CUPID-0: a dual-readout cryogenic detector for double-beta decay

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on behalf of the CUPID-0 collaboration

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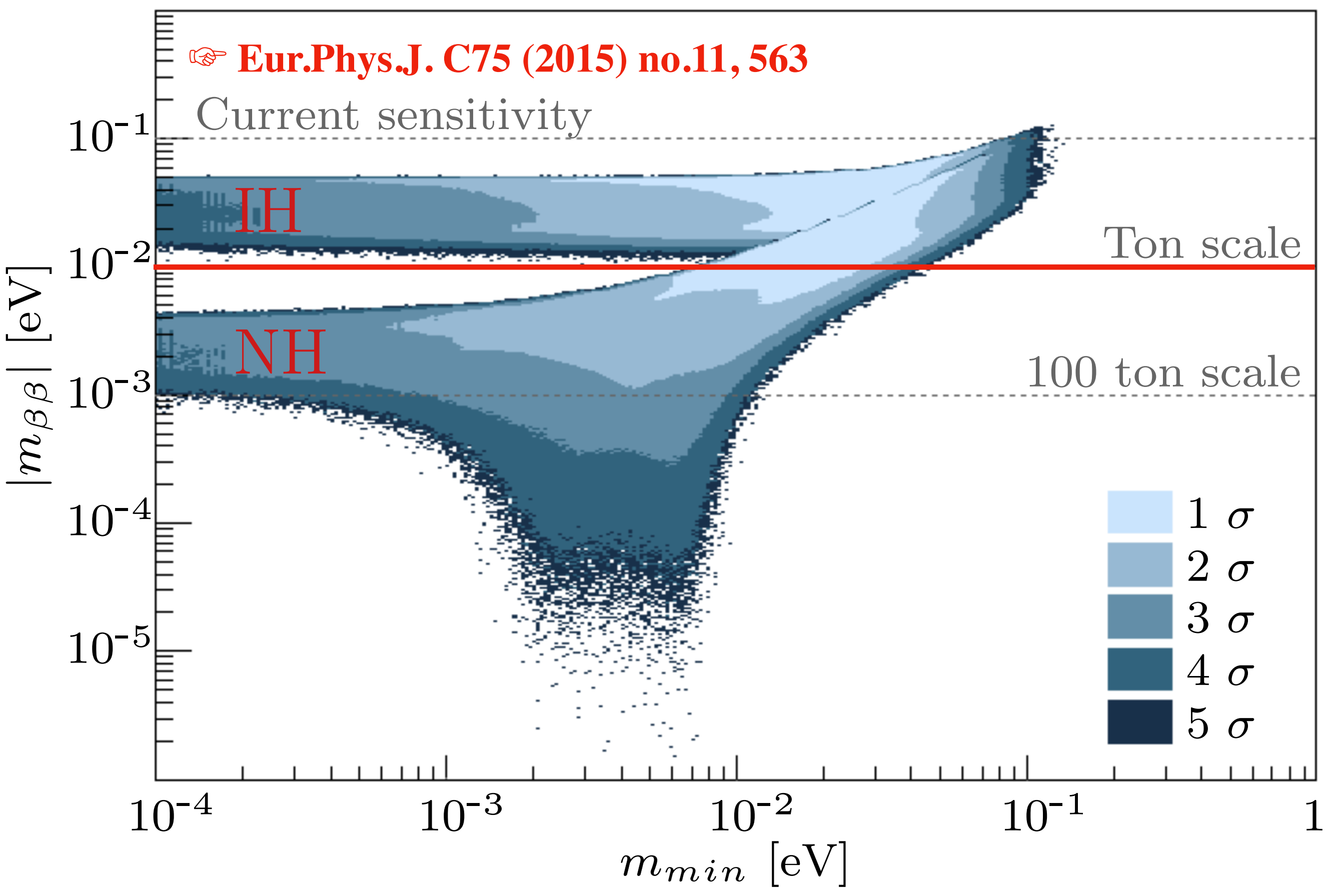
Motivation

Neutrinoless double beta decay (0νββ) is a **portal towards new physics**:

- **lepton number violation** (ΔL =2)
- insights on **neutrino mass**
- possible connection with **baryon asymmetry**



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

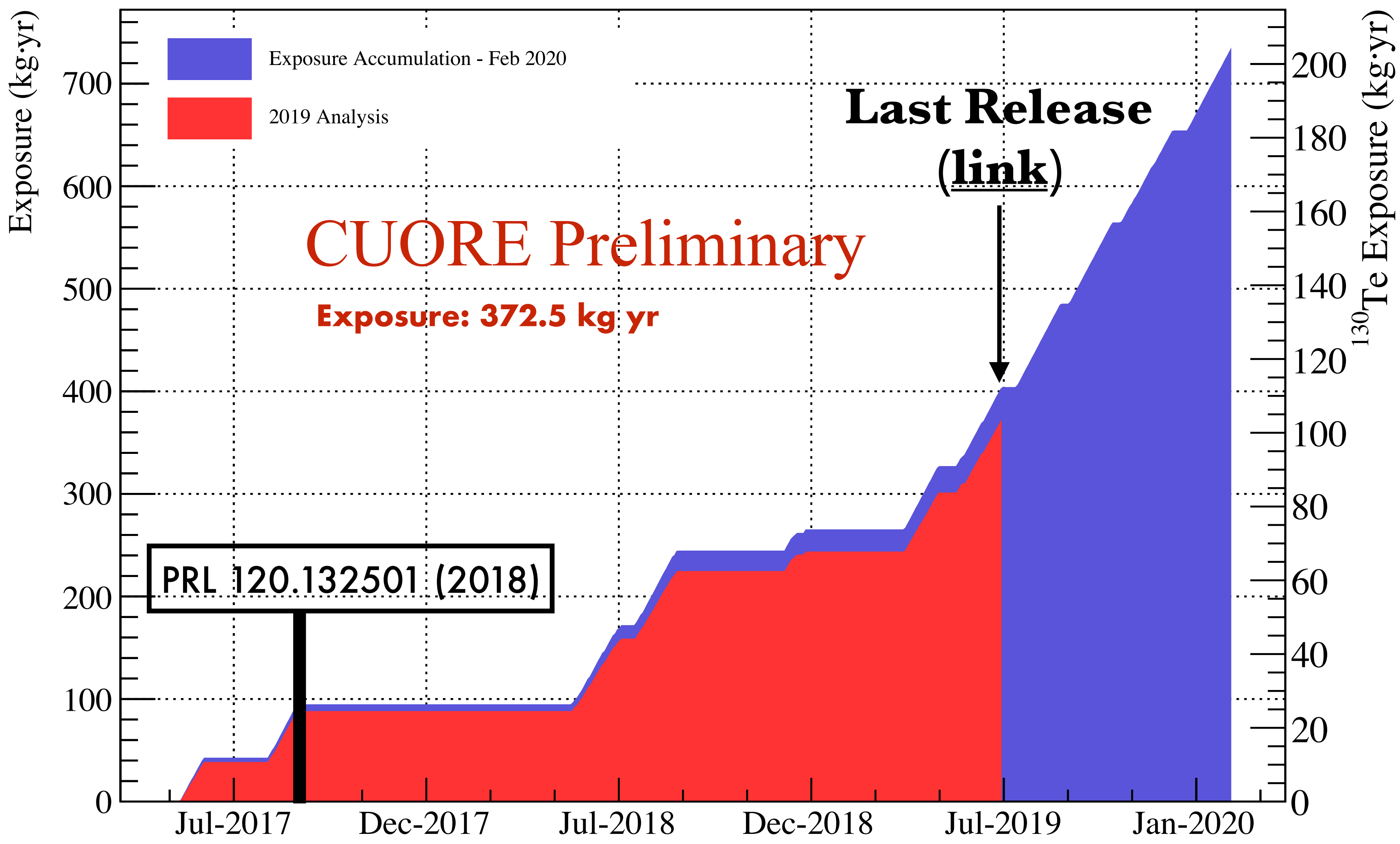
Next generation experiments will explore the whole **Inverted Hierarchy,** and almost all the 1σ region of the **Normal Hierarchy**.

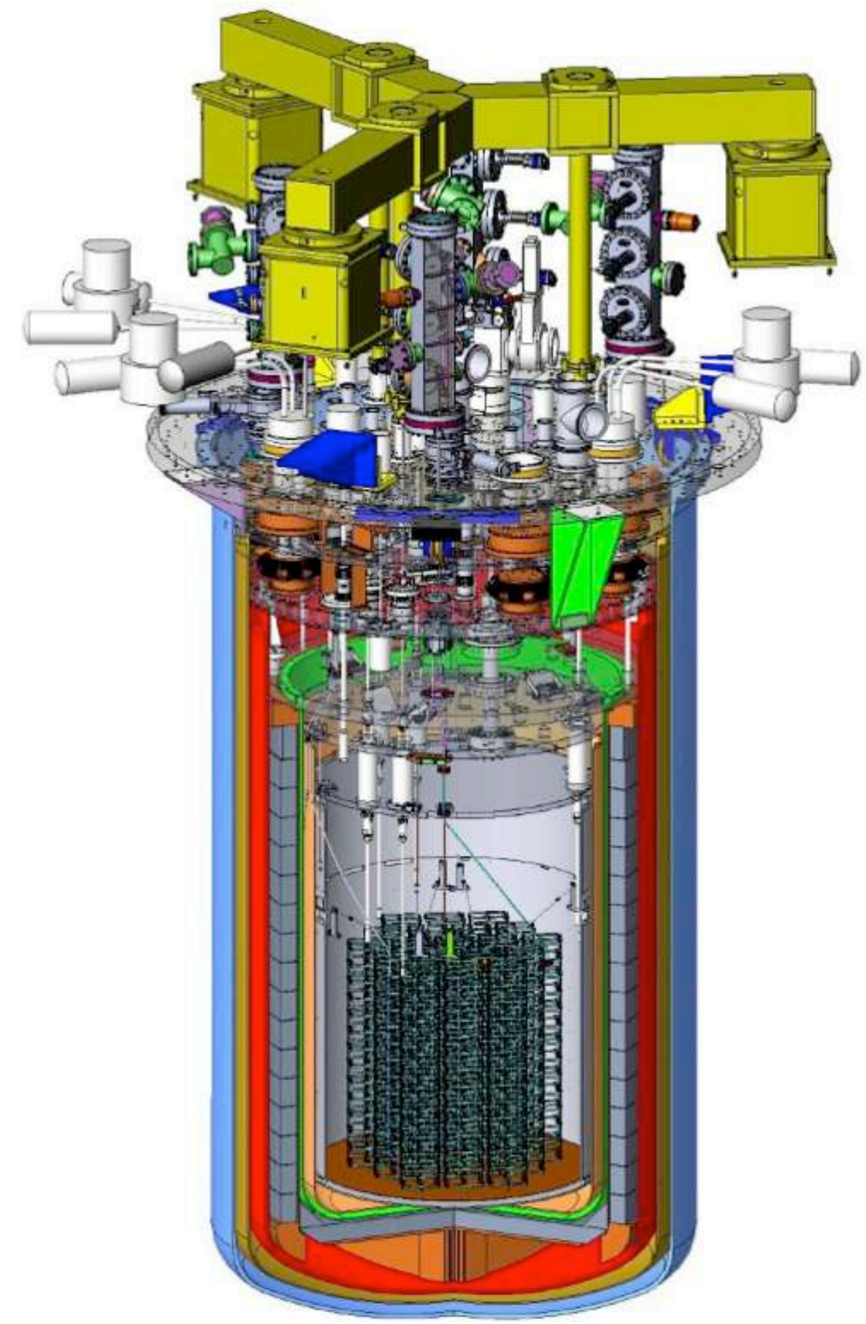
Two are the fundamental ingredients to reach the required sensitivity:

- Increase the ββ emitter (>**10^{27} nuclei**)
- Reduce the background index (<**10^{-4} counts/keV kg y**)

The CUORE experience

- ☑ Leading result on 0νββ (see Benato's Talk)
- ☑ Feasibility of a **tonne-scale experiment**
- ☑ Excellent energy resolution (0.3%)
- ☑ Full understanding of the cryogenic facility



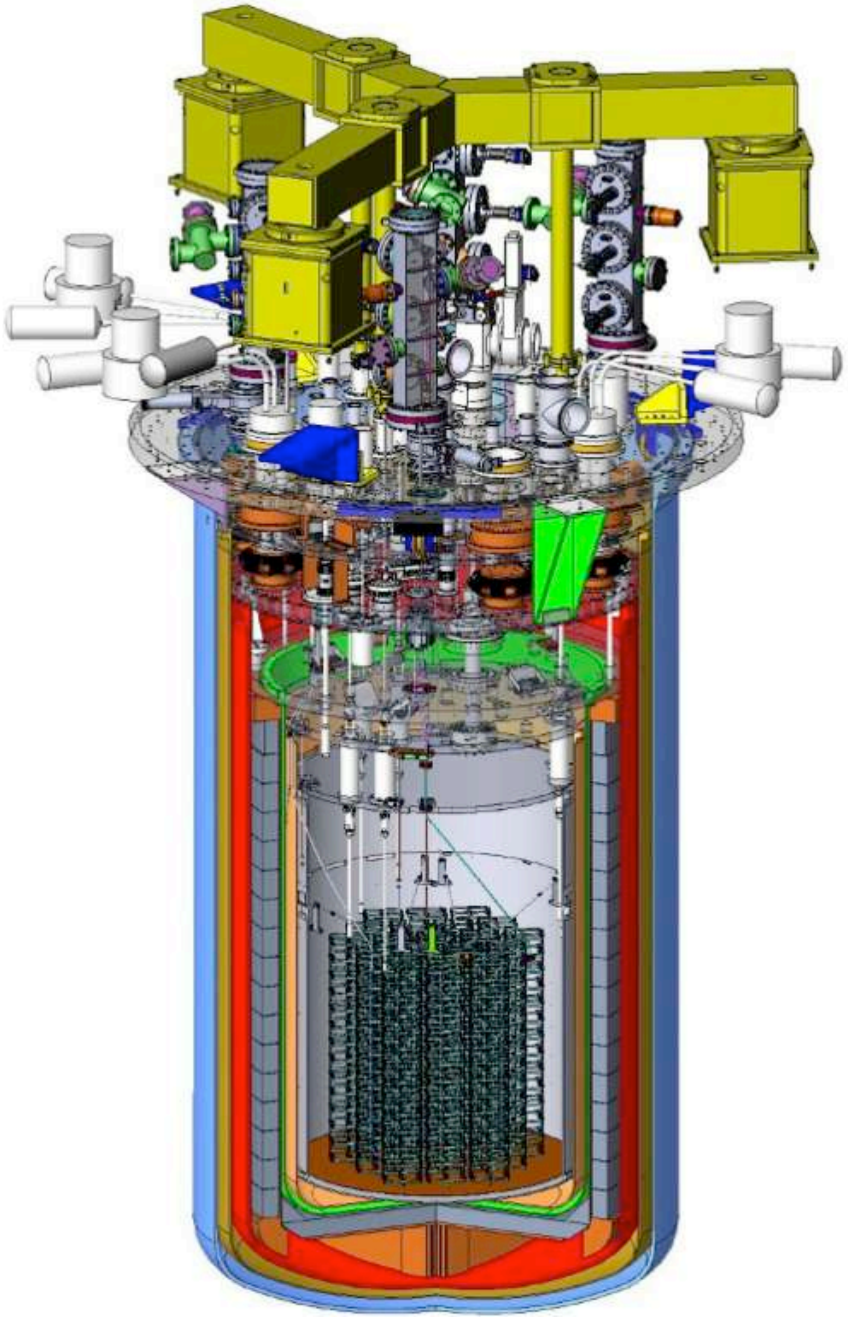


Scientific potential of the CUORE observatory will be soon exploited with other analysis.

From CUORE to CUPID

CUORE **U**pgrade with **P**article **ID**entification

Next generation experiment hosted in the same **CUORE infrastructure** at LNGS (CDR link)



GOALS:

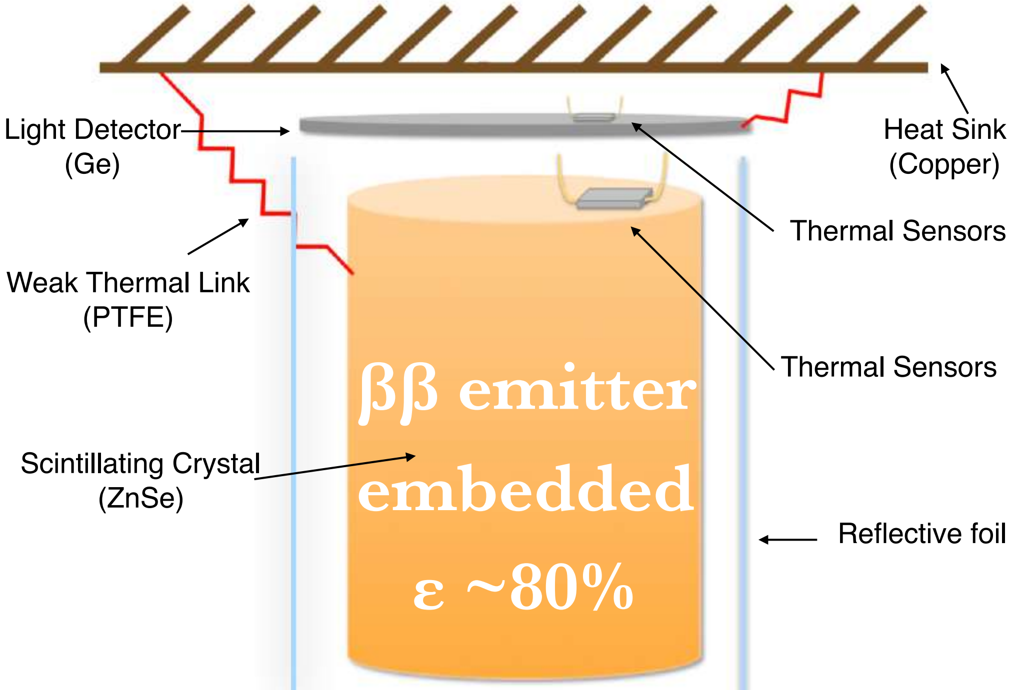
- Increase the ββ emitter (>**10^{27} nuclei**)
- Reduce the background index (<**10^{-4} counts/keV kg y**)

STRATEGY:

- Isotopic enrichment (more isotopes in the same volume)
- Background suppression by ×100 using Particle ID

CUPID-0 and **CUPID-Mo** (see Claudia Nones's Talk): two pathfinders based on **scintillating calorimeters**.

Scintillating bolometers

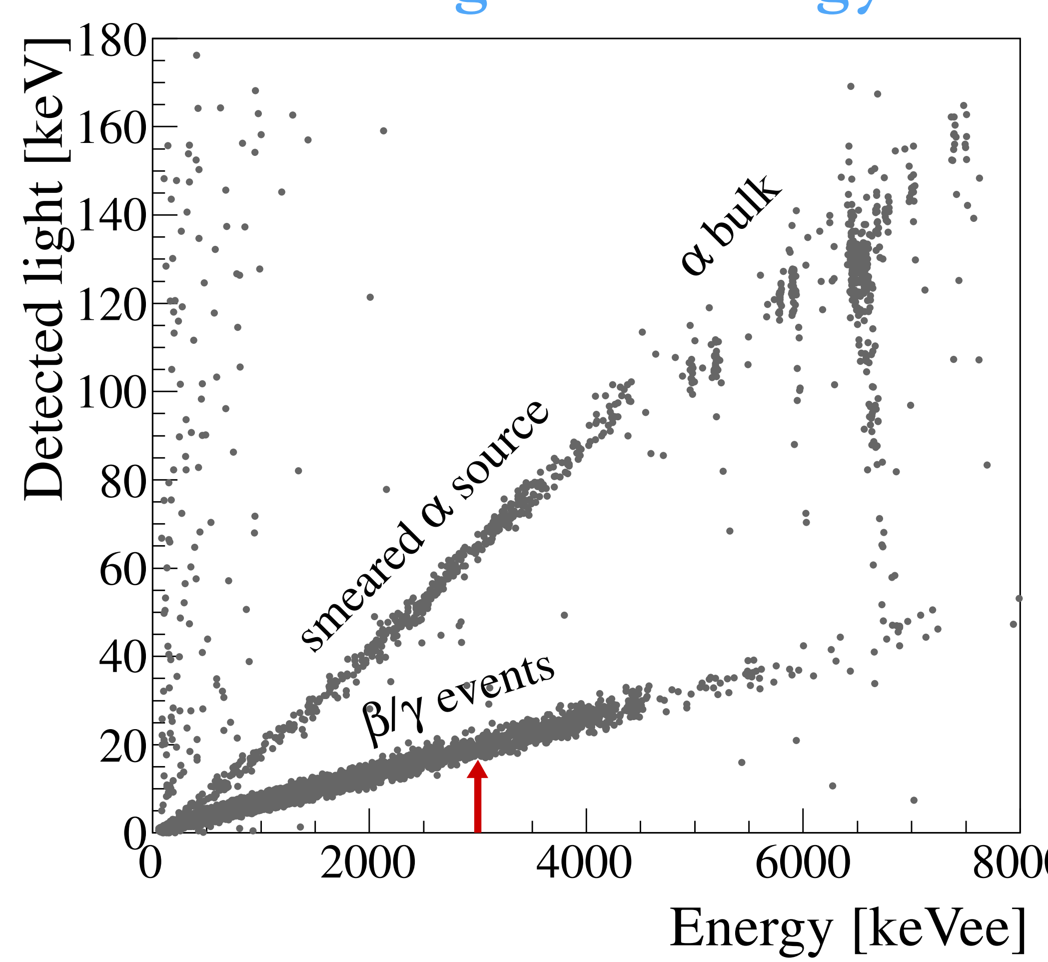


Scintillating crystals operated at **~10 mK**
Particle interaction ➜ T increasing ➜ Voltage Signal

0νββ Signature: monochromatic peak at $Q_{\beta\beta}$

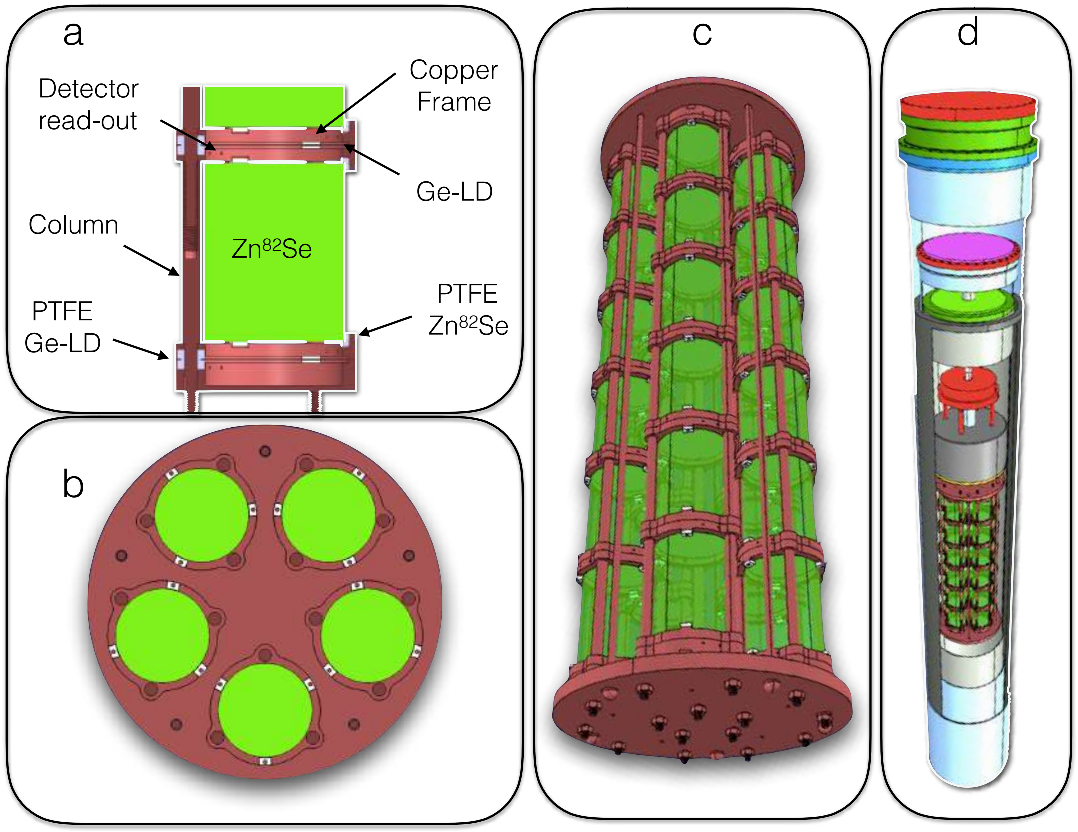
- Grown from **different ββ** emitters (only technique for a **multi-isotope** approach)
- Excellent **energy resolution** (<1%)
- Modular design allows for large **scalability**
- **$Q_{\beta\beta}$ ~ 3 MeV for ^{100}Mo and ^{82}Se** (Phase Space Factor ∝ $Q_{\beta\beta}^5$)
- **$LY_\alpha \neq LY_{\beta/\gamma}$ ➜ Particle ID**

ZnSe: Light Vs Energy



L. Pagnanini

The CUPID-0 experiment



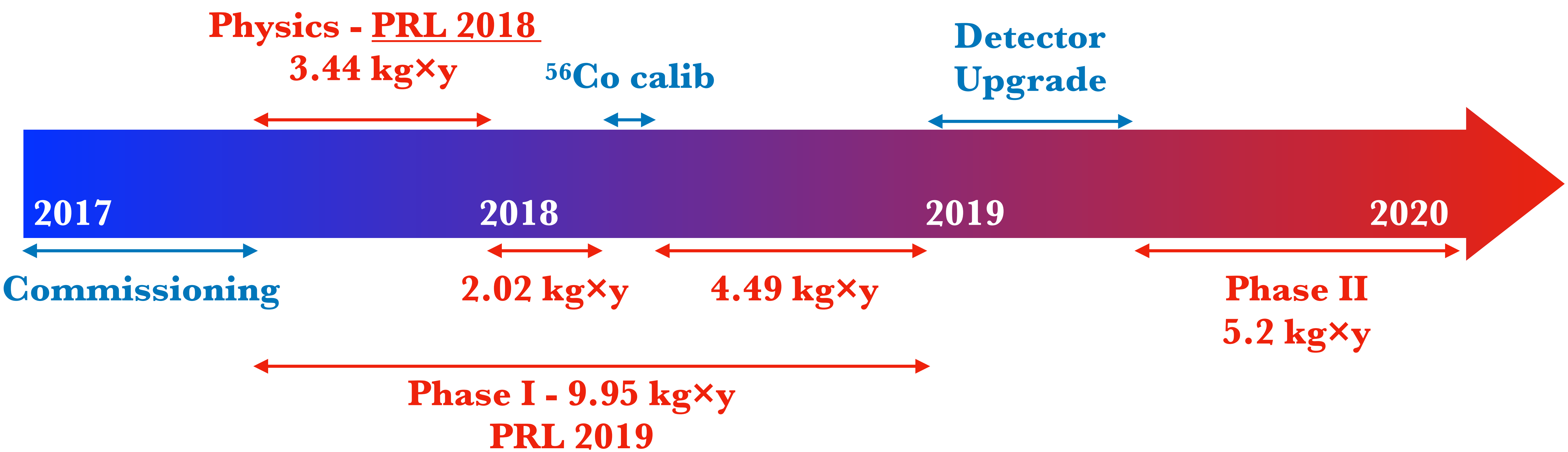
a. Single module
b. Top view
c. CUPID-0 array
d. Cryostat

https://cupid-0.lngs.infn.it

- CUPID-0 is the first **pilot experiment** of **CUPID**
- 24 **95%-enriched $Zn^{82}Se$ crystals** + 2 natural ones
- 31 Ge **light detectors**
- **Reflective** foil Vikuiti™ to increase the light collection
- Total Mass: **10.5 kg (ZnSe) - 5.17 kg (^{82}Se)**
- ^{82}Se atoms: **(3.41 ± 0.03) 10^{25}**
- $Q_{\beta\beta}$ = **(2997.9 ± 0.3) keV**
- Hosted in the CUORE-0 **Cryostat (LNGS, Italy)**

☞ **Eur. Phys. J. C (2018) 78:428 (Detector Paper)**

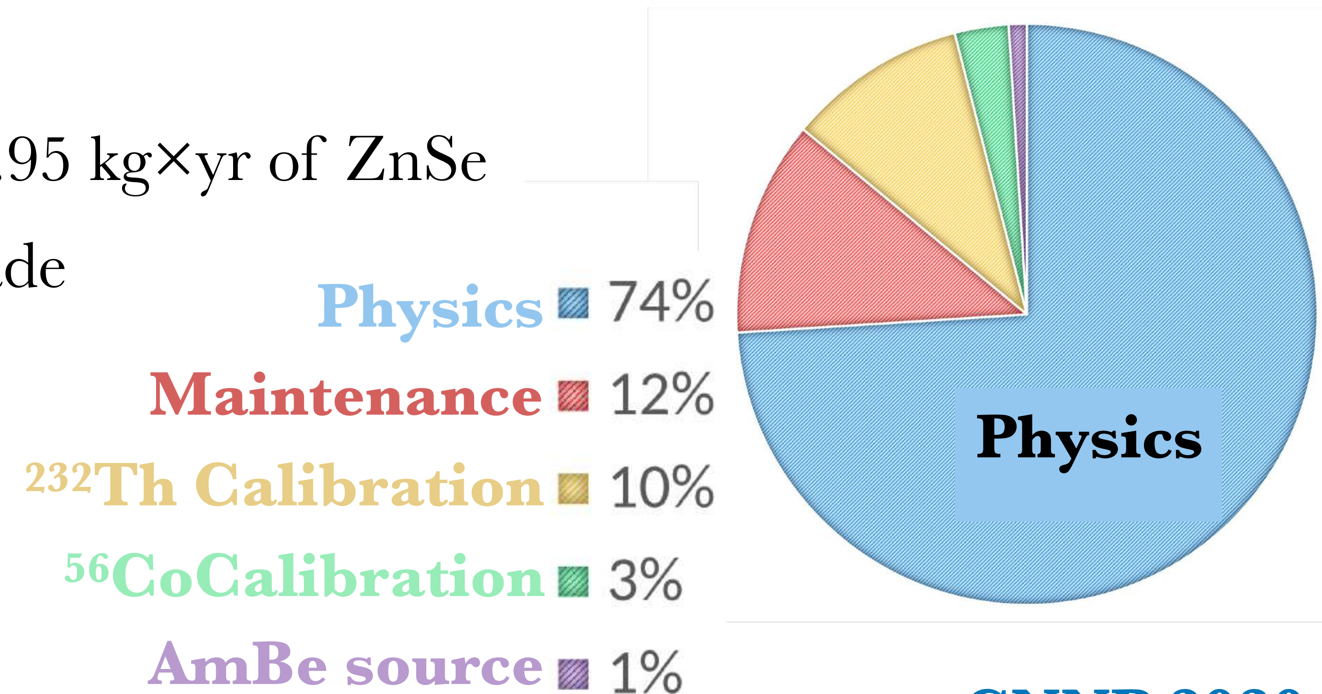
The CUPID-0's seasons



Full statistics acquired in ~1.5 years (Phase-I): 9.95 kg×yr of ZnSe

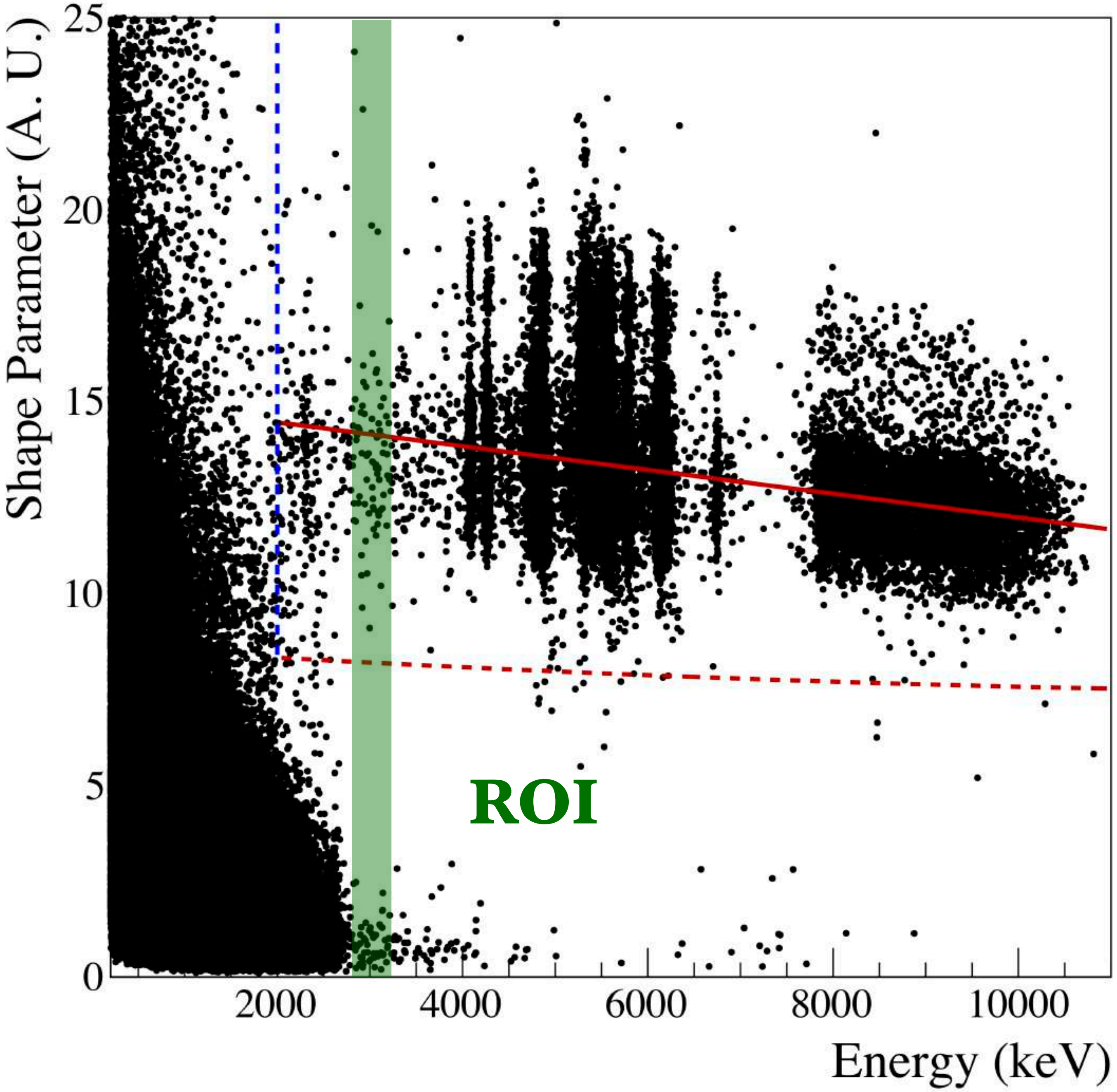
At the end of 2018 detector warm-up and upgrade

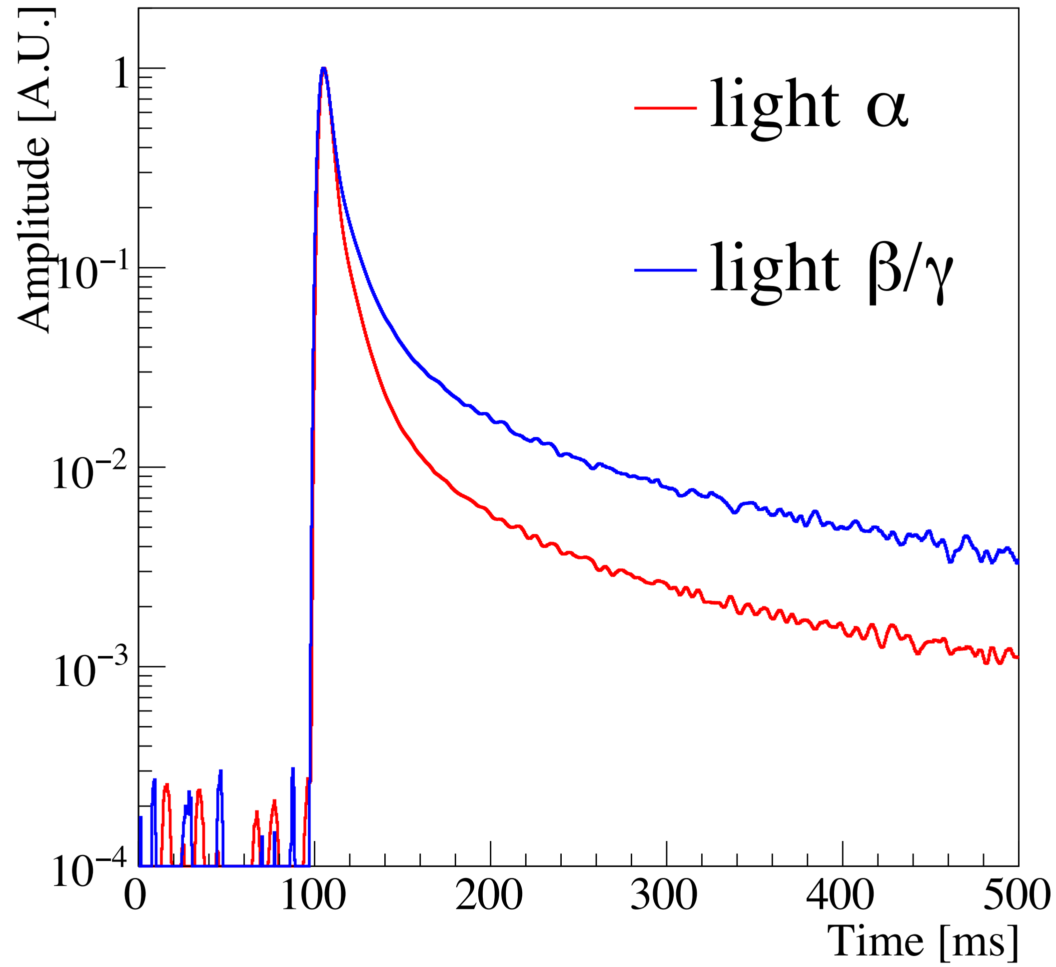
June 2019: Start Phase-II



Particle Identification

αs and β/γs feature a different **pulse shape of the light signal**, quantified by a shape parameter (i.e. right-side χ^2).





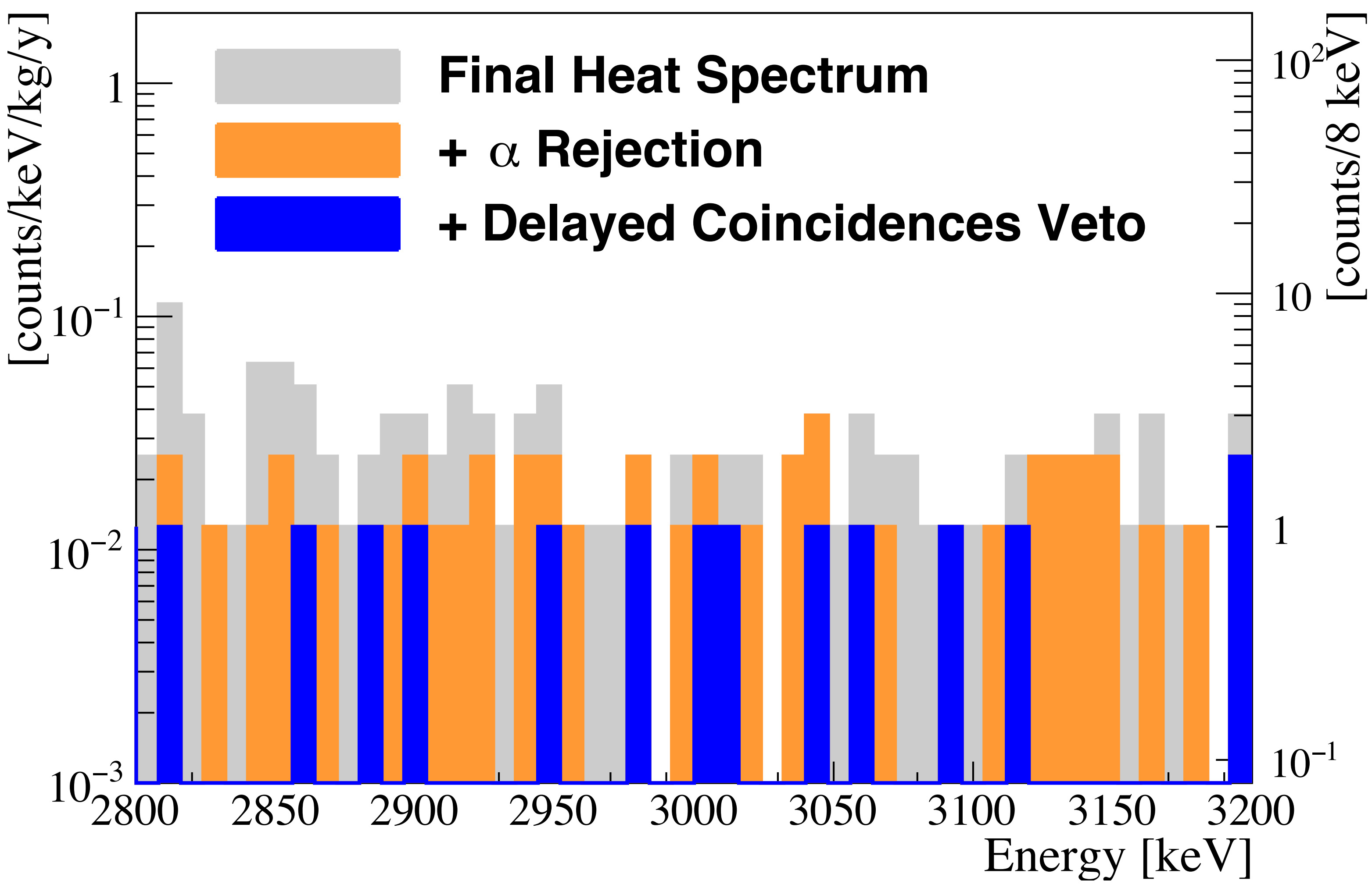
Cut optimized on the **high multiplicity events** due to muon-induced e.m. showers (pure sample of β/γs)

☑ α/β separation power: **>99.9 %**

^{82}Se 0νββ decay results

- Final Exposure (Physics Runs): **9.95 kg × y (22 Zn^{82}Se)**
- Resolution at $Q_{\beta\beta}$: **(20.05 ± 0.34) keV**
- Background: **$3.5^{-0.9}_{+1.0} \times 10^{-3}$ counts/(keV × kg × y)**
- $T_{1/2}$ (0νββ ^{82}Se) > **3.5 × 10^{24} y (90% C.I. Limit)**
  5.0 × 10^{24} y (Median Sensitivity)
- $m_{\beta\beta}$ < **(311 - 638) eV**

☞ **Phys.Rev.Lett. 123 (2019) no.3, 032501**



Selecting only particle signals:

⇒ 3.2 × 10^{-2} counts/(keV kg y)

Selecting only β/γ:

⇒ 1.3 × 10^{-2} counts/(keV kg y)

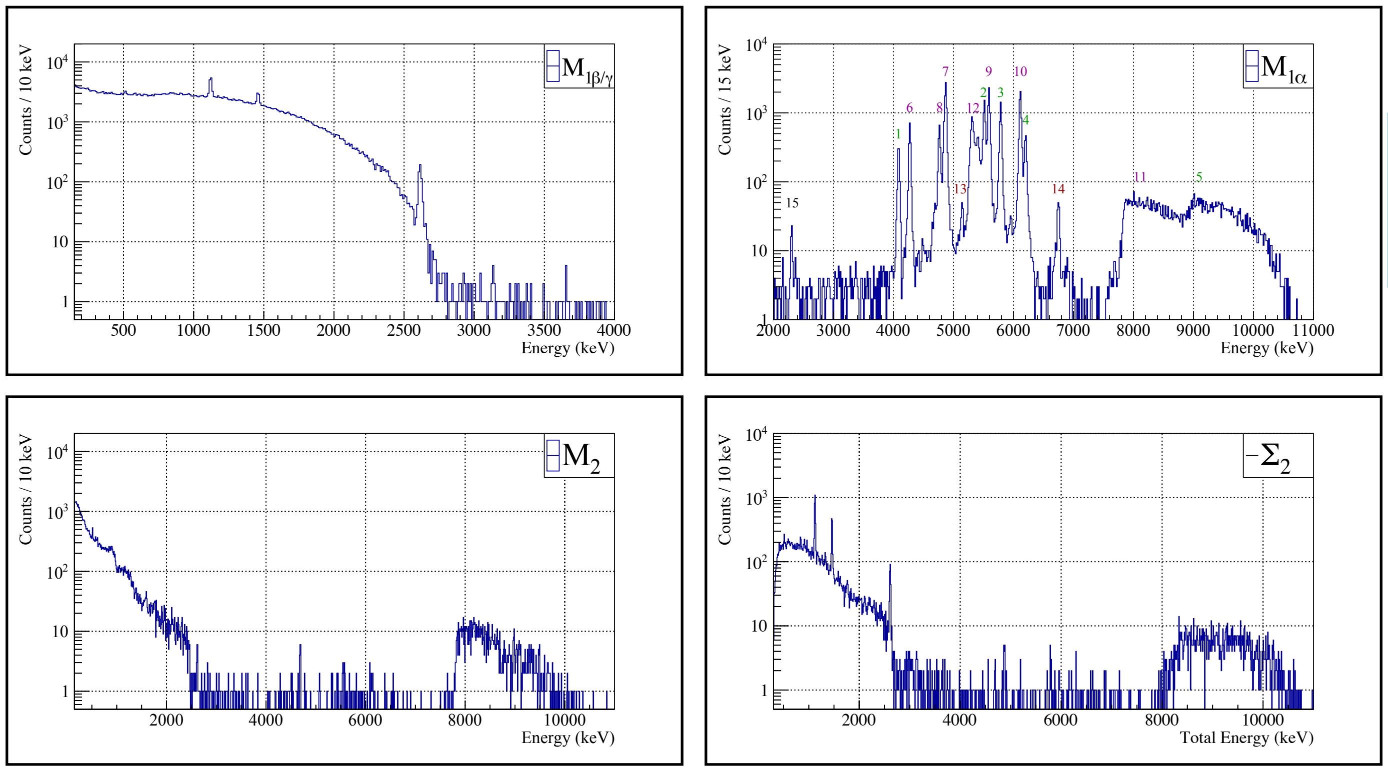
Removing ^{208}Tl events:

⇒ 3.5 × 10^{-3} counts/(keV kg y)

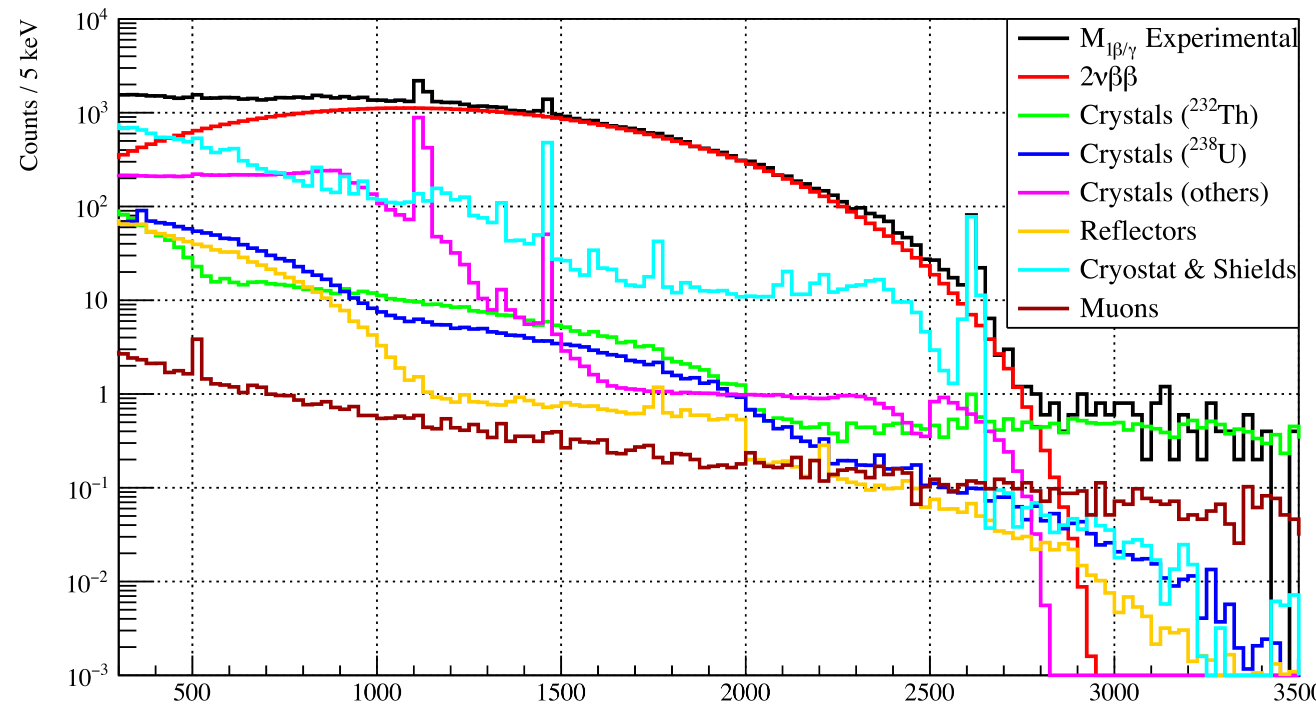
Lowest background measured for cryogenic calorimeters

Background model

Single Hit + Double Hit Events
Higher Multiplicity for Muons



Bayesian fit to the experimental data with a linear combination of **simulated spectra**



Background sources in the ROI (link)

2νββ measurement (link)

Limit on CPTV (link)

Region Of Interest

Background rate in the ROI (2.8 - 3.2 MeV) after the **delayed coincidences** cut.

Component	ROI_{bkg} rate (10^{-4}counts/(keV kg yr))	Source	ROI_{bkg} rate (10^{-4}counts/(keV kg yr))
Crystals	$11.7 \pm 0.6\ ^{+1.6}_{-0.8}$	^{232}Th– bulk	$3.4 \pm 0.6 \pm 0.1$
		^{232}Th–surf	$3.4 \pm 0.5\ ^{+1.0}_{-0.7}$
		^{238}U–surf	$4.9 \pm 0.3\ ^{+1.3}_{-0.3}$
Reflectors & Holder	$2.1 \pm 0.3\ ^{+2.2}_{-1.0}$	^{232}Th	< 3.3
		^{238}U	$1.8 \pm 0.3\ ^{+1.4}_{-0.9}$
Cryostat & Shields	$5.9 \pm 1.3\ ^{+7.2}_{-2.9}$	^{232}Th	$3.5 \pm 1.3\ ^{+7.4}_{-3.3}$
		^{238}U	$2.4 \pm 0.4\ ^{+4.1}_{-0.7}$
Subtotal	$19.8 \pm 1.4\ ^{+6.6}_{-2.7}$		
Muons	$15.3 \pm 1.3 \pm 2.5$		
$2\nu\beta\beta$	6.0 ± 0.3 ($< 3 \times 10^{-6}$ counts/(keV kg yr) in [2.95–3.05] MeV range)		
Total	$41 \pm 2\ ^{+9}_{-4}$		
Experimental	$35\ ^{+10}_{-9}$		

Insights for the next-generation detector design.
CUPID-0 Phase II will validate the current model.

☞ **Eur.Phys.J. C 79 (2019) 7:583 (Background Model)**

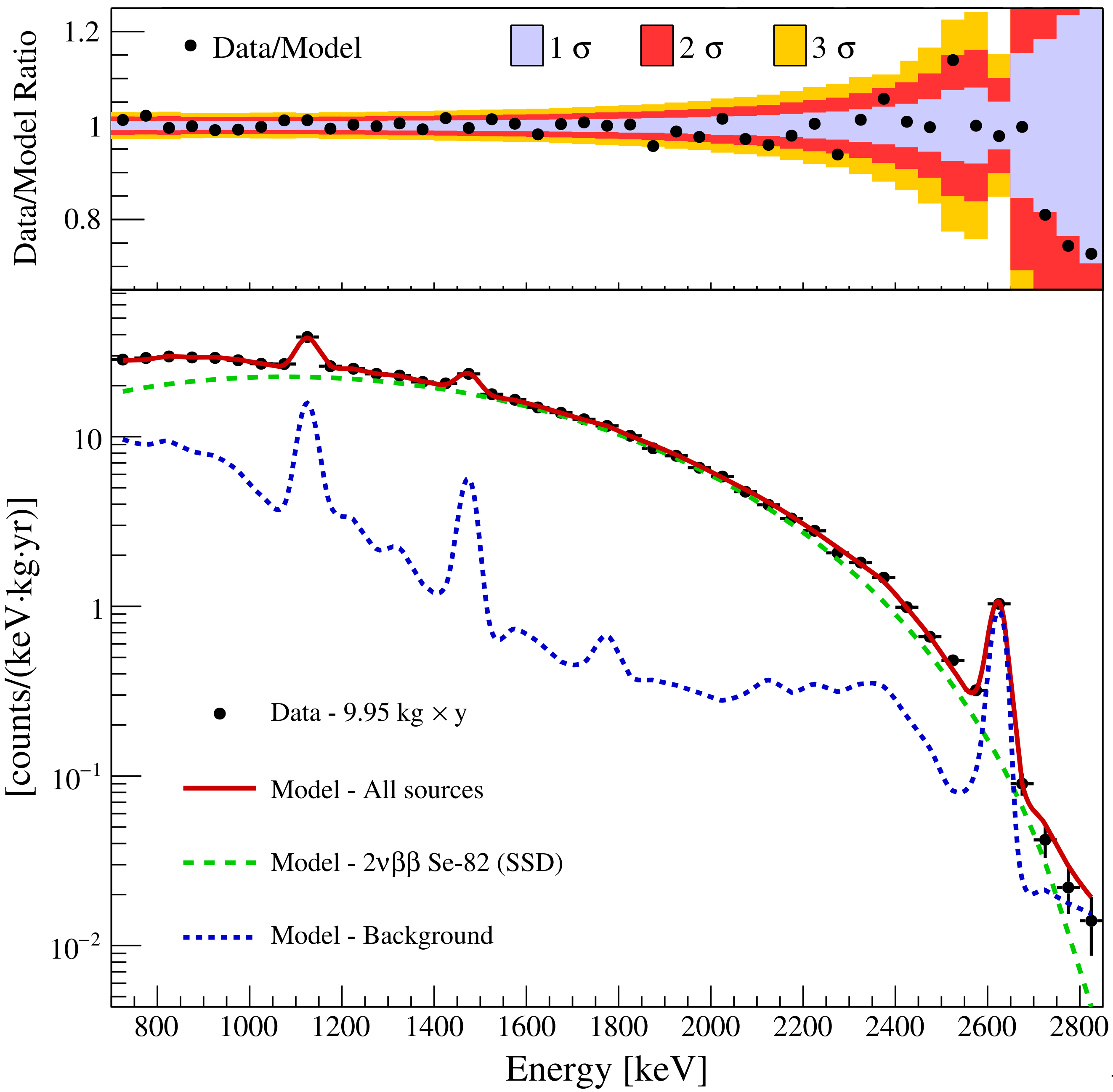
Measurement of ^{82}Se 2νββ half-life

We obtain the most precise measurement of 2νββ half-life:

$$T^{2\nu}_{1/2} = [8.60 \pm 0.03(\text{stat})\,^{+0.19}_{-0.13}(\text{syst})] \times 10^{19}\ \text{yr}.$$

	1600 - 2500	500 - 3000
S	6.2×10^4	2.7×10^5
B	0.4×10^4	0.7×10^4
S/B	~16	~4

☞ **PRL 123, 262501 (2019)**



	Systematic Source	$\Delta A_{2\nu}$
Fit	Source localization	$^{+0.36}_{-0.21}\%$
	Reduced sources list	-0.10%
	^{90}Sr/^{90}Y	-1.57%
	Fixed step binning	$+0.16\%$
	Threshold of $\mathcal{M}_{1\beta/\gamma}$	$+0.15\%$
	α identification	-0.01%
	Energy scale	-0.39%
	Prior distributions	$+0.04\%$
	Combined	$^{+0.4}_{-1.6}\%$
	Detector efficiency	$\pm 0.5\%$
	^{82}Se atoms	$\pm 1.0\%$
Model	$2\nu\beta\beta$	$\pm 1.0\%$
Total		$^{+1.6}_{-2.2}\%$

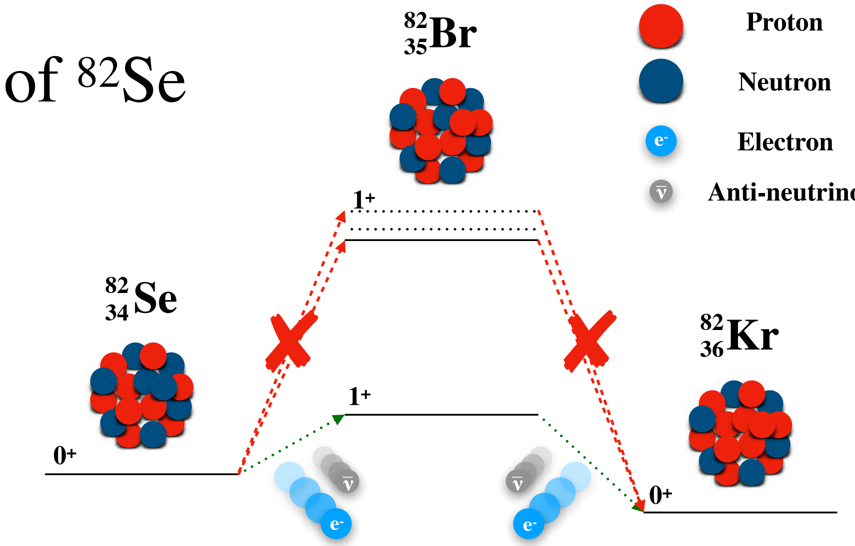
Evidence of Single-State Dominance

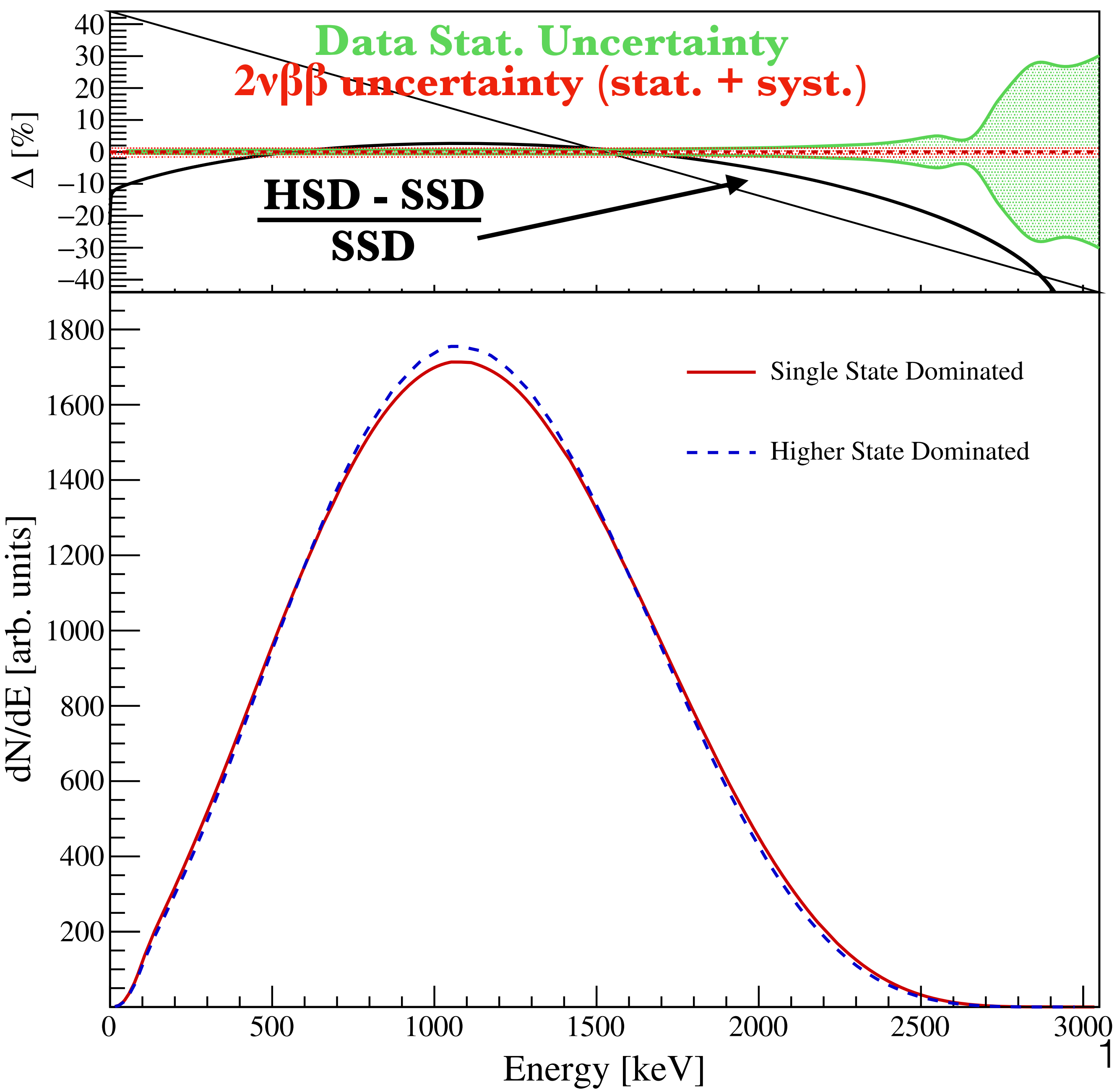
We have a strong evidence of Single State Dominance on $2\nu\beta\beta$ of ^{82}Se

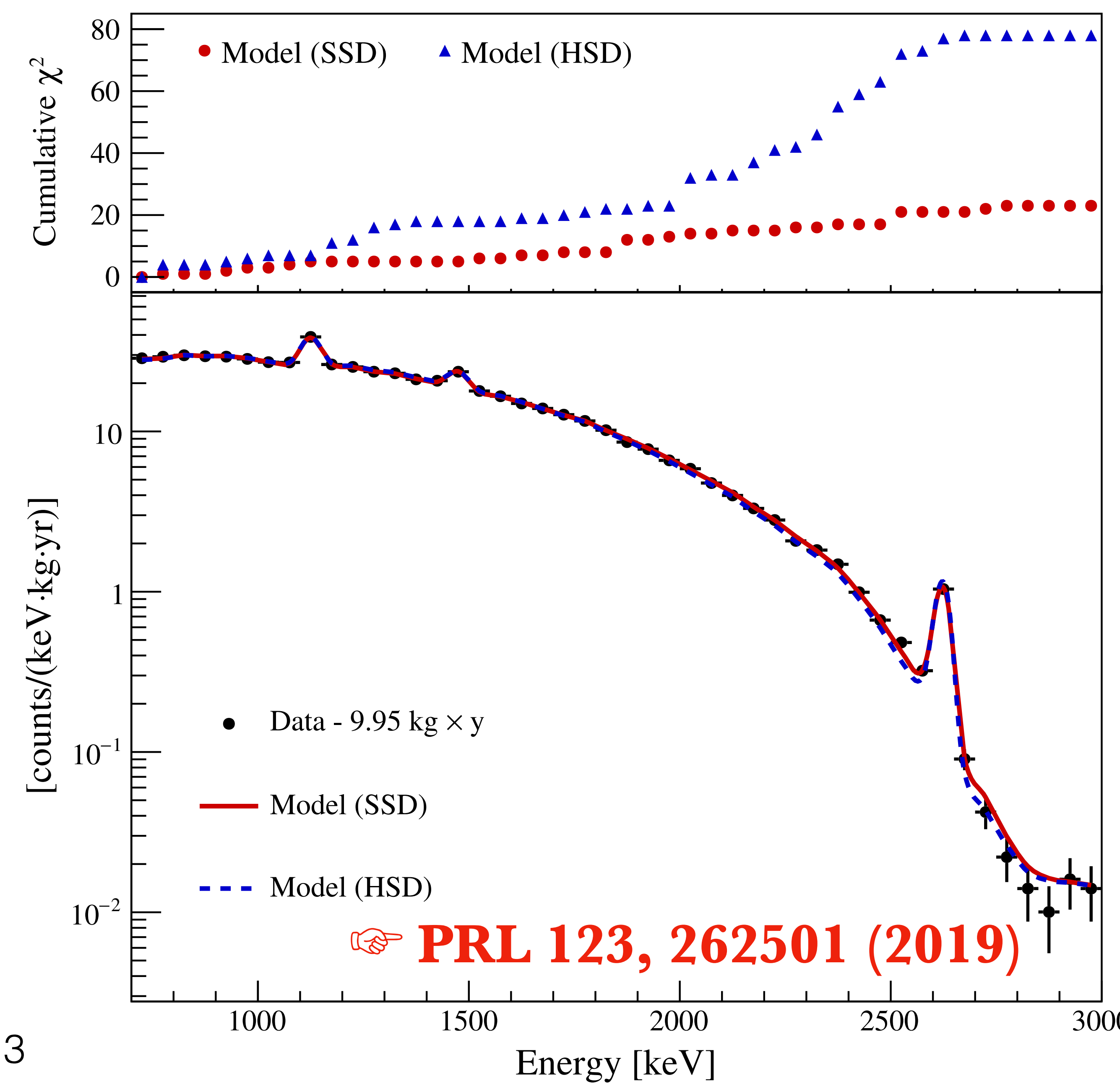
SSD: $\chi^2/\mathrm{ndf} = 255/254 = \mathbf{1.0}$

HSD: $\chi^2/\mathrm{ndf} = 360/253 = \mathbf{1.42}$

Spectra from nucleartheory.yale.edu and Jenni Kotila







Detector upgrade

Background partition (N.B. systematics in slide 11)

- ~44% muons
- ~33% contaminations ZnSe crystals
- ~17% cryostat
- ~6% reflecting foil and holders

Upgrade (January-May 2019)

- Muon-veto surrounding the cryostat (lateral +top)
- Removal of reflecting foils (coincidences)
- Addition of internal copper shield

https://cupid-0.lngs.infn.it

Conclusions

- CUPID-0 is the first ββ-decay experiment based on **scintillating cryogenic detectors (highly enriched)**
- It features an **excellent alpha-rejection,** and the **lowest background** among cryogenic calorimeter
- We obtain the best limit on ^{82}Se **0νββ and the precisest** measurement of **2νββ**
- CUPID-0 Phase II release within 2020

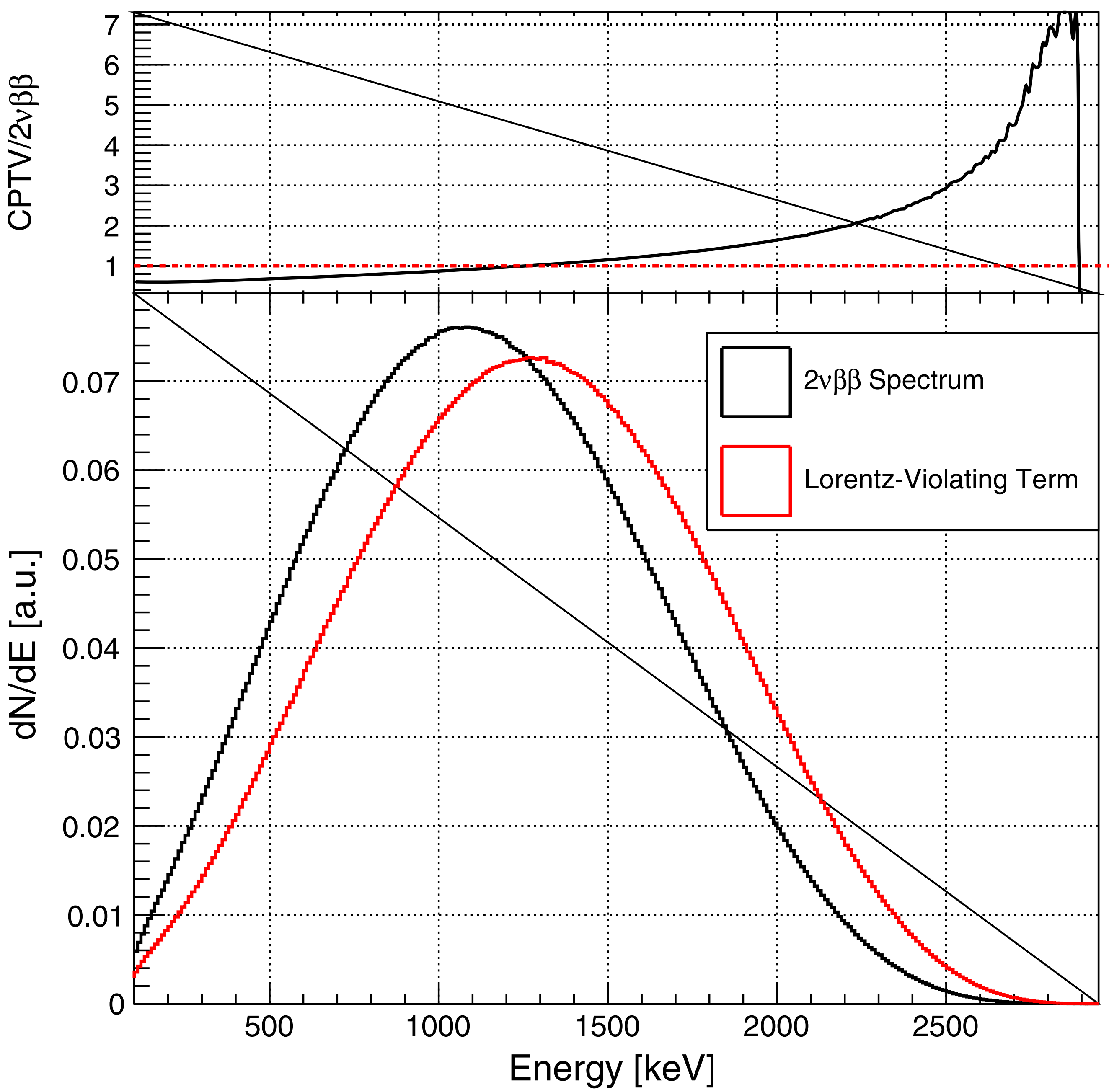
CUORE, CUPID-0, and CUPID-Mo provide the most stringent limits on 0νββ, and the most precise measurements of 2νββ **on three different isotopes**.

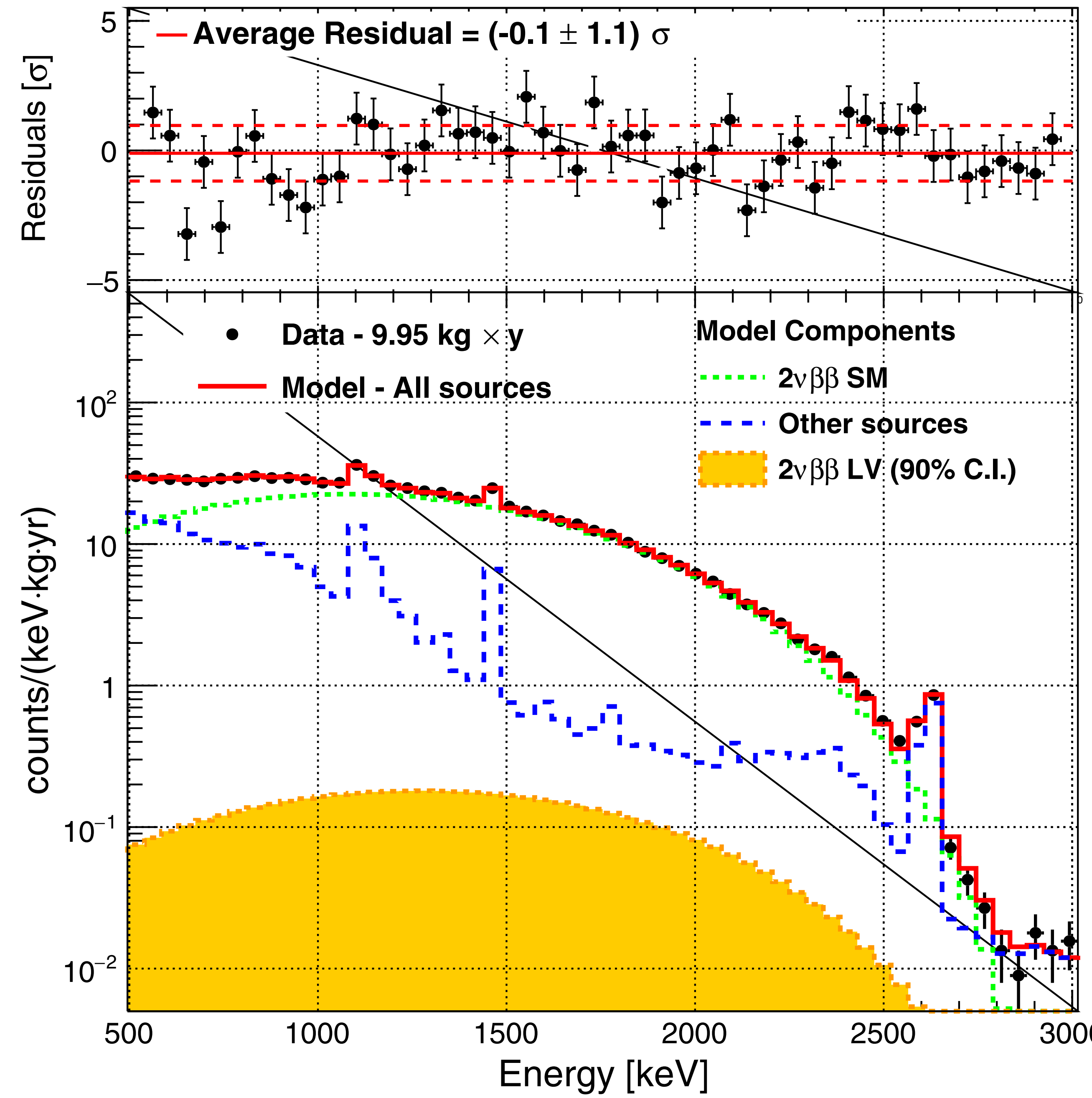
Solid foundations for the CUPID experiment!

Backup slides

Search for CPT violation

$$\frac{d\Gamma}{dE} = C \cdot \left(\frac{dI^{\mathrm{Theo}}_{2\nu,\mathrm{SM}}}{dE} + 10 \cdot \overset{\circ}{a}{}^{(3)}_{\mathrm{of}} \frac{dI^{\mathrm{Theo}}_{2\nu,\mathrm{LV}}}{dE} \right)$$





☞ **PHYS. REV. D 100, 092002 (2019)**

$$\overset{\circ}{a}{}^{(3)}_{\mathrm{of}} < 4.1 \times 10^{-6}\ \mathrm{GeV}$$

New PSF calculations:

O. Nitescu, S. Ghinescu and S. Stoica, Lorentz violation effects in 2νββ decay, arXiv:2001.04859

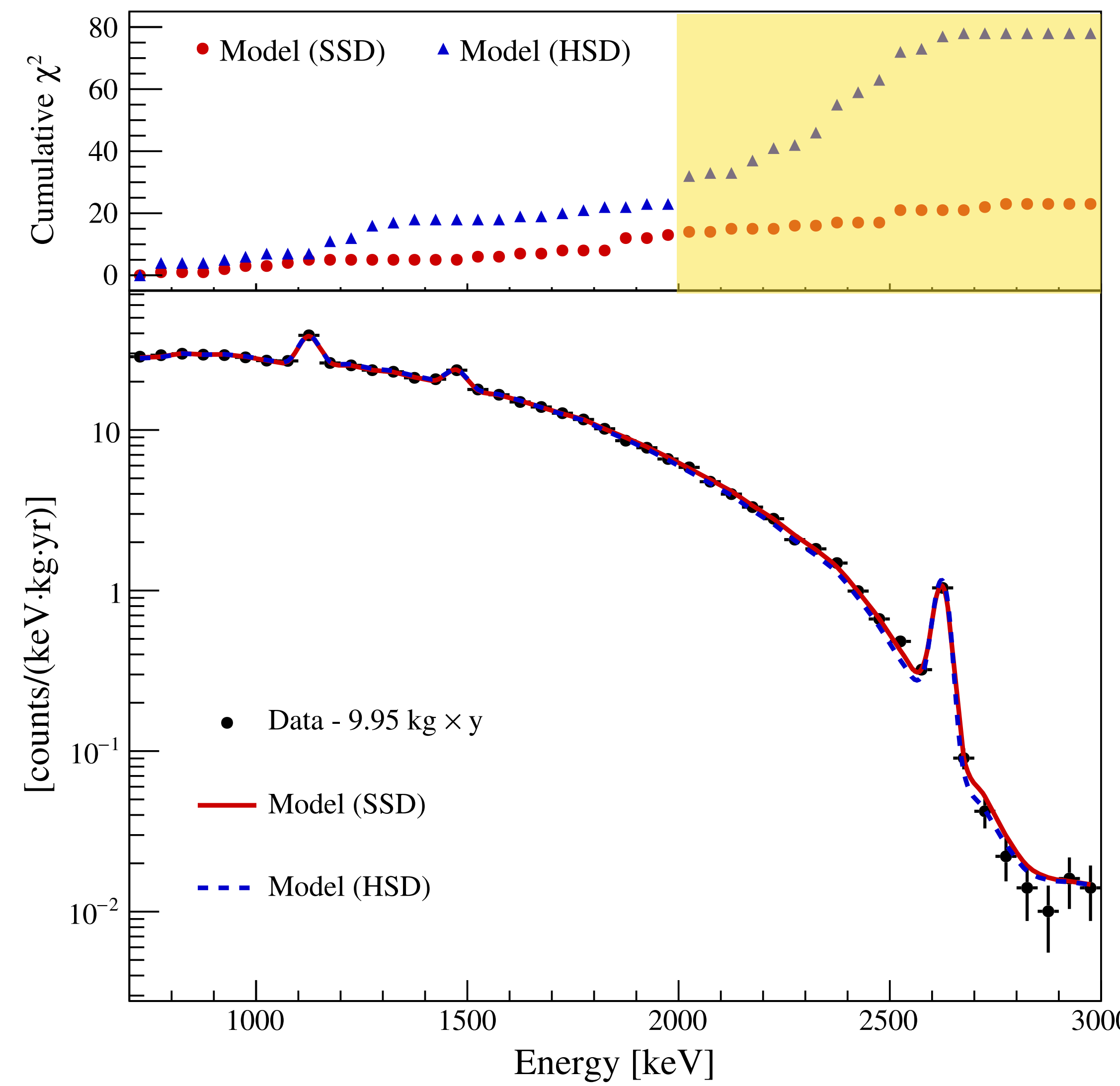
Evidence of Single-State Dominance

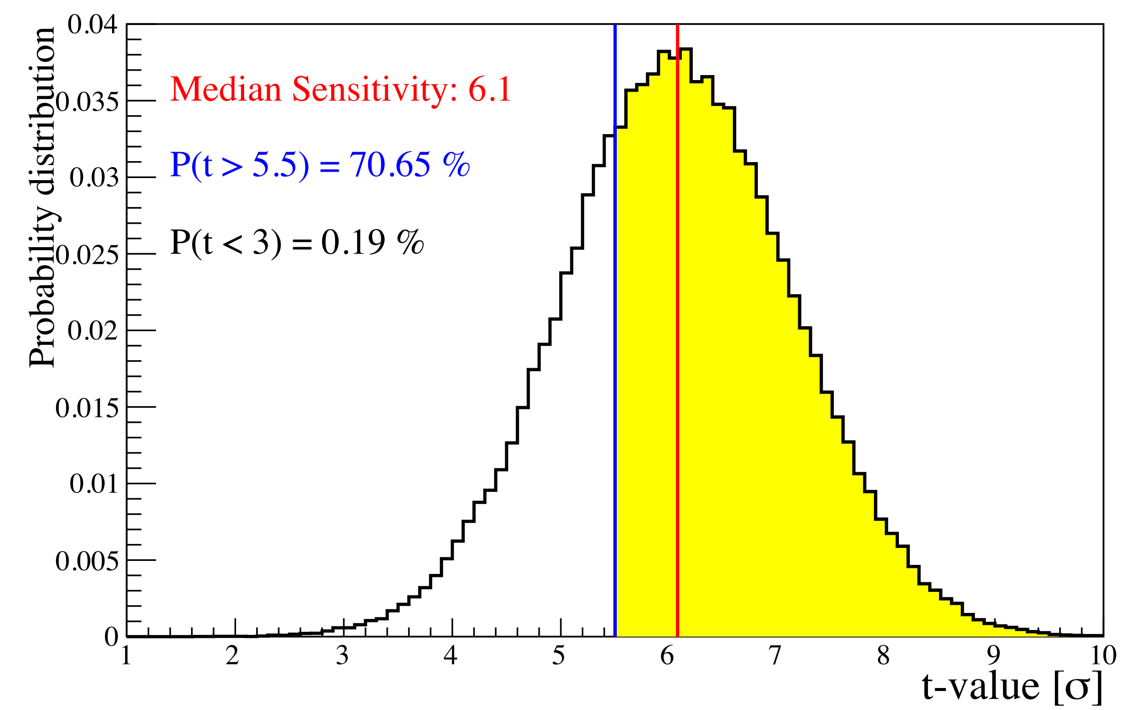
To investigate the compatibility of the two models with the data, we compare the experimental counts (N_{exp}) in the range between 2 and 3 MeV with the ones predicted by the two models (N_X where X = SSD or HSD). We quantify the accordance between data and model through the parameter

$$t_X = \frac{|N_{\text{exp}} - N_X|}{\sqrt{\sigma_{\text{exp}}^2 + \sigma_X^2}}, \tag{1}$$

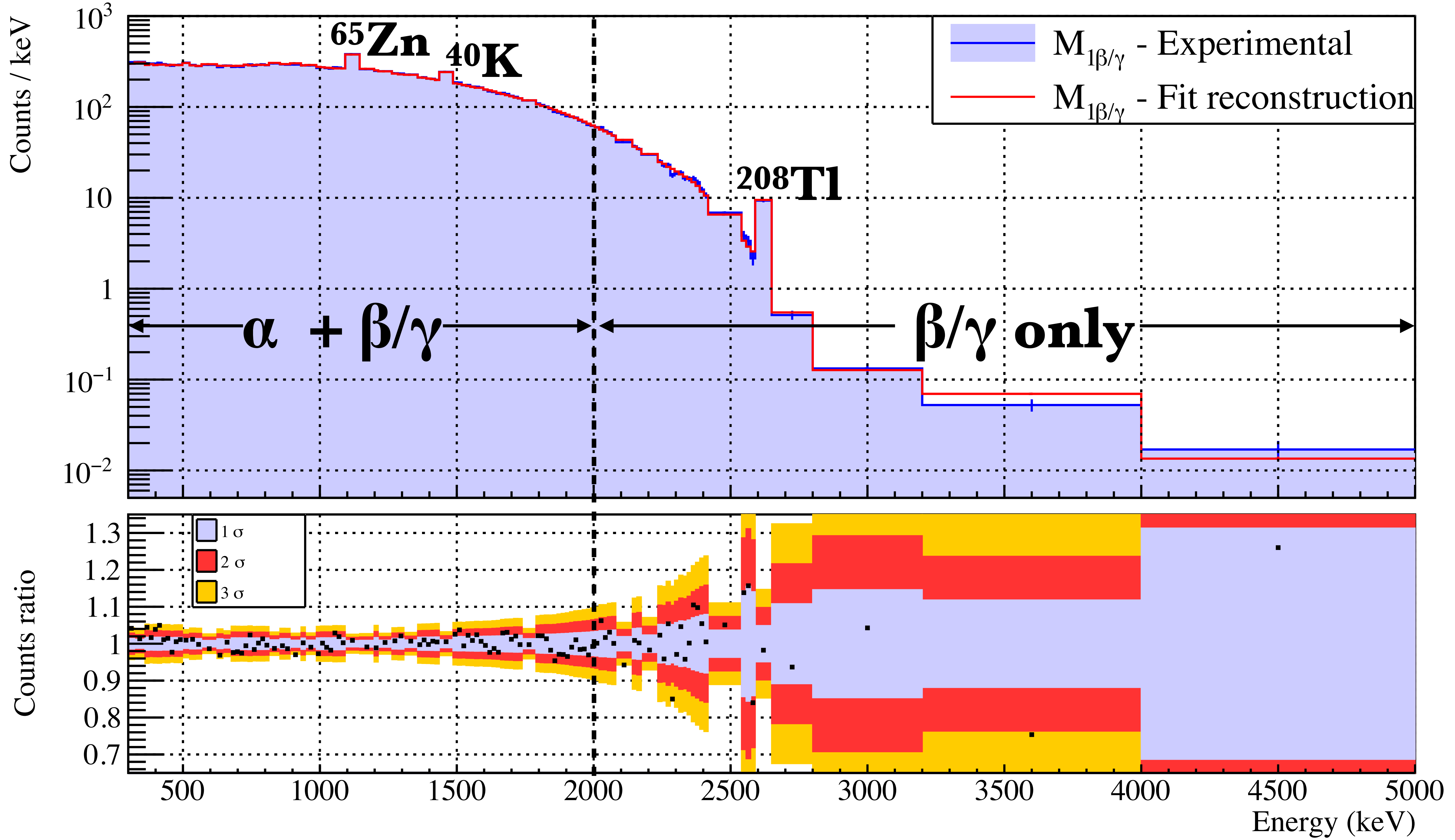
where $\sigma_{\text{exp}} = \sqrt{N_{\text{exp}}}$, and σ_X is the statistical uncertainty of the counts predicted by the model.

Spectrum	Counts	t [σ]
Experimental	14830 ± 122	
Model (SSD)	14972 ± 57	1.1
Model (HSD)	14095 ± 56	5.5

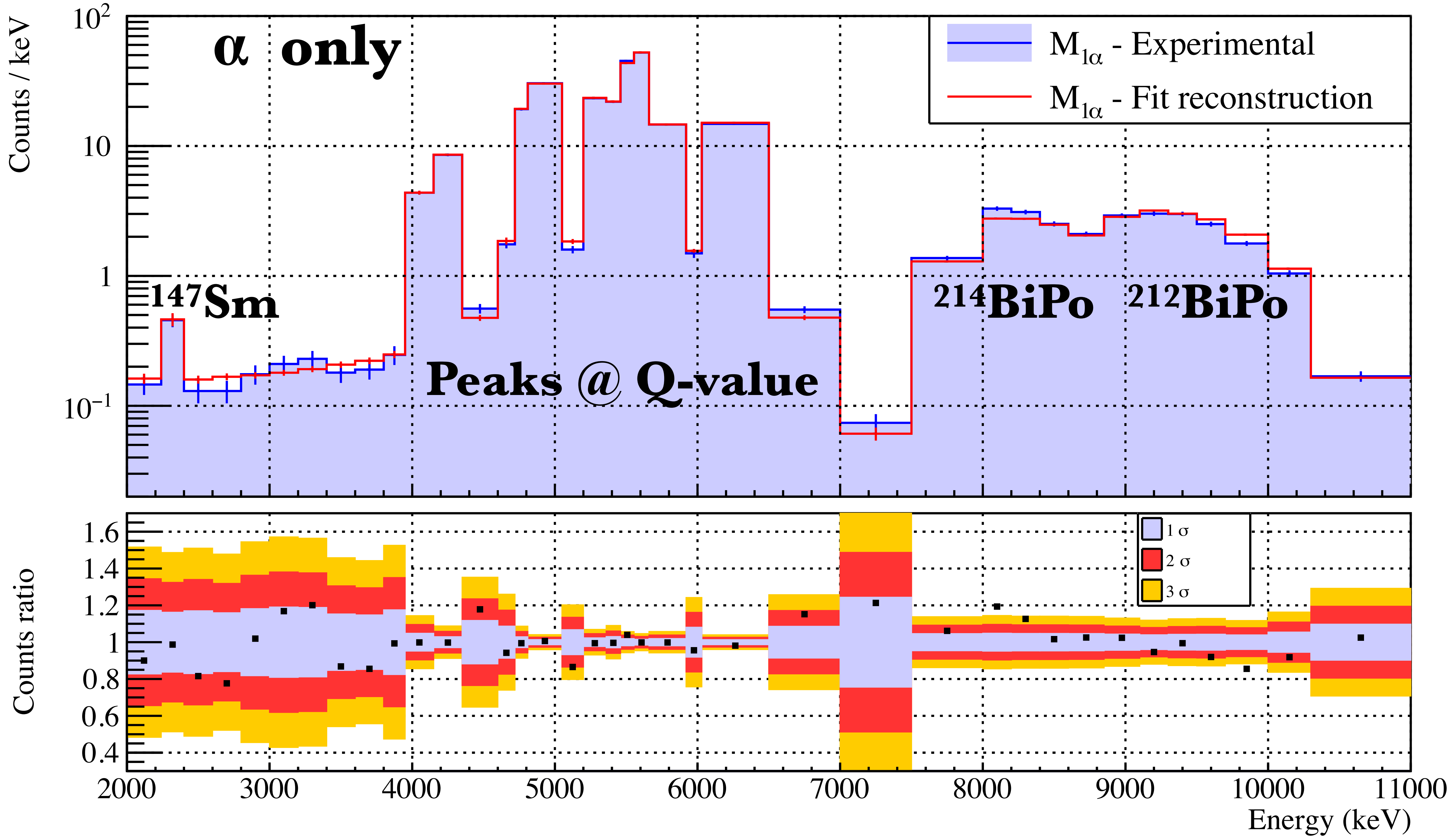




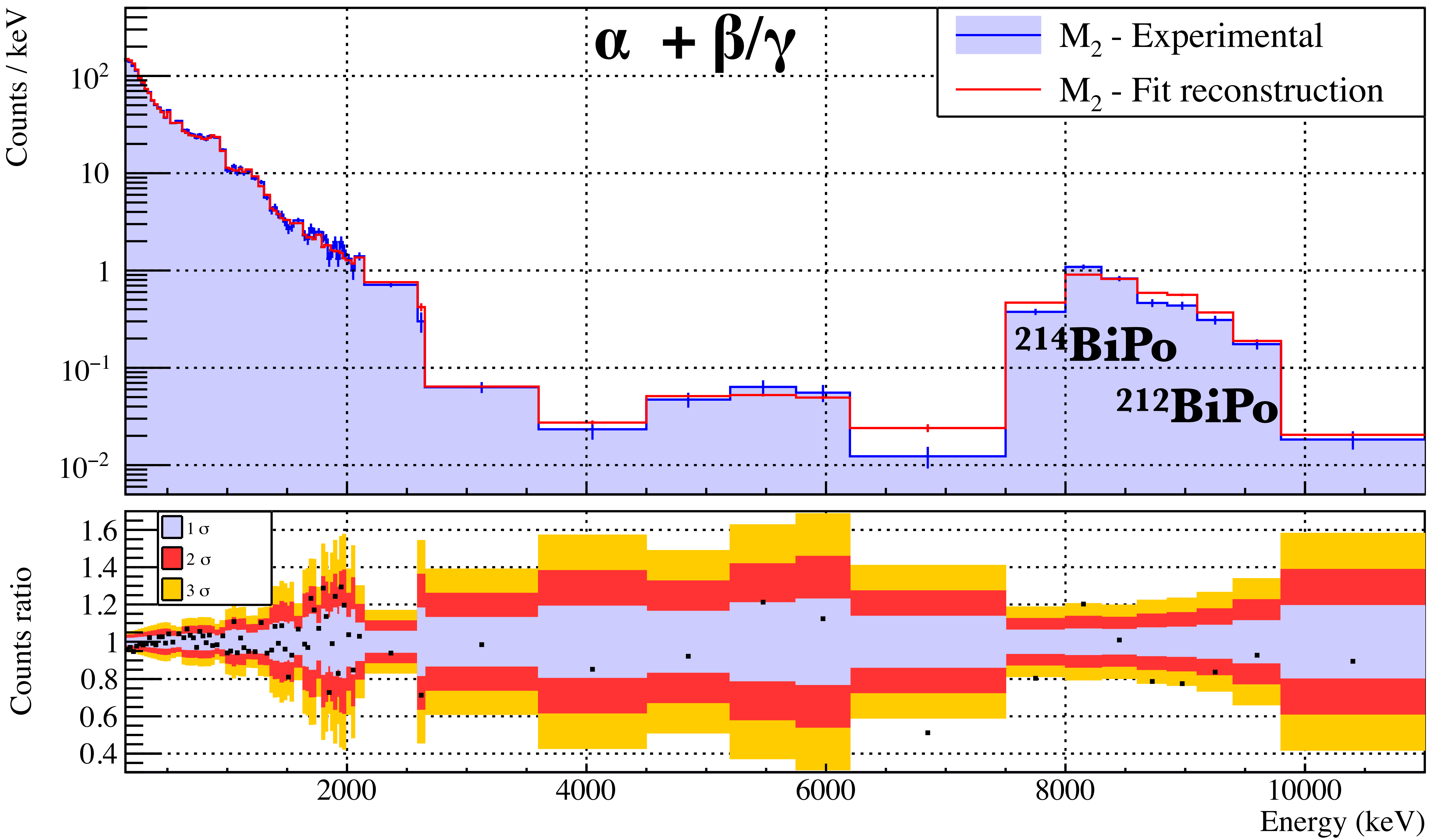
Fit Results: M1 - β/γ



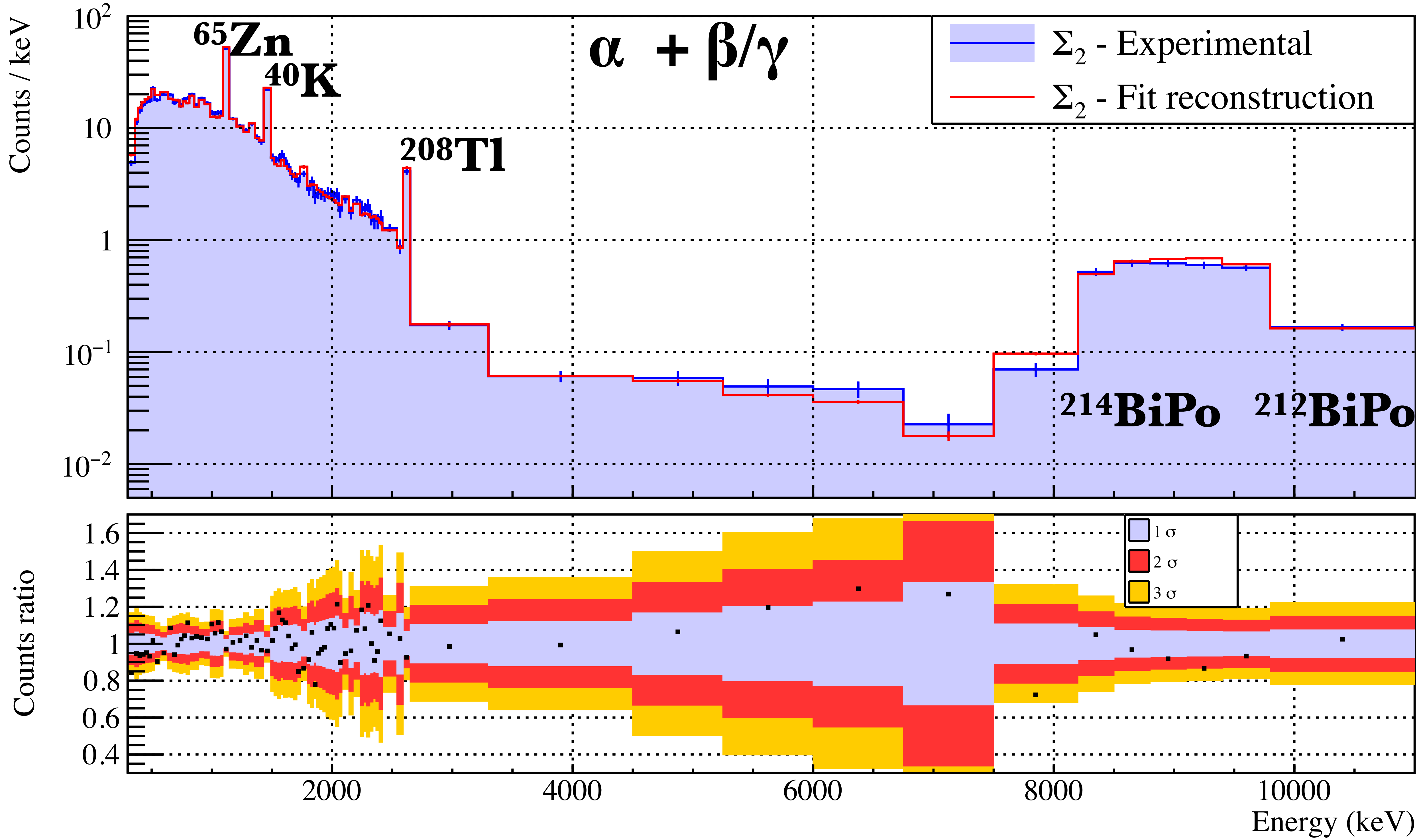
Fit Results: M1 - α



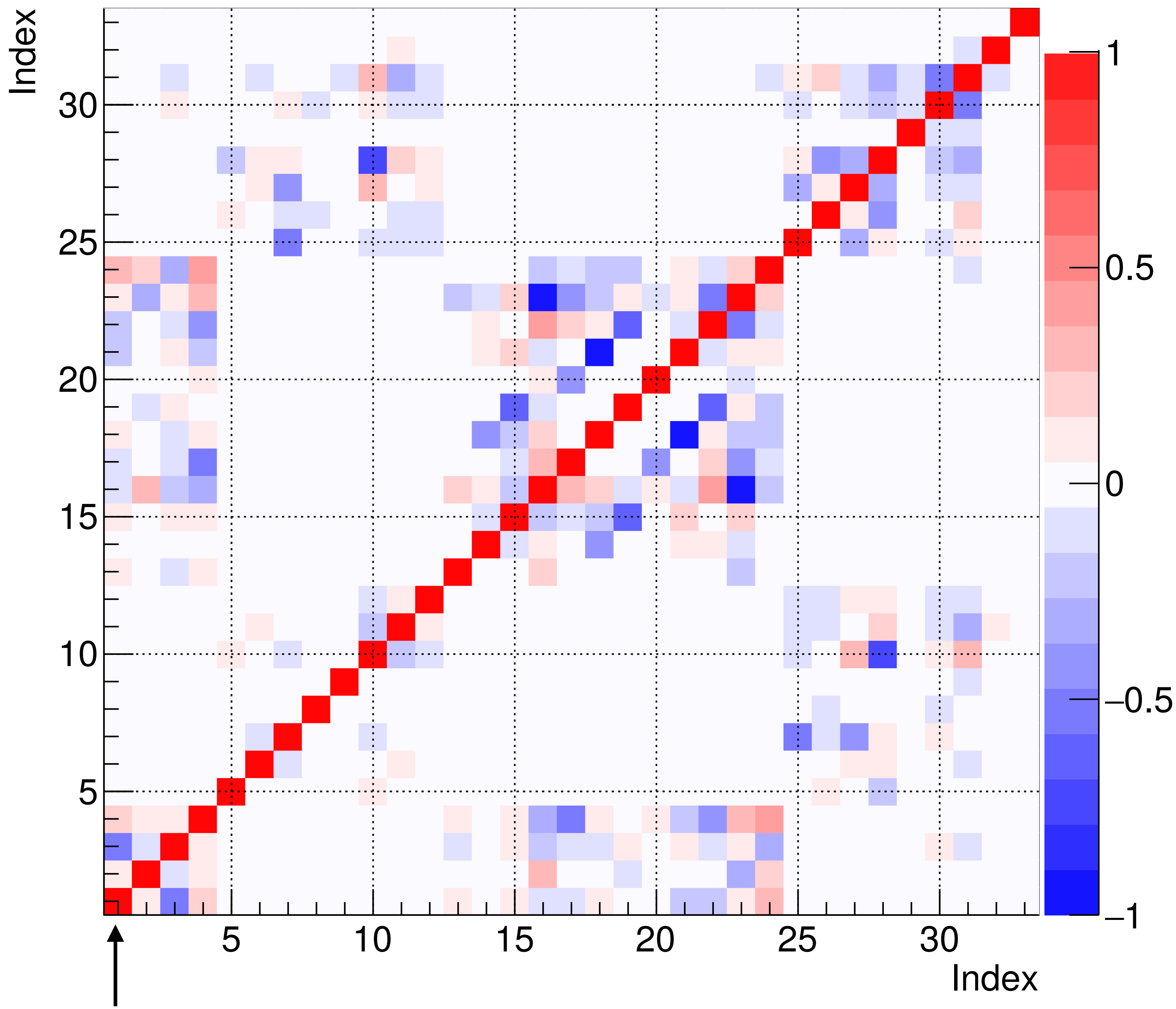
Fit Results: M2



Fit Results: Σ_2



Correlation matrix



2νββ

Double β-decay into the excited states of ^{82}Kr

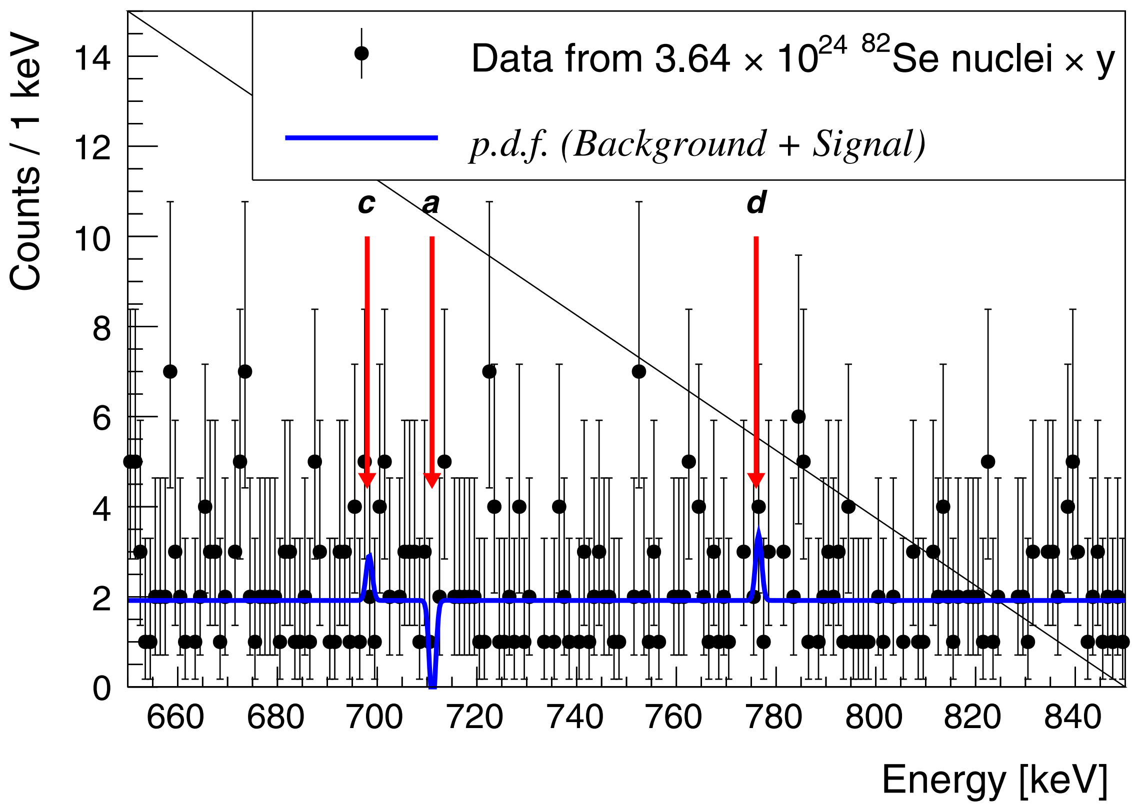
HPGe measurement with 2.5 kg of enriched ^{82}Se
(2νββ + 0νββ)

☞ Eur. Phys. J. C (2015) 75:591

$$T_{1/2}^{\beta\beta}(^{82}\mathrm{Se} \rightarrow ^{82}\mathrm{Kr}_{0_1^+}) > 3.4 \times 10^{22}\ \mathrm{y}$$

$$T_{1/2}^{\beta\beta}(^{82}\mathrm{Se} \rightarrow ^{82}\mathrm{Kr}_{2_1^+}) > 1.3 \times 10^{22}\ \mathrm{y}$$

$$T_{1/2}^{\beta\beta}(^{82}\mathrm{Se} \rightarrow ^{82}\mathrm{Kr}_{2_2^+}) > 1.0 \times 10^{22}\ \mathrm{y}$$



CUPID- 0 measurement of 0νββ

☞ Eur. Phys. J. C (2018) 78:888

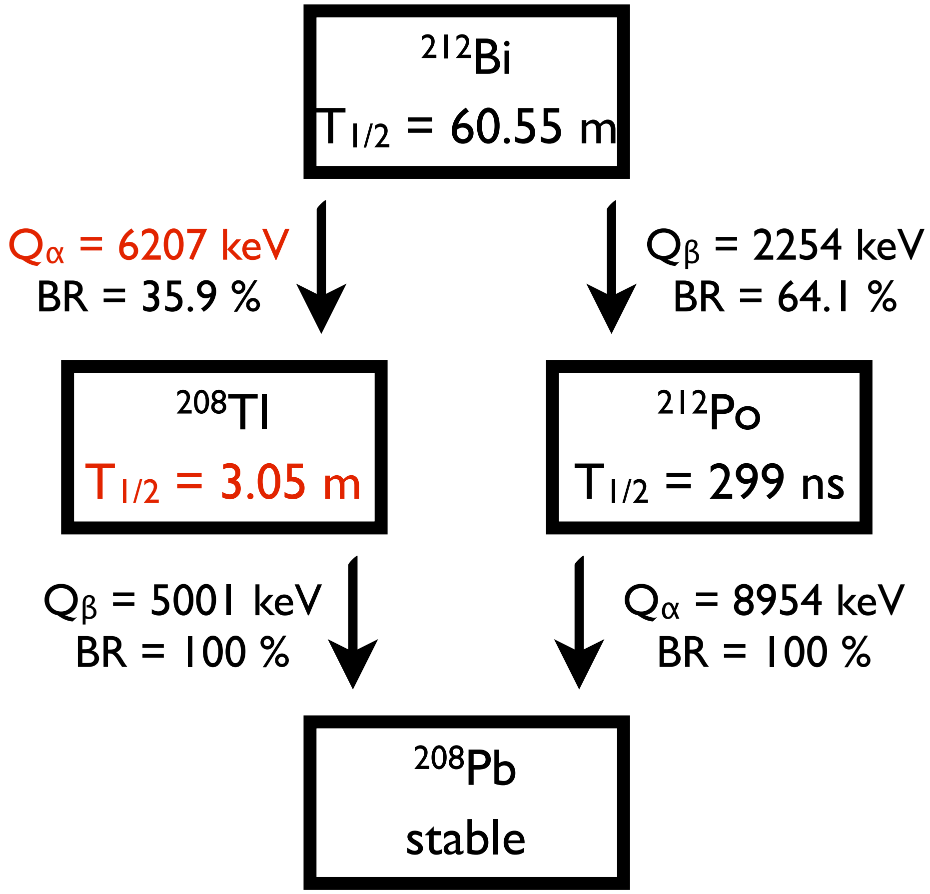
$$T_{1/2}^{\beta\beta}(^{82}\mathrm{Se} \rightarrow ^{82}\mathrm{Kr}_{0_1^+}) > 8.11 \times 10^{22}\ \mathrm{y}$$

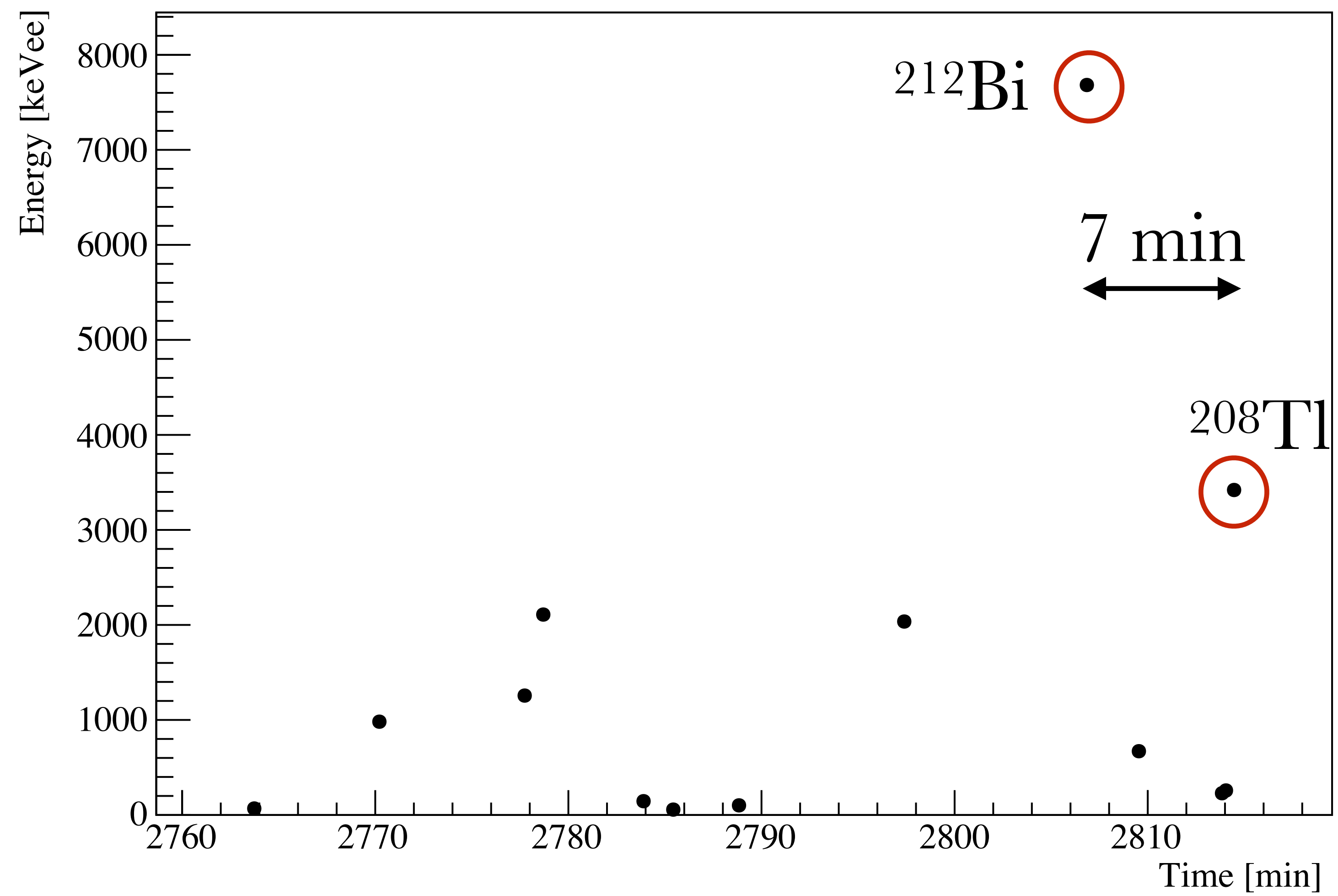
$$T_{1/2}^{\beta\beta}(^{82}\mathrm{Se} \rightarrow ^{82}\mathrm{Kr}_{2_1^+}) > 1.11 \times 10^{23}\ \mathrm{y}$$

$$T_{1/2}^{\beta\beta}(^{82}\mathrm{Se} \rightarrow ^{82}\mathrm{Kr}_{2_2^+}) > 8.40 \times 10^{22}\ \mathrm{y}$$

Soon also 2νββ on exited states from CUPID-0

Alpha delayed veto





Cascade in ^{208}Tl decay:
2615 (100%) + 583 (86%) = **3198** keV

After an α-event whose energy falls in the interval **2-6.5 MeV** a veto of **9.2 minutes** is activated to remove Tl event.
Lower limit of the energy for α-selection is chosen to include also surface contaminations.

Crystal radiopurity

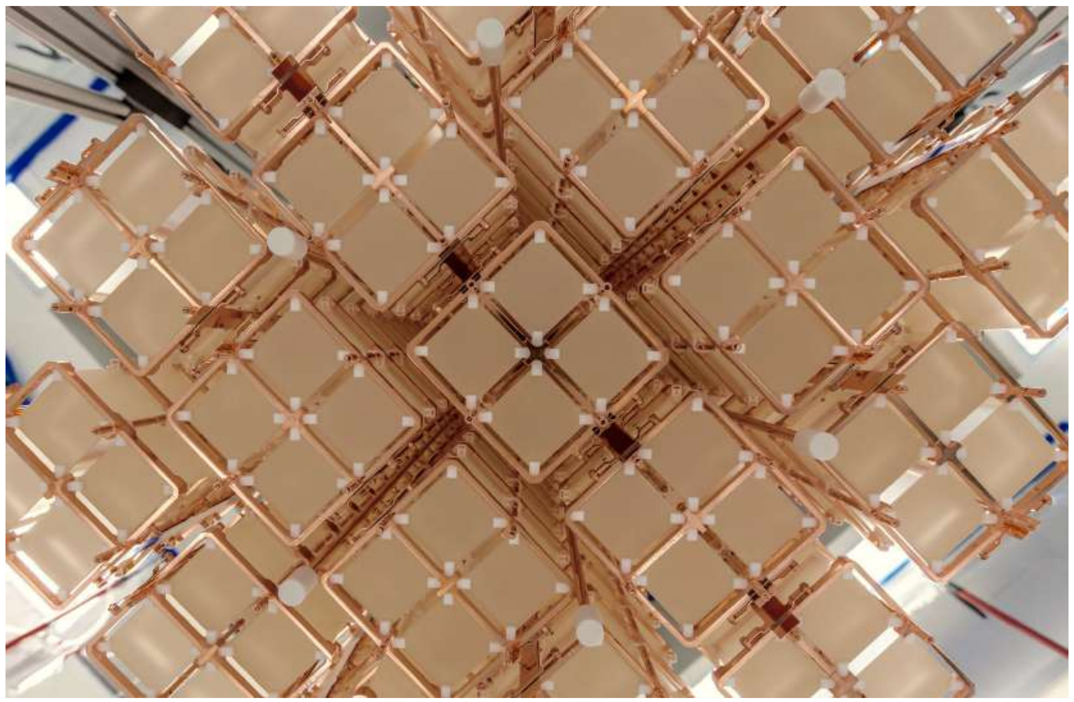
Contaminants	ZnSe - most clean [μBq/kg]	ZnSe - most dirty [μBq/kg]	CUPID - 0 [μBq/kg]
^{232}**Th**	< 0.54	8.6 ± 1.2	2.5 ± 0.2
^{228}**Th**	2.3 ± 0.8	26.9 ± 2.2	13.6 ± 0.4
^{224}Ra	2.1 ± 0.6	23.1 ± 2.0	10.9 ± 0.3
^{212}Bi	<3.7	24.2 ± 3.5	12.2 ± 0.6
^{238}**U**	< 1.2	12.7 ± 1.5	5.1 ± 0.2
^{234}**U**	1.0 ± 2.0	14.7 ± 4.3	5.3 ± 0.8
^{230}**Th**	< 2.4	16.4 ± 1.7	5.3 ± 0.2
^{226}**Ra**	3.8 ± 0.9	18.4 ± 1.8	17.0 ± 0.4
^{218}Po	3.4 ± 0.6	19.8 ± 1.9	17.4 ± 0.4
^{210}**Pb (bulk+surf)**	-	-	18.8 ± 0.6

From the first batch of crystals to the last one,
the **radiopurity improves by a factor of ten**.

CUORE to CUPID

CUPID: CUORE Upgrade with Particle ID

Mission: To discover $0\nu\beta\beta$ if $m_{\beta\beta}$ > 10 meV ($T_{1/2}(^{100}Mo)$ > 1×10^{27} yrs)

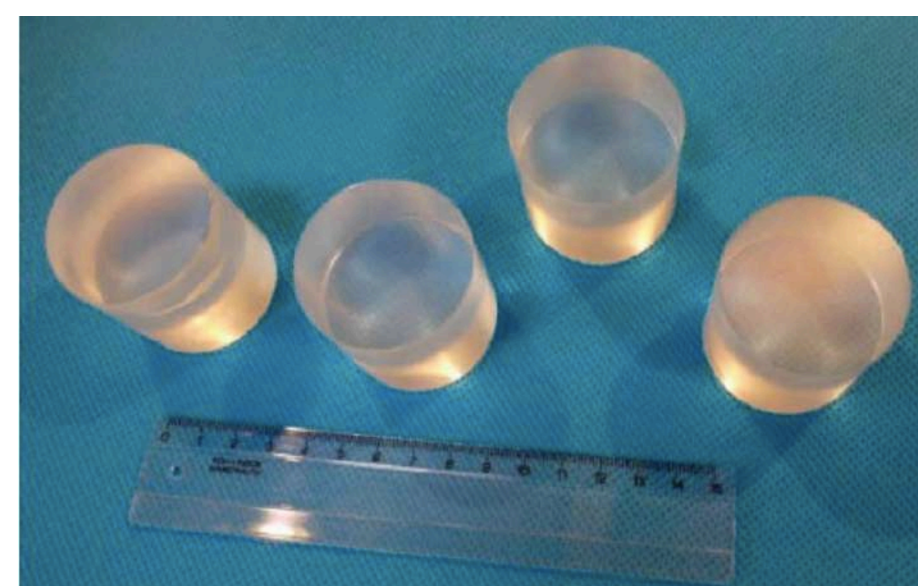


CUORE Achievements:

- Ton-scale bolometric detector is technically feasible.
- Analysis of 1000 bolometers demonstrated
- Reliable data-driven background model constructed.
- Infrastructure for next-generation experiment exists.

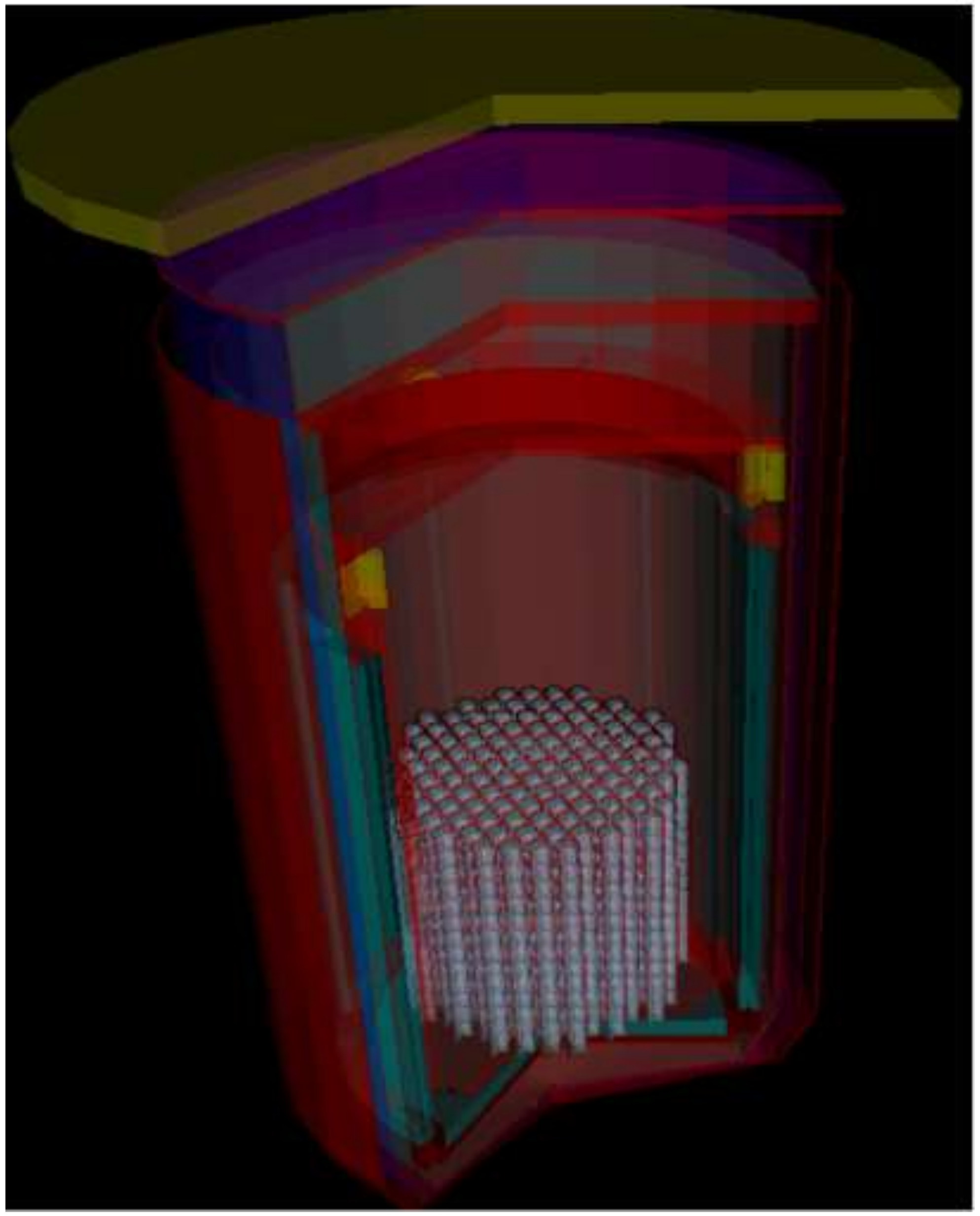
Scintillating Bolometer R&D by CUPID-0 and CUPID-Mo

- Demonstrated large-scale enriched crystal production capability
- Internal radio-purity targets met
- Demonstrated active background rejection
- Energy resolution ~5 keV demonstrated.
- Total background of ~10^{-1} cnts/ton-keV-yr achievable



CUPID Conceptual Design

- Re-use ***CUORE cryogenic infrastructure*** at LNGS
- $Li_2{}^{100}MoO_4$ scintillating crystals
- ~1500 crystals for ***270 kg of ^{100}Mo***
- Active background rejection using light/heat
- Options for ***multiple isotopes*** possible.
- TDR and ***construction readiness in 2021***



Conservative, Mature, Data Driven Baseline Design

Sensitivity comparison