Status Report of the Research Project

Model of the CUORE data and background shape studies

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Stefano POZZI

G S
S I

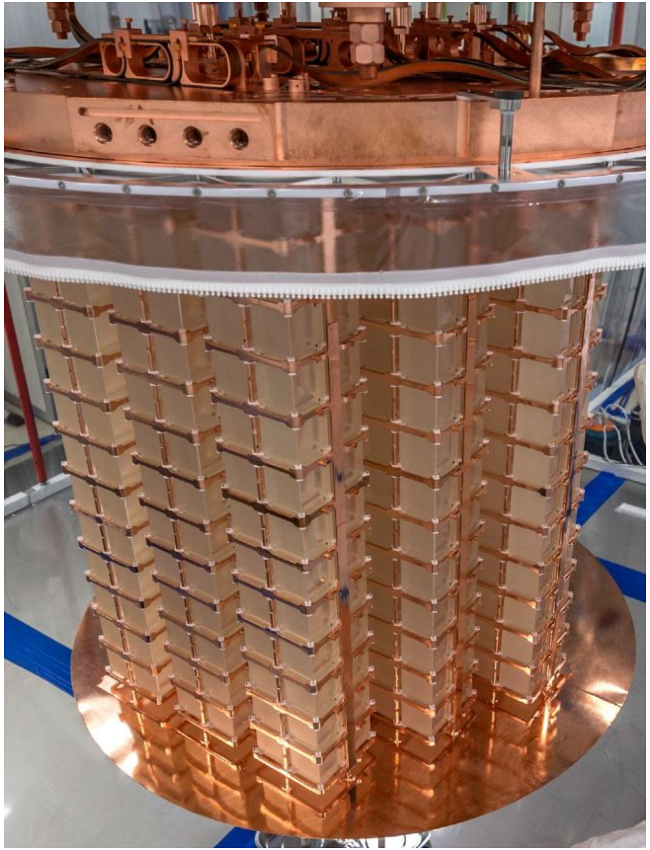
Ph.D. Program in Astroparticle Physics – XXXVI cycle

The CUORE experiment

***C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents*

- Searching from neutrinoless double beta decay ($0\nu\beta\beta$) in ^{130}Te
- Running since 2017 in the **Gran Sasso underground laboratories** in Italy (~ 3600 m.w.e.)
- **988 TeO_2 crystals operated at ~ 15 mK** with natural ^{130}Te abundance
- No evidence for neutrinoless double beta decay in ^{130}Te

  ⟶ **only background**



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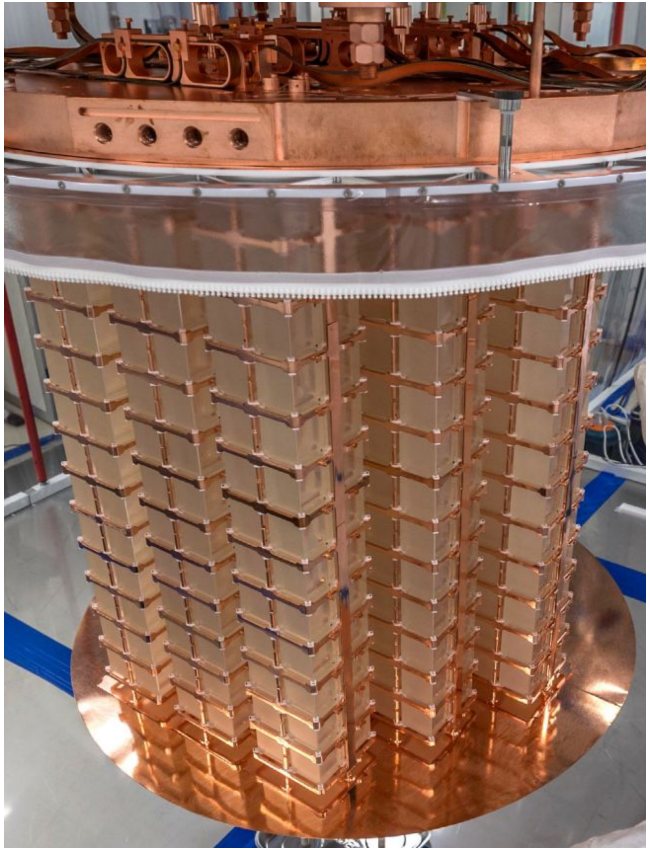

Studying the remaining background is essential to:

1. ***understand the data***
2. ***plan a future generation experiment***, CUPID in this case

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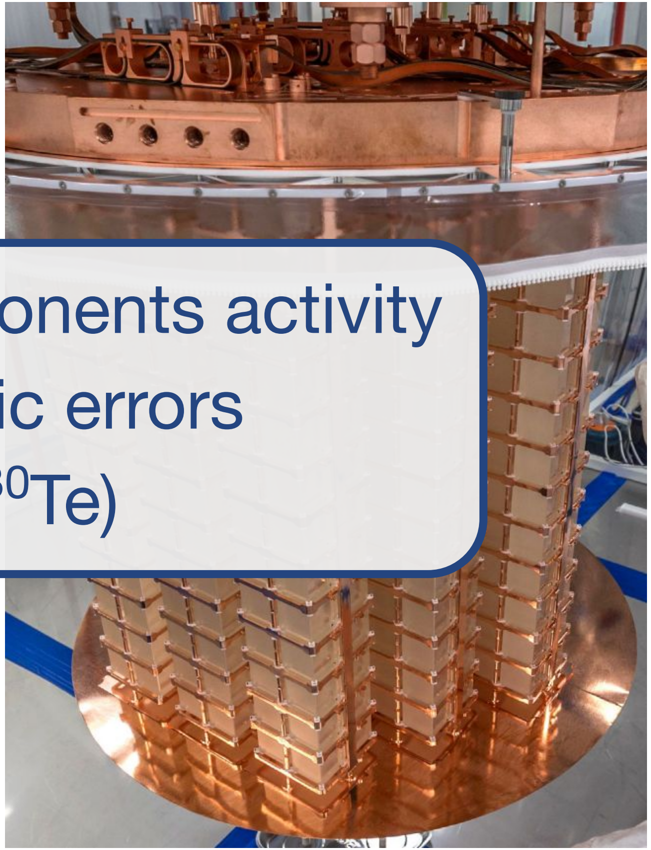
→ **only background (see Talk from K. Alfonso)**

1. Extract background components activity
2. Evaluate reliable systematic errors
3. Measure half-lifes ($2\nu\beta\beta$ - ^{130}Te)



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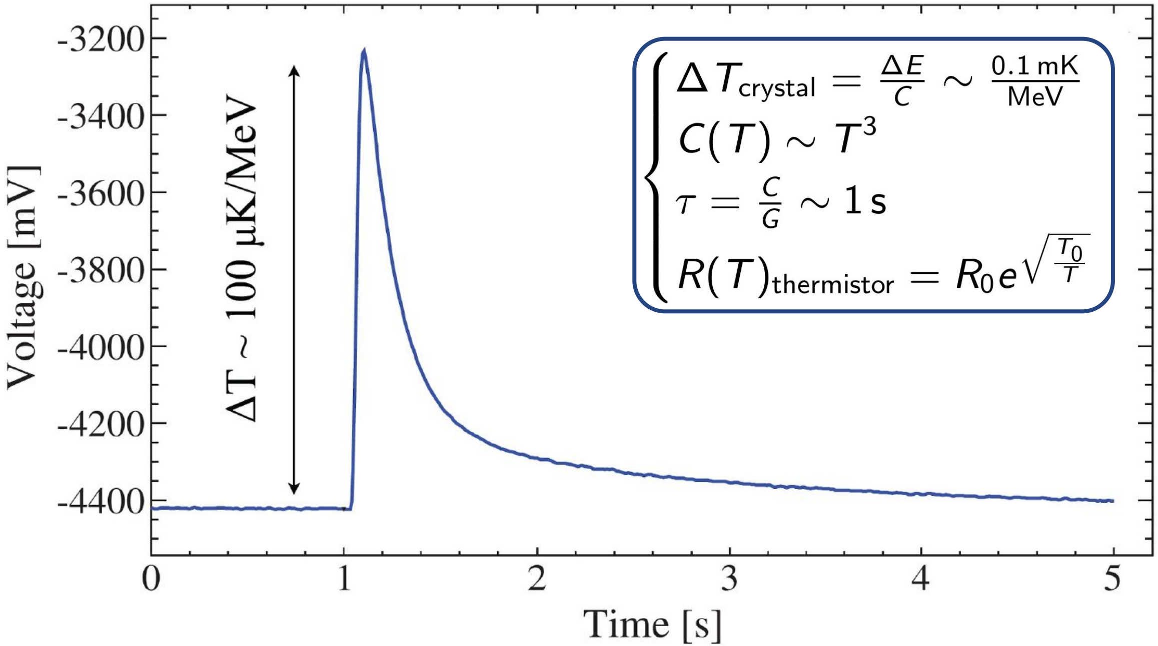
Recipe for a background model

MODEL OF THE BACKGROUND =

1. Data

Data

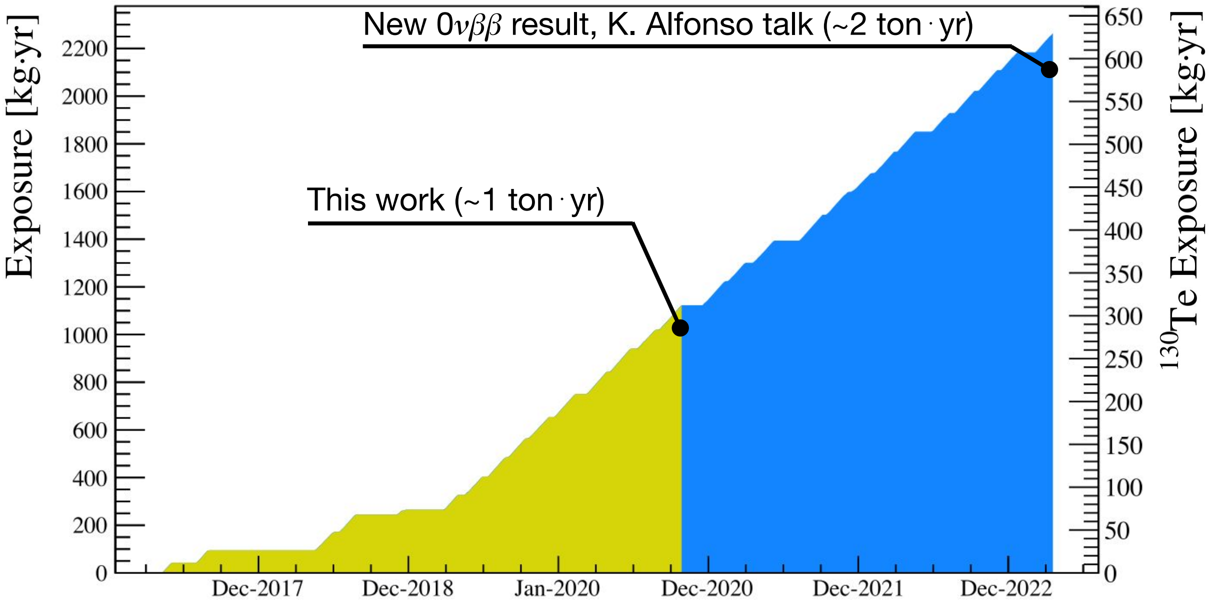
RAW DATA



Data

RAW DATA

- 15 datasets
- Total exposure of 1123 kg · yr



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↓ **LOW LEVEL ANALYSIS**

- Exclude noisy periods
  → Analyzed exposure of 1038 kg · yr
- Quality cuts
- Pulse shape analysis cuts

Data

** Sample topologies*

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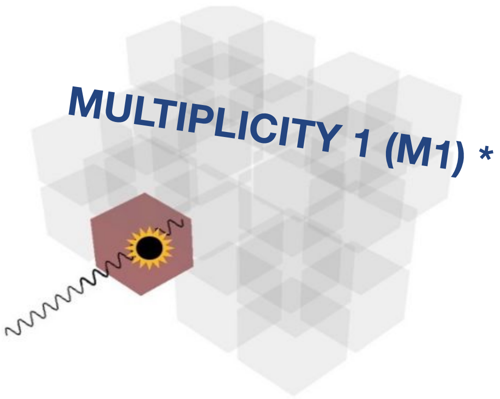
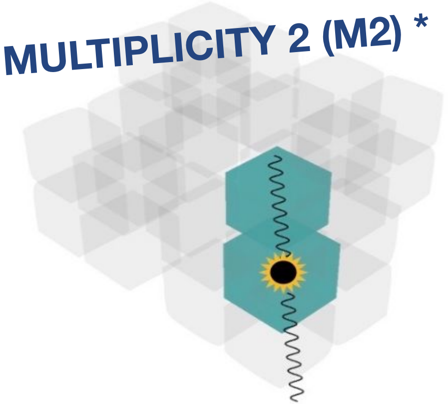
COINCIDENCES → space-time cut, optimized for the background model studies





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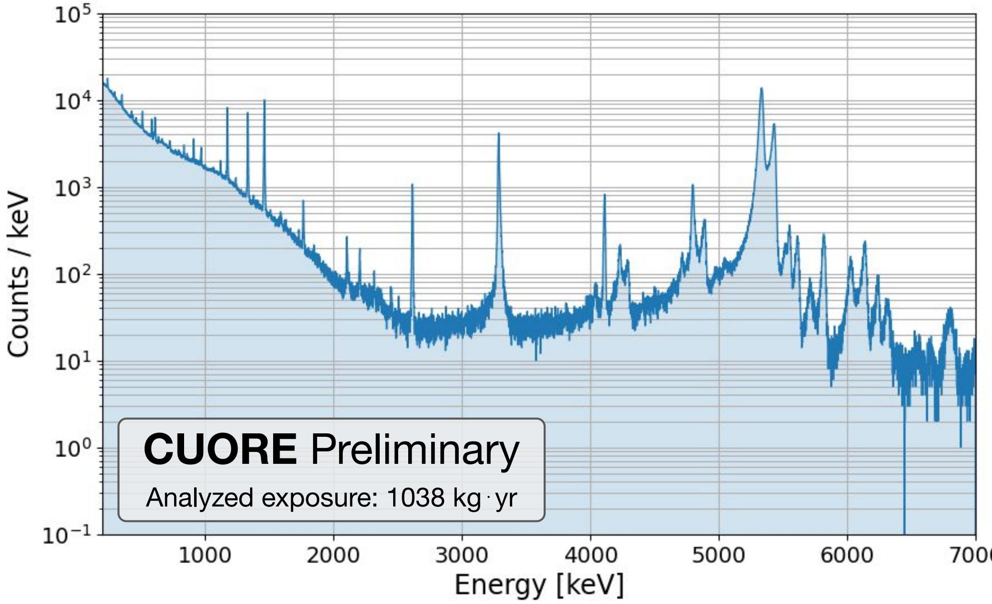
DATA (almost) READY FOR THE FIT

MULTIPLICITY 1 (M1) DATA



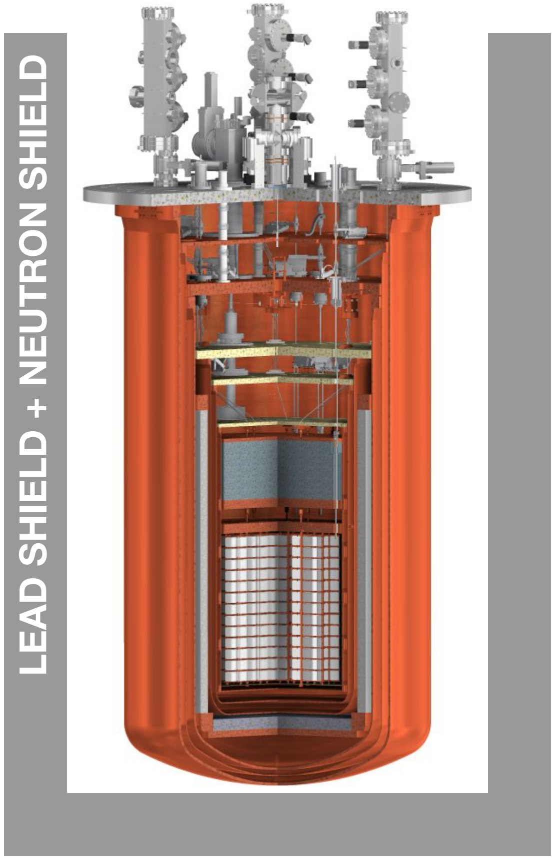
Recipe for a background model

MODEL OF THE BACKGROUND =

1. **Data** ✓
2. **Monte Carlo simulations**

MC templates

The MC templates describe ***combinations of contaminants and detector components***



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Bulk contaminations:

- Main decay chains: ^{232}Th, ^{238}U, ^{235}U
- Ubiquitous contaminants: ^{40}K, ^{60}Co
- Fallout: ^{137}Cs, ^{90}Sr, ^{207}Bi
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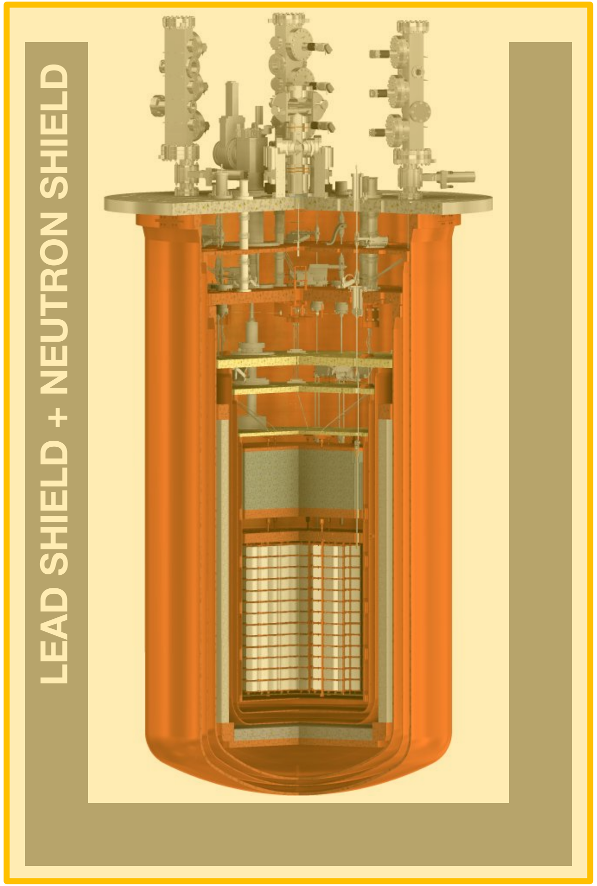
- Others: ^{147}Sm, ^{190}Pt (crystal growing)



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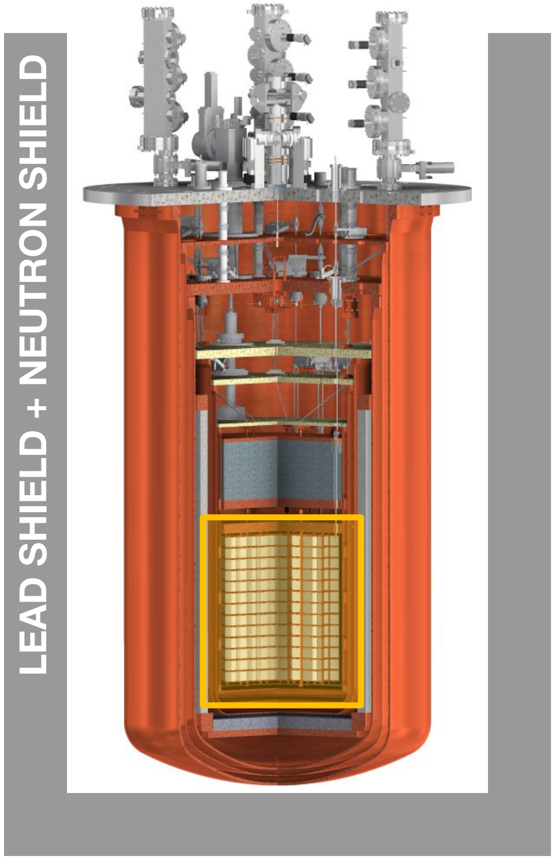
Surface contaminations:

- Simulation at different depths
- Assumed exponential profile



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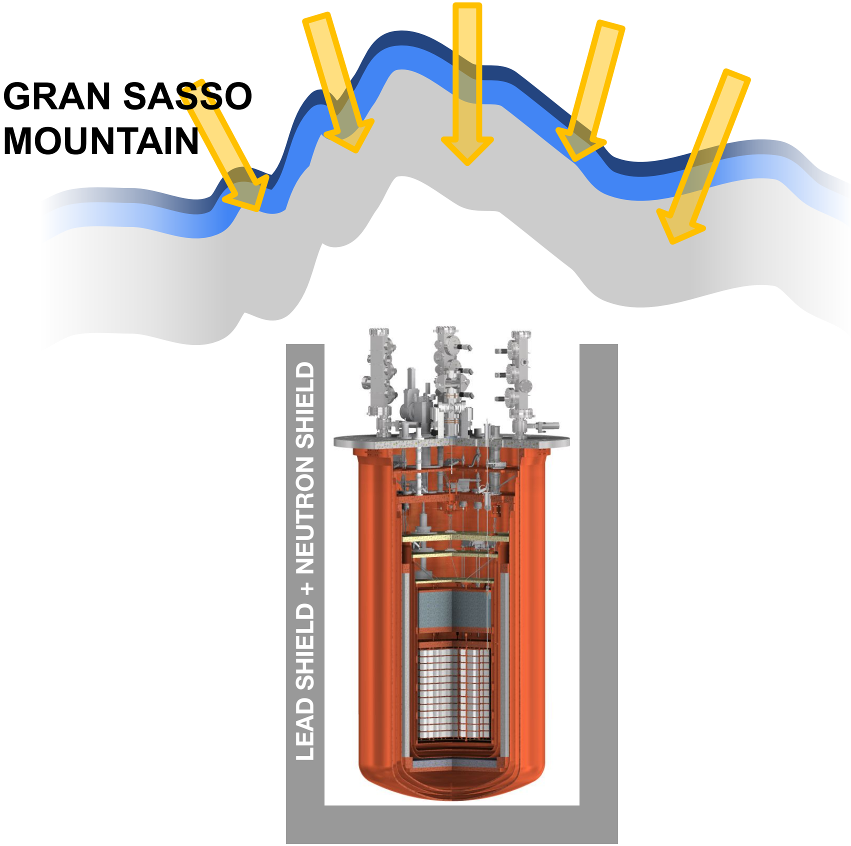
Muons:

- MACRO flux distribution
- Gran Sasso overburden map



MC templates processing

Simulation tool: *qshields (Geant4 application)*, the CUORE Monte Carlo framework

OTHER EFFECTS

Data taking

- Dead channels
- Lifetime

Analysis efficiencies

- Base cuts
- Coincidences
- Pulse shape
- Pile-up

Detector effects

- Finite energy resolution
- Lineshape
- Quenching

Recipe for a background model

MODEL OF THE BACKGROUND =

1. Data ✓
2. Monte Carlo simulations ✓
3. Fit model

The model of the background

*Binned **template** fit* → *MC simulations of contaminants in different detector components*

Bayesian → *Prior to be updated during the regression*

With MCMC → *Gibbs sampling algorithm (JAGS software)*

Model: $$\nu_{\alpha,i} = \sum_j N_j(\nu_{\alpha,i})_j$$

Likelihood: $$\mathcal{L}(\{N_j\} \mid \text{data}) = \prod_\alpha \prod_i Pois(n_{\alpha,i}, \nu_{\alpha,i})$$

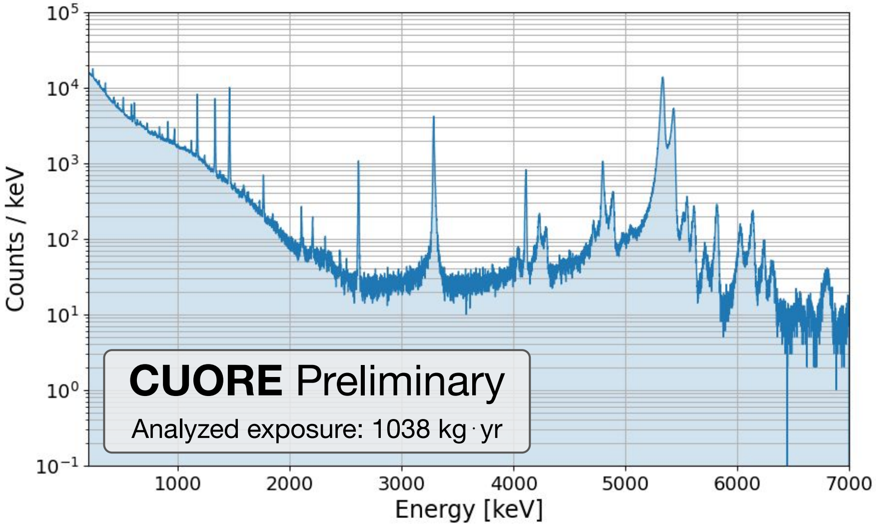
n = observed number of counts
$\boldsymbol{\nu}$ = expected number of counts
N = normalization factor
i = bin
$\boldsymbol{\alpha}$ = input energy spectrum
j = background component

Simultaneous fit of 39 energy spectra with ~70 background components

Input energy spectra

MULTIPLICITY 1

1 SINGLE SPECTRUM



Input energy spectra

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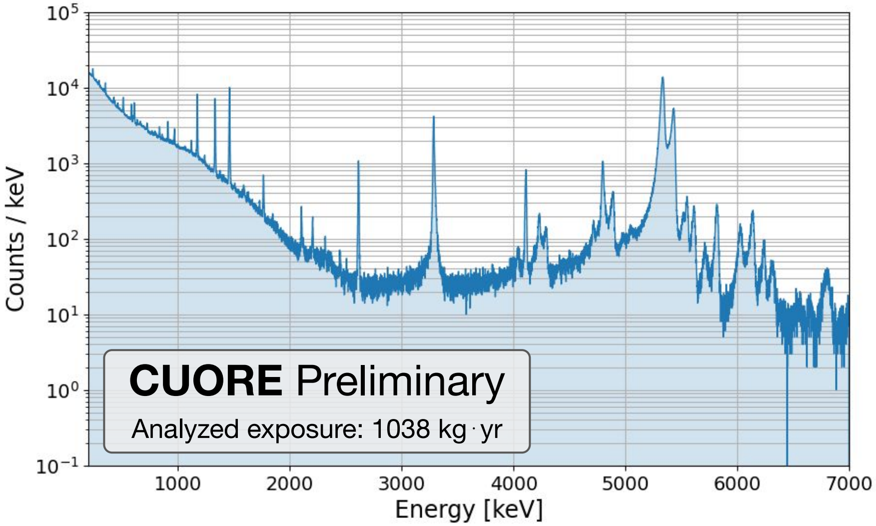
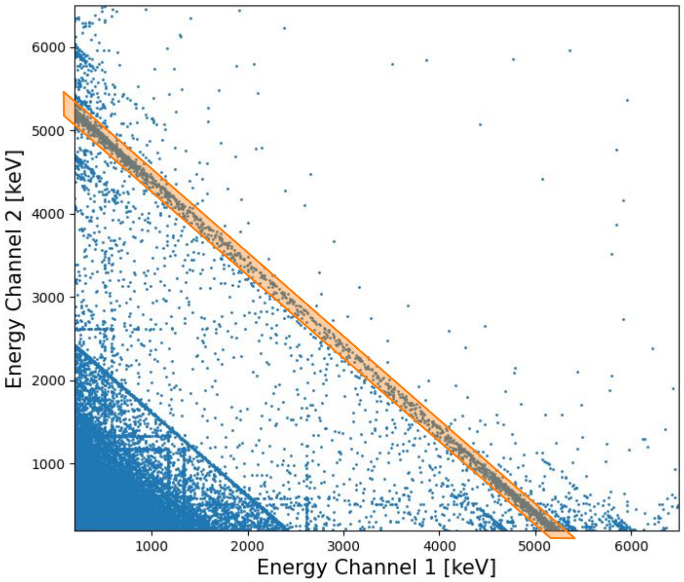


MULTIPLICITY 2

38 DIFFERENT M2 BANDS



Input energy spectra

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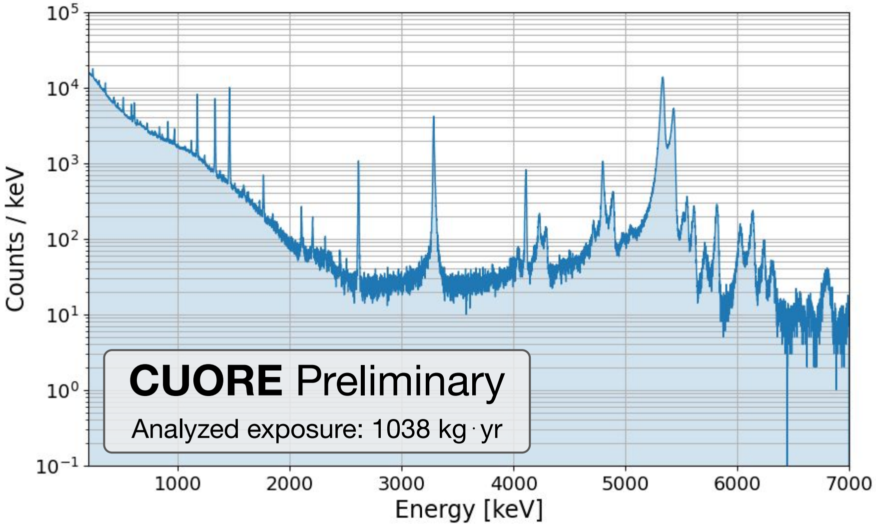

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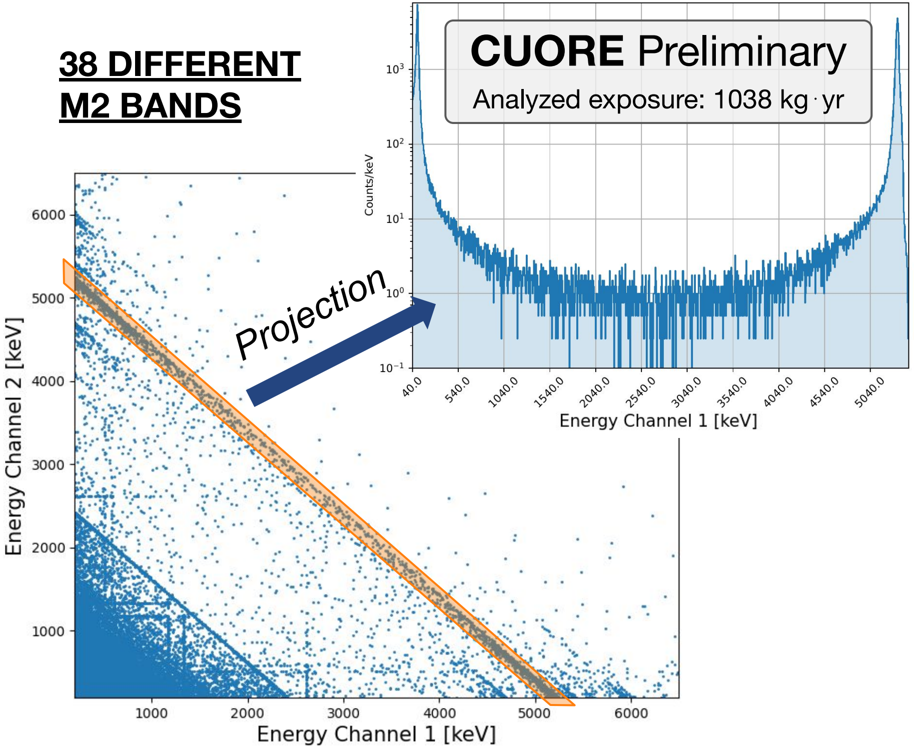


Recipe for a background model

MODEL OF THE BACKGROUND =

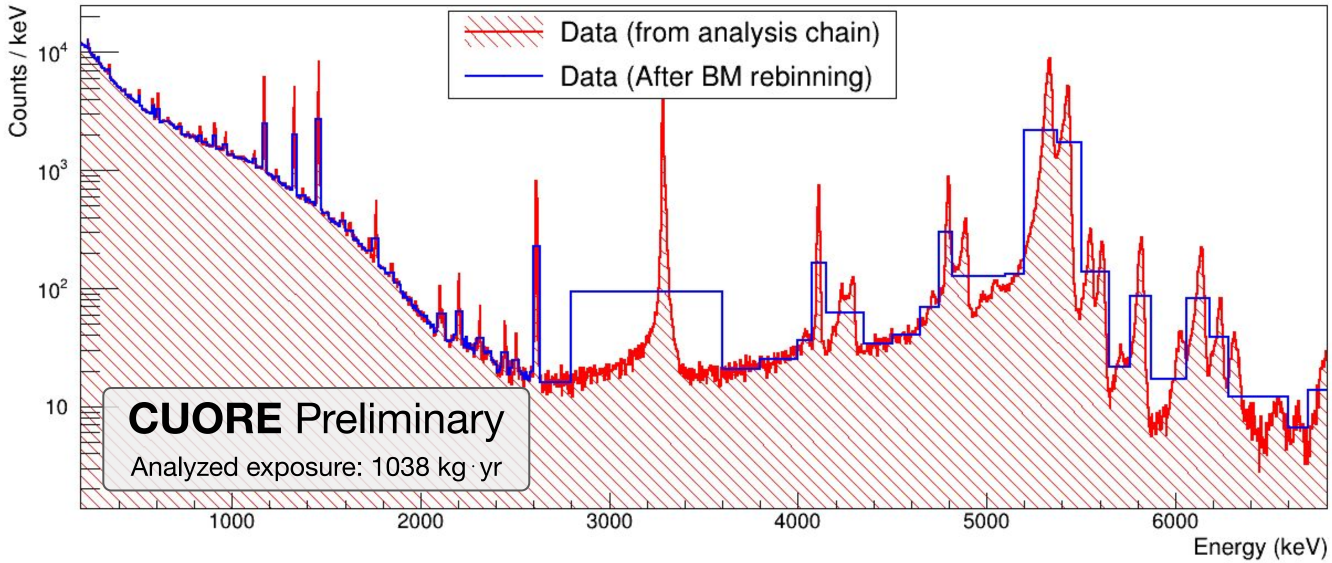
1. Data ✓
2. Monte Carlo simulations ✓
3. Fit model ✓

Binning

A rebinning procedure has been implemented:

- Around characteristic γ lines the bin size corresponds to $5\sigma(E)$
- Wide bins around characteristic M1 α lines the binning has been fixed by hand (no knowledge about peak models there)

Please Note: Minimum bin size fixed to 15 (40) keV for γ (α) regions
A minimum of 50 events is required in each bin, otherwise merge

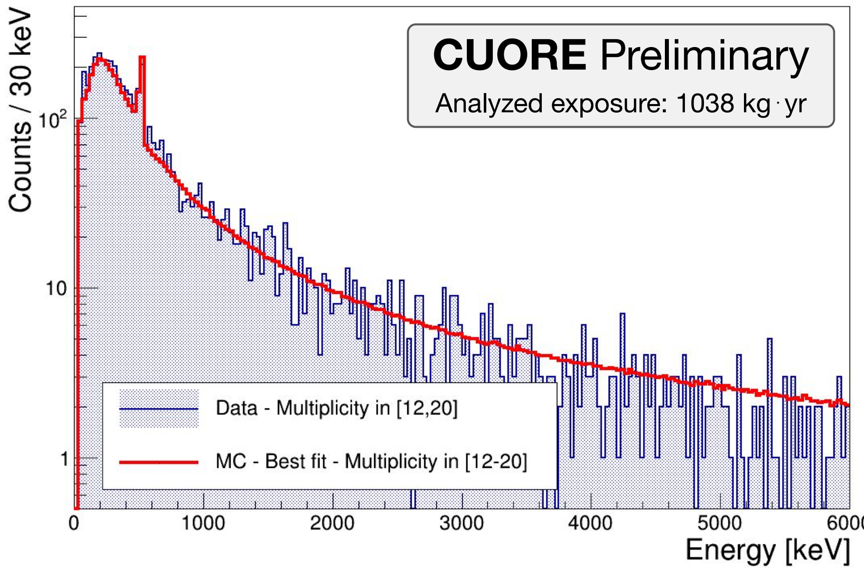


Prior distributions

The prior distributions summarize the ***a priori* knowledge** we have about a certain background components.

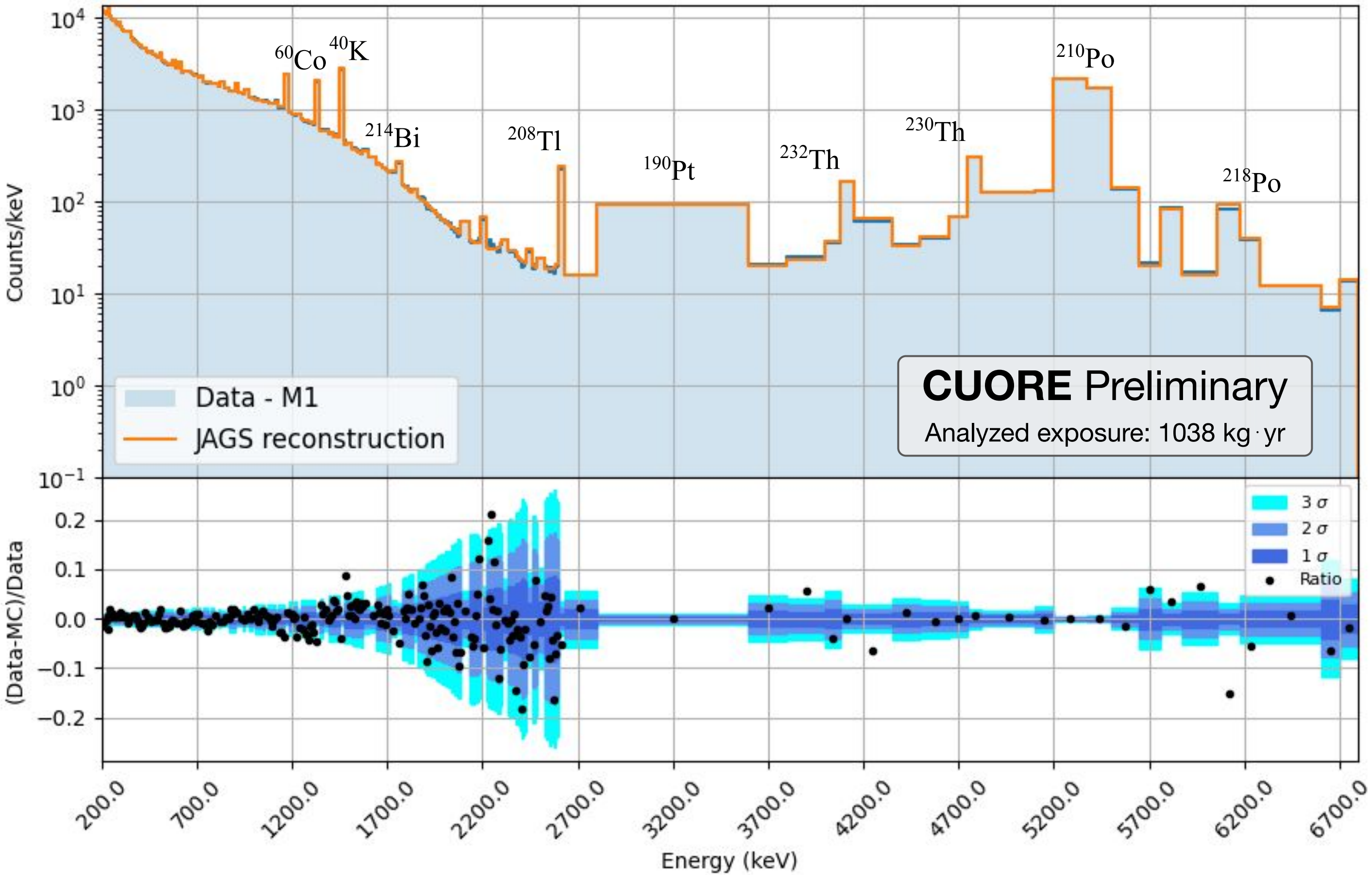
The prior distribution can be originated through different measurements:

- *Previous experiments:*
  - CUORE-0 provides many information about components used also for CUORE
- *Radioactive assays:*
  - Neutron Activation Analysis
  - HPGe measurements
- *Muons:*
  - *High multiplicity data*

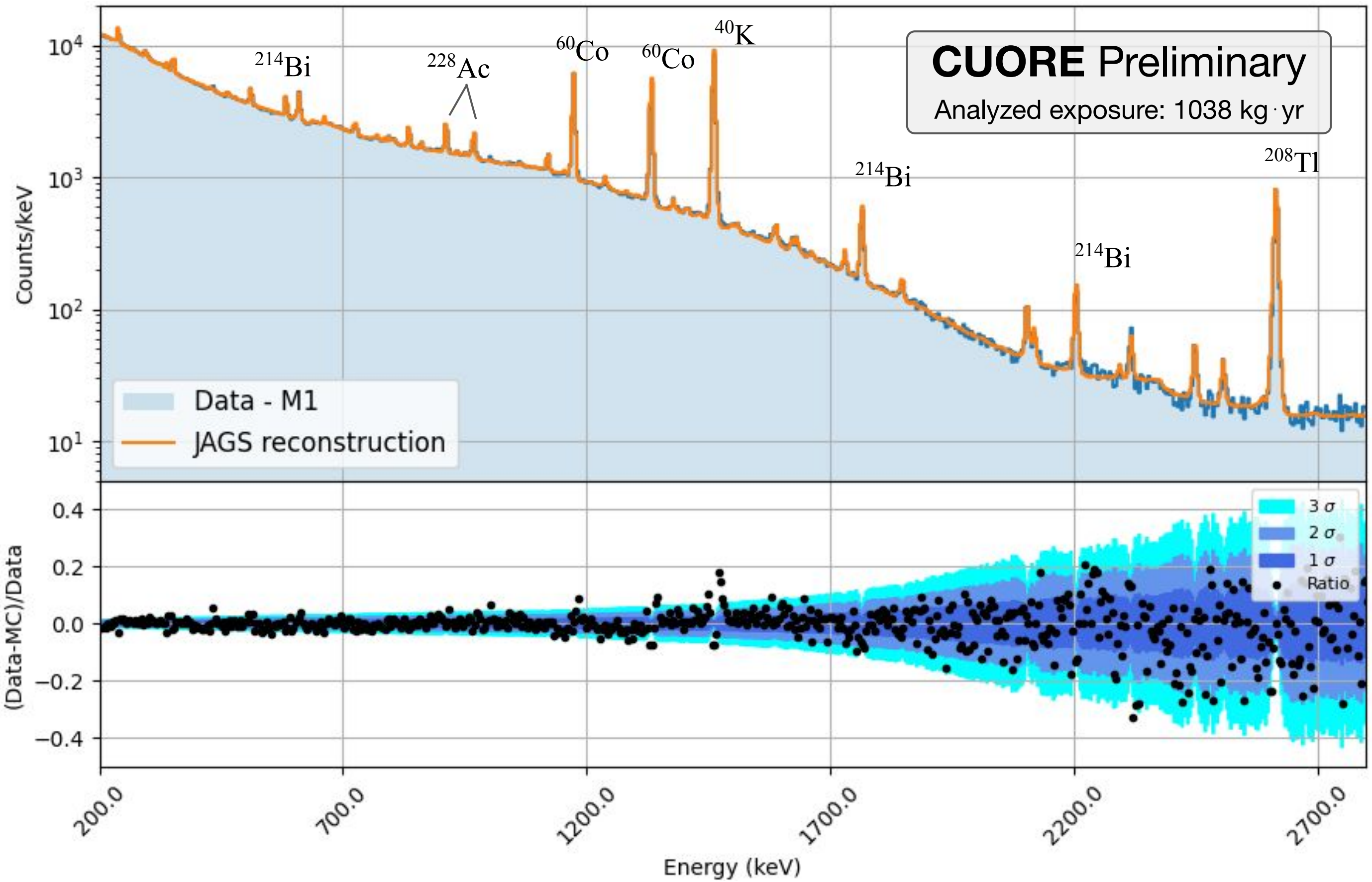


Please Note: In case a contamination doesn't have any dedicated measurement we fix a default uniform prior between 0 and the maximum normalization factor (not to surpass data + fluctuations)

Results: M1 data reconstruction

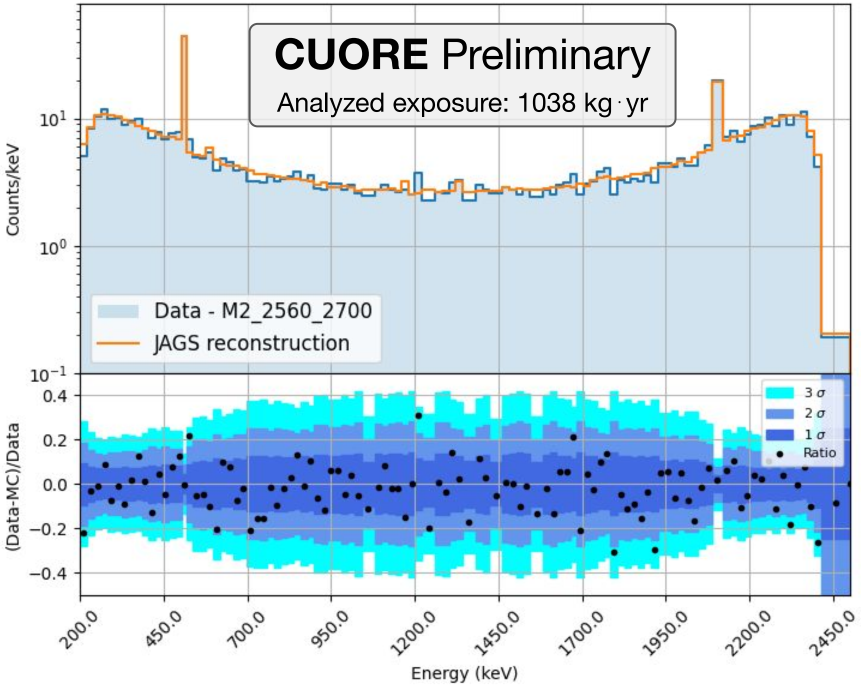


Visual check with thinner binning

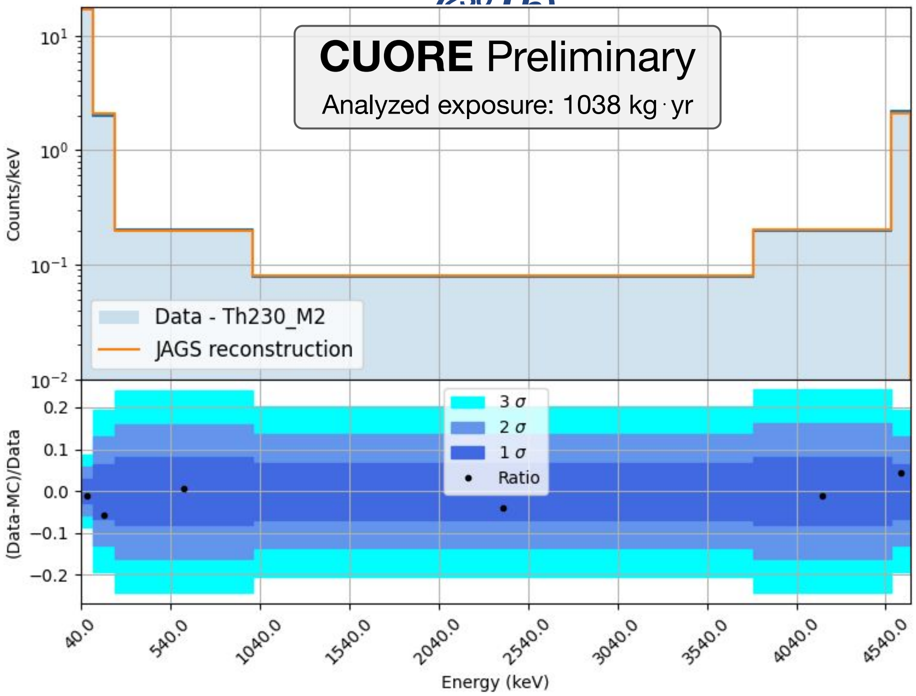


Results: M2 bands data reconstruction

Energy Sum ∈ (2560,2700) keV (^{208}Tl)



Energy Sum ∈ (4760,4820) keV (^{230}Th)



Systematics

Assumptions (possible source of systematics)

- *Contaminations equal on all the crystals*
- *Contaminations* are simulated *uniformly* on the shieldings and copper components
- The background is *stable with time*

→ *Repeat the fit to characterize and extract reliable systematic errors*

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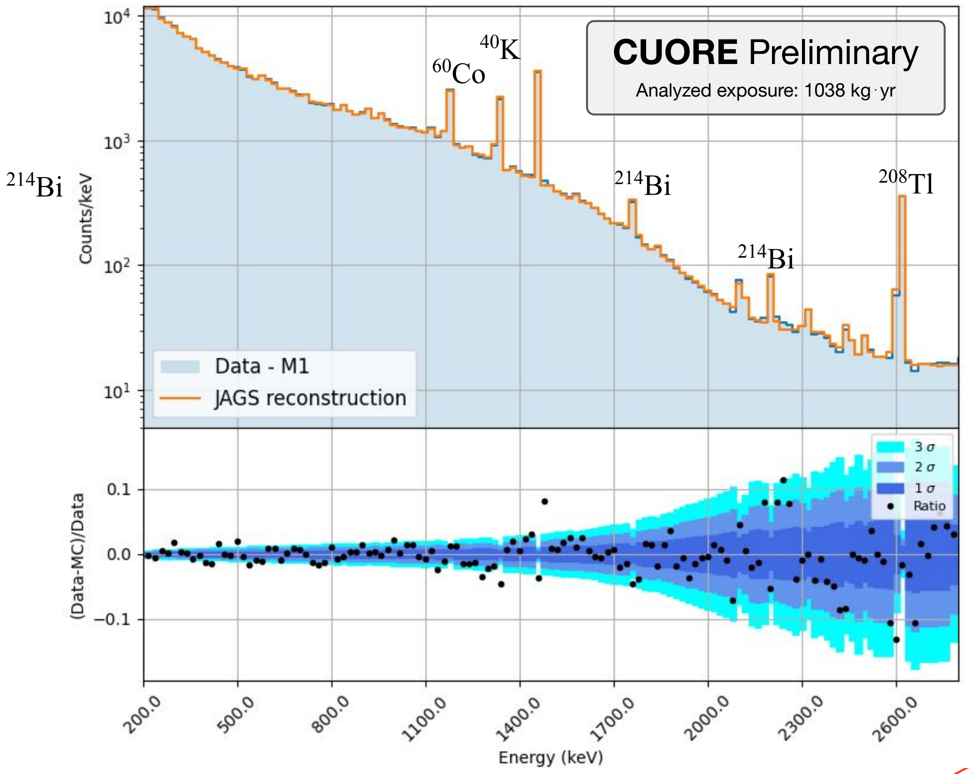
INCLUDED SYSTEMATICS

→ *Binning*

20 keV UNIFORM BINNING



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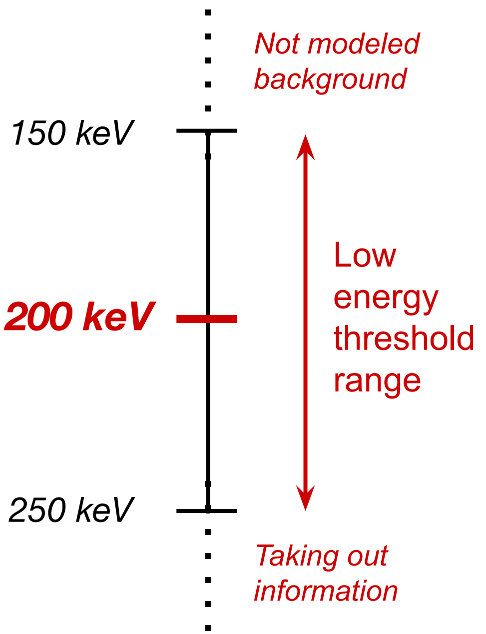
INCLUDED SYSTEMATICS

→ *Binning*

→ *Low Energy threshold*

LOW ENERGY THRESHOLD



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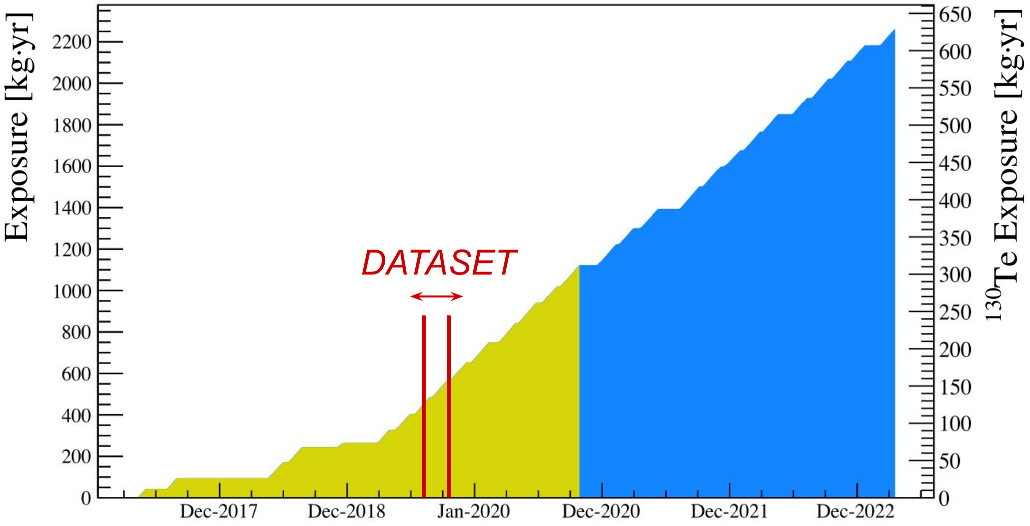
→ *Time*

TIME



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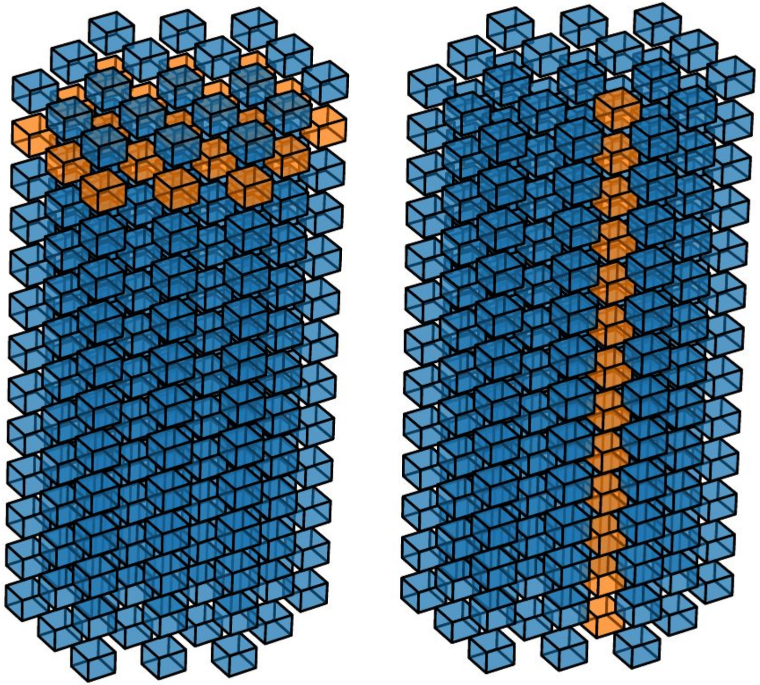
→ *Time*

→ *Geometry (Floors, Towers)*

GEOMETRY



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INCLUDED SYSTEMATICS

→ *Binning*

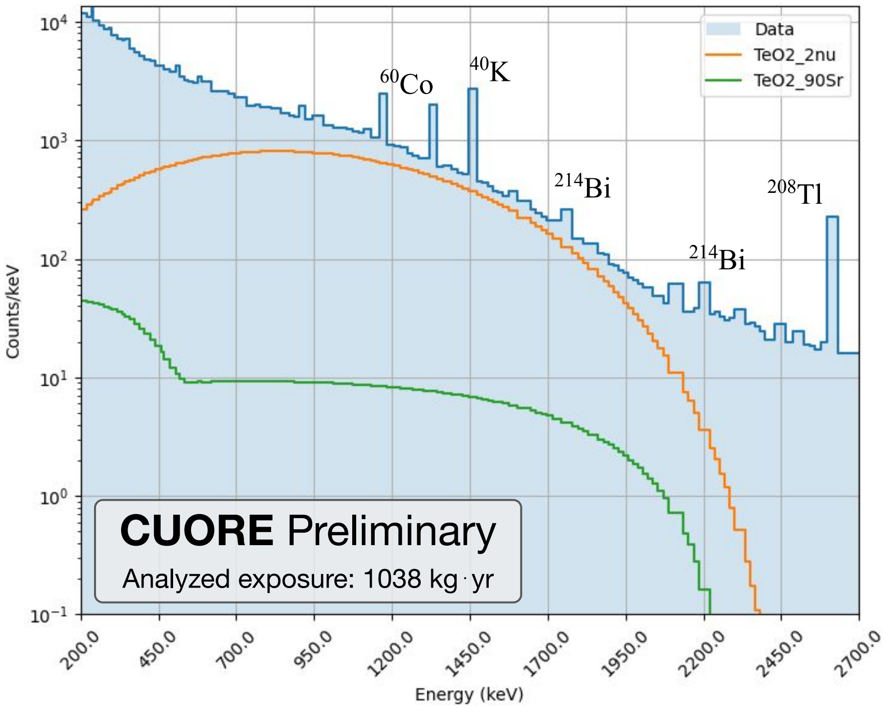
→ *Low Energy threshold*

→ *Time*

→ *Geometry (Floors, Towers)*

→ *^{90}Sr contamination*

^{90}Sr CONTAMINATION



Please Note: Contribution from posterior average

Impact of the results

Fit on the entire energy region

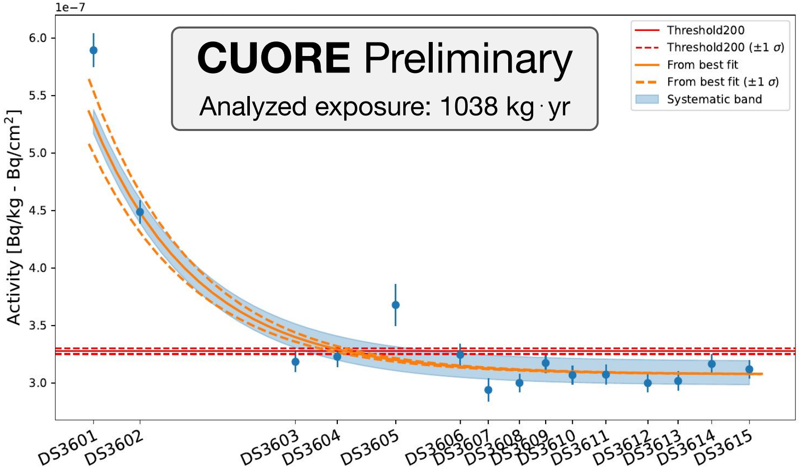
- Better constraints on contaminations
- Lower correlation between background components

→ *Input to CUPID background (data driven) budget*

Track time varying activities

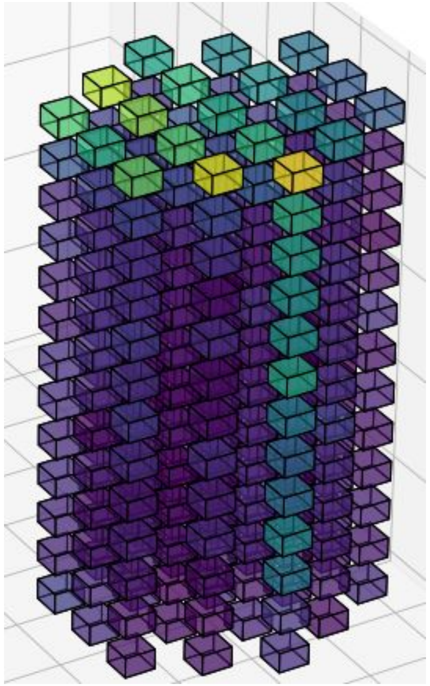
- Reconstruct initial activity
- Study chain breaking (contamination history)

^{210}Po surface contamination in CuNOSV (10 nm)



Non uniformities

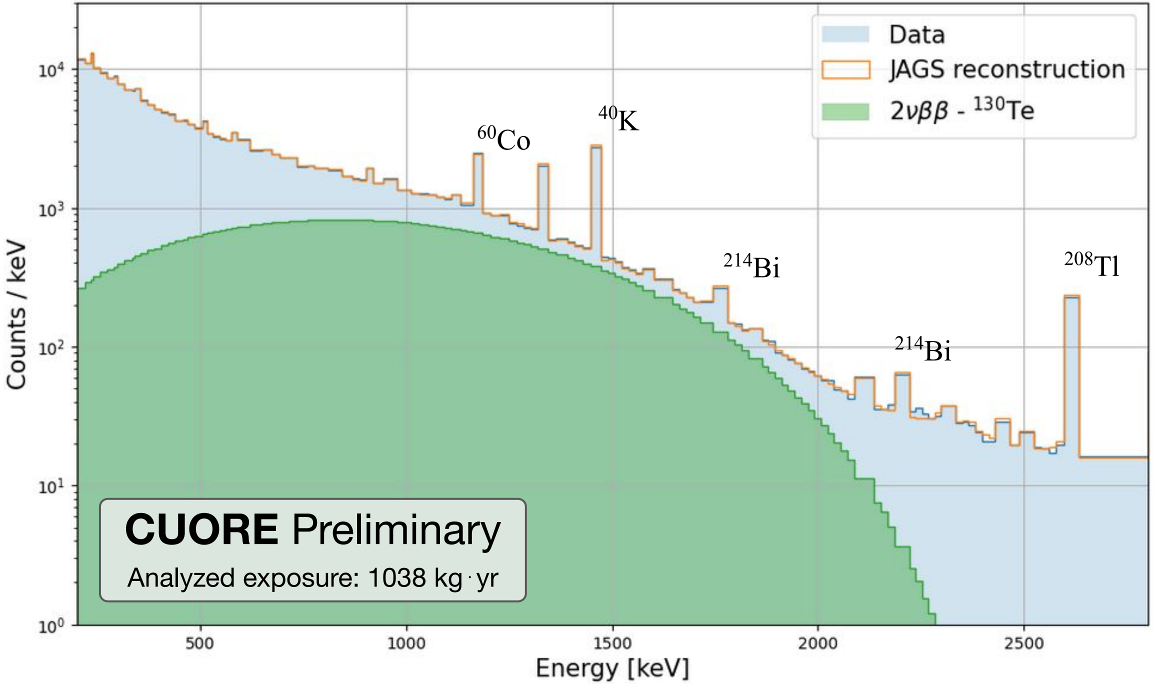
- Point-like or localized sources (^{40}K - TeO_2 bulk)
- Recontaminations (^{210}Po - TeO_2 surface)



Preliminary discussion: $2\nu\beta\beta$ half-life

New measurement of $2\nu\beta\beta$ half-life in ^{130}Te

Optimizing systematics uncertainties evaluation to perform the precision measurement



ACCESS

In the case of the CUORE BM, many background contributions are forbidden beta decays (i.e. ^{210}Bi, ^{210}Pb, ^{40}K, ^{90}Sr)

→ ***Measure with precision their shape is essential to:***

1. *Test theoretical models* checking which one is applying the correct approximation to reproduce experimental data
2. *Measure the axial-coupling* g_A (primary importance in case of 0ν discovery) in different momentum regions
3. *Lower uncertainties in precision measurement* of the shape of $\beta\beta$ decays

The Array of Cryogenic Calorimeters to Evaluate Spectral Shapes (**ACCESS**) will do this

Foreseen measurements →

Crystal ready

First results!

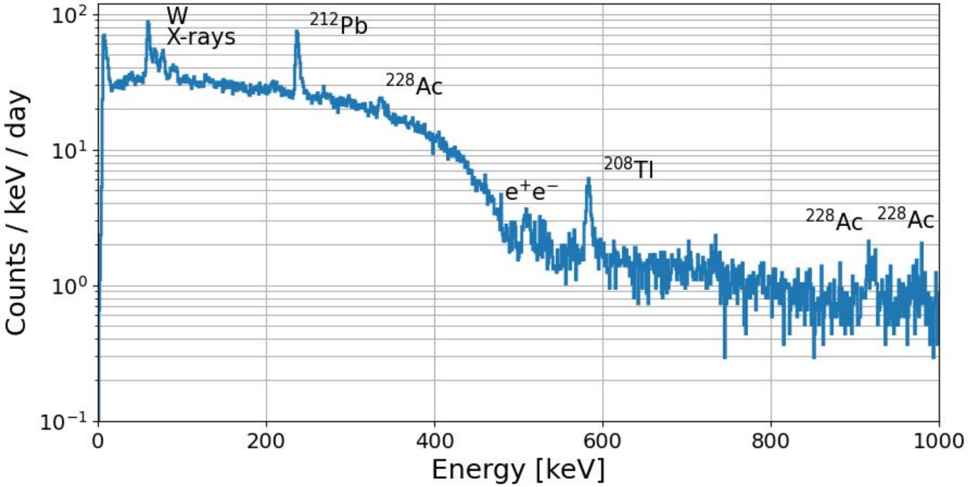
Physics Case	Isotope	Q_β [keV]	Half-life [yr]	Natural Abundance or Target Doping
Nuclear Physics	^{99}**Tc**	293.8	2.11×10^5	0.25 ppb
	^{113}Cd	316	7.70×10^{15}	13.47 %
	^{115}In	496	4.41×10^{14}	95.7 %
Background in ν-physics and Dark Matter search	^{90}**Sr**	545.9	28.8	30 ppq
	^{39}**Ar**	565	269	0.15 ppt
	^{42}**Ar**	599	32.9	20 ppq
	^{210}Bi	1161.2	0.014	^{238}U decay chain
Cosmic Neutrino background detection	^{151}**Sm**	76.4	94.7	0.20 ppt
	^{210}Pb	63.5	22.2	^{238}U decay chain

Eur. Phys. J. Plus **138**, 445 (2023)

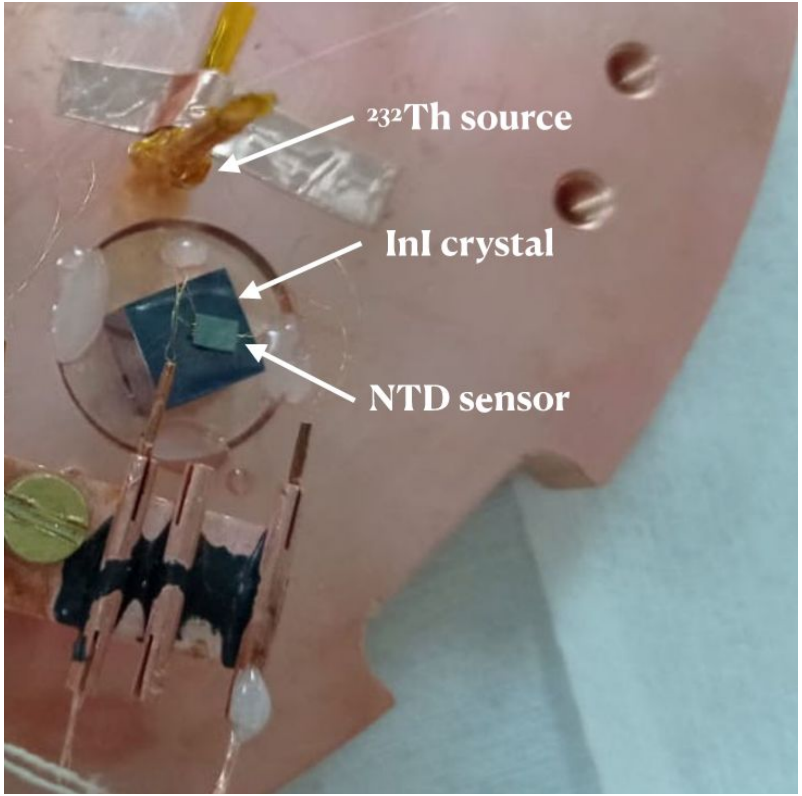
First measurement

First measurement of the ACCESS project with Indium Iodine crystal (^{115}In 96% abundance)

Effective lifetime of ~ 129 hours



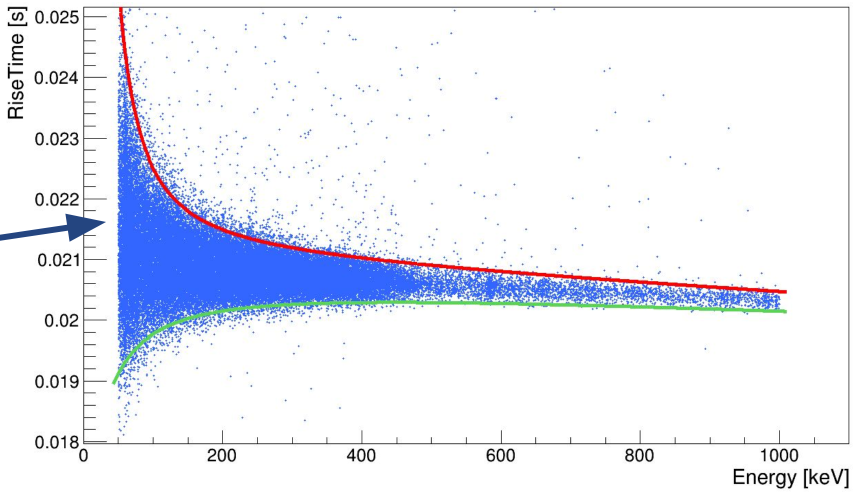
***Eur. Phys. J. Plus* 138, 445 (2023)**



The analysis

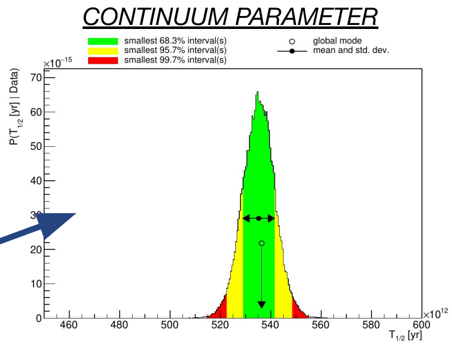
1. Performed ***low level analysis*** optimizing cuts and performance
   - From triggering to calibration of collected data

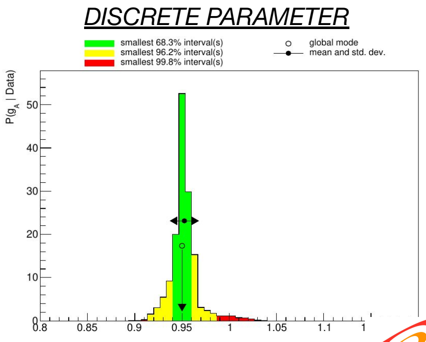
2. ***Careful efficiency evaluation*** not to distort the energy spectrum shape
   - Rectangular cuts to avoid pile-up and bad pulses
   - More complex cuts on pulse shape



3. Built a ***background model*** of the setup by means of Geant4 Monte Carlo simulations
   - Convolution with energy and timing response of the detector
   - Introduced unresolvable pile-up

4. Developed ***Bayesian fitting framework (BAT)***
   - Extracts half-life and background contributions
   - Possibility to determine parameters using simultaneously multiple theoretical templates





Preliminary results

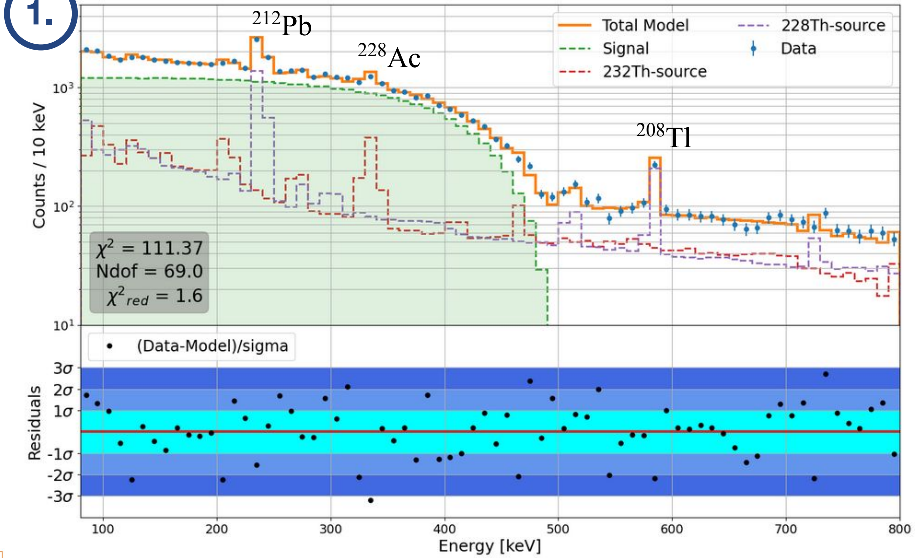
We are going to present the results in 2 ways:

1. *Overall best fit* (sampling over all the model parameters)
2. Fix parameters (sNME) and *perform a match of the half-life coming from experimental data and theory*

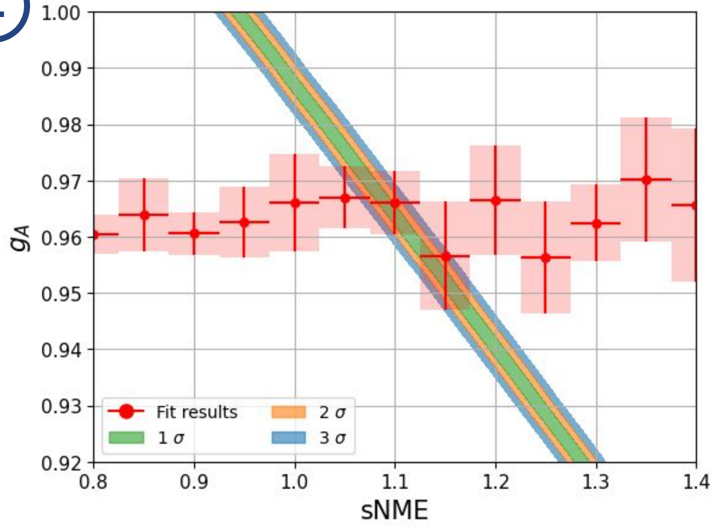
→ <u>Precise determination of physical parameters</u>

→ <u>Test model predictions</u>

1.



2.



G S S I

CUORE

Conclusions and perspectives

CUORE

- ✓ Developed and concluded the first comprehensive model of the CUORE data
- ✓ The fit is stable and gives satisfying data reconstruction
- ~ The BM Internal note passes internal review and collaboration review → writing collaboration technical paper
- … Ready to optimize few aspects to come out with the $2\nu\beta\beta$ half-life measurement and shape studies on that → collaboration paper after the current one

ACCESS

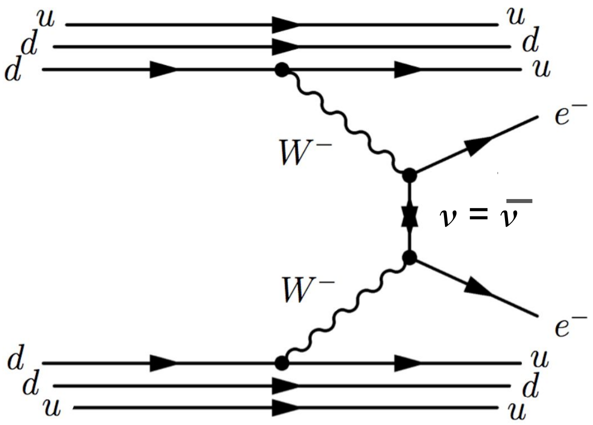
- ✓ Project presented and first detector design study concluded → paper out
- ✓ First measurement with ^{115}In concluded
- ~ Analysis of the measurement gave very exciting outcome → writing paper
- … Other measurements are planned

BACKUP SLIDES

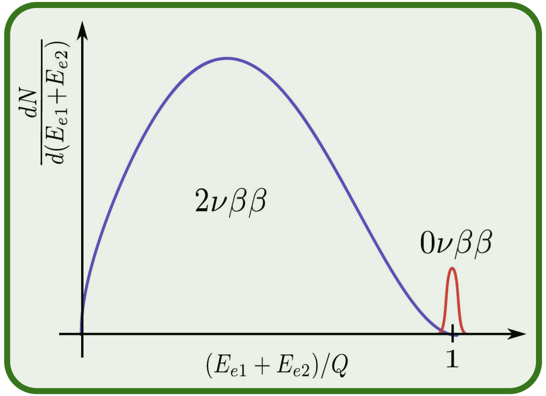
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

WHY IT'S IMPORTANT

- Beyond SM ($\Delta L = 2$)
- **Constraints on neutrino mass** hierarchy and scale
- **Neutrino nature:** Majorana / Dirac



THE ENERGY SPECTRUM



THE SENSITIVITY

$$S^{0\nu} \propto \sqrt{\frac{M\,T}{B\,\Delta}}$$

- $M\,T$ → Mass · Active Time
- Δ → Energy resolution in the ROI
- B → Background index

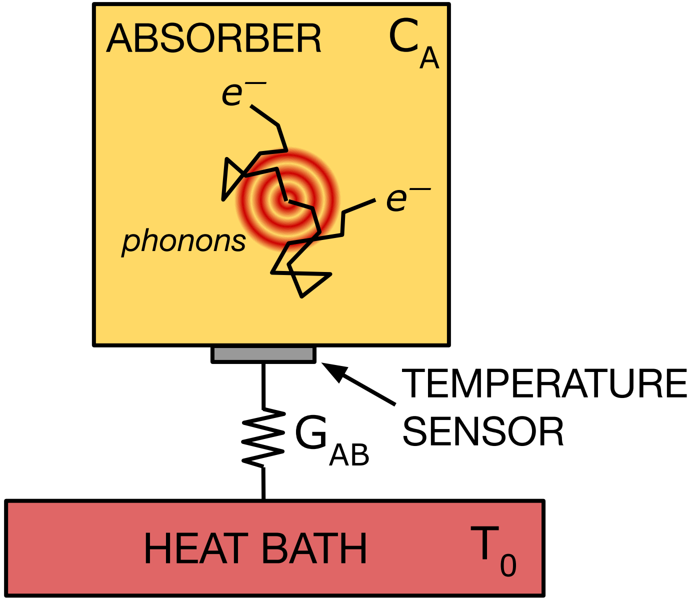
PARAMETER OF INTEREST

$$T^{1/2}_{0\nu} = \left[G_{0\nu} |\mathcal{M}_{0\nu}|^2 g_A^4 \left(\frac{m^2_{\beta\beta}}{m^2_e} \right) \right]^{-1}$$

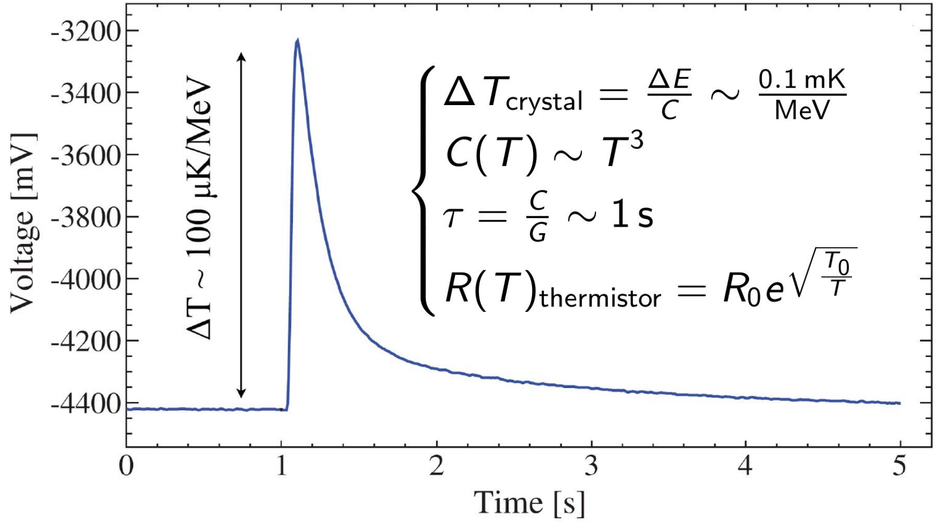
- $T^{1/2}_{0\nu}$: Experimental observable
- $G_{0\nu}$: Phase space factor (computed)
- $|\mathcal{M}_{0\nu}|^2$: Nuclear physics (models + experiments)
- $m_{\beta\beta}$: Majorana mass (parameter of interest)

Cryogenic calorimeters technique

Source ≡ Detector ➡ High efficiency

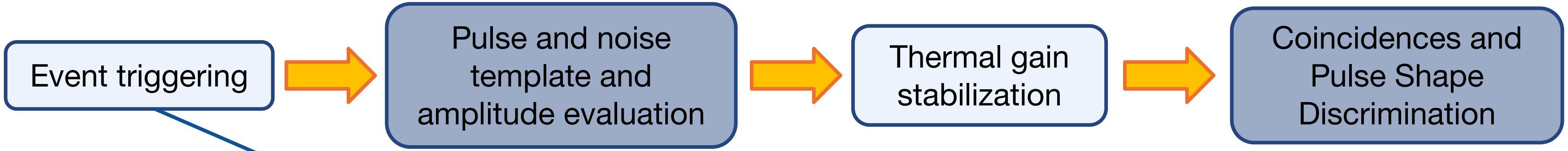


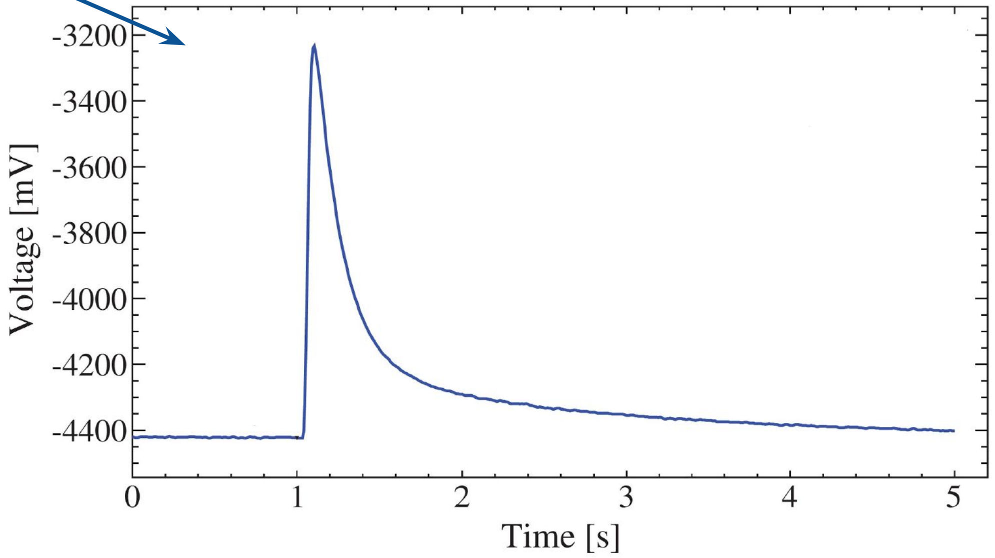
SAMPLE PULSE



Low temperatures ➡
- **✔ E resolution (≳0.3%)**
- **✘ Slow signals (~1s)**

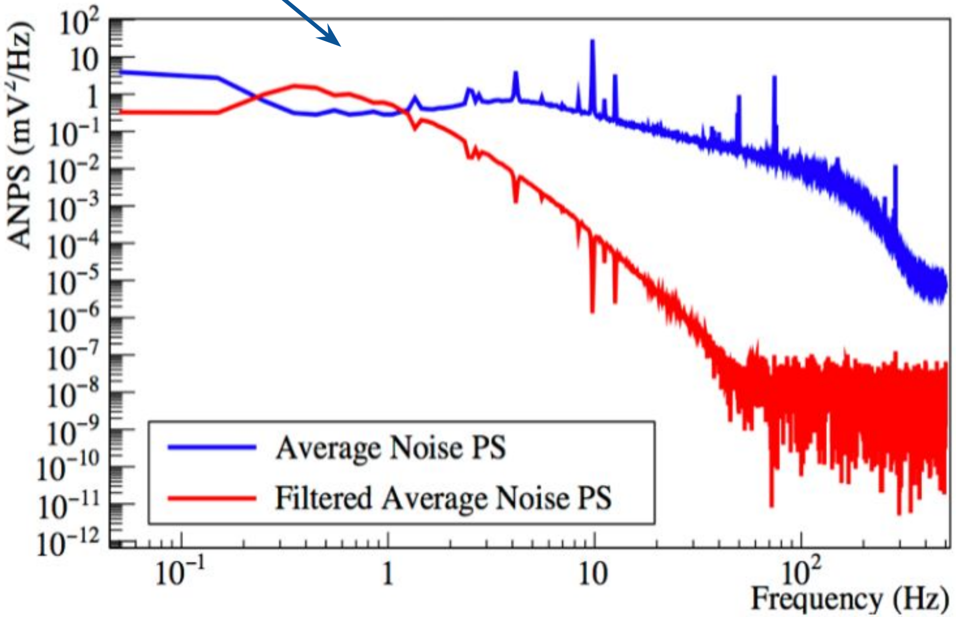
Data analysis chain





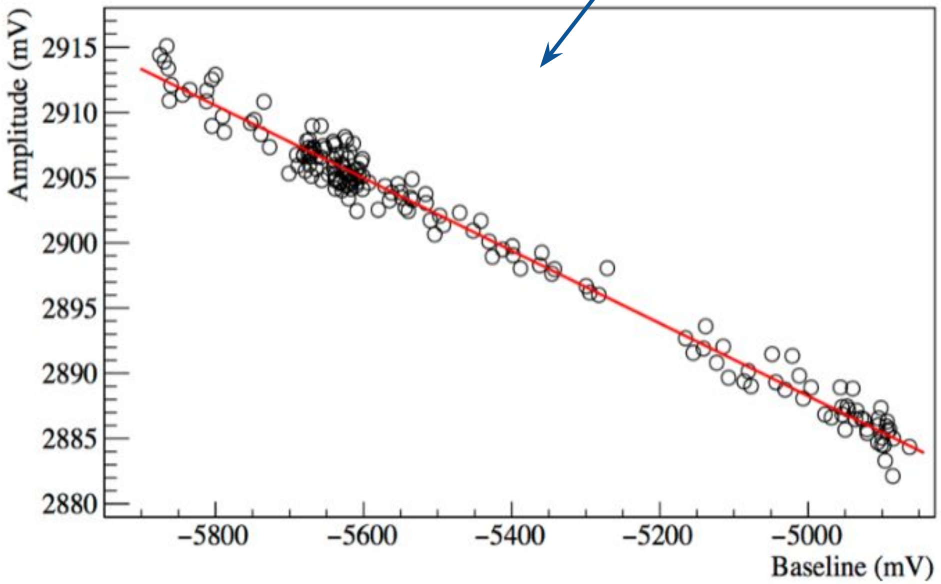
Data analysis chain

Event triggering → Pulse and noise template and amplitude evaluation → Thermal gain stabilization → Coincidences and Pulse Shape Discrimination



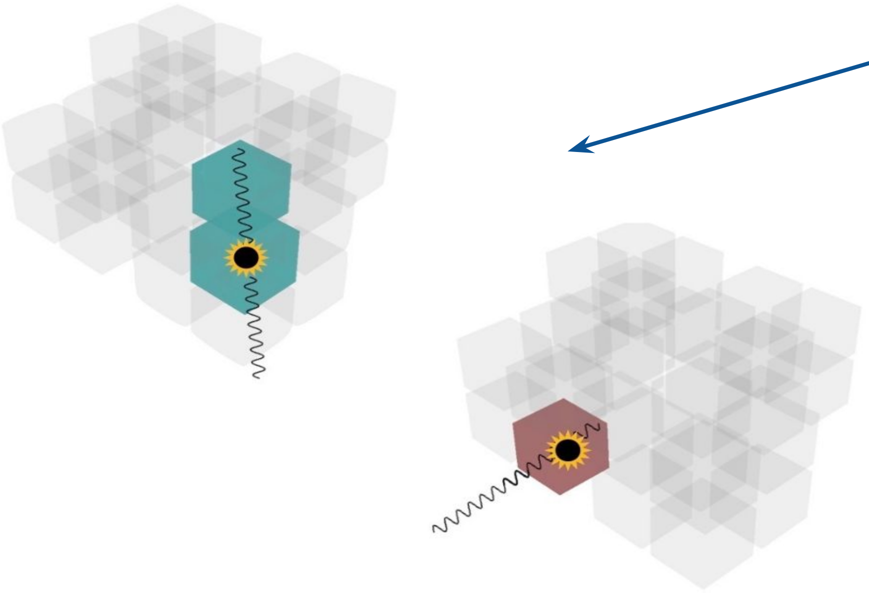
Data analysis chain

Event triggering → Pulse and noise template and amplitude evaluation → Thermal gain stabilization → Coincidences and Pulse Shape Discrimination



Data analysis chain

Event triggering → Pulse and noise template and amplitude evaluation → Thermal gain stabilization → Coincidences and Pulse Shape Discrimination



$$RE = \sqrt{\sum_{i=1}^{n} (\mathbf{x}_i - (\mathbf{x} \cdot \mathbf{w})\mathbf{w}_i)^2}$$

n = waveform length

x = waveform

w = Principal Component Analysis parameter

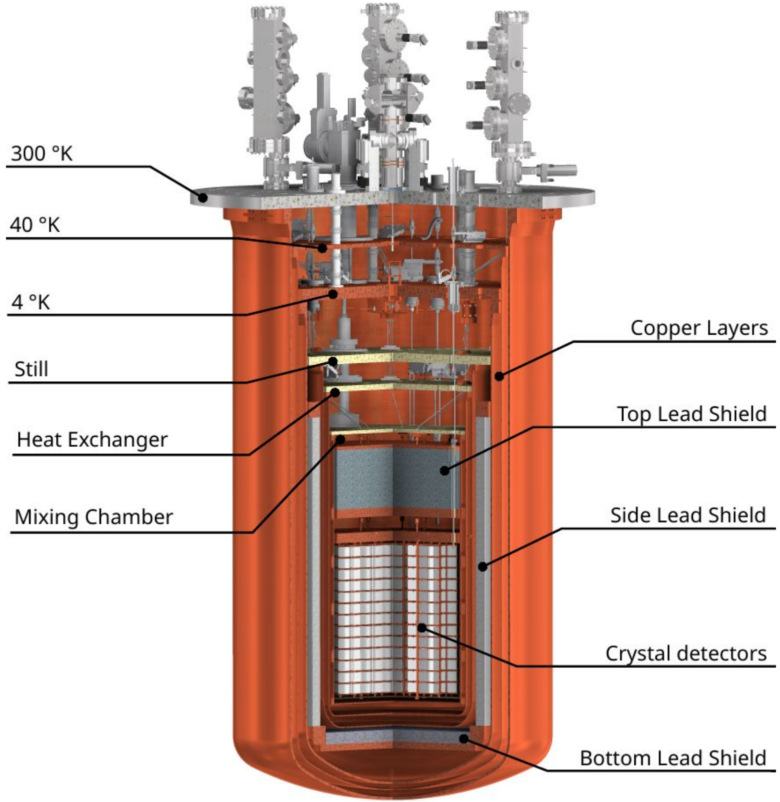
CUORE shieldings

EXTERNAL SHIELDING

- Gran Sasso mountain, 3600 m.w.e
- Lead shield: > 25 cm thick
- Neutrons shield: 18 cm PE + 2 cm H_3BO_3 powder

INTERNAL SHIELDING

- 6 nested copper shields (thermal)
- 6 cm thick Roman lead shield around
- Innermost copper shield made of CuNOSV
- 30 cm thick top lead shield + 6.4 cm CuNOSV



Monte Carlo processing

1. Convert the MC detector numbering to the DAQ detector numbering
2. Apply an approximate α quenching factor, ignoring the energy dependence (Sec. 3.2.1)
3. Assign an absolute time to each event (Sec. 3.2.2)
4. Randomly assign a dataset to each event. The fraction of events belonging to each dataset is obtained by the ratio of its raw exposure to the total (table 2.1)
5. Deactivate dead channels (117, 169, 792, 923)
6. Integration: combine events that happen on the same channel within a short time window ($\Delta t_I = 0.005$ s) into a single event whose energy is the sum of the input energies. This is equivalent to an unresolved pileup
7. Apply energy resolution using the lineshape parameters for each channel-dataset pair. The official lineshape files (both for the lineshape at 2615 keV and for the energy scaling of its parameters) are used in this step; they are stored in the cuoremc git repository, under `cuoremc/ares/data/Nature2021`.
8. Apply the energy thresholds (40 keV $>$ E $>$ 10000 keV)
9. Evaluate pile-up in a 10 seconds window (Sec. 3.2.2). This accounts for pile-up that we can resolve; as a consequence, all involved pulses are rejected
10. Evaluate time coincidences with a $\pm$30 ms time window and 15 cm distance cut
11. Apply the per-dataset PCA efficiency curve. A wider PCA cut than the one used for the $0\nu\beta\beta$ analysis is applied here, to maximize efficiency in a wider energy range [3]
12. Apply the per-dataset base cut efficiency (table 8, [8])
13. Apply a per-channel, per-dataset livetime efficiency (Sec. 3.2.3)
14. Remove channels that have 0 exposure (table 2.2)
15. Multiplet validation: fully eliminate multiplets that contain a removed channel, for any reason (e.g. PCA, base cuts, livetime efficiency)

Quenching factor (item 2)

Pile-up effects (items 6, 9)

Finite energy resolution/threshold + lineshape (items 7, 8)

Coincidences (item 10)

Efficiencies (items 11–15)

Spectra features

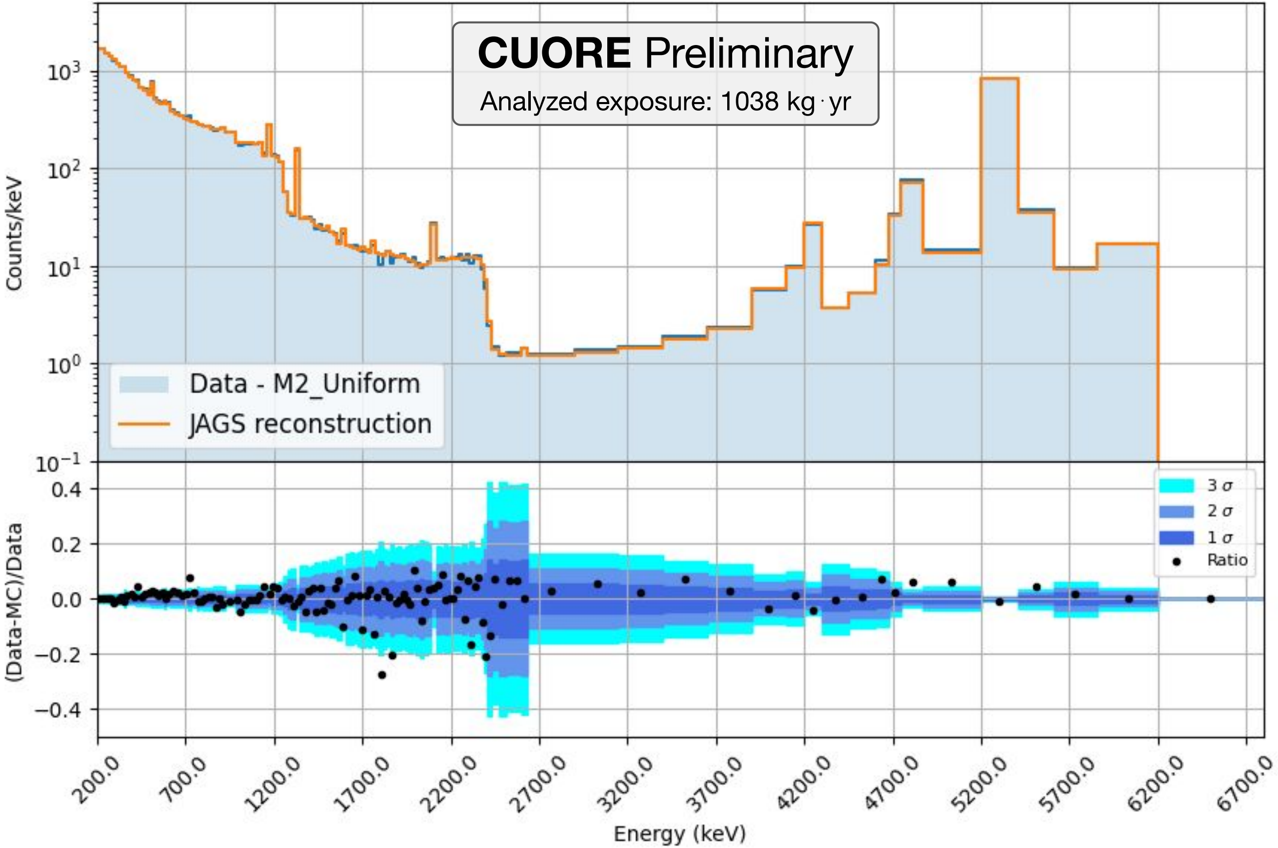
MULTIPLICITY 1 LINES

Energy [keV]	Isotope	Energy [keV]	Isotope	Energy [keV]	Isotope
238.6	^{212}Pb	768.4	^{214}Bi	1377.7	^{214}Bi
295.2	^{214}Pb	794.9	^{228}Ac	1460.5	^{40}K
338.3	^{228}Ac	803	^{210}Po	1588.2	^{228}Ac
351.9	^{214}Pb	834.8	^{54}Mn	1620.5	^{212}Bi
427.8	^{125}Sb	860.6	^{208}Tl	1630.6	^{228}Ac
433.9	^{108m}Ag	911.2	^{228}Ac	1729.6	^{214}Bi
463	^{228}Ac	934.1	^{214}Bi	1764.5	^{214}Bi
511	e+e- annihilation	964	^{228}Ac	1847.4	^{214}Bi
583.2	^{208}Tl	969	^{228}Ac	2103.5	^{208}Tl (SE)
609.3	^{214}Bi	1001	^{234m}Pa	2118.5	^{214}Bi
614.3	^{108m}Ag	1063.6	^{207}Bi	2204.1	^{214}Bi
657.7	^{110m}Ag	1120.3	^{214}Bi	2316.5	^{147}Sm
665.4	^{214}Bi	1173.2	^{60}Co	2447.9	^{214}Bi
722.9	^{108m}Ag	1238.1	^{214}Bi	2505.6	^{60}Co
727.3	^{212}Bi	1332.5	^{60}Co	2614.5	^{208}Tl

MULTIPLICITY 2 LINES

Energy [keV]	Isotope	Energy [keV]	Isotope
328	^{228}Ac	821.5	^{60}Co (SE)
351.9	^{214}Pb	835.7	^{228}Ac
409.5	^{228}Ac	911.2	^{228}Ac
427.9	^{125}Sb	950	^{40}K (SE)
434.2	^{108m}Ag	969	^{228}Ac
511	e+e- annihilation	1120.3	^{214}Bi
583.2	^{208}Tl	1173.2	^{60}Co
609.3	^{214}Bi	1332.5	^{60}Co
722.9	^{110m}Ag	1592.5	^{208}Tl (DE)
768.4	^{214}Bi	1764.5	^{214}Bi
794.9	^{228}Ac	2103.5	^{208}Tl (SE)

Results: M2 data projection



Results: contamination table example

Component	Contaminant	Best fit [Bq/kg]	Binning	Threshold	Single Dataset	with90Sr	SingleFloor	SingleTower
Crystals	^{110m}Ag	$(3.74 \pm 0.48) \times 10^{-7}$	$+1.35$		$^{+1.55}_{-1.89}$	-1.39	$^{+1.22}_{-0.86}$	$+1.12$ (*)
	^{125}Sb	$(2.98 \pm 0.11) \times 10^{-6}$	$+0.34$	$+0.17$	$+0.34$		$^{+0.44}_{-0.54}$	$^{+2.15}_{-1.41}$
	^{147}Sm	$(9.47 \pm 1.18) \times 10^{-9}$			$^{+6.84}_{-2.60}$		$^{+2.76}_{-2.53}$	$^{+5.42}_{-6.06}$
	^{190}Pt	$(1.94 \pm 0.01) \times 10^{-6}$	-0.02		$^{+0.03}_{-0.04}$		$^{+0.15}_{-0.13}$	$^{+0.24}_{-0.26}$
	^{210}Pb	$(1.55 \pm 0.02) \times 10^{-6}$	-0.42		$+0.26$		$^{+0.24}_{-0.41}$	$^{+0.53}_{-1.55}$
	^{226}Ra $-^{210}$ Pb	$< 4.87 \times 10^{-10}$						
	^{228}Ra $-^{208}$ Pb	$(1.28 \pm 0.04) \times 10^{-7}$	-0.10		-0.23		$^{+0.18}_{-0.46}$	$^{+0.16}_{-1.27}$ (*)
	^{230}Th only	$(4.17 \pm 0.07) \times 10^{-7}$	-1.15		-0.53		$^{+0.27}_{-0.65}$	-1.51
	^{231}Pa $-^{207}$ Pb	$< 1.36 \times 10^{-9}$						
	^{232}Th only	$(2.79 \pm 0.05) \times 10^{-7}$	-0.12		-0.20		$^{+0.87}_{-0.44}$	$^{+0.49}_{-1.45}$ (*)
	^{235}U $-^{231}$ Pa	$(5.54 \pm 0.43) \times 10^{-8}$	-0.84		$^{+1.12}_{-1.75}$		$^{+1.26}_{-0.81}$	$^{+0.87}_{-2.62}$
	^{238}U $-^{230}$ Th	$< 9.31 \times 10^{-10}$						
	^{130}Te $- 2\nu\beta\beta$	$(2.97 \pm 0.01) \times 10^{-5}$	-0.02		$^{+0.09}_{-0.07}$	-0.08	$^{+0.03}_{-0.05}$	$+0.05$
	^{40}K	$(4.39 \pm 0.12) \times 10^{-6}$	$+0.32$	$^{+0.16}_{-0.32}$	$^{+0.67}_{-0.96}$	$+0.26$	$^{+0.22}_{-1.07}$	$+2.43$
	^{60}Co	$(3.25 \pm 1.51) \times 10^{-8}$	$+3.92$		$+3.10$ (*)		$+10.73$	$+21.45$

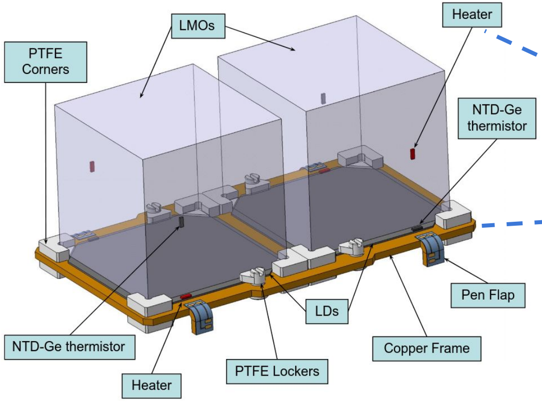
CUPID R&D: BDPT

Big Collaboration effort

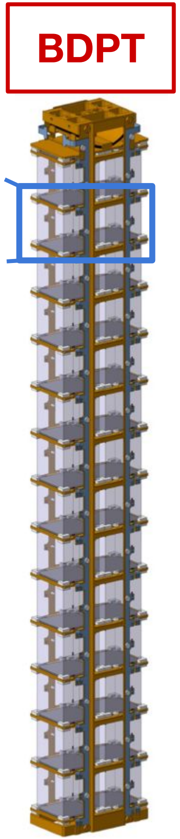
- **28 LMOs crystal**
  - Testing different *producers*
  - Testing different *growing techniques* (Bridgman, Czochralski)
  - Testing different *thermistor glues* (Araldite, UV, …)

- **30 Ge LDs**
  - Testing different *coatings* (sputtering, evaporation)

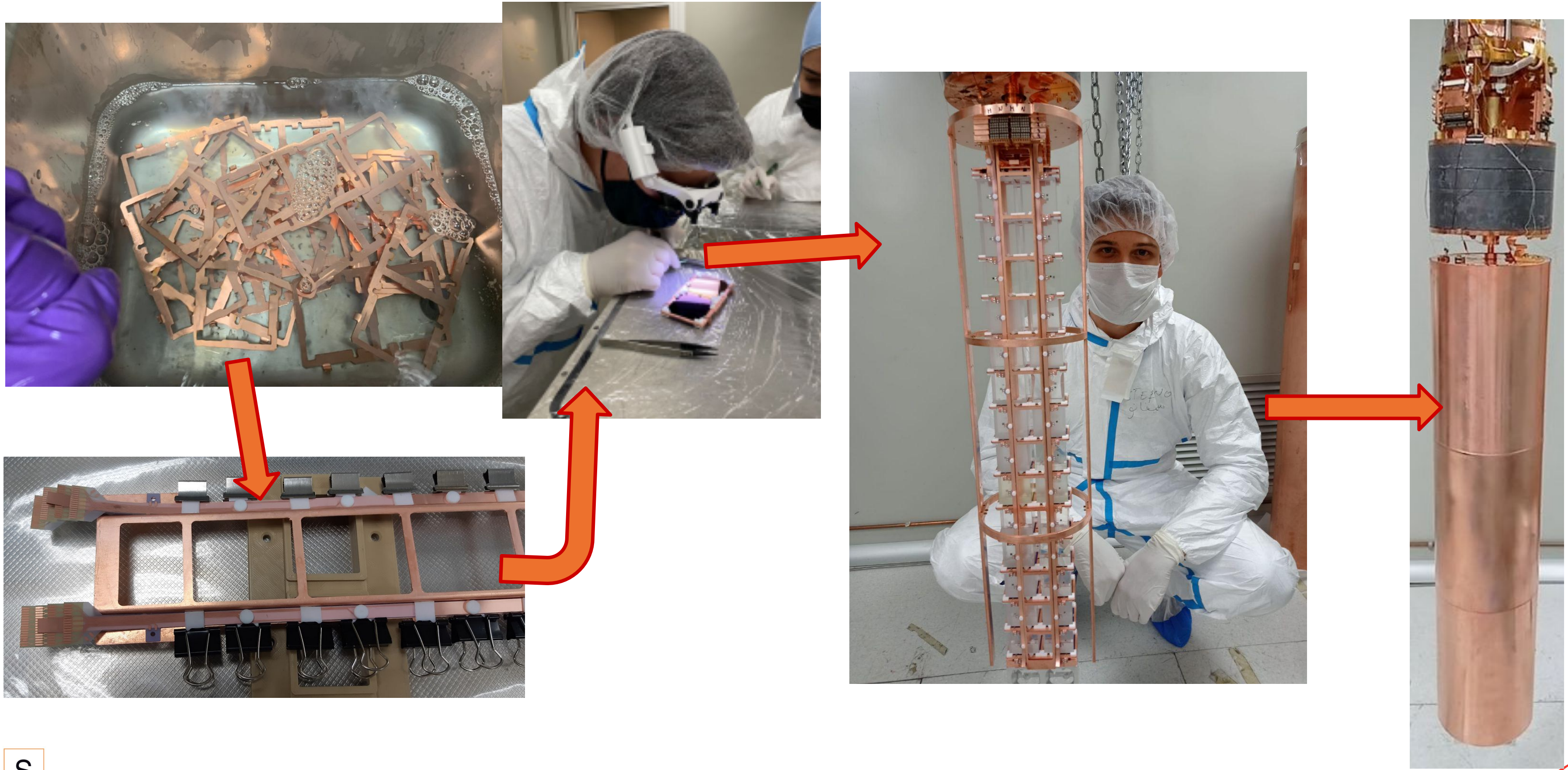
- Characterization and validation of a new DAQ



New frame design

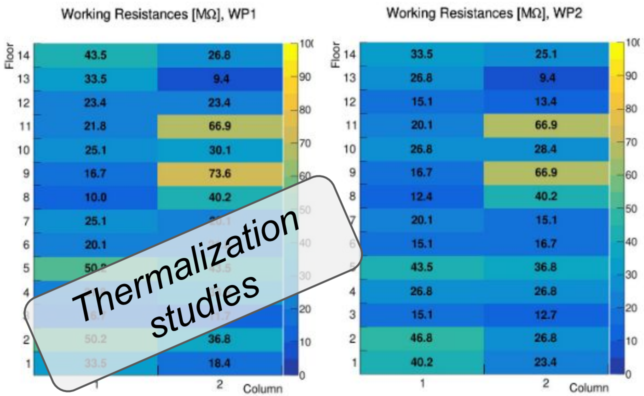


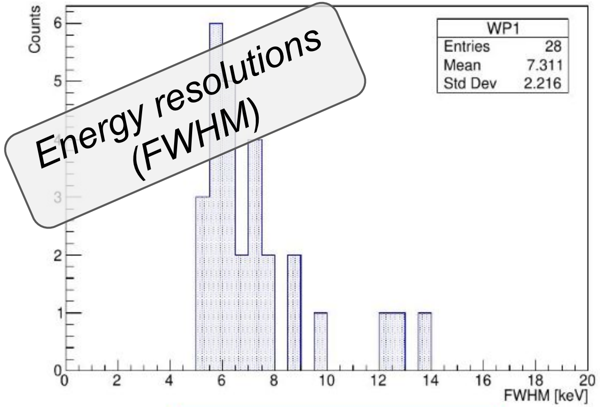
CUPID R&D: tower construction



CUPID R&D: results

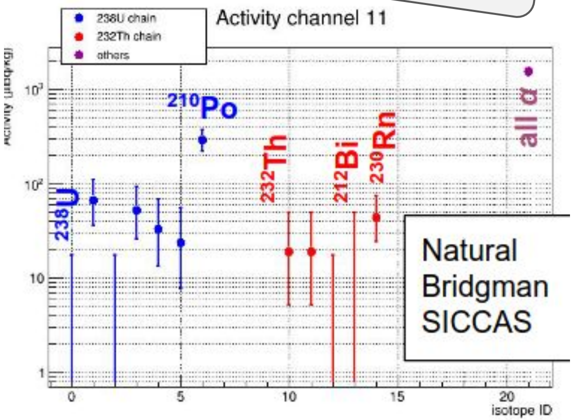
Many results on crystals



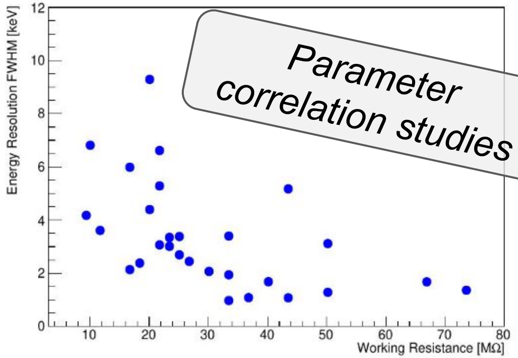


Average FHWH ~ 7.3 keV

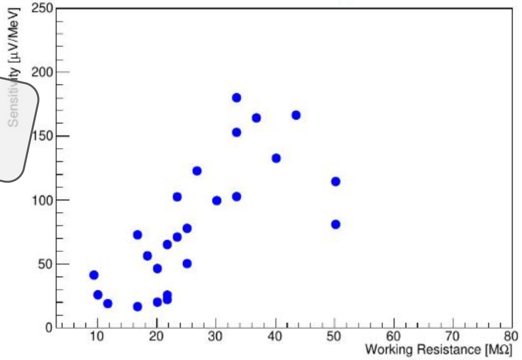
Alpha contaminations



Baseline Resolution



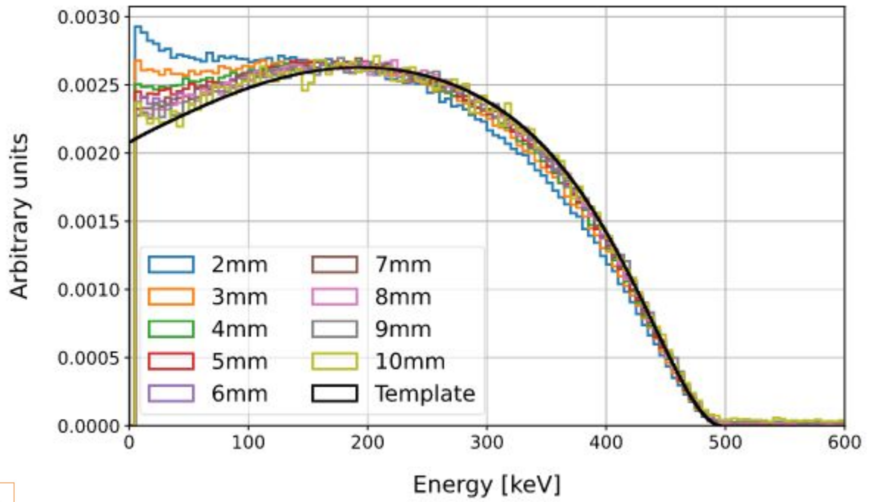
Sensitivity

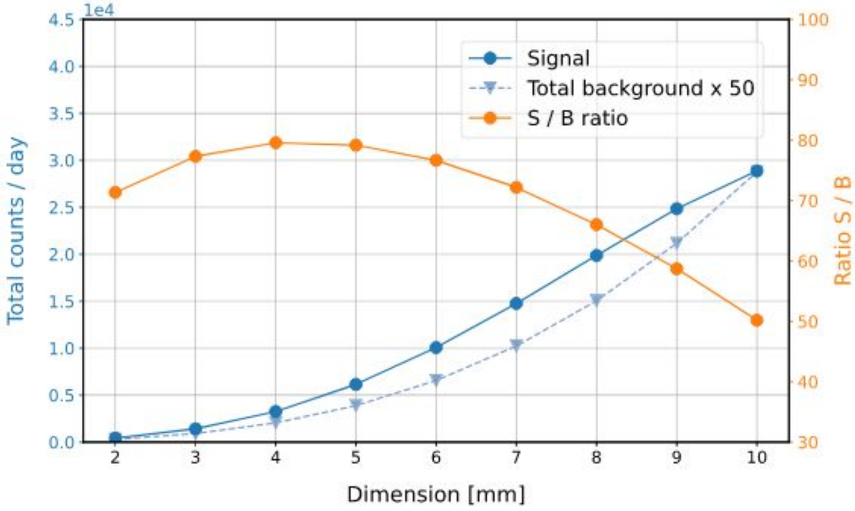


Noise exceed in light detectors
→ new runs to test improvements in the mechanical structure

ACCESS white paper

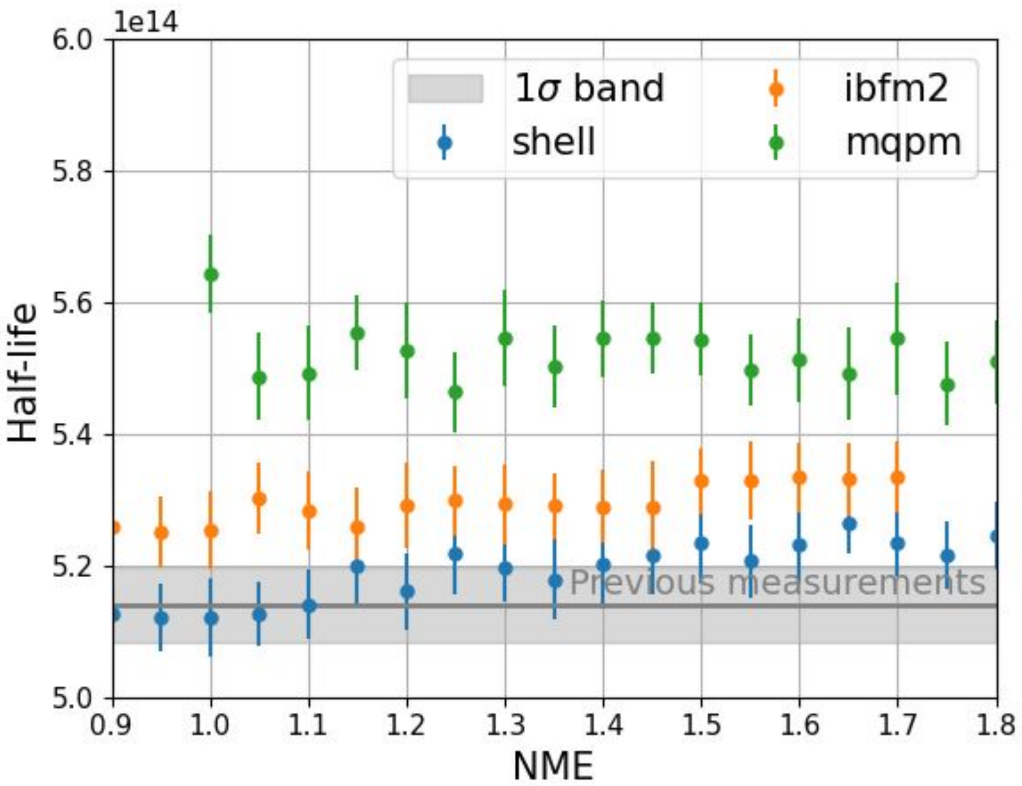
Abstract The ACCESS (Array of Cryogenic Calorimeters to Evaluate Spectral Shapes) project aims to establish a novel technique to perform precision measurements of forbidden β-decays, which can serve as an important benchmark for nuclear physics calculations and represent a significant background in astroparticle physics experiments. ACCESS will operate a pilot array of cryogenic calorimeters based on natural and doped crystals containing β-emitting radionuclides. In this way, natural (e.g. ^{113}Cd and ^{115}In) and synthetic isotopes (e.g. ^{99}Tc) will be simultaneously measured with a common experimental technique. The array will also include further crystals optimised to disentangle the different background sources, thus reducing the systematic uncertainty. In this paper, we give an overview of the ACCESS research program, discussing a detector design study and promising results of ^{115}In.





ACCESS ^{115}In results

Param.	*shell*	*mqpm*	*ibfm*
gA (best)	0.96	0.96	1.17
gA (matched)	0.97	0.99	1.16
sNME (best)	1.65	5 (limit)	0.95
sNME (matched)	1.10	1.45	1.10
T (best)	[5.18,5.30]	[5.42,5.57]	[5.22,5.35]
T (matched)	[5.09,5.20]	[5.49,5.60]	[5.23,5.34]

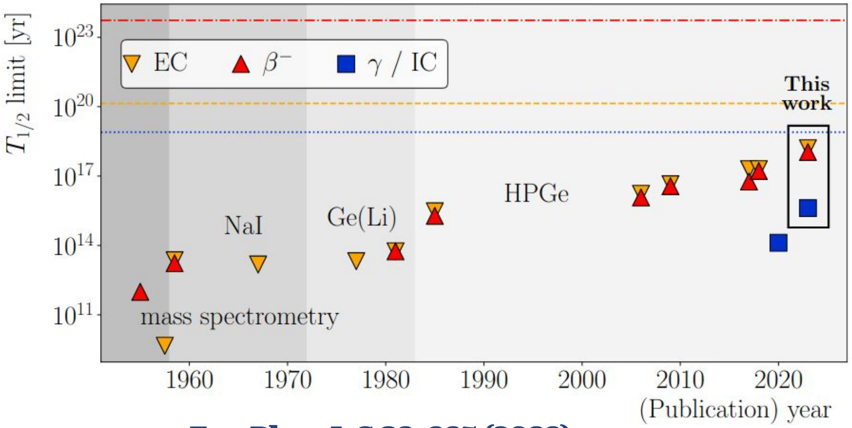


Other projects

^{180m}Ta search

Study of the longest-live metastable state presently known with ULB-HPGe detectors @ LNGS

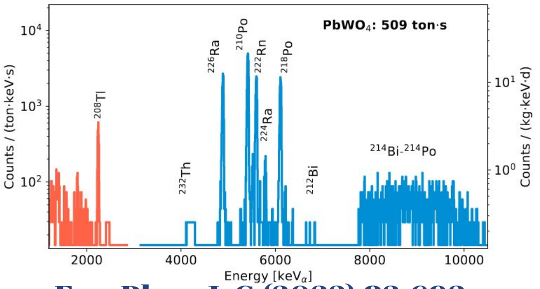
- Low level analysis, optimizations
- Simultaneous fit of different expected features → no decay found, limit 90% C.I.



Eur. Phys. J. C 83, 925 (2023)

RES-NOVA

Radiopurity of a $PbWO_4$ crystal @ LNGS



Eur. Phys. J. C (2022) 82:692

Background characterization and shielding design for the future RES-NOVA experiment