

First results from the **CUORE** background model

Stefano Ghislandi on behalf of the CUORE collaboration



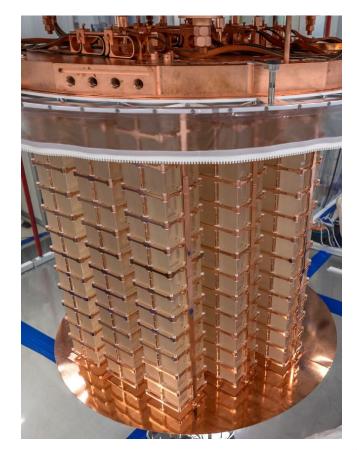




The CUORE experiment

Cryogenic Underground Observatory for Rare Events

- Searching from neutrinoless double beta decay $(0v\beta\beta)$ in ¹³⁰Te
- Running since 2017 in the **Gran Sasso underground**laboratories in Italy (~ 3600 m.w.e.)
- **988 TeO₂ crystals operated at ~ 15 mK** with natural ¹³⁰Te abundance
- No evidence for neutrinoless double beta decay in ¹³⁰Te
 - → only background (see Talk from K. Alfonso)







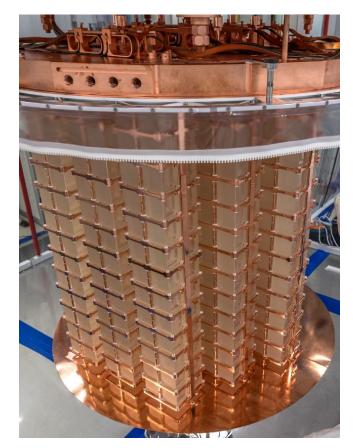
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Studying the remaining background is essential to:

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







Cryogenic Underground Observatory for Rare Events

- Searching from neutrinoless double beta decay $(0\nu\beta\beta)$ in ¹³⁰Te
- Running since 2017 in the Gran Sassa underground
 - 1. Extract background components activity
 - 2. Evaluate reliable systematic errors
- No e 3. Measure half-lifes $(2\nu\beta\beta ^{130}\text{Te})$

Studying the remaining background is essential to:

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

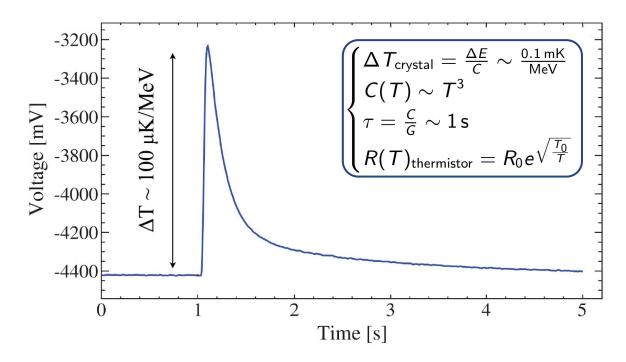




MODEL OF THE BACKGROUND = 1. Data



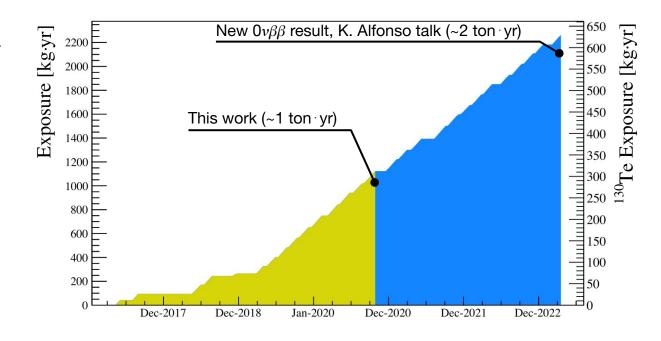








- 15 datasets
- Total exposure of 1123 kg·yr







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- Total exposure of 1123 kg·yr



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





* Sample topologies

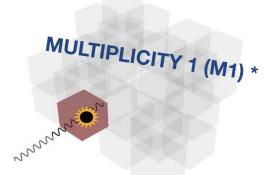
RAW DATA

- 15 datasets
- Total exposure of 1123 kg yr

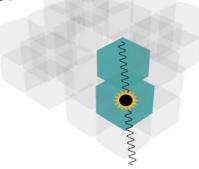


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COINCIDENCES → space-time cut, optimized for the background model studies











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- Total exposure of 1123 kg · yr

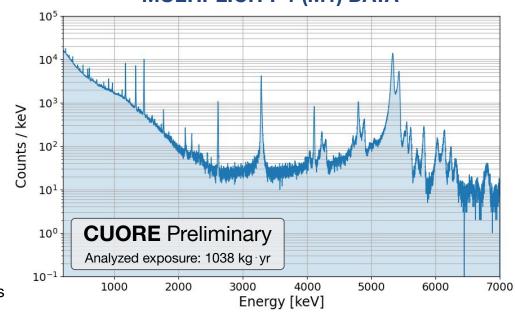


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DATA READY FOR THE FIT

MULTIPLICITY 1 (M1) DATA









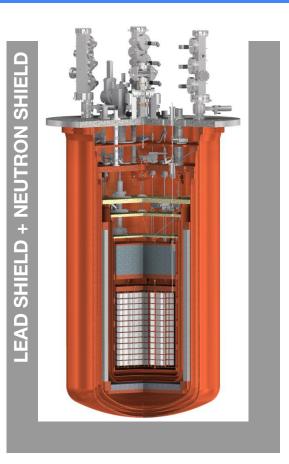
1. Data 🗸

2. Monte Carlo simulations





The MC templates describe combinations of contaminants and detector components





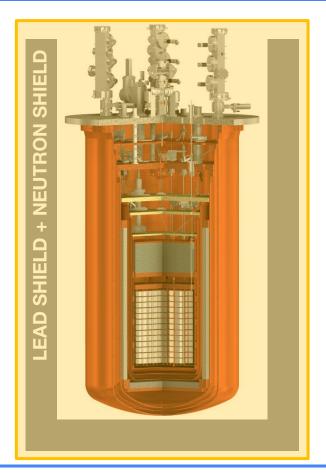


MC templates

The MC templates describe combinations of contaminants and detector components

Bulk contaminations:

- Main decay chains: ²³²Th, ²³⁸U, ²³⁵U
- Ubiquitous contaminants: ⁴⁰K, ⁶⁰Co
- Fallout: ¹³⁷Cs, ⁹⁰Sr, ²⁰⁷Bi
- Activation: ¹²⁵Sb, ⁵⁴Mn, ^{110m}Ag, ^{108m}Ag
- Others: ¹⁴⁷Sm, ¹⁹⁰Pt (crystal growing)







MC templates

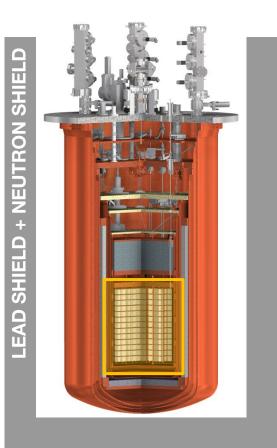
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Surface contaminations:

- Simulation at different depths
- Assumed exponential profile







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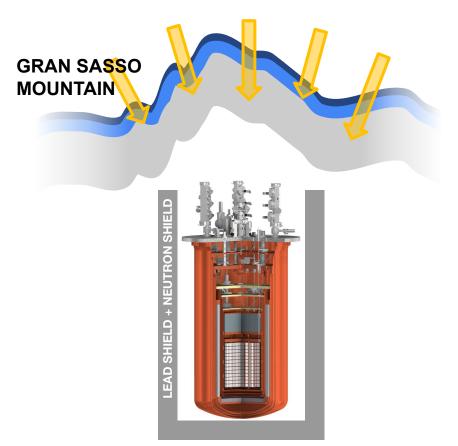
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Surface contaminations:

- Simulation at different depths
- Assumed exponential profile

Muons:

- MACRO flux distribution
- Gran Sasso overburden map







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







1. Data 🗸

2. Monte Carlo simulations

Fit model





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:
$$\langle C_{i,\alpha}^{\mathrm{meas}} \rangle = \sum_{j} N_{j} \langle C_{ij,\alpha}^{\mathrm{MC}} \rangle$$

C = number of counts

N = normalization factor

i = bin

 α = input energy spectrum

j = background component

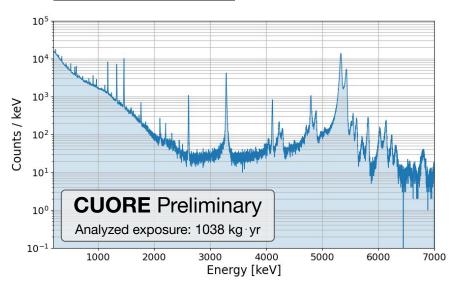
$$\textit{Likelihood:} \quad \mathcal{L} = \prod_{i,\alpha} \operatorname{Pois}(C_{i,\alpha}^{\operatorname{meas}} | \langle C_{i,\alpha}^{\operatorname{meas}} \rangle) \prod_{j} \operatorname{Pois}(C_{ij,\alpha}^{\operatorname{MC}} | \langle C_{ij,\alpha}^{\operatorname{MC}} \rangle)$$





MULTIPLICITY 1

1 SINGLE SPECTRUM

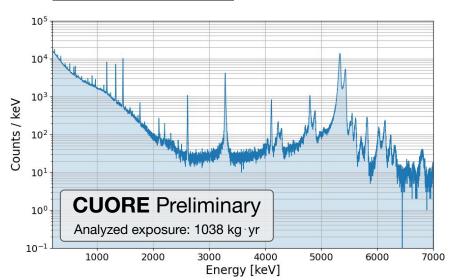






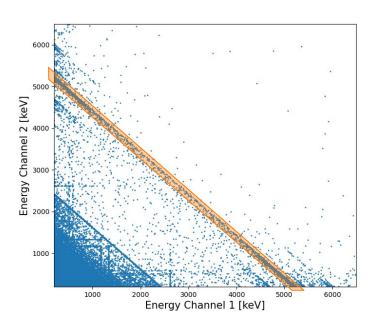
MULTIPLICITY 1

1 SINGLE SPECTRUM



MULTIPLICITY 2

27 DIFFERENT M2 BANDS

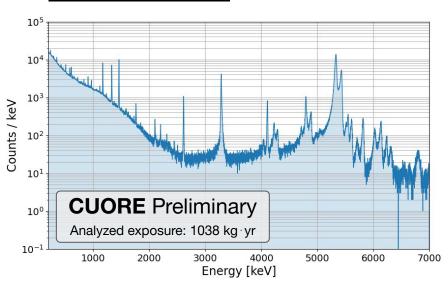




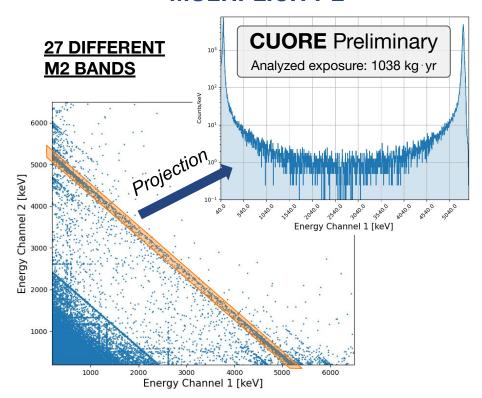


MULTIPLICITY 1

1 SINGLE SPECTRUM



MULTIPLICITY 2









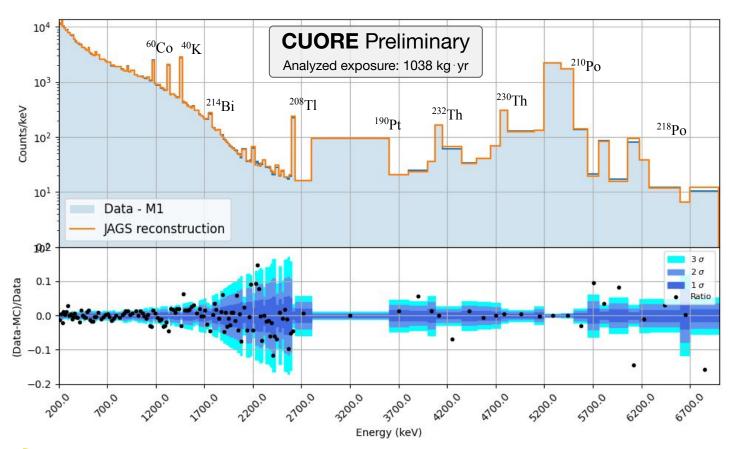
1. Data 🗸

2. Monte Carlo simulations

3. Fit model 🗸







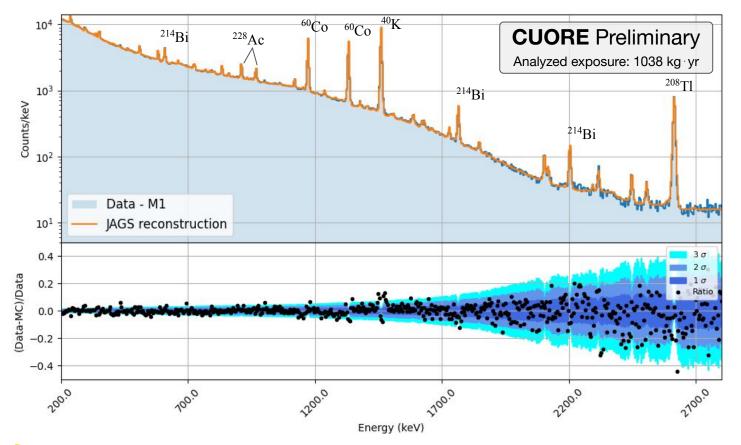
<u>Variable binning</u> to integrate lineshape limited knowledge

Good fit quality all over the energy spectrum





Visual check with thinner binning

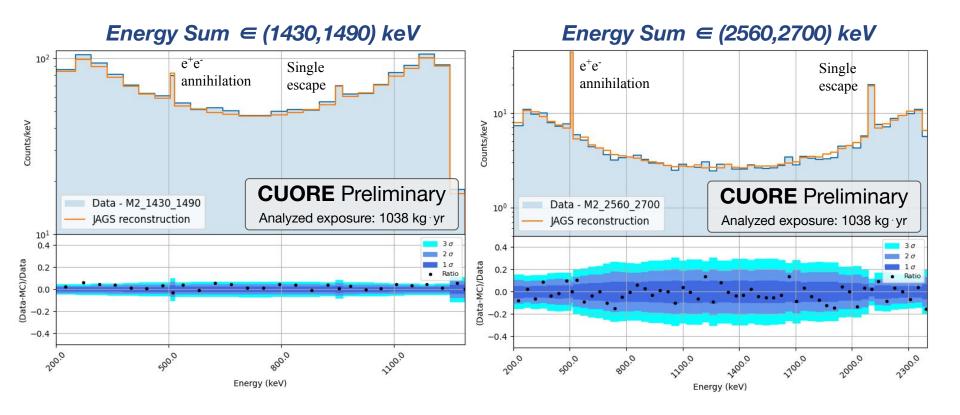


All the gamma spectrum features reconstructed

Ideal for precision studies in this region

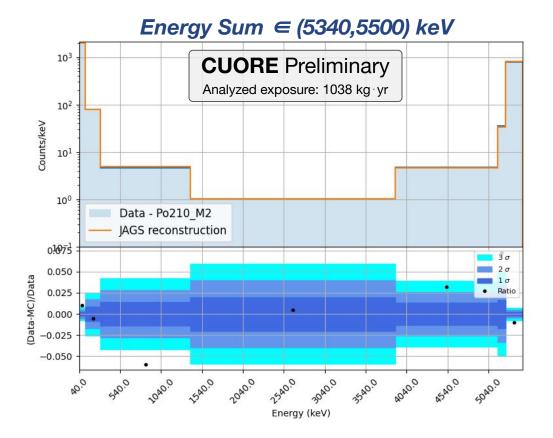
















Assumptions (possible source of systematics)

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







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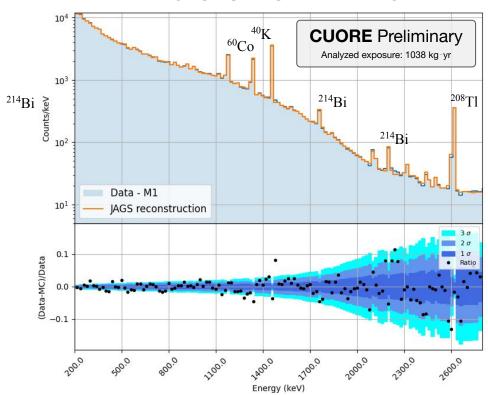
- Contaminations equal on all the crystals
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INCLUDED SYSTEMATICS

→ Binning

20 keV UNIFORM BINNING







Assumptions (possible source of systematics)

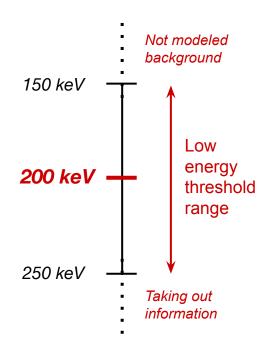
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INCLUDED SYSTEMATICS

- → Binning
- → Low Energy threshold

LOW ENERGY THRESHOLD







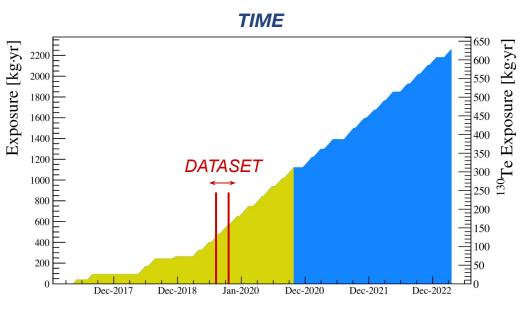
Assumptions (possible source of systematics)

- 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

INCLUDED SYSTEMATICS

- → Binning
- → Low Energy threshold
- \rightarrow Time







Assumptions (possible source of systematics)

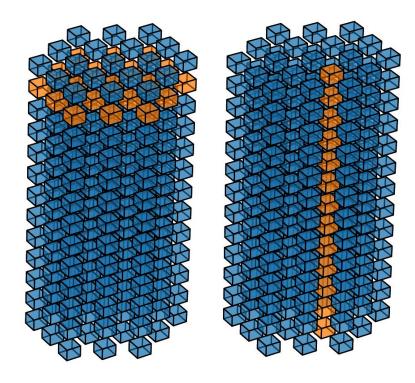
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INCLUDED SYSTEMATICS

- → Binning
- → Low Energy threshold
- \rightarrow Time
- → Geometry (Floors, Towers)

GEOMETRY





Assumptions (possible source of systematics)

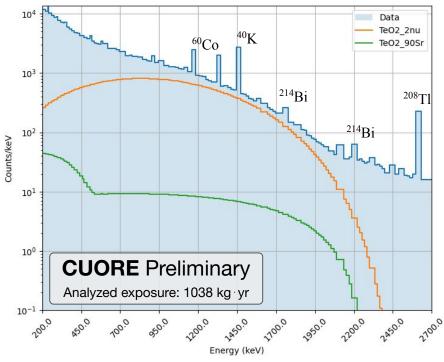
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INCLUDED SYSTEMATICS

- → Binning
- → Low Energy threshold
- \rightarrow Time
- → Geometry (Floors, Towers)
- → ⁹⁰Sr contamination

⁹⁰Sr CONTAMINATION



Please Note: Contribution from posterior average





Assumptions (possible source of systematics)

- Contaminations equal on all the crystals
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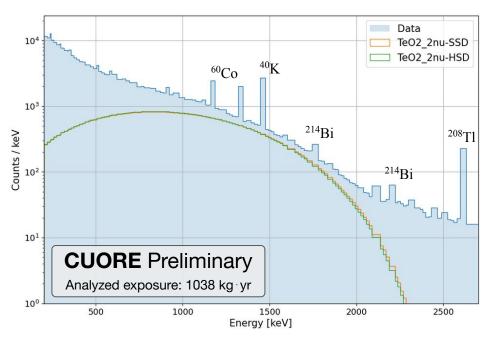


Repeat the fit to characterize and extract reliable systematic errors

INCLUDED SYSTEMATICS

- → Binning
- → Low Energy threshold
- \rightarrow Time
- → Geometry (Floors, Towers)
- → ⁹⁰Sr contamination
- \rightarrow Nuclear model (SSD vs HSD) (2 $\nu\beta\beta$ only)

NUCLEAR MODEL







Impacts

Experimental Setup characterization

Fit on the entire energy region

- Better constraints on contaminations
- Lower correlation between background components



Track time varying activities

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

Non uniformities

- Point-like or localized sources
- Recontaminations





Experimental Setup characterization

Fit on the entire energy region

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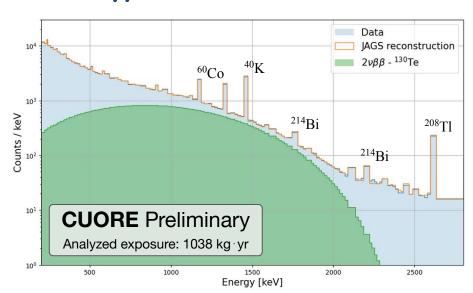
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$2\nu\beta\beta$ half-life measurement



BLINDED HALF-LIFE:

 $2\nu\beta\beta$ systematic uncertainties under finalization

outcome in the form of arbitrary normalization factors





Conclusions and Perspectives

RESULT

- Model of the background defined → stable and reliable fit
- ☐ Good reconstruction in both M1 and M2 multiplicities

WHAT WE CAN DO NOW

- Contamination activities
 - Contamination studies and experimental setup characterization
- \square 2 $\nu\beta\beta$ half-life
 - Half-life measurement
 - Shape studies (SSD, HSD, improved model, exotic physics)

Access to new double beta

decays

- > 128Te first fit (limit)
- → ¹²⁰Te enhanced studies
- Higher multiplicities analyses

HOW TO IMPROVE

- Systematics-limited → ongoing studies on non-uniformities, detector fiducialization, ...
- Going to *lower energies* → lot of interesting physics there
- ☐ Including parallel study on *delayed coincidences*





















SAN LUIS OBISPO



Thanks for the attention!

















Massachusetts Institute of Technology





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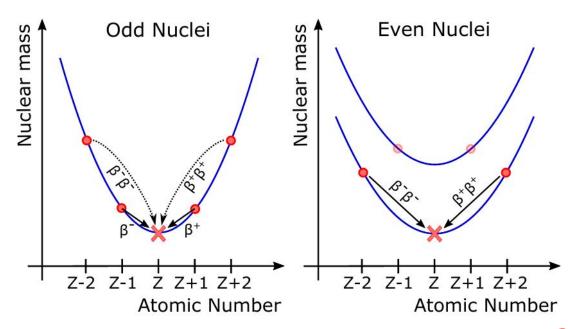
BACKUP SLIDES

Double Beta Decay $(2\nu\beta\beta)$

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

 $\beta^+\beta^+$ $(A,Z) \longrightarrow (A,Z-2) + 2e^+ + 2\nu_e$

- 2nd order SM process
- Only even mass number nuclei (i.e. ⁷⁶Ge, ⁸²Se, ¹⁰⁰Mo, ¹²⁸Te, ¹³⁰Te, ¹³⁶Xe)
- \Box Half-lives in the order of 10^{18} - 10^{21} yr
- Precision measurements of the spectral shape → tests of the nuclear models



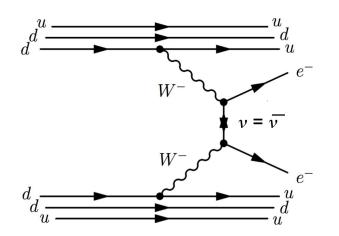




Neutrinoless Double Beta Decay $(0\nu\beta\beta)$

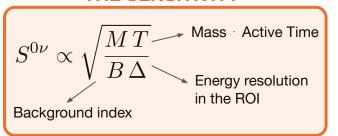
WHY IT'S IMPORTANT

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

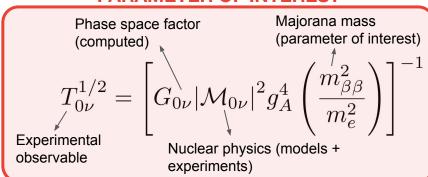


THE ENERGY SPECTRUM $\begin{array}{c|c} \hline (E_{e1} + E_{e2})/Q & 1 \end{array}$

THE SENSITIVITY



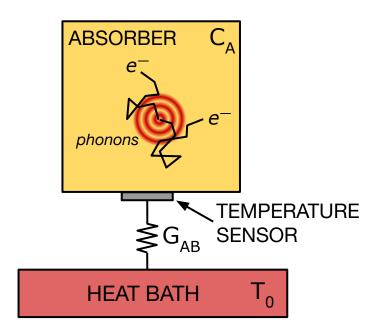
PARAMETER OF INTEREST



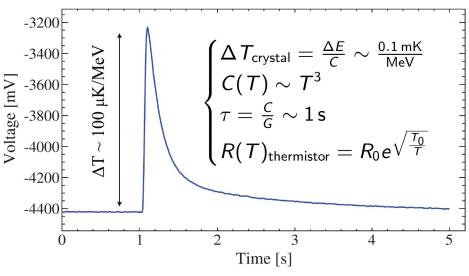




Source ≡ Detector High efficiency



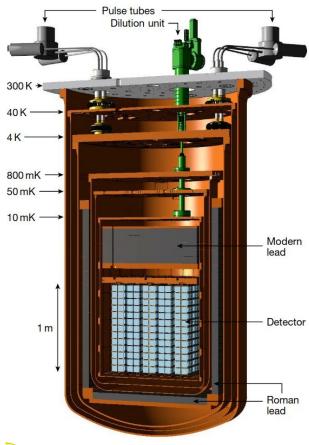
SAMPLE PULSE



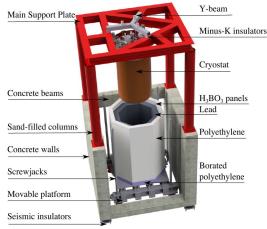


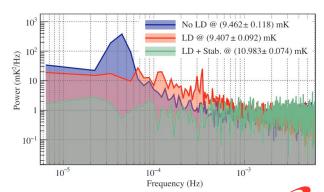


The CUORE infrastructure



- Dilution refrigerator with 4μW @ 10 mK cooling power
 - <u>Cryogenics 102 (2019) 9-21</u>
- Radiopurity and mechanical stability constraints
- <u>External decoupling system</u> for vibration isolation
- Pulse Tubes <u>noise active</u>
 <u>cancellation</u> system + linear drives
 - <u>Cryogenics 93, 55-56 (2018)</u>

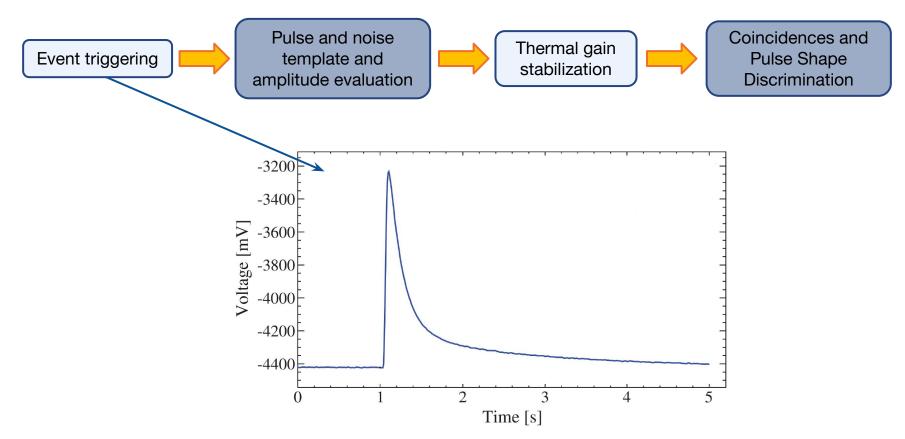








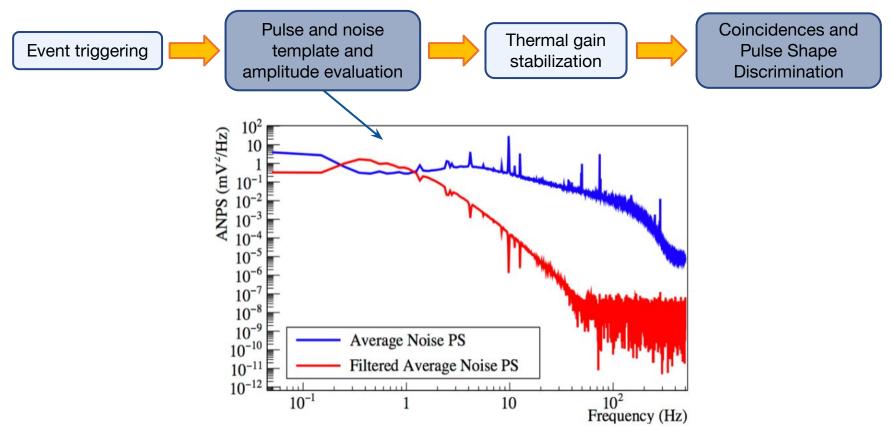
Analysis chain







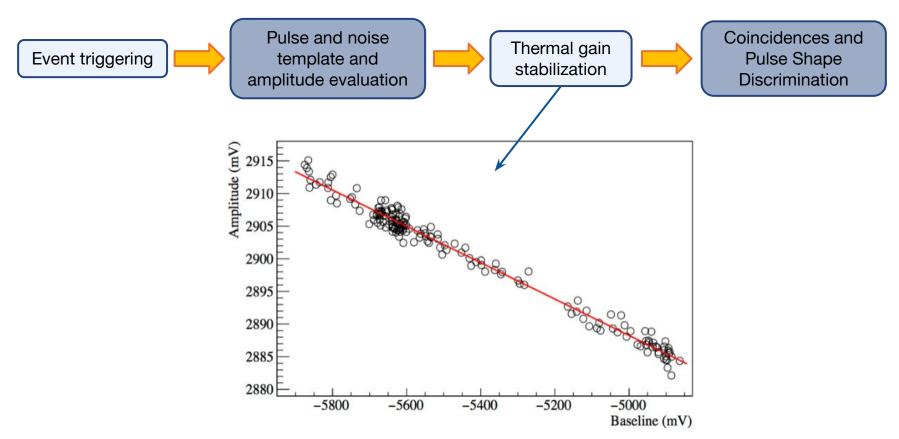






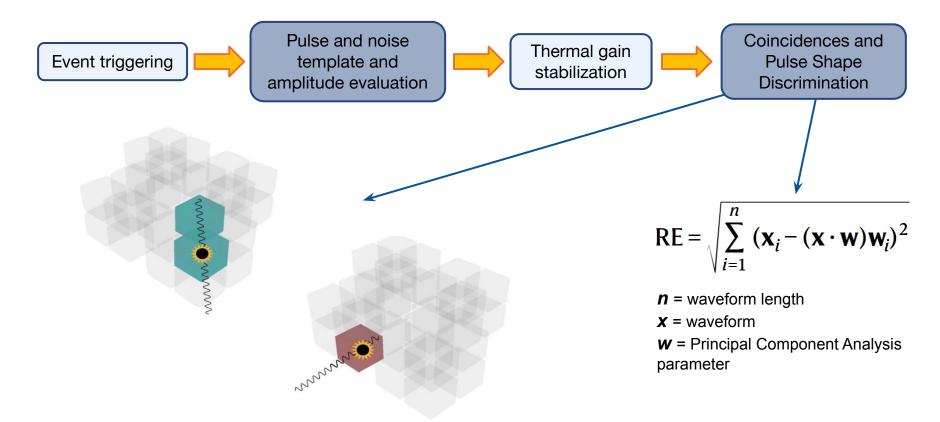


Analysis chain













Data binning

E region [keV]	Tag	Bin size [keV] (*)
200 - 2700	γ region	15 (**)
2700 - 7000	α region	40

- (*) A minimum number of 50 events is required in the bin, otherwise merge
- (**) Around characteristic γ lines the bin size is fixed to $5\sigma(E)$ (energy resolution at the energy of the peak) to avoid lineshape-related complications

MULTIPLICITY 1 LINES

MULTIPLICITY 2 LINES

Energy [keV]	Isotope	Energy [keV]	Isotope	Energy [keV]	Isotope	Energy [keV]	Isotope	Energy [keV]	Isotope
238.6	²¹² Pb	768.4	$^{214}\mathrm{Bi}$	1377.7	$^{214}\mathrm{Bi}$	328	$^{228}\mathrm{Ac}$	821.5	⁶⁰ Co (SE)
295.2	²¹⁴ Pb	794.9	^{228}Ac	1460.5	$^{40}\mathrm{K}$	351.9	$^{214}\mathrm{Pb}$	835.7	$^{228}\mathrm{Ac}$
338.3	²²⁸ Ac	803	²¹⁰ Po	1588.2	²²⁸ Ac	409.5	$^{228}\mathrm{Ac}$	911.2	$^{228}\mathrm{Ac}$
351.9	²¹⁴ Pb	834.8	$^{54}\mathrm{Mn}$	1620.5	$^{212}\mathrm{Bi}$	427.9	$^{125}\mathrm{Sb}$	950	40 K (SE)
427.8	$^{125}\mathrm{Sb}$	860.6	²⁰⁸ Tl	1630.6	^{228}Ac	434.2	$^{108\mathrm{m}}\mathrm{Ag}$	969	$^{228}\mathrm{Ac}$
433.9	$^{108\mathrm{m}}\mathrm{Ag}$	911.2	²²⁸ Ac	1729.6	$^{214}\mathrm{Bi}$	511	e+e- annihilation	1120.3	$^{214}\mathrm{Bi}$
463	$^{228}\mathrm{Ac}$	934.1	²¹⁴ Bi	1764.5	$^{214}\mathrm{Bi}$	583.2	²⁰⁸ Tl	1173.2	$^{60}\mathrm{Co}$
511	e+e- annihilation	964	$^{228}\mathrm{Ac}$	1847.4	$^{214}\mathrm{Bi}$	609.3	$^{214}\mathrm{Bi}$	1332.5	⁶⁰ Co
583.2	²⁰⁸ Tl	969	²²⁸ Ac	2103.5	208 Tl (SE)	722.9	$^{110\mathrm{m}}\mathrm{Ag}$	1592.5	²⁰⁸ Tl (DE)
609.3	$^{214}\mathrm{Bi}$	1001	^{234m} Pa	2118.5	$^{214}\mathrm{Bi}$	768.4	²¹⁴ Bi	1764.5	²¹⁴ Bi
614.3	$^{108\mathrm{m}}\mathrm{Ag}$	1063.6	$^{207}\mathrm{Bi}$	2204.1	$^{214}\mathrm{Bi}$	794.9	^{228}Ac	2103.5	²⁰⁸ Tl (SE)
657.7	$^{110\mathrm{m}}\mathrm{Ag}$	1120.3	²¹⁴ Bi	2316.5	$^{147}\mathrm{Sm}$	194.9	Ac	2105.5	11 (512)
665.4	$^{214}\mathrm{Bi}$	1173.2	⁶⁰ Co	2447.9	$^{214}\mathrm{Bi}$				
722.9	$^{108\mathrm{m}}\mathrm{Ag}$	1238.1	$^{214}\mathrm{Bi}$	2505.6	⁶⁰ Co				
727.3	$^{212}\mathrm{Bi}$	1332.5	⁶⁰ Co	2614.5	²⁰⁸ Tl				





Complete MC list

BULK CONTAMINATIONS

Component	Contaminant	Component	Contaminant
Crystals	$^{110m}\mathrm{Ag}$	CuNOSV no TSP	⁴⁰ K
	$^{125}\mathrm{Sb}$	TSP	$^{40}\mathrm{K}$
	$^{147}\mathrm{Sm}$	600mK	²³² Th
	¹⁹⁰ Pt		²³⁸ U
	$^{210}\mathrm{Pb}$		$^{40}\mathrm{K}$
	226 Ra $-^{210}$ Pb		⁶⁰ Co
	$^{228}{ m Ra}-^{208}{ m Pb}$	4K	²³² Th
	²³⁰ Th only	5-004-000	²³⁸ U
	231 Pa $-^{207}$ Pb		$^{40}\mathrm{K}$
	²³² Th only		⁶⁰ Co
	$^{235}U - ^{231}Pa$	Roman Lead	$^{108m}\mathrm{Ag}$
	$^{238}{ m U}$ $-^{230}$ Th		²³² Th
	$^{130}\text{Te} - 2\nu\beta\beta$		238U
	$^{40}\mathrm{K}$	External Lead	²⁰⁷ Bi
	⁶⁰ Co	_	²¹⁰ Bi
CuNOSV	$^{137}\mathrm{Cs}$	Top Lead	$^{210}{ m Bi} - 206Pb$
	²³² Th		²³² Th
	²³⁸ U		238U
	$^{54}\mathrm{Mn}$	Muons	
	⁶⁰ Co	Muons	

SURFACE CONTAMINATIONS

Component	Contaminant	Component	Contaminant
Crystals	$\begin{array}{c} 210 \mathrm{Pb} - 0.001 \mu \mathrm{m} \\ 226 \mathrm{Ra} - ^{210} \mathrm{Pb} - 0.01 \mu \mathrm{m} \\ 228 \mathrm{Ra} - ^{208} \mathrm{Pb} - 0.01 \mu \mathrm{m} \\ 230 \mathrm{Th} \ \mathrm{only} - 0.01 \mu \mathrm{m} \\ 235 \mathrm{U} - ^{207} \mathrm{Pa} - 0.01 \mu \mathrm{m} \\ 232 \mathrm{Th} \ \mathrm{only} - 0.01 \mu \mathrm{m} \\ 235 \mathrm{U} - ^{207} \mathrm{Pa} - 0.01 \mu \mathrm{m} \\ 235 \mathrm{U} - ^{207} \mathrm{Pa} - 0.01 \mu \mathrm{m} \\ 238 \mathrm{U} - ^{200} \mathrm{Th} - 0.01 \mu \mathrm{m} \\ 210 \mathrm{Pb} - 0.1 \mu \mathrm{m} \\ 226 \mathrm{Ra} - ^{210} \mathrm{Pb} - 0.1 \mu \mathrm{m} \\ 228 \mathrm{Ra} - ^{208} \mathrm{Pb} - 0.1 \mu \mathrm{m} \\ 230 \mathrm{Th} \ \mathrm{only} - 0.1 \mu \mathrm{m} \\ \end{array}$	CuNOSV	$\begin{array}{c} 2^{10} \mathrm{Pb} - 1 \mu \mathrm{m} \\ 2^{26} \mathrm{Ra} - 2^{10} \mathrm{Pb} - 1 \mu \mathrm{m} \\ 2^{28} \mathrm{Ra} - 2^{208} \mathrm{Pb} - 1 \mu \mathrm{m} \\ 2^{28} \mathrm{Ra} - 2^{208} \mathrm{Pb} - 1 \mu \mathrm{m} \\ 2^{30} \mathrm{Th} \mathrm{only} - 1 \mu \mathrm{m} \\ 2^{32} \mathrm{Th} \mathrm{only} - 1 \mu \mathrm{m} \\ 2^{32} \mathrm{Th} \mathrm{only} - 1 \mu \mathrm{m} \\ 2^{38} \mathrm{U} - 2^{30} \mathrm{Th} - 1 \mu \mathrm{m} \\ 2^{10} \mathrm{Pb} - 0.01 \mu \mathrm{m} \\ 2^{31} \mathrm{Pa} - 2^{07} \mathrm{Pb} - 0.01 \mu \mathrm{m} \\ 2^{32} \mathrm{Th} - 0.01 \mu \mathrm{m} \\ 2^{35} \mathrm{U} - 2^{31} \mathrm{Pa} - 0.01 \mu \mathrm{m} \\ 2^{38} \mathrm{U} - 0.01 \mu \mathrm{m} \\ 2^{10} \mathrm{Pb} - 0.1 \mu \mathrm{m} \\ 2^{10} \mathrm{Pb} - 10 \mu \mathrm{m} \end{array}$
	$^{232} Th \ only - 0.1 \mu m$ $^{238} U - ^{230} Th - 0.1 \mu m$ $^{210} Pb - 10 \mu m$ $^{226} Ra - ^{210} Pb - 10 \mu m$ $^{228} Ra - ^{208} Pb - 10 \mu m$ $^{230} Th \ only - 10 \mu m$ $^{232} Th \ only - 10 \mu m$ $^{232} Th \ only - 10 \mu m$ $^{238} U - ^{230} Th - 10 \mu m$	50mK 10mK	$^{232} Th - 10 \mu m$ $^{238} U - 10 \mu m$ $^{210} Pb - 1 \mu m$ $^{210} Bi - 0 \mu m$ $^{210} Pb - 0.01 \mu m$ $^{231} Pa - ^{207} Pb - 0.01 \mu m$ $^{232} Th - 0.01 \mu m$ $^{235} U - ^{231} Pa - 0.01 \mu m$ $^{238} U - 0.01 \mu m$

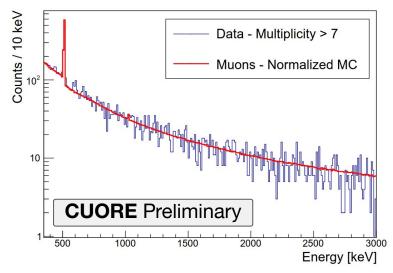




The prior distributions summarize the *a priori* knowledge we have about a certain background components.

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)



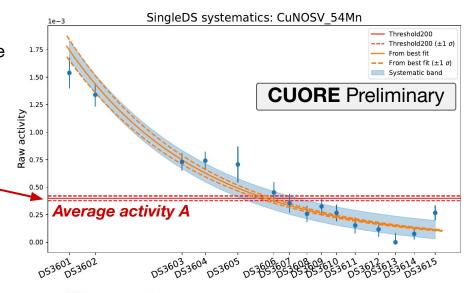


Time varying activities

Few CUORE contaminations (60Co, 125Sb, 210Pb, 54Mn) have an half-life comparable with the experiment live-time

$$A = rac{\sum_{DS} c_{DS}}{\sum_{DS} E_{DS}}$$
 Average activity all along the datasets

$$\tilde{A}(t) = \tilde{A_0}e^{-t/\tau}$$
 Time dependence of the activity (whose average is A)



Initial Activity
$$\tilde{A_0} = \frac{AE_{tot}}{\tau \sum_{DS} \left[e^{-\frac{T_{i,DS}}{\tau}} - e^{-\frac{T_{f,DS}}{\tau}} \right]}$$





CUORE shieldings

EXTERNAL SHIELDING

- ☐ Gran Sasso mountain, 3600 m.w.e
- Lead shield: > 25 cm thick
- Neutrons shield: 18 cm PE + 2 cm H₃BO₃ 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

