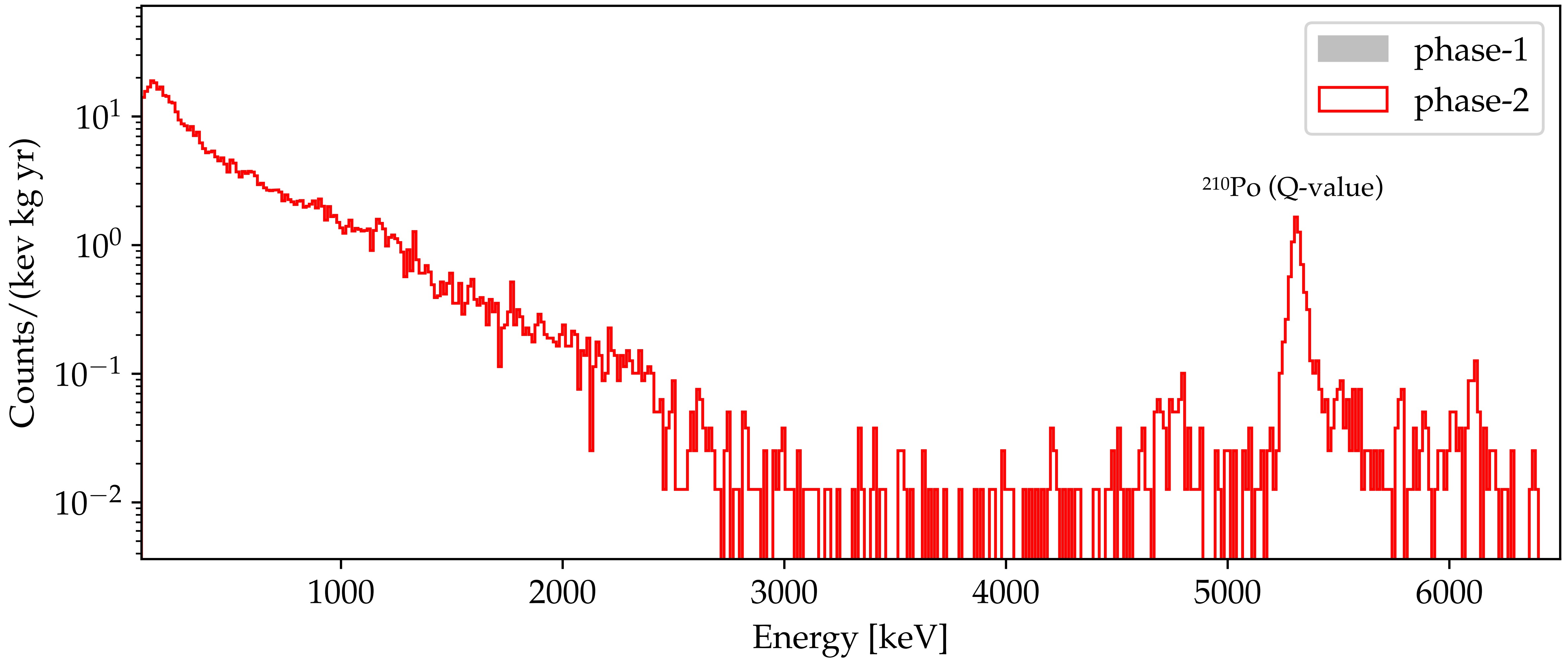
From phase-I to phase-II - M2 and M2sum

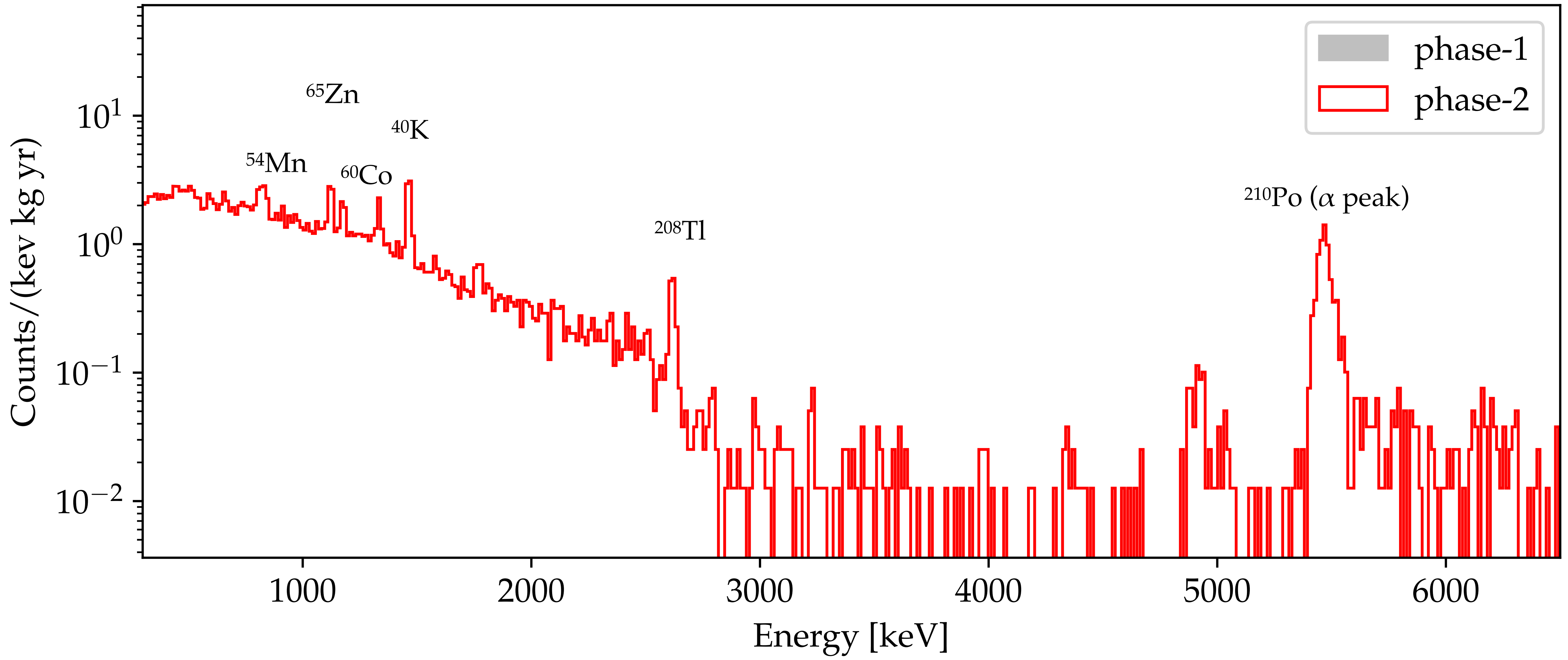
Multiplicity = 2 → events hitting two crystals simultaneously

$\mathscr{M}_2$= single energy deposition in both the crystals

Σ_2= sum of the two energies deposited (peak structures)







Background model - Fit

Binned simultaneous Maximum Likelihood fit using a Bayesian framework with a Markov Chain Monte Carlo (MCMC) approach.

Expectation value of the counts in the *i-th* bin $\left\langle C^{\mathrm{exp}}_{i,\delta} \right\rangle = \sum_{j=1}^{m} N_j \cdot \left\langle C^{\mathrm{MC}}_{ij,\delta} \right\rangle$

From the Bayes theorem the *joint posterior pdf* is defined as

$$\mathrm{Posterior}\left(N_j, \left\langle C^{\mathrm{MC}}_{ij,\delta} \right\rangle \mid C^{\mathrm{exp}}_{i,\delta}, C^{\mathrm{MC}}_{ij,\delta}\right) = \prod_{i,\delta} \mathrm{Pois}\left(C^{\mathrm{exp}}_{i,\delta} \mid \left\langle C^{\mathrm{exp}}_{i,\delta} \right\rangle\right) \times \prod_{j} \mathrm{Prior}\left(N_j\right)$$
$$\times \prod_{ij,\delta} \mathrm{Pois}\left(C^{\mathrm{MC}}_{ij,\delta} \mid \left\langle C^{\mathrm{MC}}_{ij,\delta} \right\rangle\right) \times \mathrm{Prior}\left(\left\langle C^{\mathrm{MC}}_{ij,\delta} \right\rangle\right)$$

$$\mathrm{Activity}[\frac{\mathrm{Bq}}{\mathrm{kg}}] = \frac{N_j^{Fit} \cdot N^{MC}}{\mathrm{Mass[kg]} \times \mathrm{livetime[s]}}$$

2νββ half-life measurement

Final result

$$T_{1/2}^{2\nu} = \left[8.69 \pm 0.05(\text{stat.})^{+0.06}_{-0.09}(\text{syst.})\right] \times 10^{19}\text{yr}$$

Using as Phase Space Factor the value

$$G^{2\nu} = (1.996 \pm 0.028) \times 10^{-18}$$

The final result on the nuclear matrix element is:

$$\mathscr{M}_{2\nu}^{eff} = 0.0760 \; {}^{+\,0.0006}_{-\,0.0007}$$

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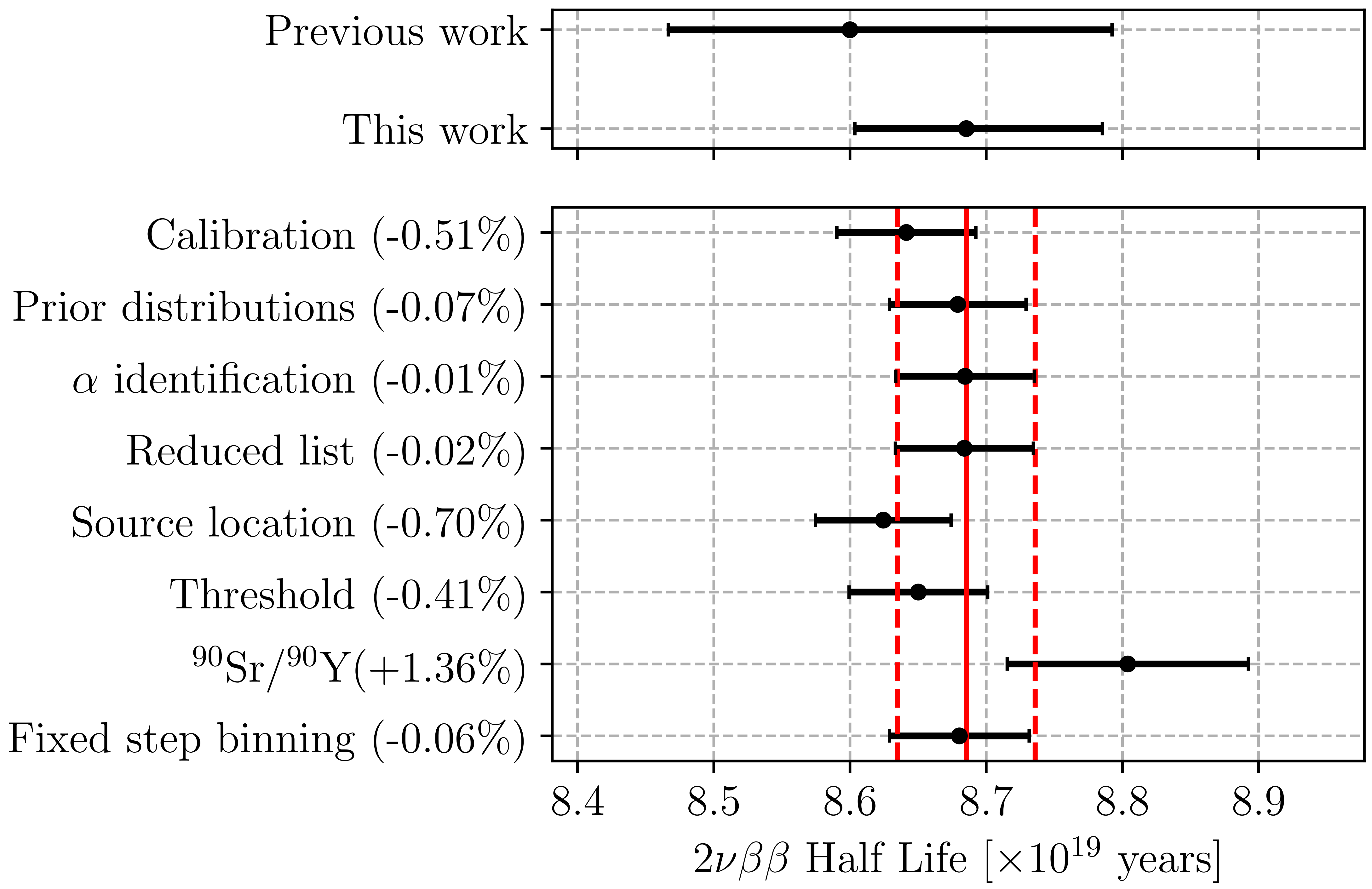
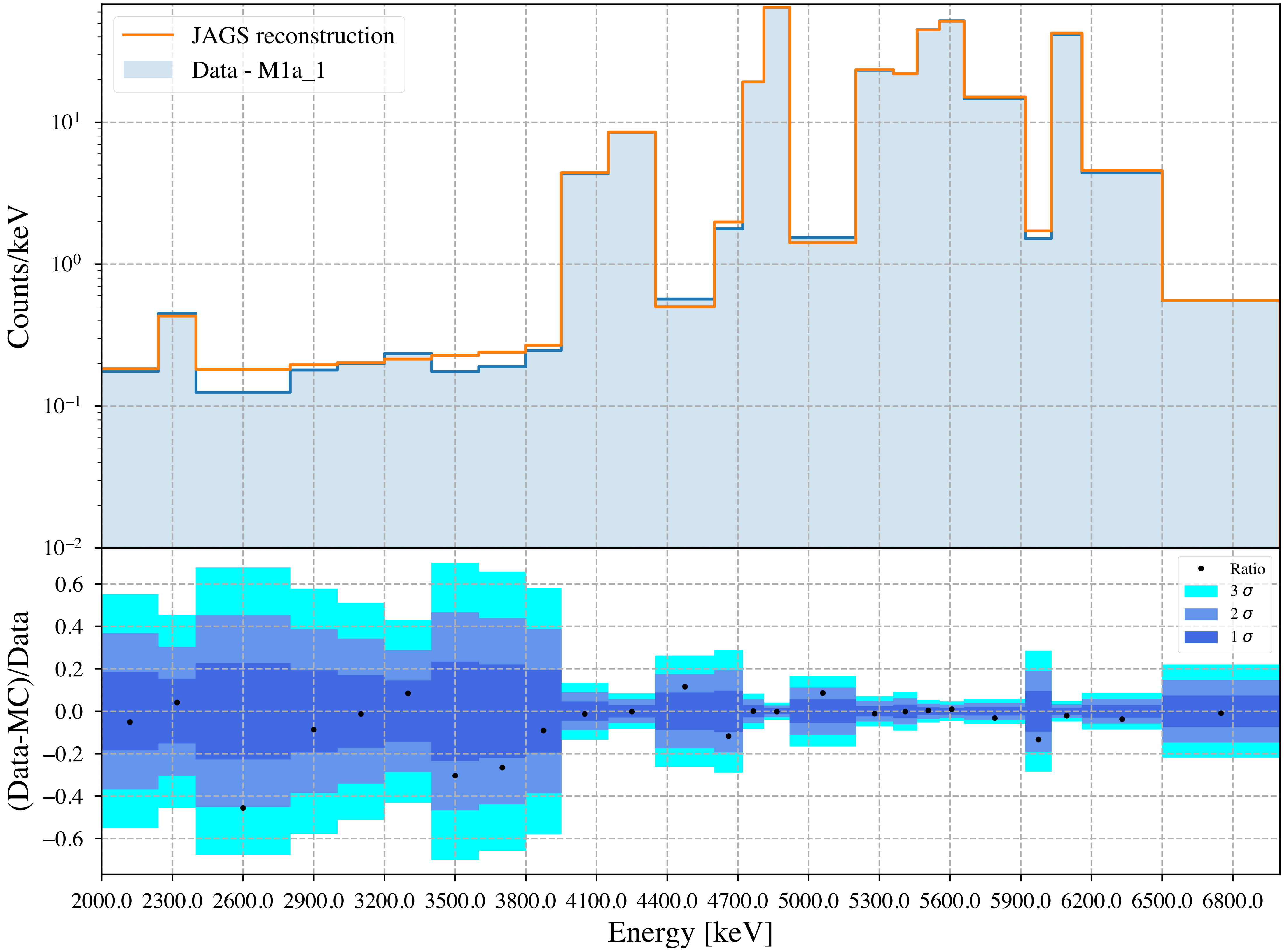
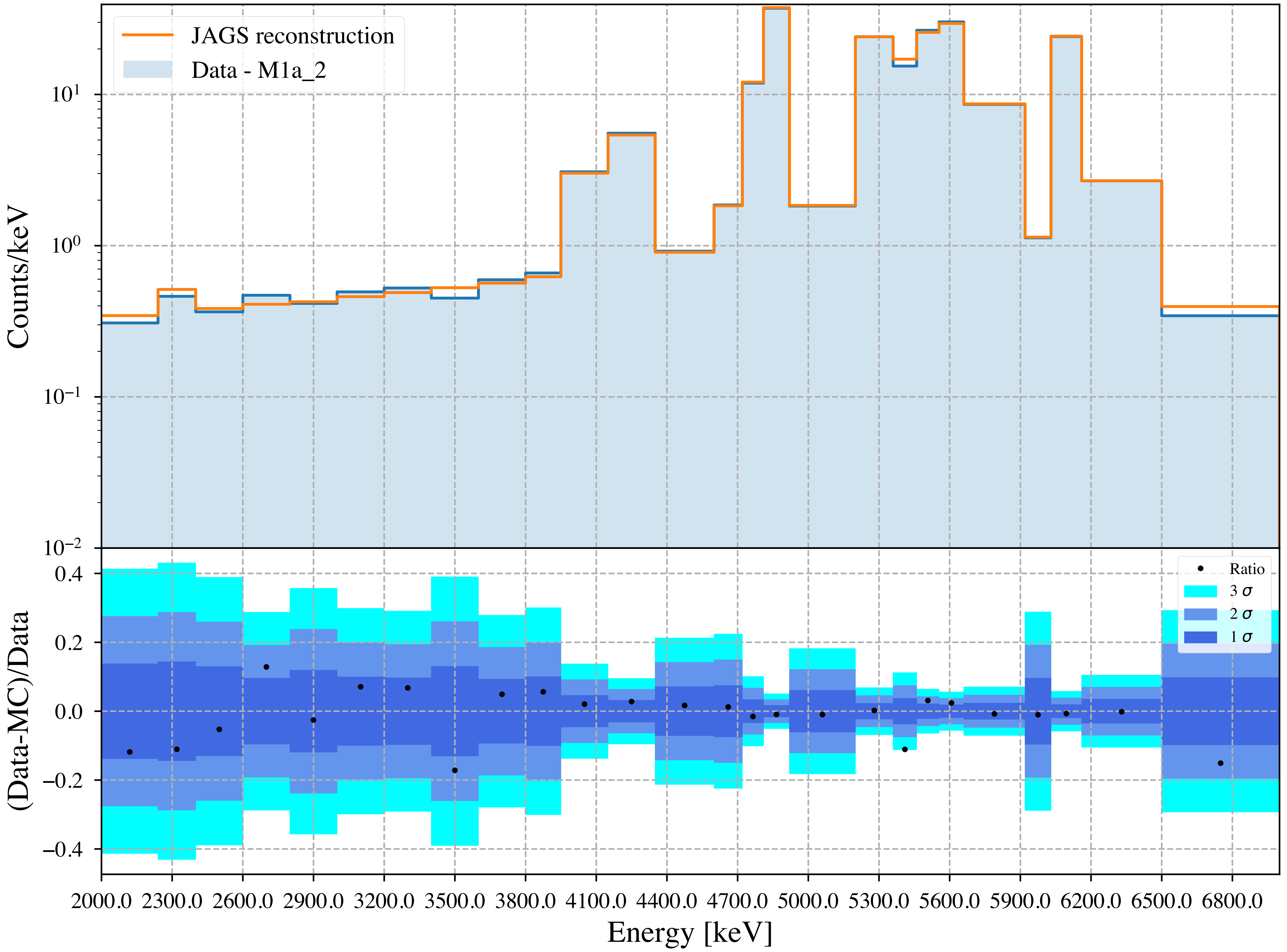


CUPID-0 Fit reconstruction M1a

PhaseI

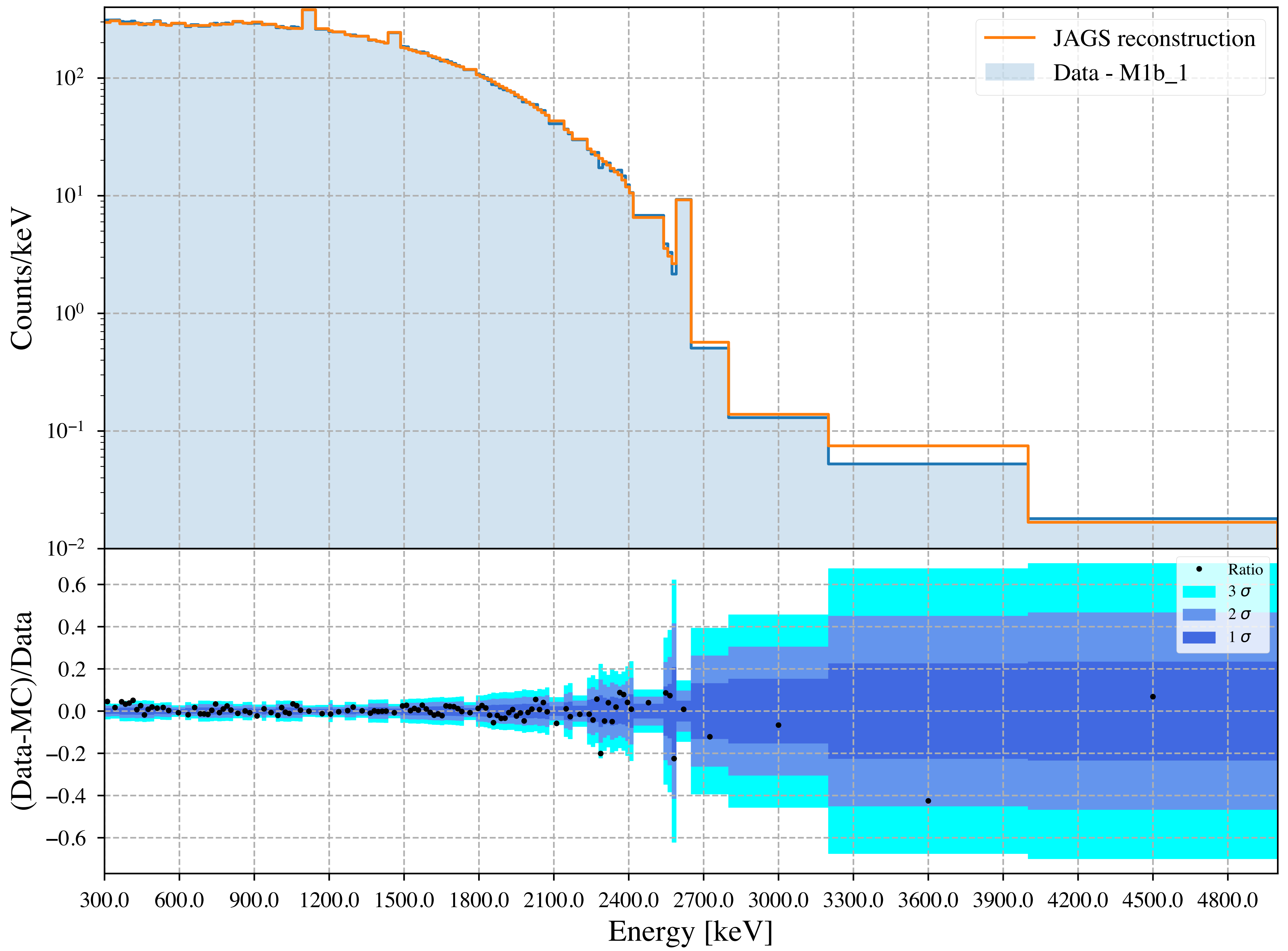


PhaseII

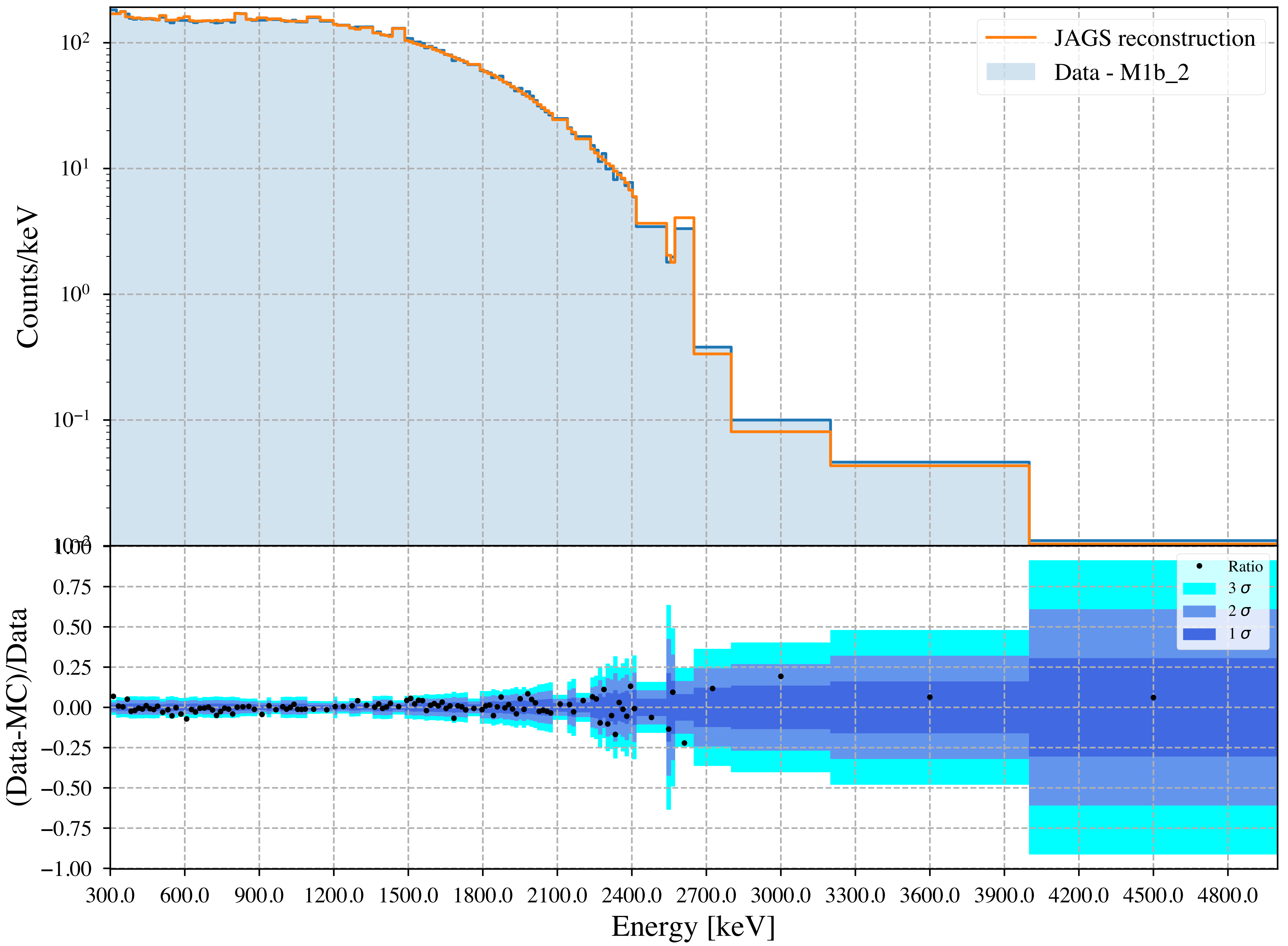


CUPID-0 Fit reconstruction M1b

PhaseI

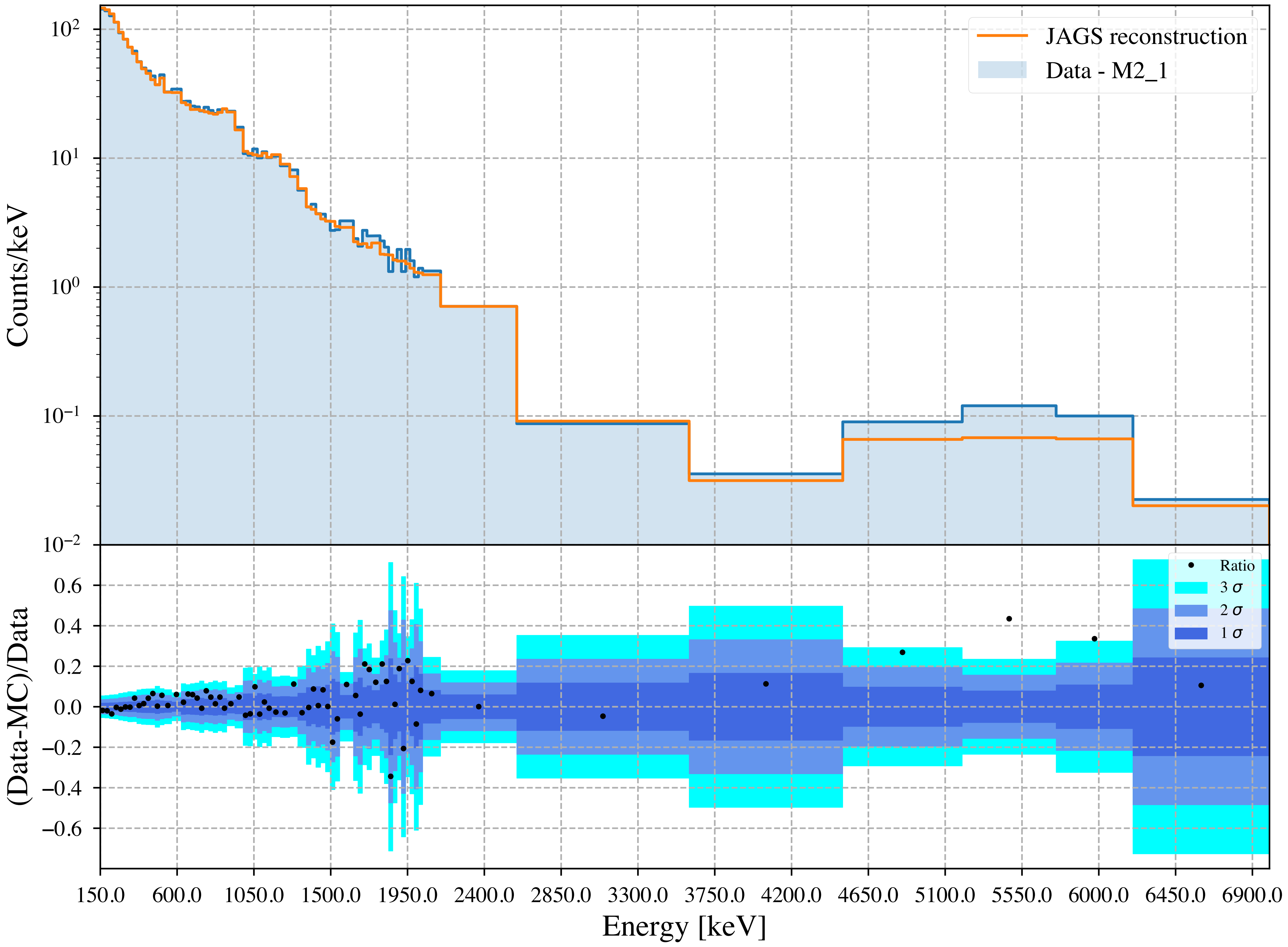


PhaseII

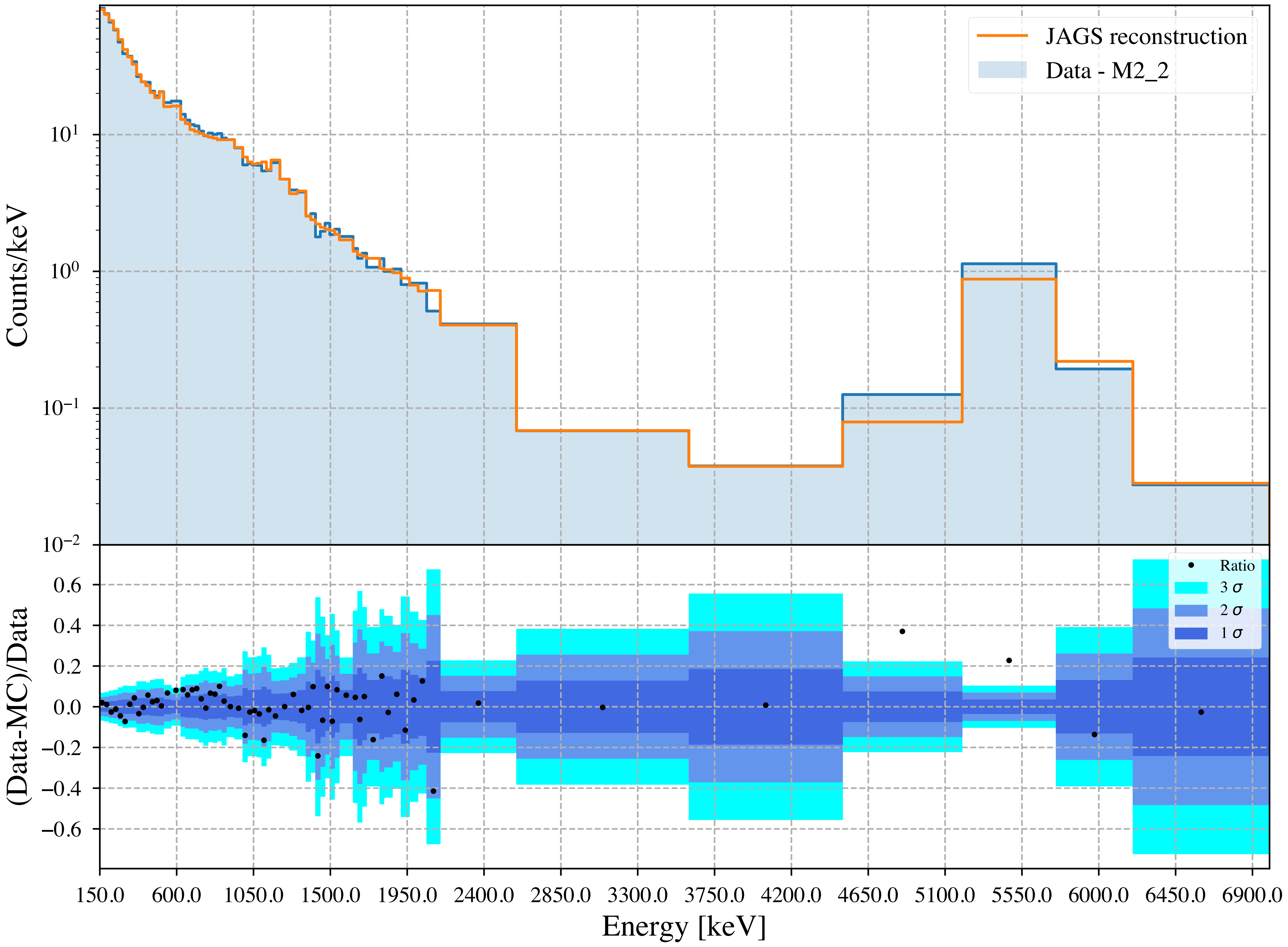


CUPID-0 Fit reconstruction M2

PhaseI

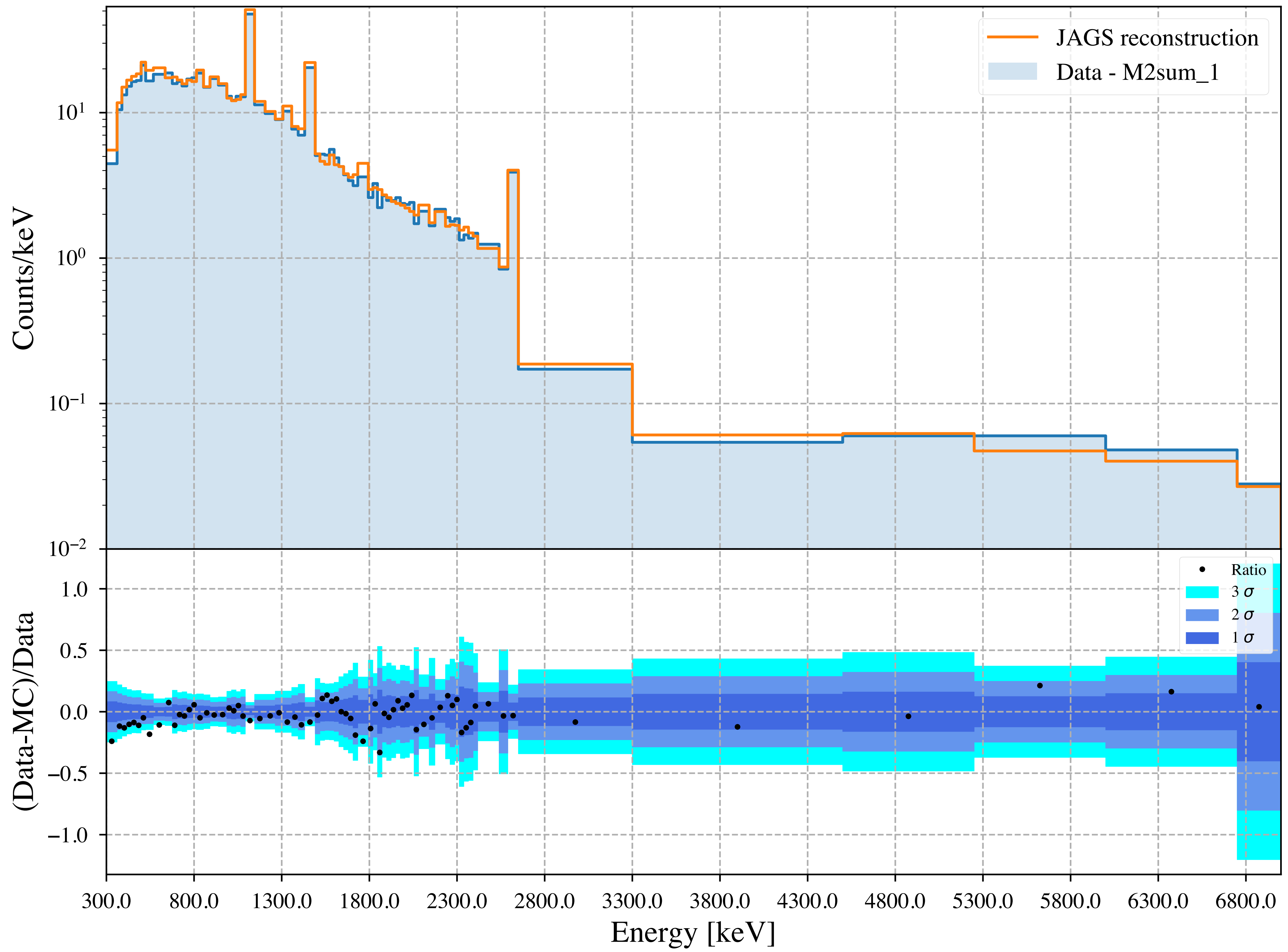


PhaseII

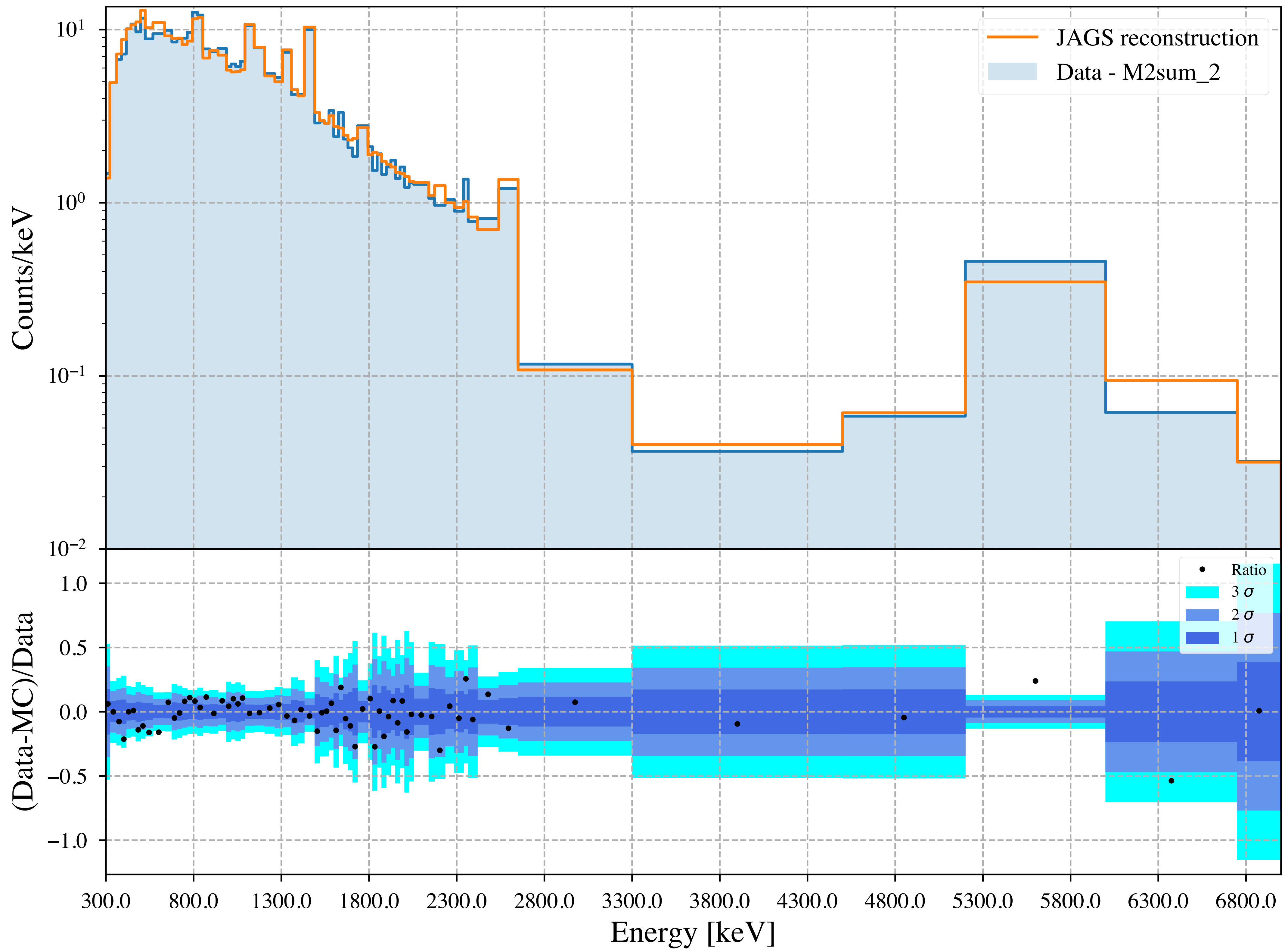


CUPID-0 Fit reconstruction M2sum

PhaseI



PhaseII



CUPID-0 crystal contaminations

Bulk Source	Specific Activity [Bq/kg] phase-I	phase-II	Constrained	Prior [Bq/kg]
^{82}Se $2\nu\beta\beta$	$(9.87 \pm 0.02)\times10^{-4}$		yes	Uniform
^{65}Zn	$(3.63 \pm 0.06)\times10^{-4}$	$(0.71 \pm 0.06)\times10^{-4}$	no	Uniform
^{40}K	$(6.0 \pm 0.3)\times10^{-5}$		yes	Uniform
^{60}Co	$(1.3 \pm 0.3)\times10^{-5}$	$(1.3 \pm 0.4)\times10^{-5}$	no	Uniform
^{147}Sm	$(1.3 \pm 0.3)\times10^{-7}$		yes	Uniform
^{238}U to ^{226}Ra	$(5.48 \pm 0.08)\times10^{-6}$		yes	Uniform
^{226}Ra to ^{210}Pb	$(1.47 \pm 0.02)\times10^{-5}$		yes	Uniform
^{210}Pb	$< 1.4 \times10^{-7}$		yes	Uniform
^{232}Th to ^{228}Ra	$(2.74 \pm 0.08)\times10^{-6}$		yes	Uniform
^{228}Ra	$(1.26 \pm 0.03)\times10^{-5}$		yes	Uniform
^{235}U to ^{231}Pa	$(6.2 \pm 0.7)\times10^{-7}$		yes	Uniform
Surface Source	**Specific Activity [Bq/cm^2] phase-I**	**phase-II**	**Constrained**	**Prior [Bq/cm^2]**
^{226}Ra to ^{210}Pb (10nm)	$(2.8 \pm 0.2)\times10^{-8}$		yes	$\mathcal{G}(1.49, 0.01)\cdot$Bulk
^{228}Ra (10nm)	$(6.8 \pm 1.1)\times10^{-9}$		yes	$\mathcal{G}(4.190, 0.008)\cdot$Bulk
^{226}Ra to ^{210}Pb (10μm)	$< 2.0 \times10^{-9}$		yes	Uniform
^{228}Ra (10μm)	$(2.8 \pm 1.5)\times10^{-9}$		yes	Uniform
^{210}Pb (1nm)	$(3.39 \pm 0.08)\times10^{-8}$	$(1.39 \pm 0.03)\times10^{-7}$	no	Uniform

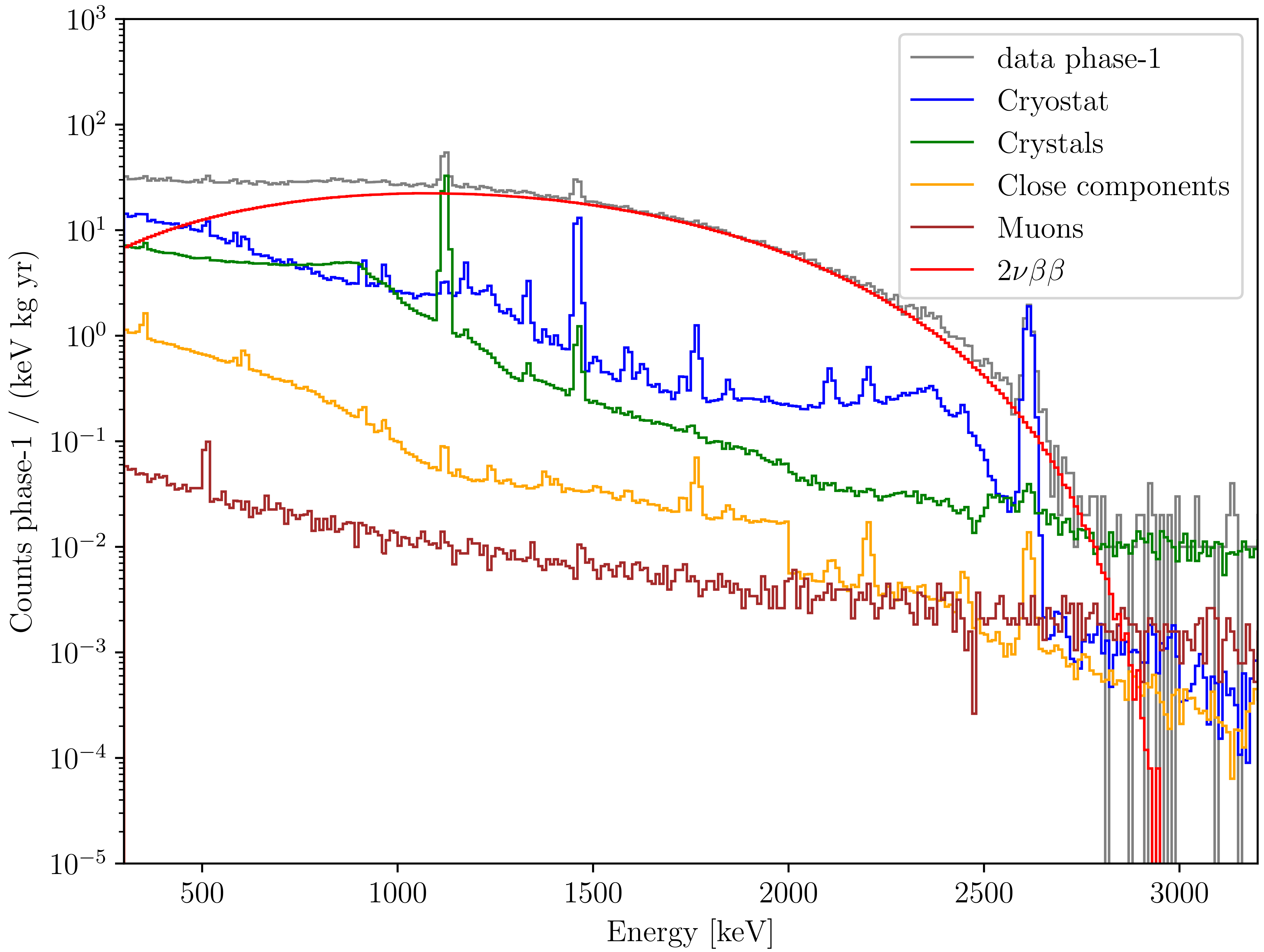
CUPID-0 close components contaminations

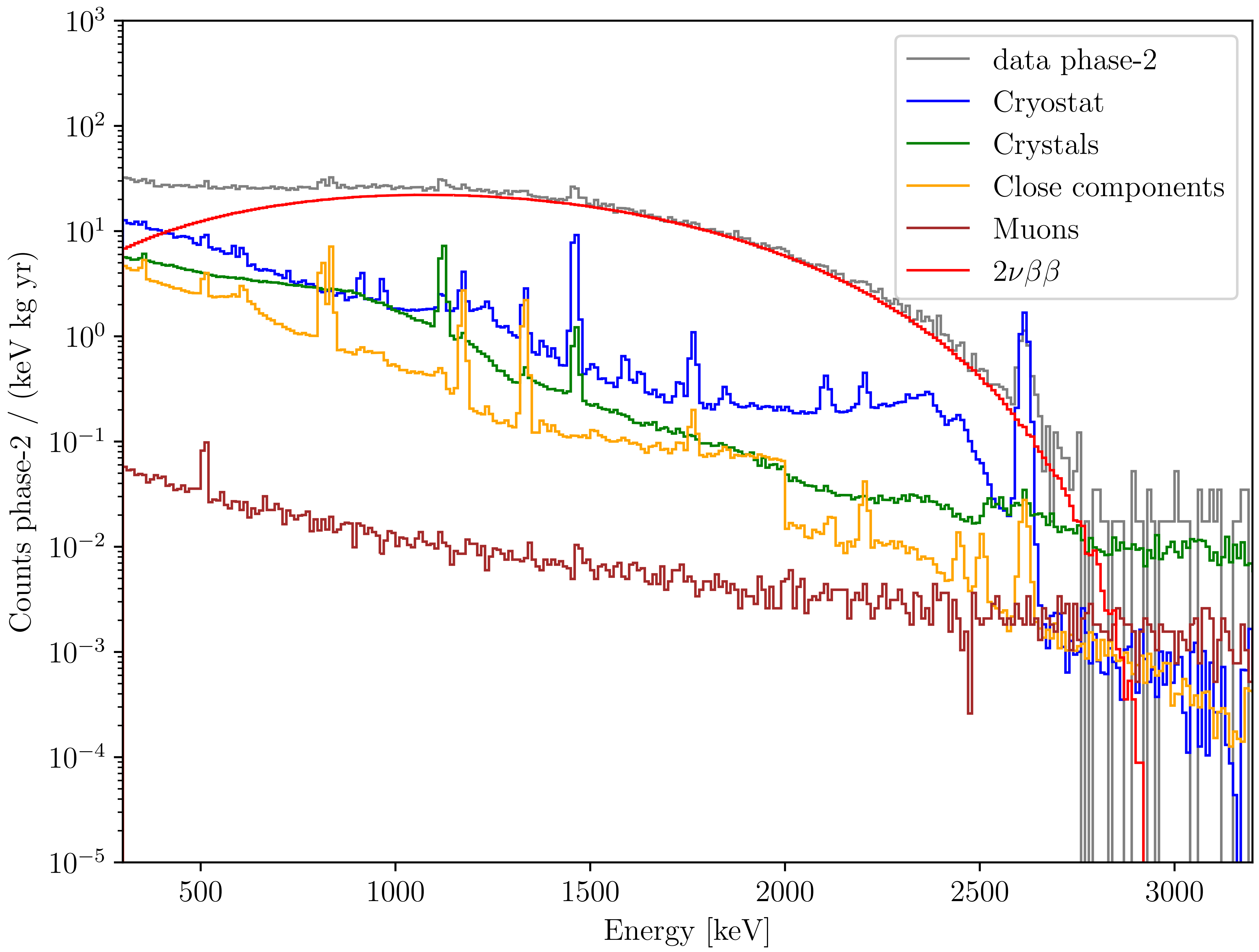
Bulk source	Volume	Specific Activity [Bq/kg] phase-I	phase-II	Constrained	Prior [Bq/kg]
^{54}Mn	*Holders*	$(3.7 \pm 0.5)\times10^{-4}$	-	-	Uniform
^{54}Mn	*10mK*	-	$(6.3 \pm 0.6)\times10^{-5}$	-	Uniform
^{58}Co	*10mK*	-	$(5.7 \pm 0.6)\times10^{-5}$	-	Uniform
^{60}Co	*10mK*	-	$(4.5 \pm 2.4)\times10^{-5}$	-	Uniform
Surface source	**Volume**	**Specific Activity [Bq/cm^2] phase-I**	**phase-II**	**Constrained**	**Prior [Bq/cm^2]**
^{232}Th(10μm)	*Holders*	$(5.2 \pm 0.2)\times10^{-9}$		yes	$\mathcal{G}(5.0, 0.2) \times 10^{-9}$
^{238}U(10μm)	*Holders*	$(1.3 \pm 0.2)\times10^{-8}$		yes	$\mathcal{G}(1.4, 0.2) \times 10^{-8}$
^{232}Th(10μm)	*Reflectors*	$< 7.7 \times10^{-10}$	-	-	Uniform
^{238}U(10μm)	*Reflectors*	$< 2.7 \times10^{-9}$	-	-	Uniform
^{210}Pb(10μm)	*Reflectors*	$(1.9 \pm 0.5)\times10^{-8}$	-	-	Uniform
^{210}Pb(10nm)	*Reflectors*	$(8.1 \pm 0.3)\times10^{-8}$	-	-	Uniform
^{232}Th(10μm)	*10mK*	-	$< 2.2 \times10^{-8}$	-	Uniform
^{238}U(10μm)	*10mK*	-	$(6.1 \pm 1.8)\times10^{-8}$	-	Uniform
^{210}Pb(10μm)	*10mK*	-	$(2.1 \pm 1.2)\times10^{-7}$	-	Uniform
^{210}Pb(10nm)	*10mK*	-	$(5.5 \pm 0.2)\times10^{-7}$	-	Uniform
^{210}Pb(1μm)	*10mK*	-	$(1.7 \pm 0.2)\times10^{-7}$	-	Uniform

CUPID-0 cryostat contaminations

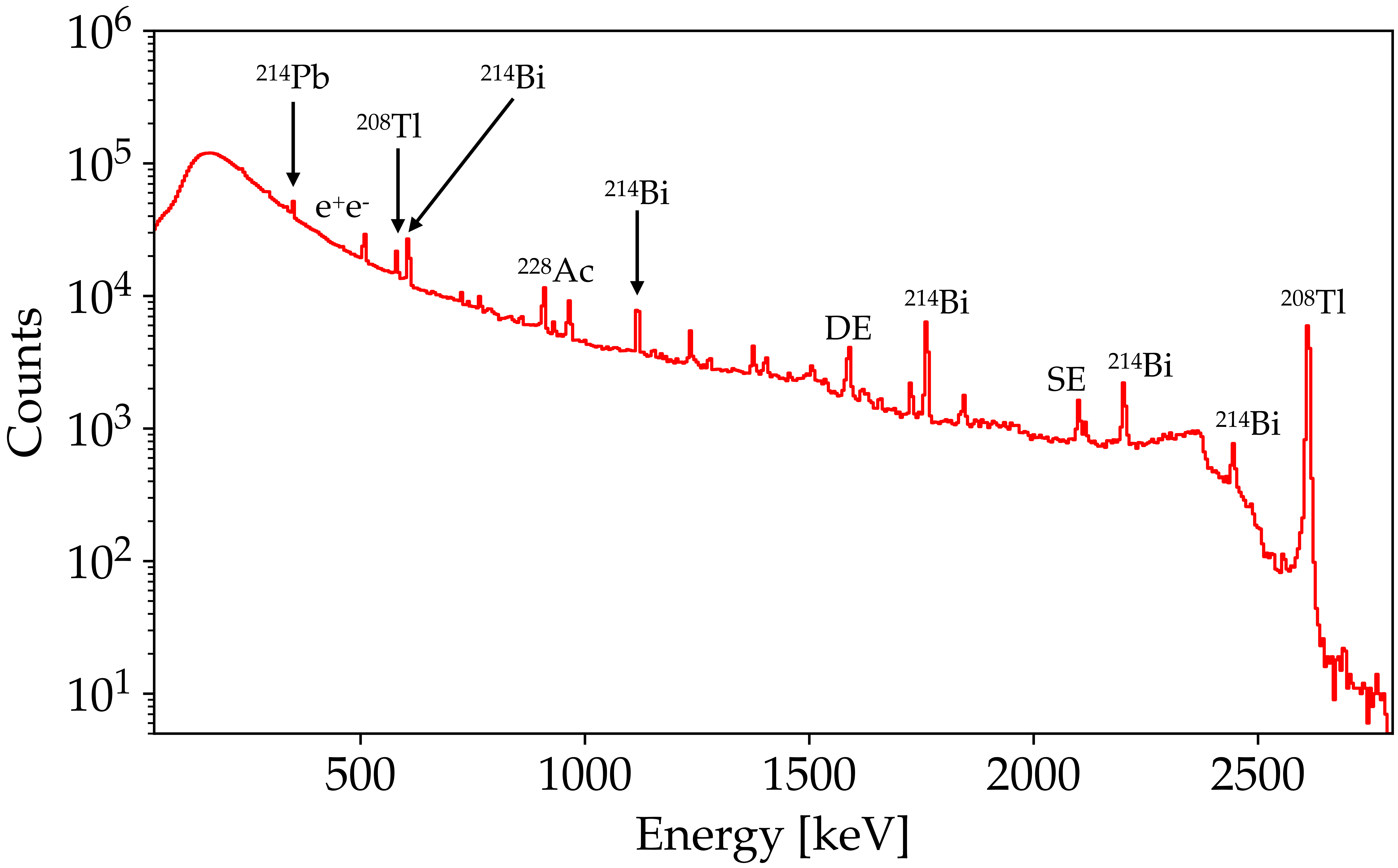
Bulk source	Volume	Specific Activity [Bq/kg] phase-I	Specific Activity [Bq/kg] phase-II	Constrained	Prior [Bq/kg]
^{232}Th	*CryoInt*	$(4.5 \pm 2.6)\times10^{-4}$		yes	Uniform
^{238}U	*CryoInt*	$(4.4 \pm 2.1)\times10^{-4}$		yes	Uniform
^{40}K	*CryoInt*	$(2.7 \pm 0.7)\times10^{-3}$	$(4.1 \pm 0.5)\times10^{-3}$	no	Uniform
^{60}Co	*CryoInt*	$(7.4 \pm 1.4)\times10^{-5}$	$(8.9 \pm 5.6)\times10^{-5}$	no	Uniform
^{232}Th	*CryoExt+ExtPb*	$(3.8 \pm 0.6)\times10^{-4}$		yes	Uniform
^{238}U	*CryoExt+ExtPb*	$(4.6 \pm 0.9)\times10^{-4}$		yes	Uniform
^{40}K	*CryoExt+ExtPb*	$(3.8 \pm 0.8)\times10^{-3}$	$< 1.3 \times10^{-3}$	no	Uniform
^{210}Pb	*ExtPb*	(8.0 ± 0.3)		yes	Uniform
^{60}Co	*CryoExt*	$(3.0 \pm 0.8)\times10^{-5}$	$< 6.5 \times10^{-5}$	no	$\mathcal{G}(2.5, 0.9) \times 10^{-5}$
^{232}Th	*IntPb*	$(3.2 \pm 2.2)\times10^{-5}$		yes	Uniform
^{238}U	*IntPb*	$< 3.7 \times10^{-5}$		yes	Uniform

Background model - reconstruction

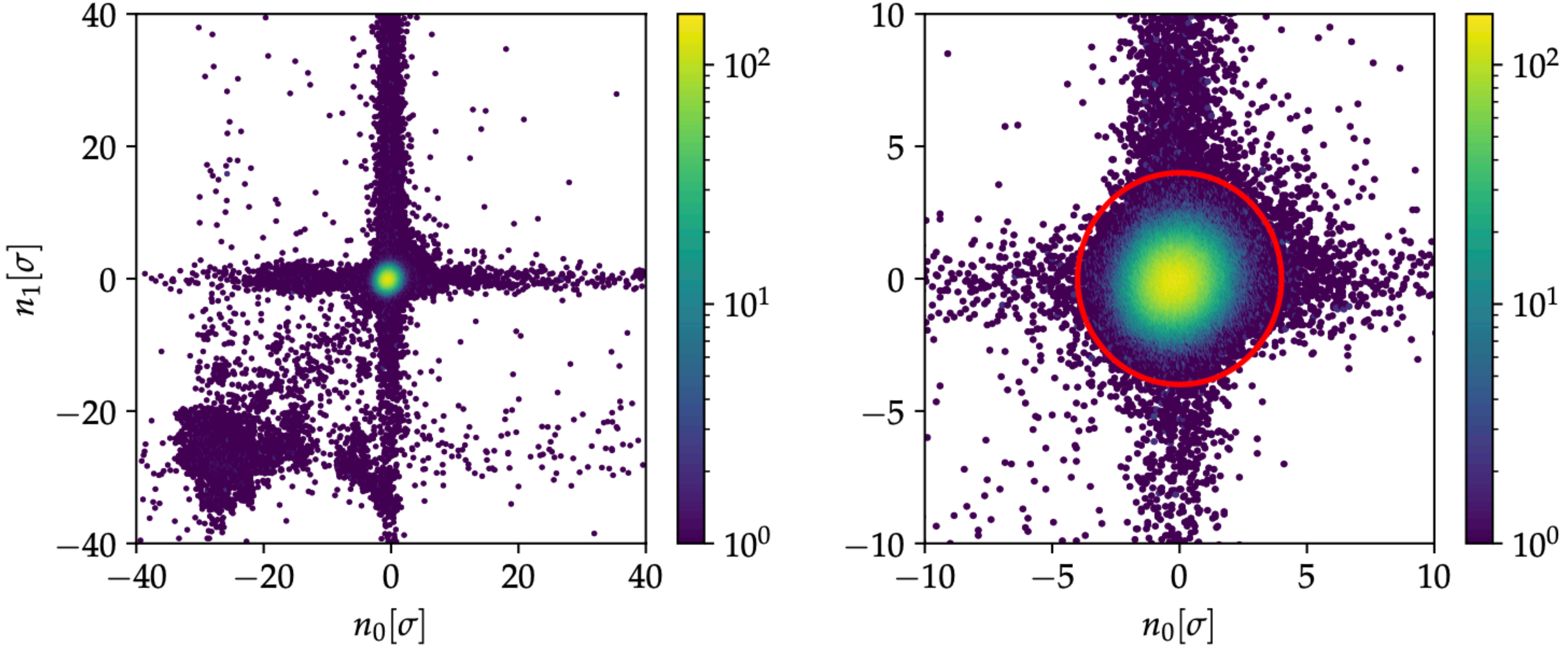




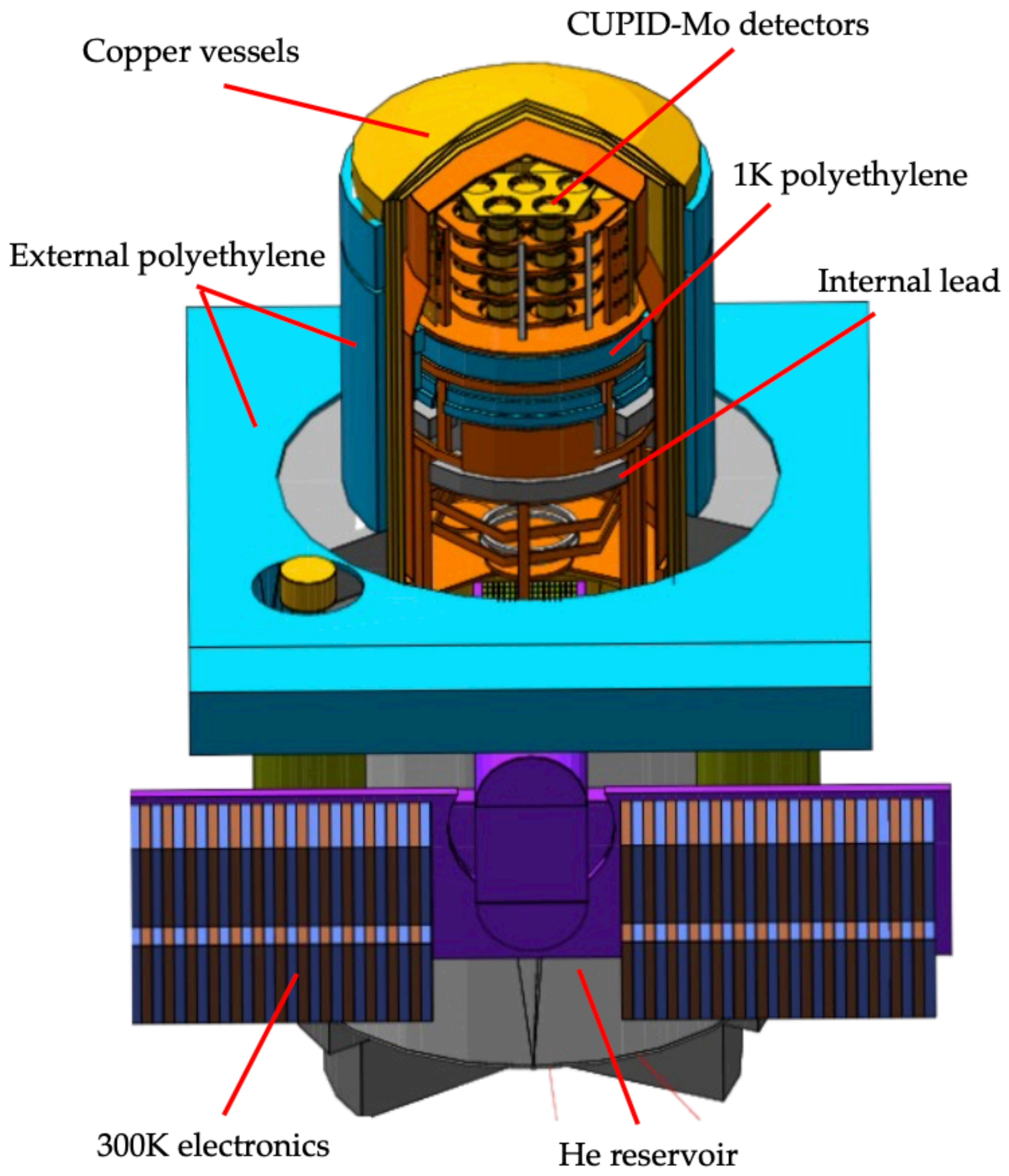
CUPID-Mo calibration spectrum



CUPID-Mo particle identification



CUPID-Mo simulations



Measurement of ^{100}Mo 2νββ spectral shape

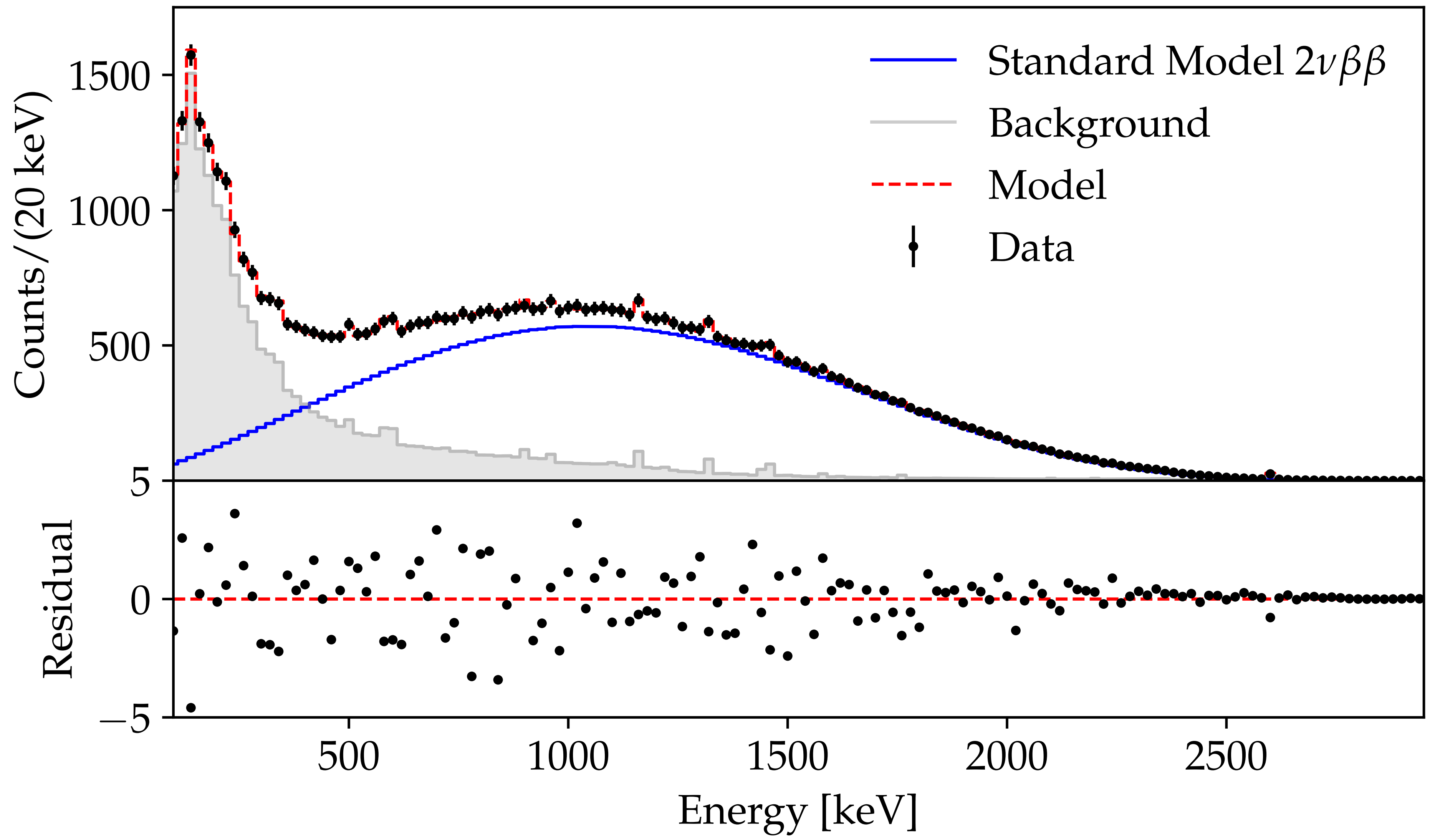
- The model of the spectral shape has been implemented in the background model fit and the value of $\xi_{31}^{2\nu}$ is kept as free parameter

- **First measurement** of the $\xi_{31}^{2\nu}$ parameter compatible with the SSD prediction:
  $\xi_{31}^{2\nu} = 0.45 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst.})$

Systematic test	Uncert. $T_{1/2}$[%]	Uncert. $\xi_{3,1}$ [%]
Source location	0.83	0.9
^{90}Sr+^{90}Y	$+1.0^{a}$	-4.9^{a}
Minimal model	0.24	7.7
Binning	0.37	1.4
Energy bias	$^{+0.11}_{-0.16}$	$^{+3.5}_{-3.7}$
Bremsstrahlung	$^{+0.13}_{-0.22}$	$^{+6.0}_{-6.8}$
MC statistics	0.11	1.4
Efficiency	1.2	-
Isotopic abundance	0.2	-

^{100}Mo 2νββ half-life

$7.07 \pm 0.02(\text{stat.}) \pm 0.1(\text{syst.}) \times 10^{18}$



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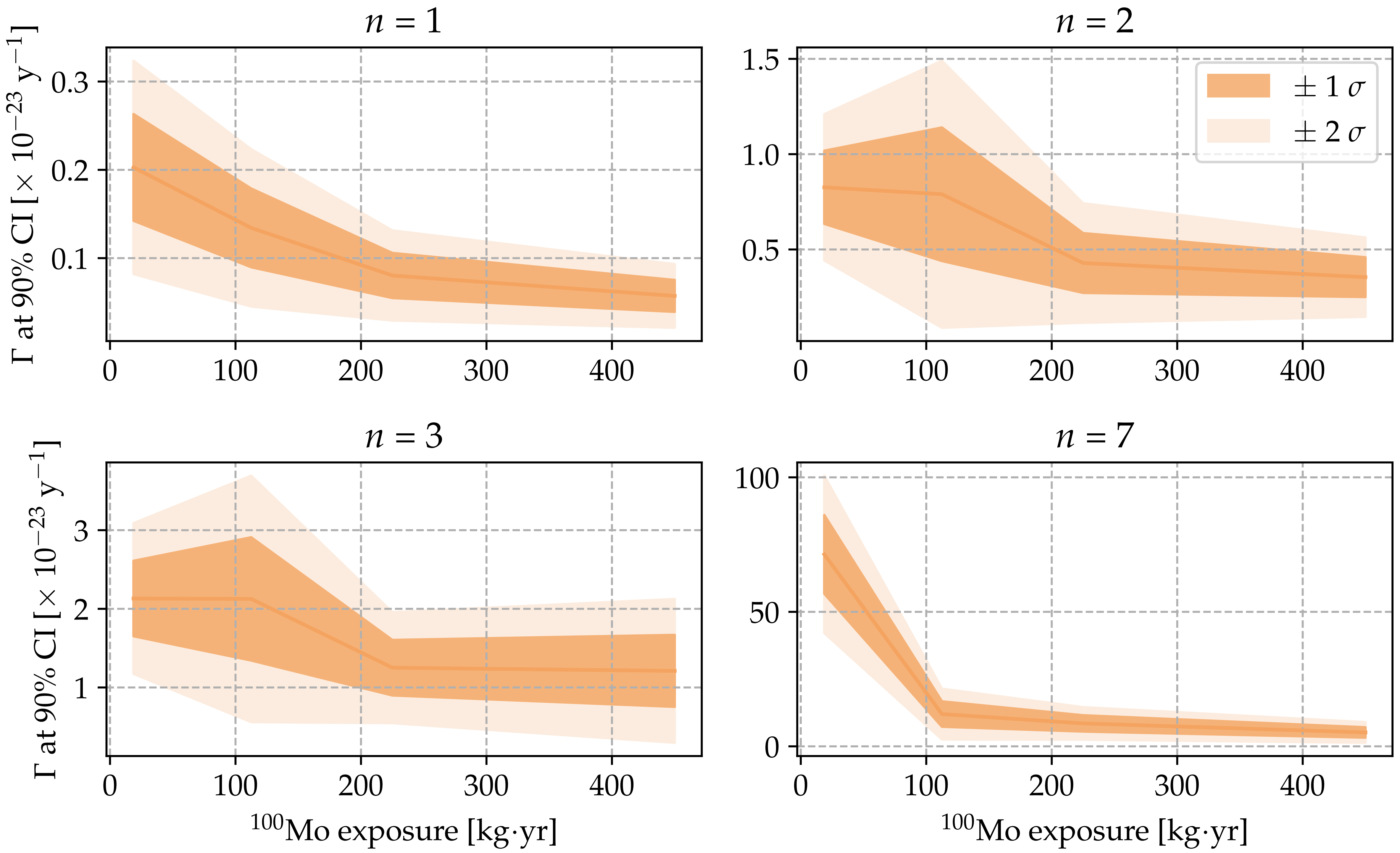
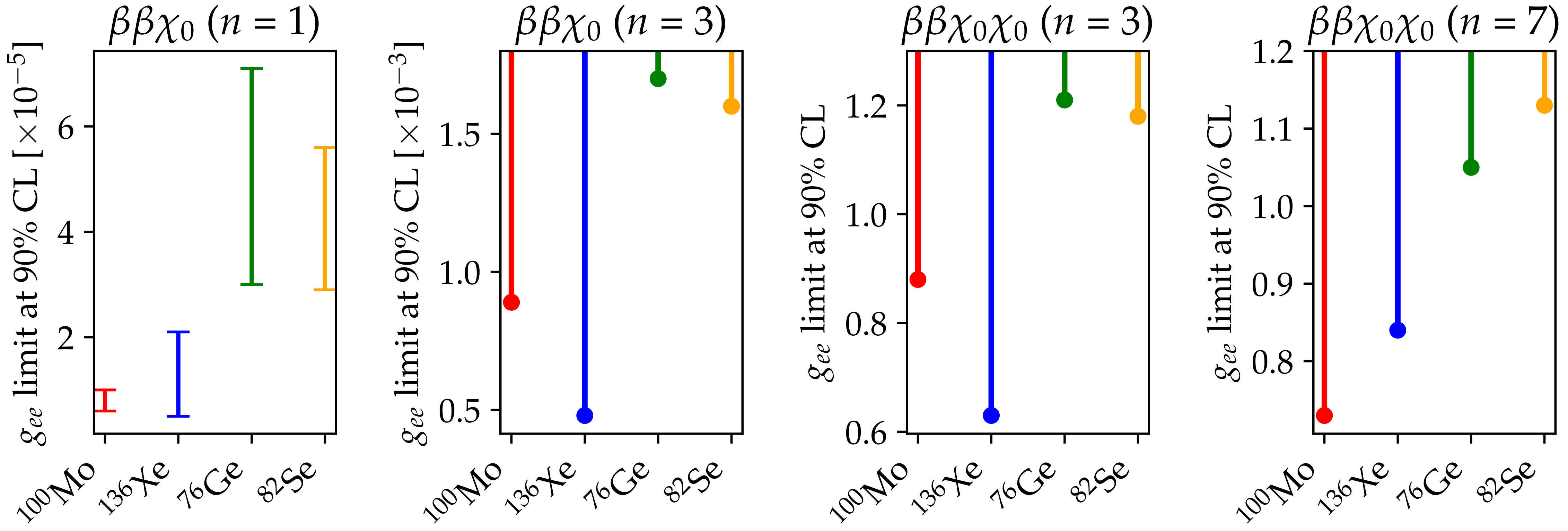
Sensitivity: Majoron decays

- Exposure scan corresponding to 1 month, 6 months, 1 year and 2 years of data taking (about 19, 112, 225, and 450 kg·yr of ^{100}Mo)
- With 450 kg·yr of ^{100}Mo the CUPID median exclusion sensitivity on the neutrino-Majoron coupling will be competitive with the limits obtained with ^{136}Xe



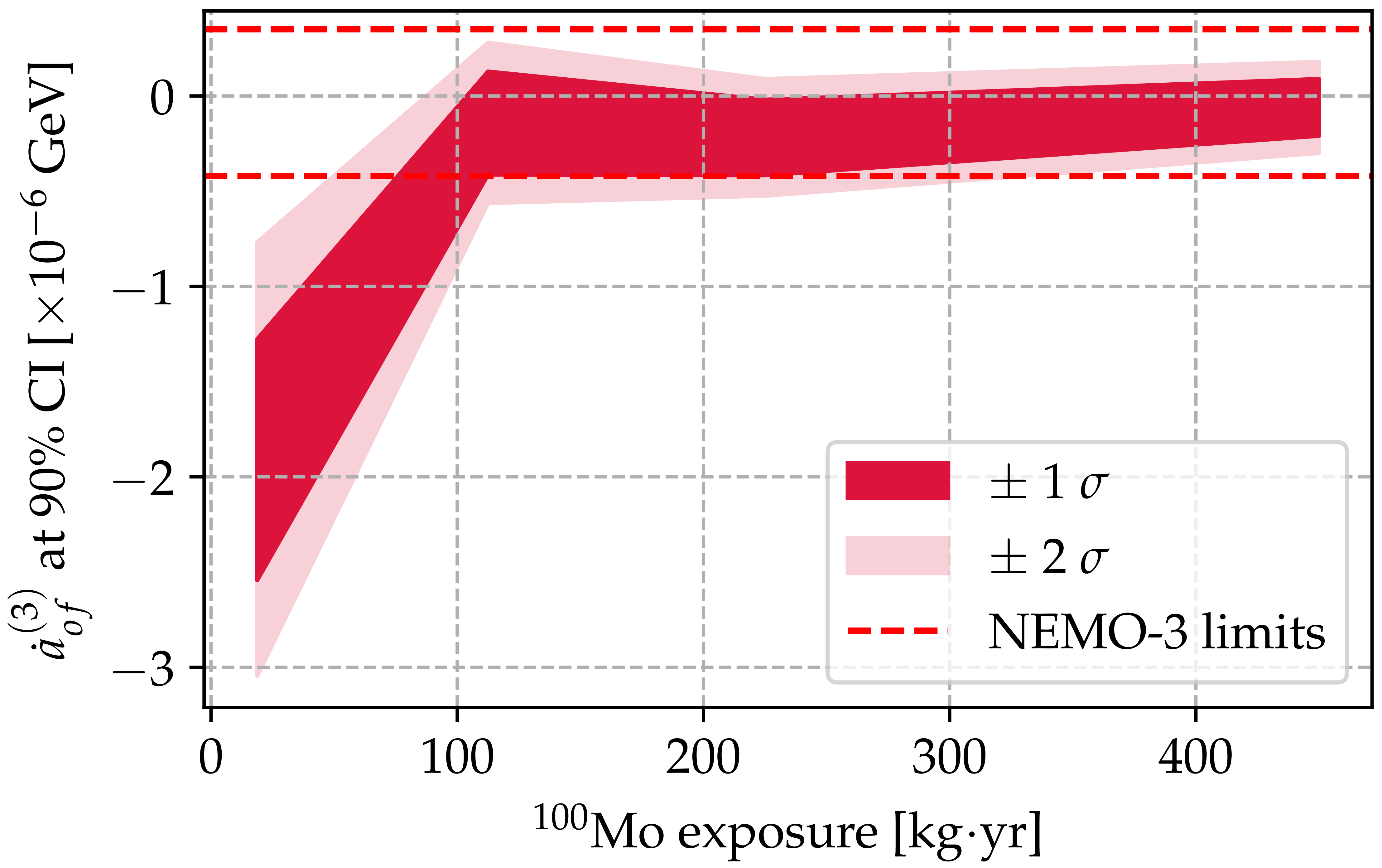
Decay mode	CUPID exclusion sensitivity $T_{1/2}$ [yr]	CUPID exclusion sensitivity g_{ee}^{M}	NEMO-3 [46, 135] $T_{1/2}$ [yr]	NEMO-3 [46, 135] g_{ee}^{M}
$\beta\beta\chi_0$ ($n = 1$)	1.2×10^{24}	$(0.6 - 1.0) \times 10^{-5}$	4.4×10^{22}	$(3.0 - 5.1) \times 10^{-5}$
$\beta\beta\chi_0$ ($n = 2$)	2.0×10^{23}	-	9.9×10^{21}	-
$\beta\beta\chi_0$ ($n = 3$)	7.5×10^{22}	0.0089	4.4×10^{21}	0.023
$\beta\beta\chi_0\chi_0$ ($n = 3$)	7.5×10^{22}	0.88	4.4×10^{21}	1.42
$\beta\beta\chi_0\chi_0$ ($n = 7$)	1.9×10^{22}	0.73	1.2×10^{21}	1.15



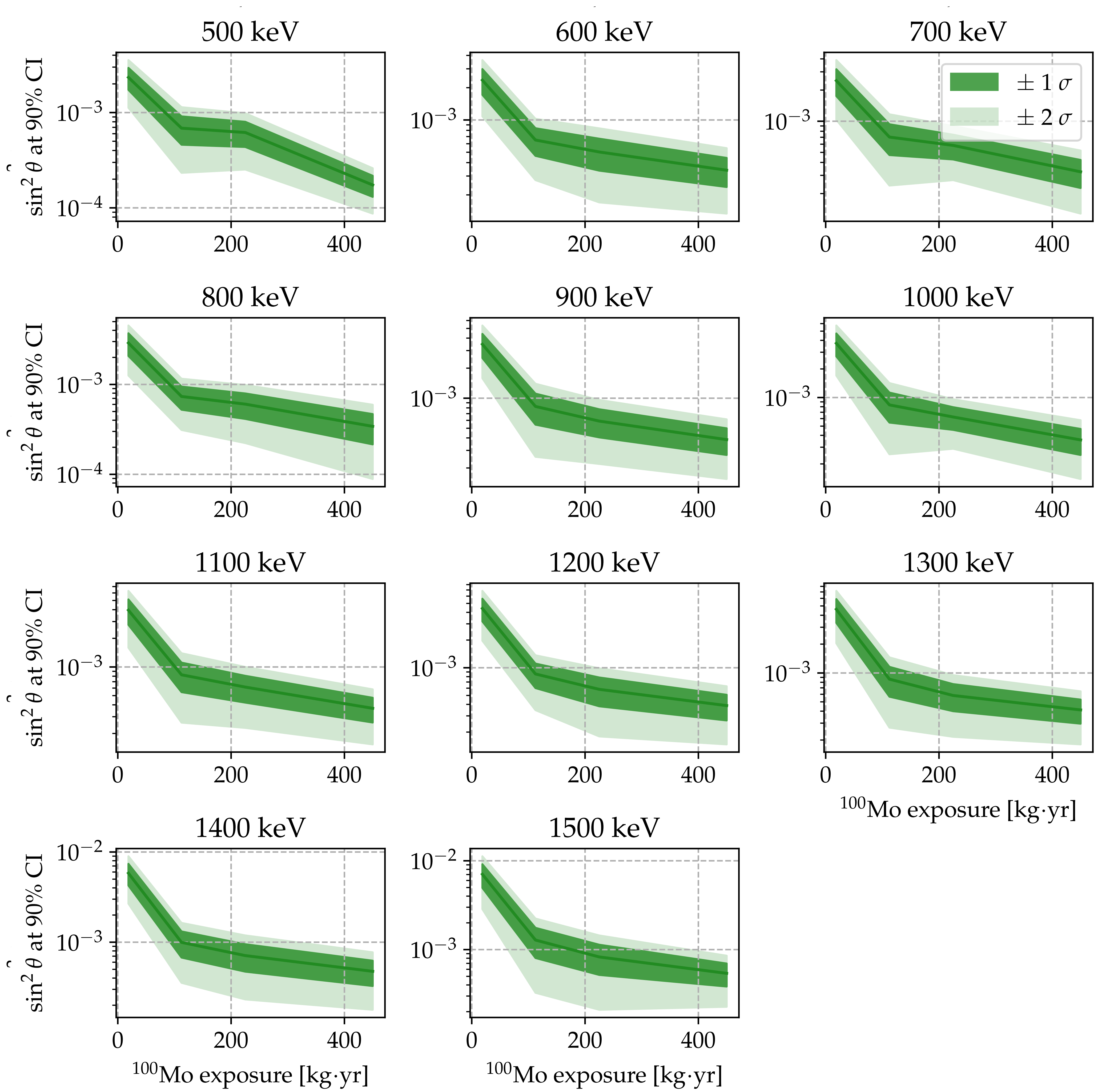
Sensitivity: Lorentz violation

- Negative fluctuations produce a bias when the background sources do not have enough statistic to be constrained in the fit.
- With 450 kg·yr of ^{100}Mo we expect to reach the most stringent limit on the countershaded operator among 0νββ experiments

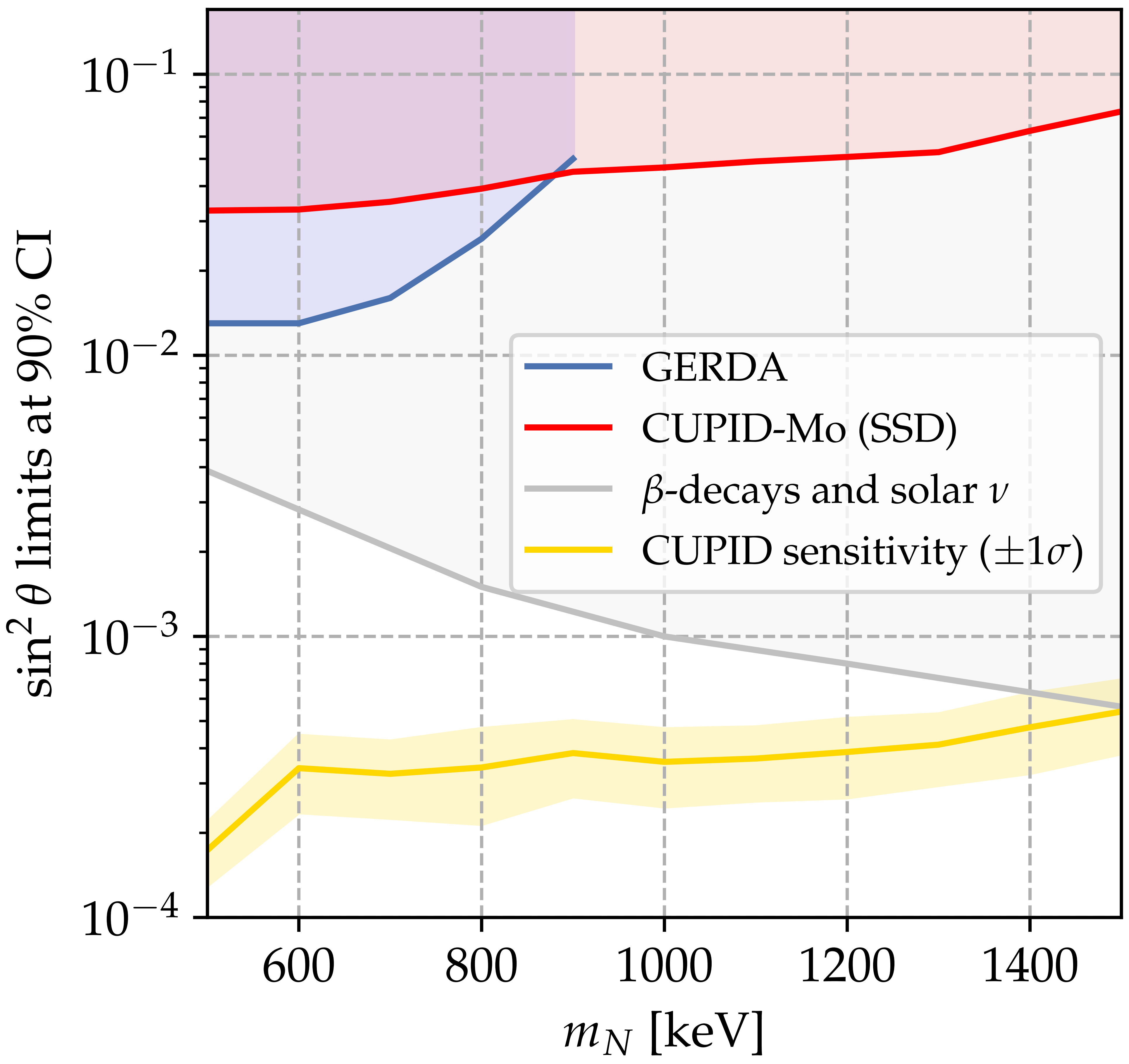
CUPID	$-2.2 \cdot 10^{-7} < \dot{a}_{of}^{(3)} < 7.5 \cdot 10^{-8}$
Isotope	Limit on $\dot{a}_{of}^{(3)}$ [GeV]
^{76}Ge	$(-2.7 < \dot{a}_{of}^{(3)} < 6.2) \cdot 10^{-6}$
^{82}Se	$\dot{a}_{of}^{(3)} < 4.1 \cdot 10^{-6}$
^{136}Xe	$-2.65 \cdot 10^{-5} < \dot{a}_{of}^{(3)} < 7.6 \cdot 10^{-6}$
^{116}Cd	$\dot{a}_{of}^{(3)} < 4.0 \cdot 10^{-6}$
^{100}Mo	$(-4.2 < \dot{a}_{of}^{(3)} < 3.5) \cdot 10^{-7}$
^{3}H	$\lvert\dot{a}_{of}^{(3)}\rvert < 3.0 \cdot 10^{-8}$



Sensitivity: Sterile neutrino emission



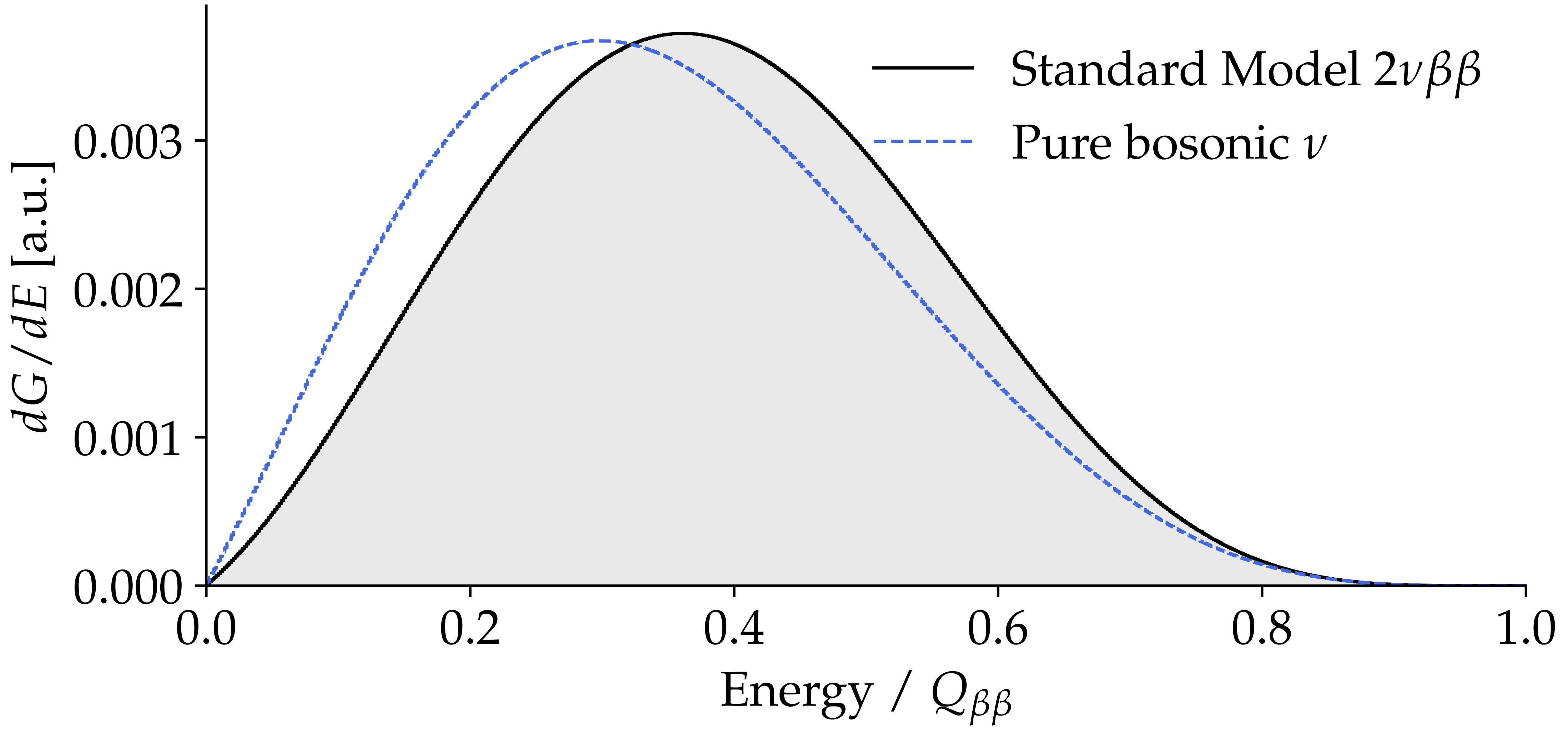
CUPID median exclusion sensitivity with 450 kg·yr of ^{100}Mo



Sensitivity: Bosonic neutrinos

$$\Gamma_{2\nu\beta\beta} = \cos^4\chi\Gamma_f + \sin^4\chi\Gamma_b$$

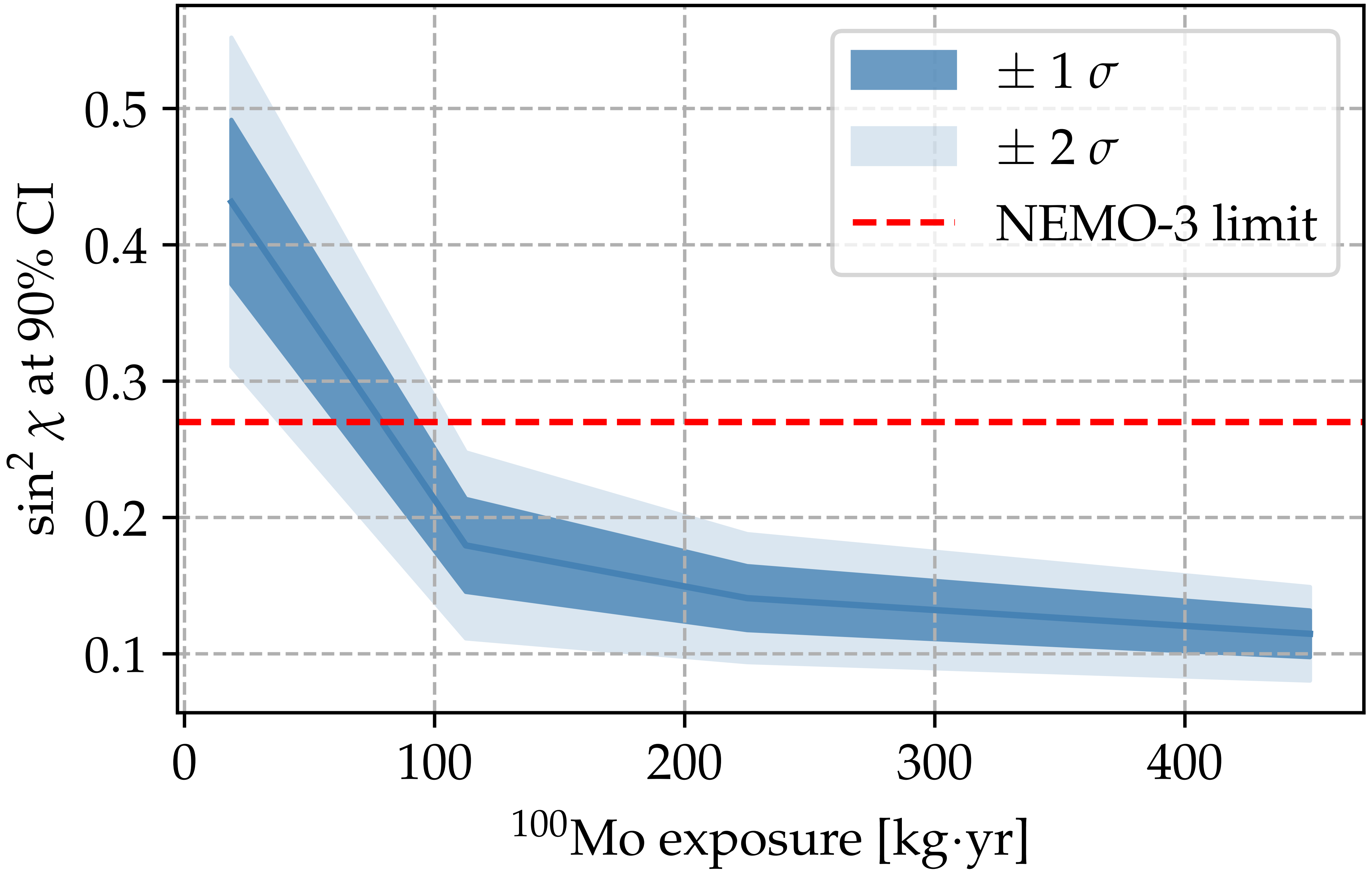
$\sin^4\chi$ represents the bosonic fraction of the neutrino wave function, Γ_f and Γ_b are theoretically calculated (model dependent)



The actual limit from NEMO-3 is

$$\sin^2\chi < 0.27$$

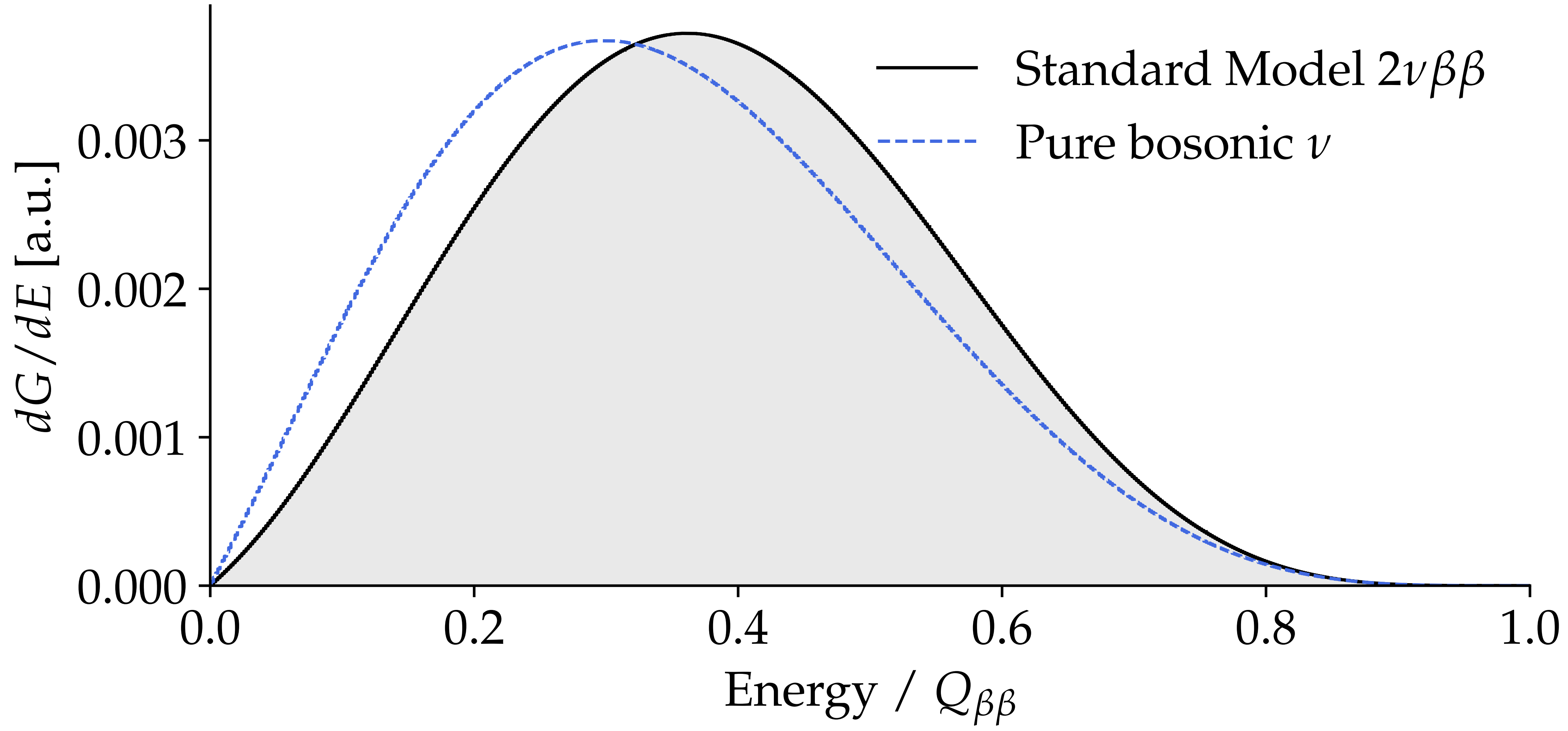
The mean exclusion sensitivity of CUPID with 450 kg·yr of ^{100}Mo is



Sensitivity: Bosonic neutrinos

$$\Gamma_{2\nu\beta\beta} = \cos^4\chi\Gamma_f + \sin^4\chi\Gamma_b$$

$\sin^4\chi$ represents the bosonic fraction of the neutrino wave function, Γ_f and Γ_b are theoretically calculated (model dependent)



The actual limit from NEMO-3 is

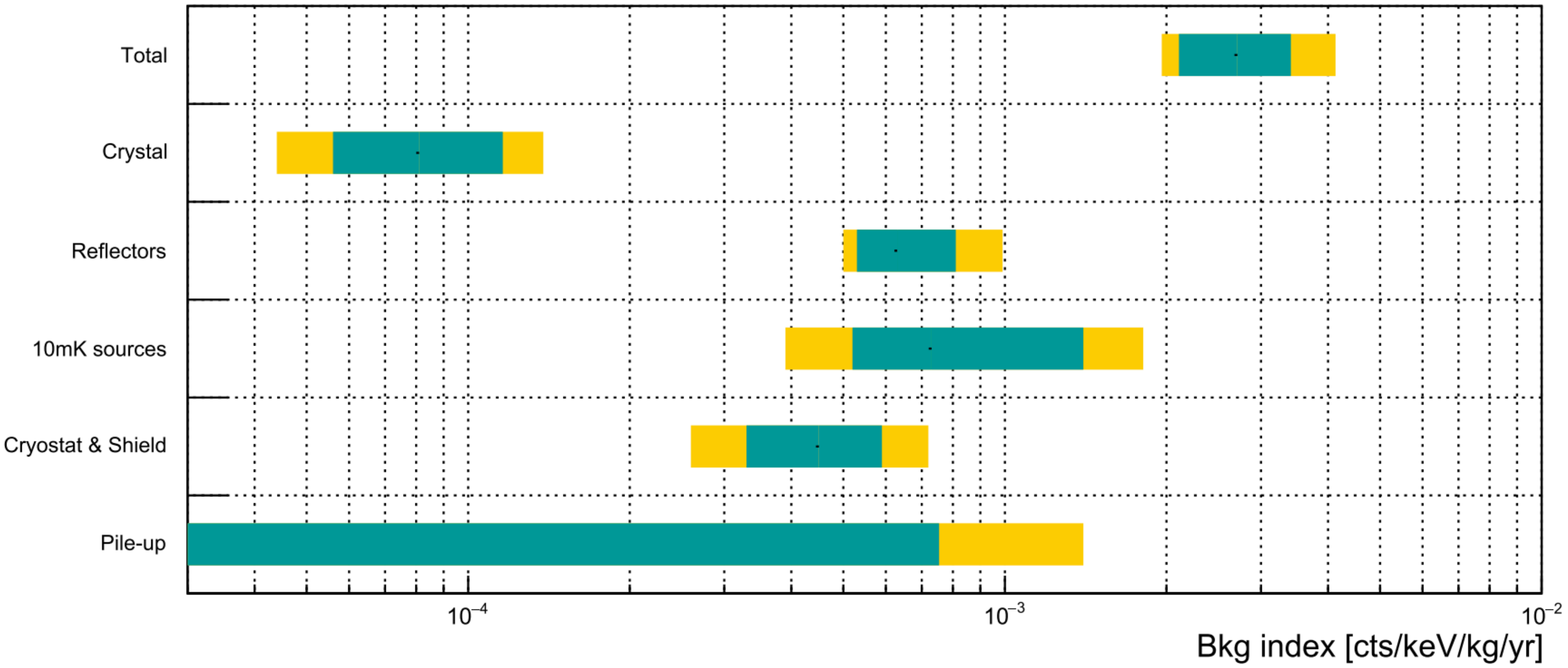
$$\sin^2\chi < 0.27 \text{ at } 90\% \text{ CL}$$

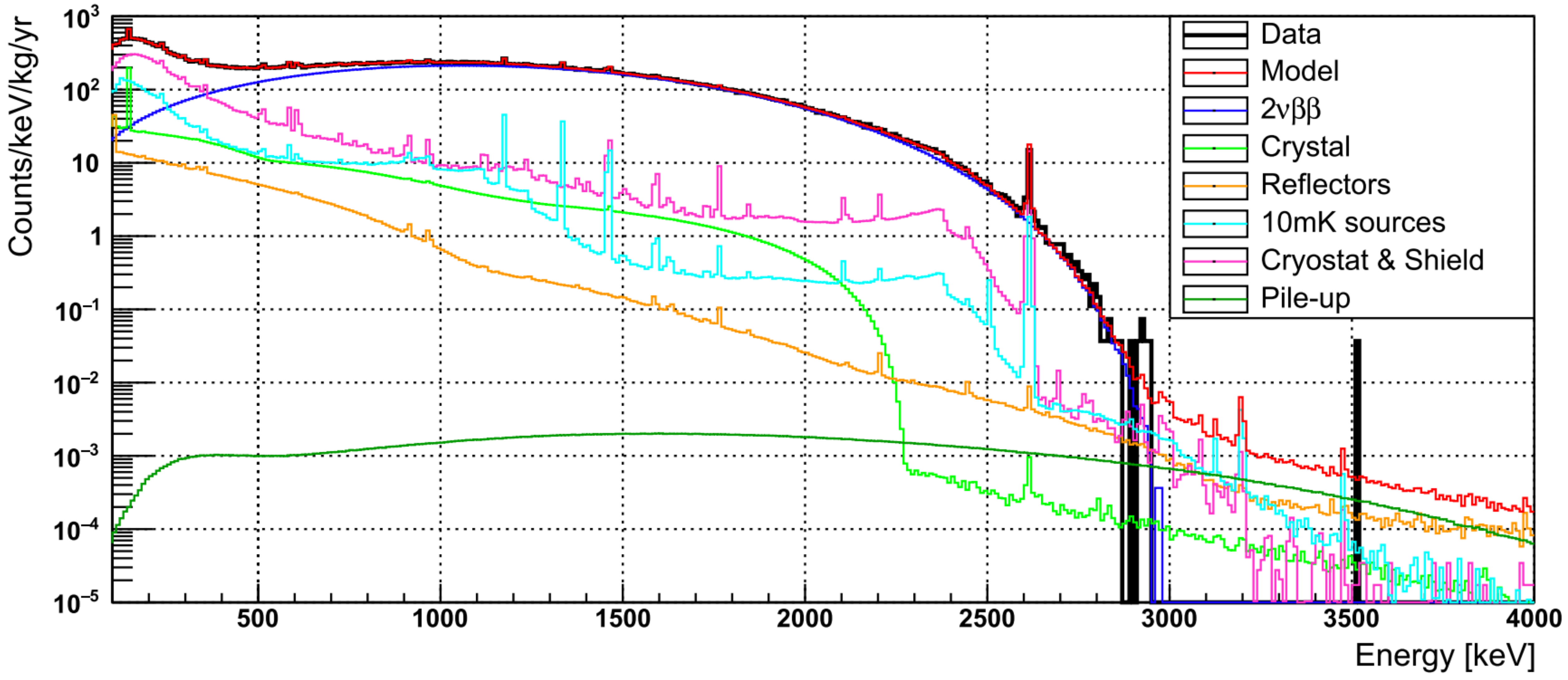
The mean exclusion sensitivity of CUPID with 450 kg·yr of ^{100}Mo is

$$\sin^2\chi < 0.11 \text{ at } 90\% \text{ CI}$$

Background in the ROI for CUPID-Mo

- Radio purity of Li_2MoO_4 crystals sufficient to reach the goals of CUPID
- Higher contribution from cryostat copper components → Cryostat not optimised for 0νββ searches





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