# New results from the CUORE experiment

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on behalf of the CUORE collaboration

*58th Rencontres de Moriond 2024*
*Electroweak Interactions & Unified Theories*

*24 - 31 March 2024*

# Elusive neutrinos

*Neutrinos are the lightest known elementary fermions*.

Open questions:

- How the neutrino mass eigenstates are ordered (normal/inverted hierarchy) ?
- Which are the neutrino mass absolute values?
- Why the neutrino mass is so small wrt to the other SM particles?
- The neutrinos - neutral leptons - are Dirac or Majorana particles?

**Experimental searches**

- Neutrino flavour oscillations
- Sterile neutrino searches
- Sum of neutrino masses
- Direct neutrino mass measurement
- **Majorana nature of neutrino**

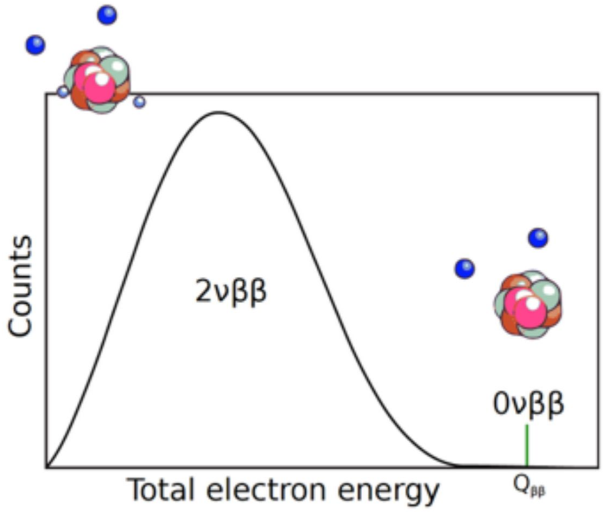
Neutrinoless double beta decay (0νββ)

# Searching for 0νββ decay

- Beyond Standard Model process (ΔL = 2)

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

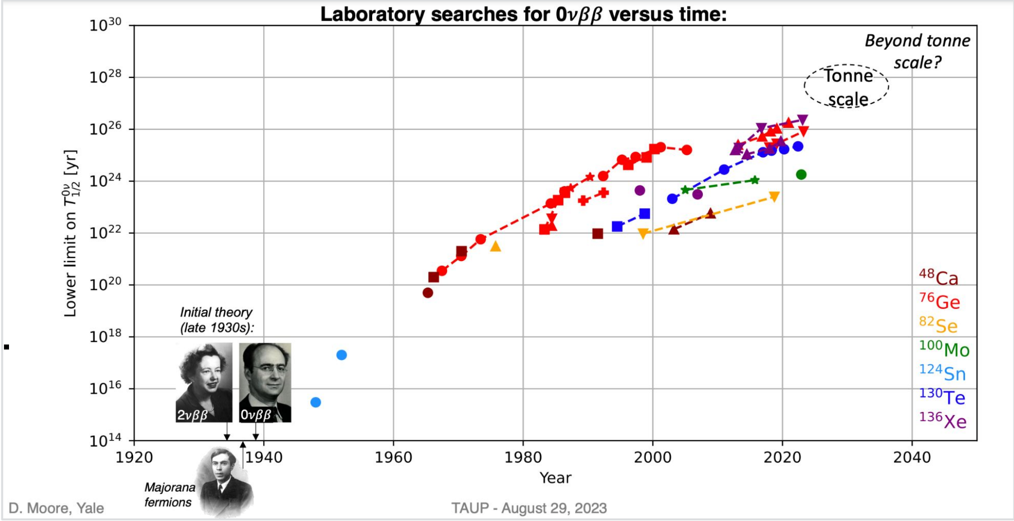
- Not yet observed: $T^{1/2}_{0\nu\beta\beta} > 10^{22\text{-}26}$ yr



**Impacts of a potential observation of 0νββ decay**:
- Existence of Lepton Number violating processes
- Presence of a Majorana term for the neutrino mass, $m_{\beta\beta}$

→ Constraints on neutrino mass hierarchy and scale
→ Hint on origin of matter/anti-matter asymmetry (baryogenesis via leptogenesis involving Majorana neutrinos)

**Broad experimental program** to search for 0νββ decay with different isotopes: $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{116}$Cd, $^{130}$Te, $^{136}$Xe ...



ββ decay review - D.Moore (TAUP2023)

# The CUORE experiment

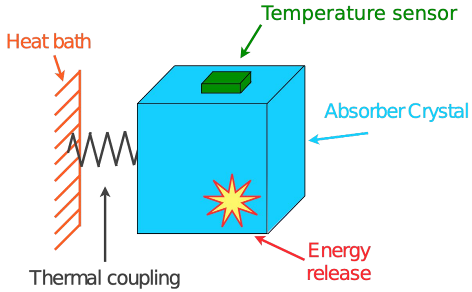
**Cryogenic Underground Observatory for Rare Events**

Cryogenic experiment at tonne-scale,
utilising $^{(nat)}TeO_2$ thermal detectors operated at ~10 mK
Located at Laboratori Nazionali del Gran Sasso (Italy)

Search for rare events and for physics beyond the Standard Model

**Search for 0νββ decay of $^{130}$Te** ($Q_{\beta\beta}$ = 2527.51 keV)

Why thermal detectors for 0νββ search



- $E_{dep}$ converted into ΔT (phonons)
- Detector = ββ source
- Large calorimeters (~kg scale)
  - Sensitive **from keV to MeV** scale
  - Optimal **energy resolution 0.1%**@MeV

Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902, https://doi.org/10.1016/j.ppnp.2021.103902

# The CUORE challenge

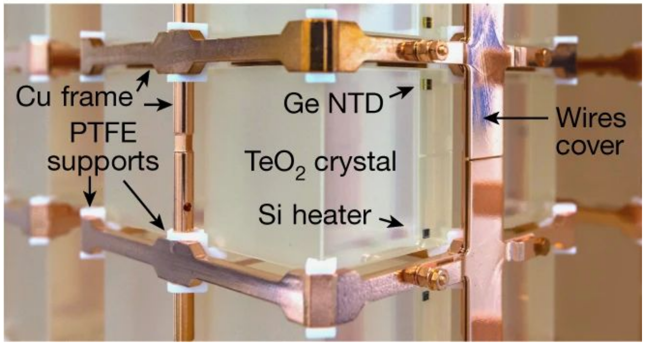
**Low temperature and low vibrations**

988 $TeO_2$ detectors operated as calorimeters at ~10 mK stable over time

- Multistage cryogen-free cryostat
- Mechanical vibration isolation: passive and active systems

**Low background**

- Deep underground location
- Strict radio-purity controls on materials and assembly
- Passive shields from external and cryostat radioactivity
- Detector: high granularity and self-shielding

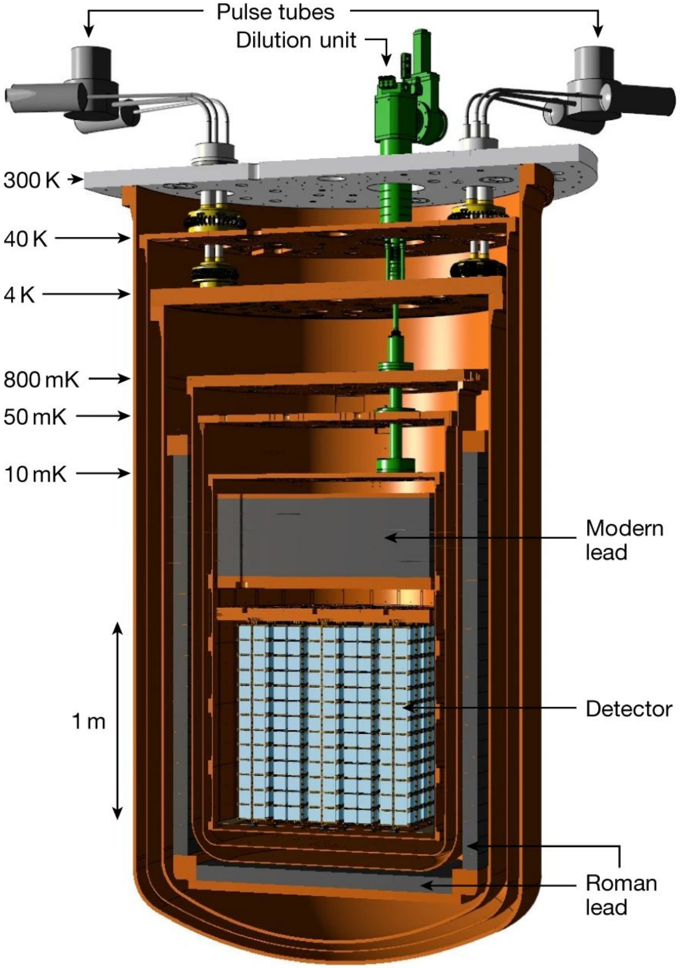


@10 mK

$\Delta T_{crystal}$ ~ 100 μK/MeV

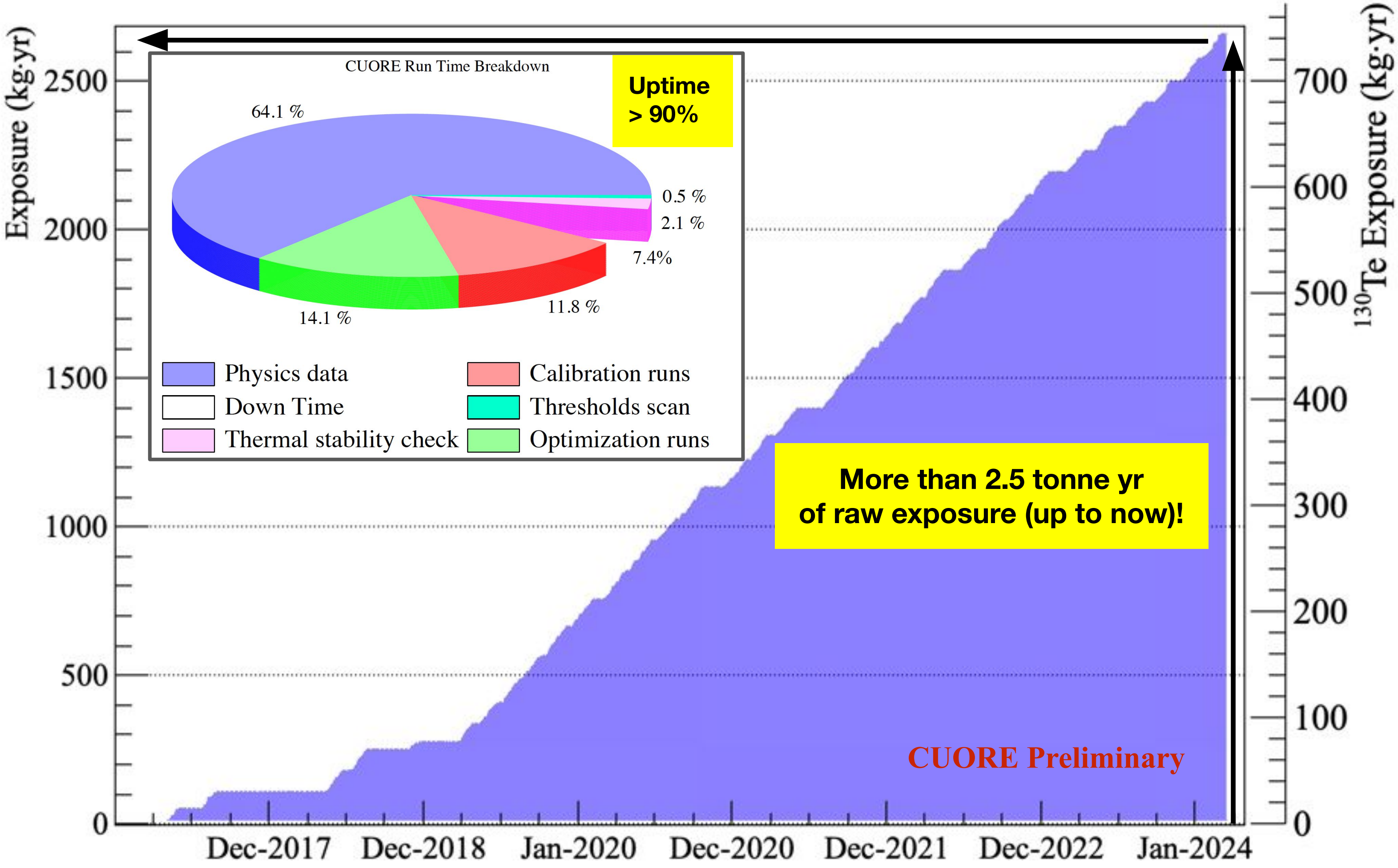
$\Delta V_{NTD}$ ~ 400 μV/MeV

Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902, https://doi.org/10.1016/j.ppnp.2021.103902



Dell'Oro S. et al., Cryogenics 102, 9, (2019) https://doi.org/10.1016/j.cryogenics.2019.06.011

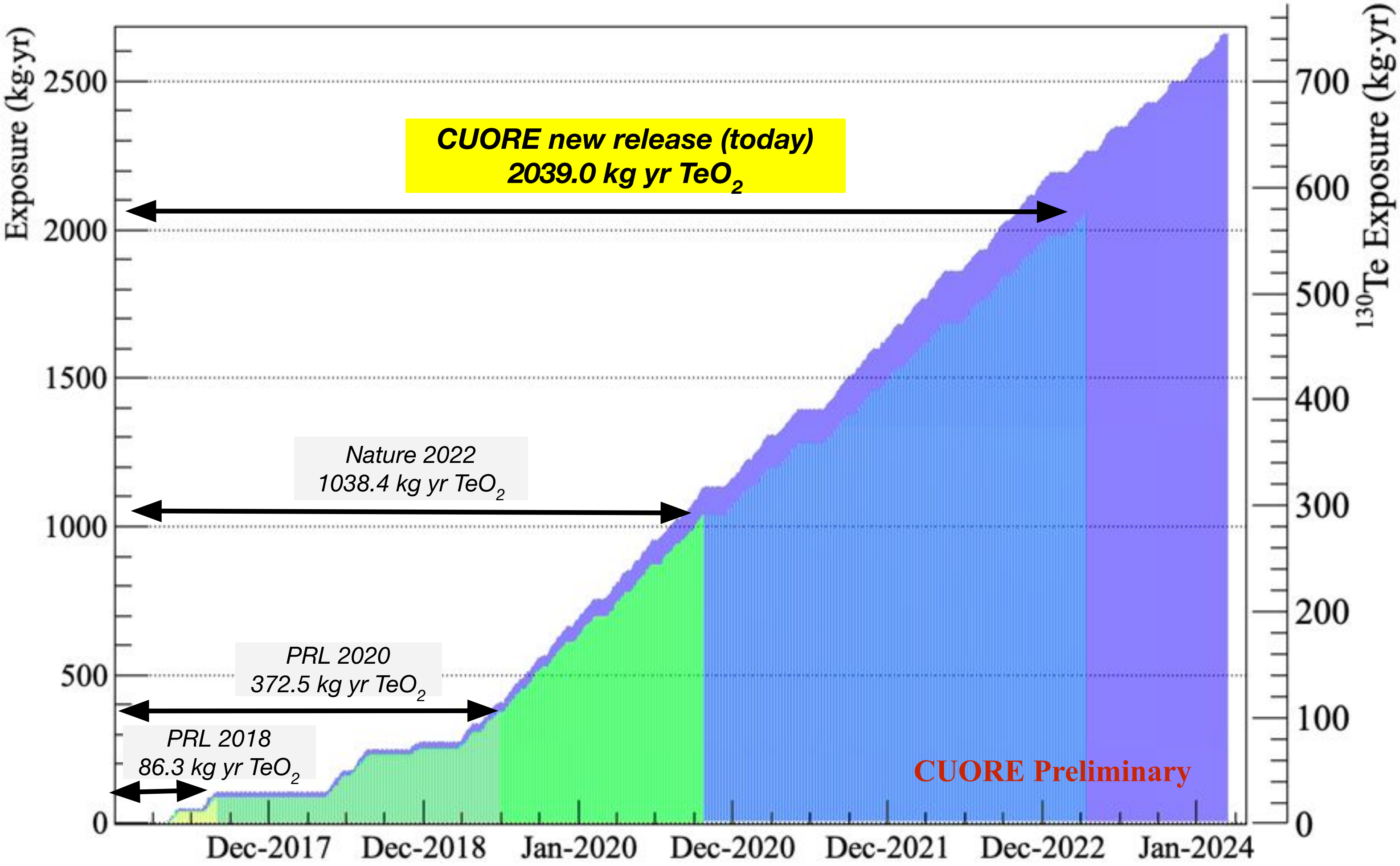
# CUORE: data-taking



**Uptime > 90%**

**More than 2.5 tonne yr of raw exposure (up to now)!**

# CUORE: new data release



***CUORE new release (today)***
***2039.0 kg yr $TeO_2$***

*Nature 2022*
*1038.4 kg yr $TeO_2$*

*PRL 2020*
*372.5 kg yr $TeO_2$*

*PRL 2018*
*86.3 kg yr $TeO_2$*

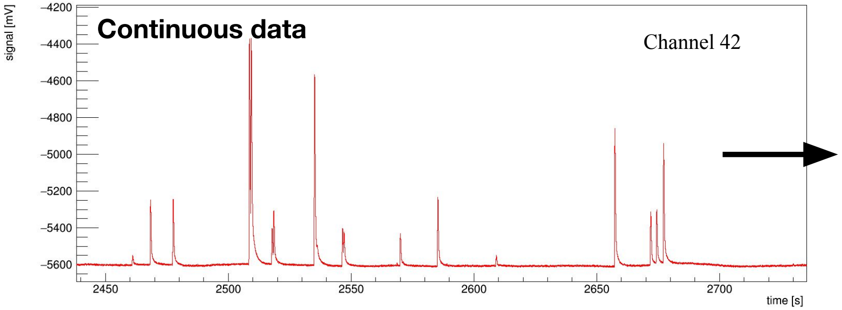
Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 120, 132501, (2018), https://doi.org/10.1103/PhysRevLett.120.132501

Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 124, 122501, (2020), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501

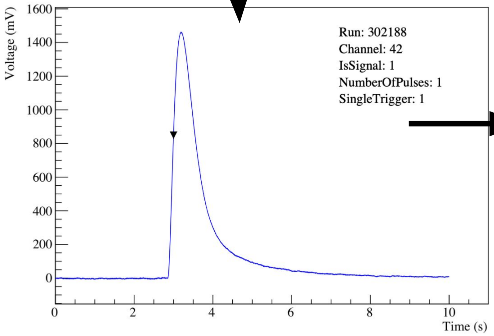
Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

# CUORE data production chain

**From single detectors waveform data stream**



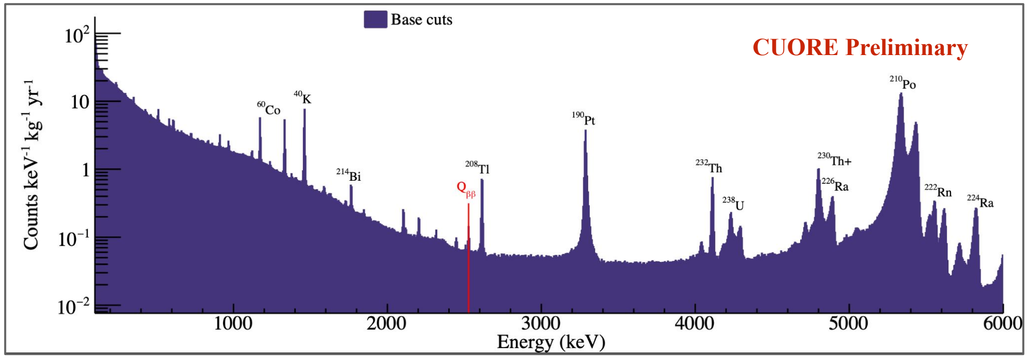
Denoising → Optimum trigger



**Event: physics pulse**

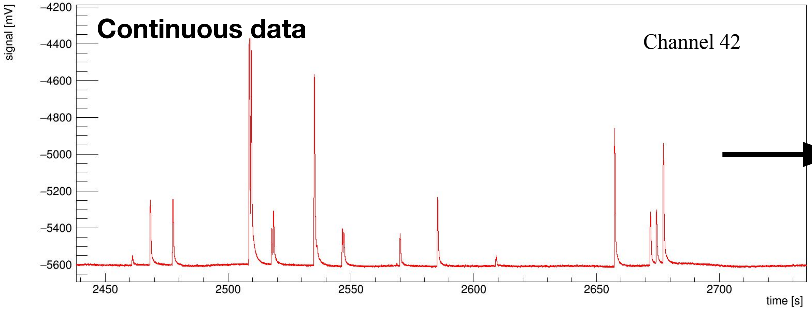
Optimum Filter → Gain Correction → Energy Calibration → Coincidences → PCA

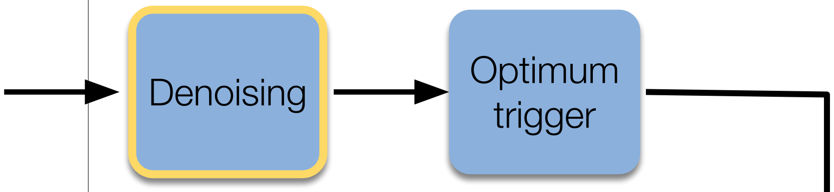
**To a cumulative energy spectrum**



# CUORE data production chain

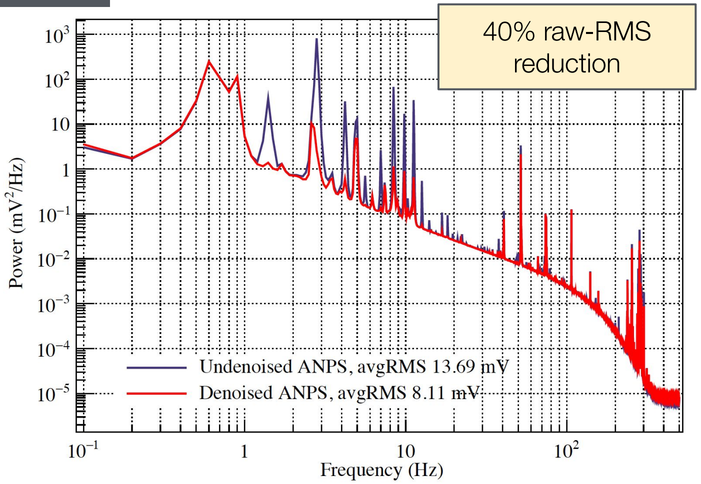
**From single detectors waveform data stream**





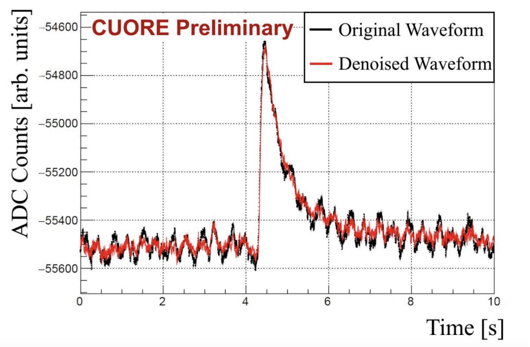
**New of this data release**

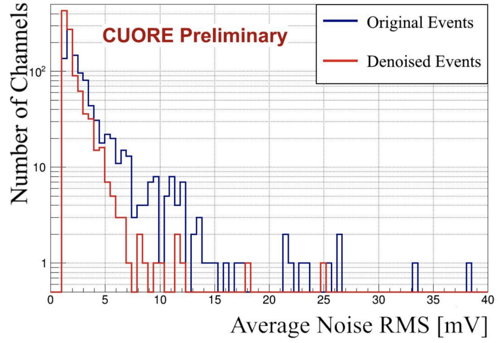
**Denoising the continuous data**
Installed diagnostic devices (seismometers, accelerometers, antennae, microphones): identify and measure noise sources in different frequency intervals. Remove noise from calorimeter channels using both the correlated noise between the different aux-devs and the correlated noise between each aux-dev and each detector



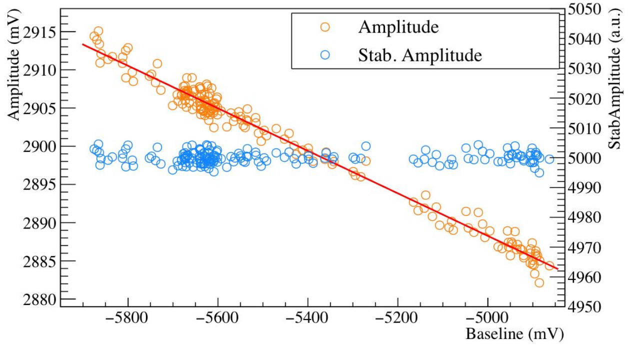
40% raw-RMS reduction

Vetter, K.J., Beretta, M., Capelli, C. *et al.*, *Eur. Phys. J. C* 84, 243 (2024). https://doi.org/10.1140/epjc/s10052-024-12595-y



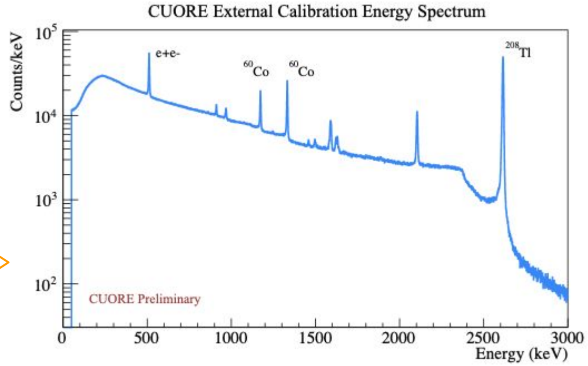


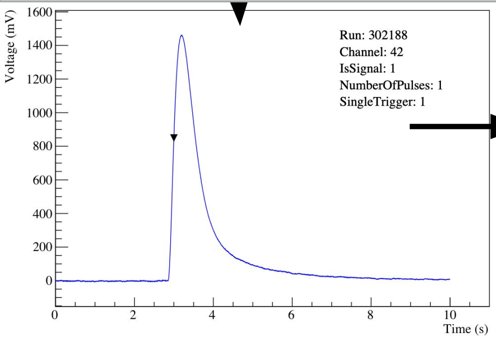
# CUORE data production chain



Thermal gain stabilization using fixed energy pulses to improve resolution

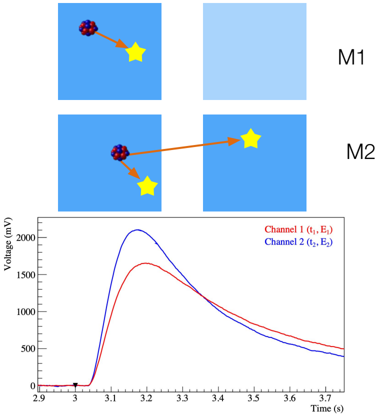
External calibration system:
$^{232}$Th+$^{60}$Co sources
from 511 keV to 2615 keV
Pulse amplitude to energy conversion



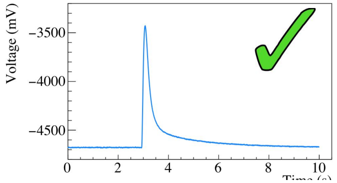


**Event: physics pulse**

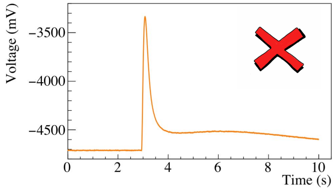
Optimum Filter → Gain Correction → Energy Calibration → Coincidences → PCA



Identify events at different multiplicities utilizing the detector granularity



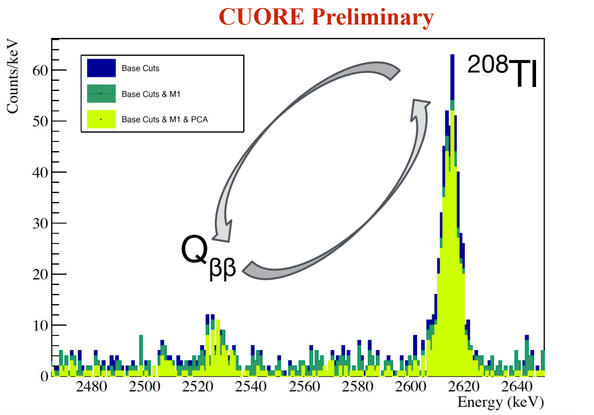
Reject non-physical and spurious pulses with PCA

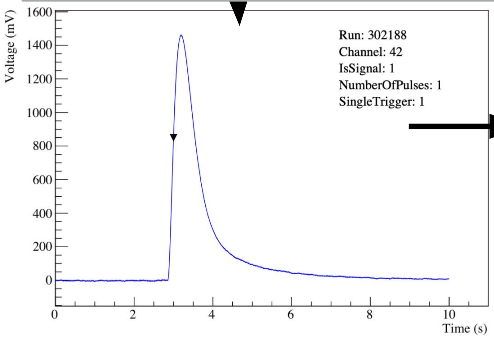


# CUORE data production chain

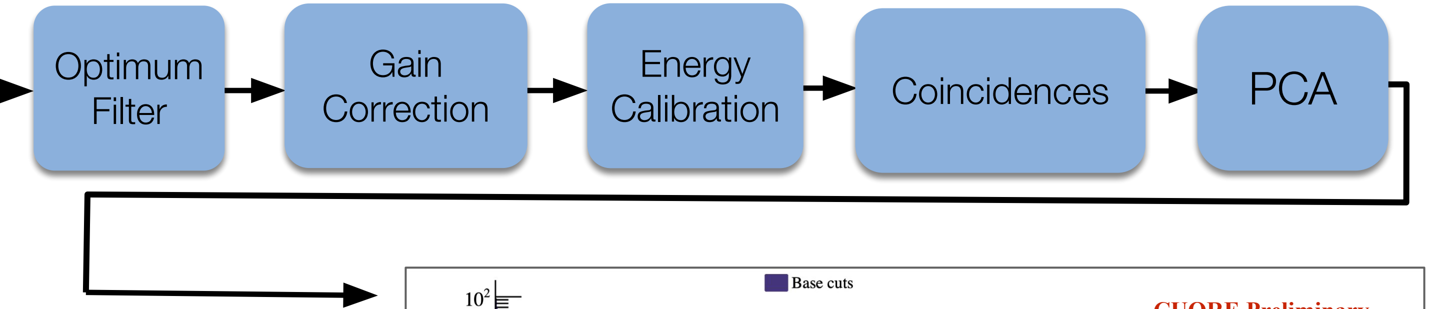
**Blinding the data**

- Blind the data at $Q_{\beta\beta}$ before finalizing data quality cuts
- Salting technique: move ~10% events from +/- 20 keV of 2615 keV to the $Q_{\beta\beta}$ and viceversa → produces an artificial peak around $Q_{\beta\beta}$
- When all data analysis procedures are fixed the data are eventually unblinded



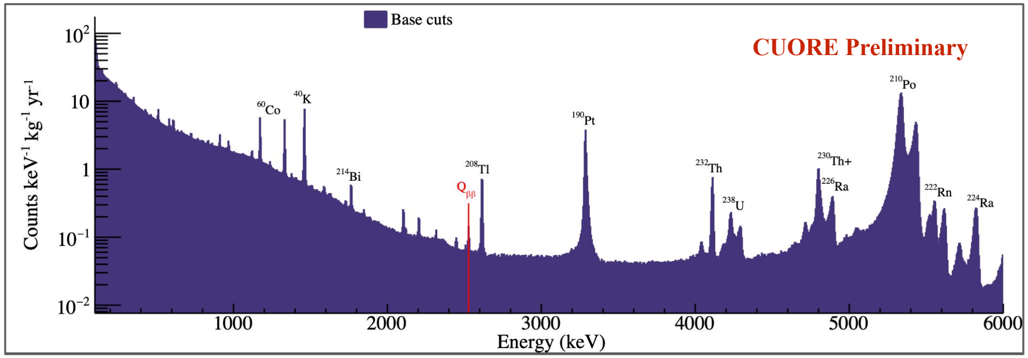


**Event: physics pulse**



Optimum Filter → Gain Correction → Energy Calibration → Coincidences → PCA

**To a cumulative energy spectrum**



Blinded physics spectrum (all channels)

# CUORE performance

**CUORE 2 TonneYr release (this result)**

28 datasets analyzed: from May 2017 to April 2023

Number of detectors surviving the data production chain: ~914 (avg) per dataset

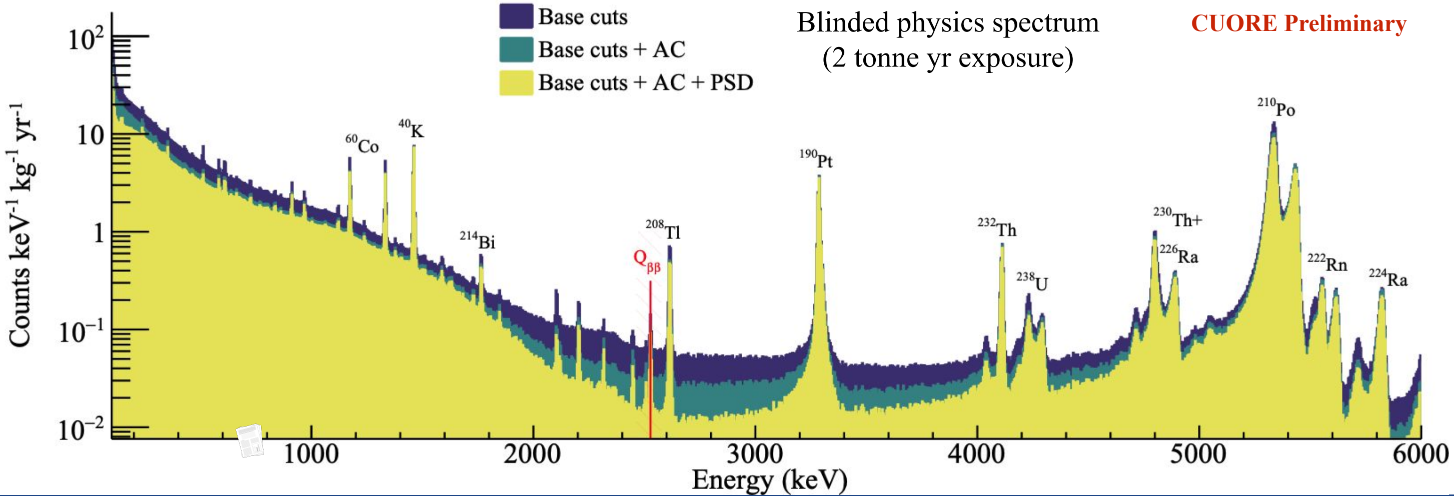
**Total exposure for 0νββ decay search**
2039.0 kg yr $TeO_2$,
567.0 kg yr $^{130}Te$

**Quality cuts**: identify single site events corresponding to single particle-like pulses

- BaseCuts: $\varepsilon_{BC}$ = 95.624(2) %
- Anti-coincidence (M1): $\varepsilon_{AC}$ = 99.80(5) %
- PCA: $\varepsilon_{PCA}$= 97.9(2) %

Total efficiency
93.4(2)%

**Choose M1 events for main 0νββ search**:
From MC study, ~88% of 0νββ decay events are contained in a single crystal



# CUORE performance

**Peak lineshape**

Reference $^{208}$Tl gamma peak at 2615 keV from calibration data

→ Sufficient statistics to fit the detector response in an energy region close to $Q_{\beta\beta}$

Fit model:

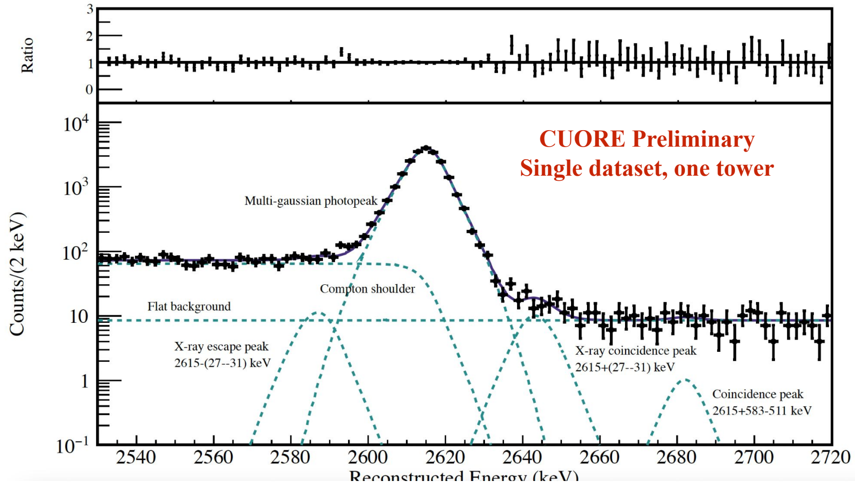
- Multi-Gaussian response function
- Multi-compton background
- Flat background
- Coincidence/escape peaks

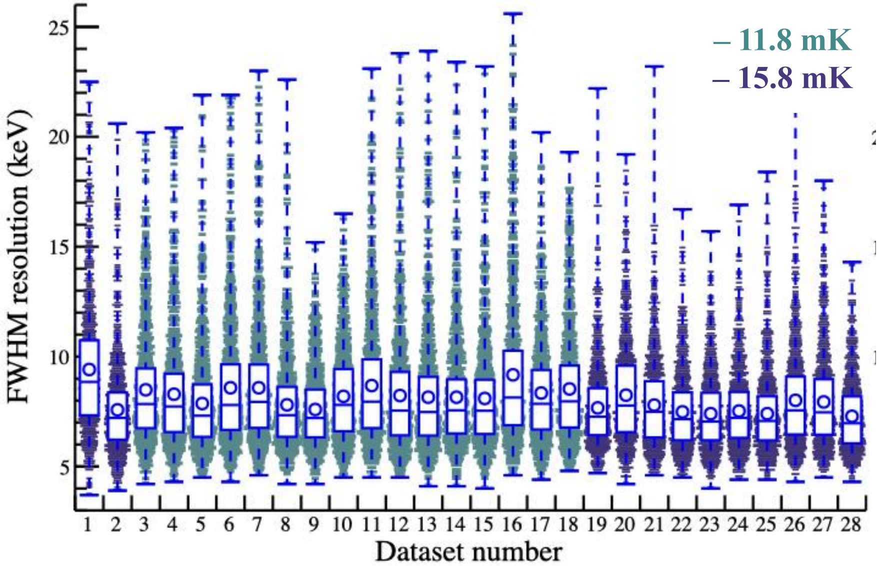
Fit at channel-dataset level

**Energy resolution at 2615 keV**

**FWHM = 7.550(24) keV**

(*harmonic mean - exposure weighted*)





# $^{130}$Te 0νββ decay search

**Physics data: resolution study and blinded fit**

Resolution scaling

Fit background physics peaks with lineshape model, and extract energy resolution and peak position. Define a scaling factor to obtain the correct energy resolution at $Q_{\beta\beta}$

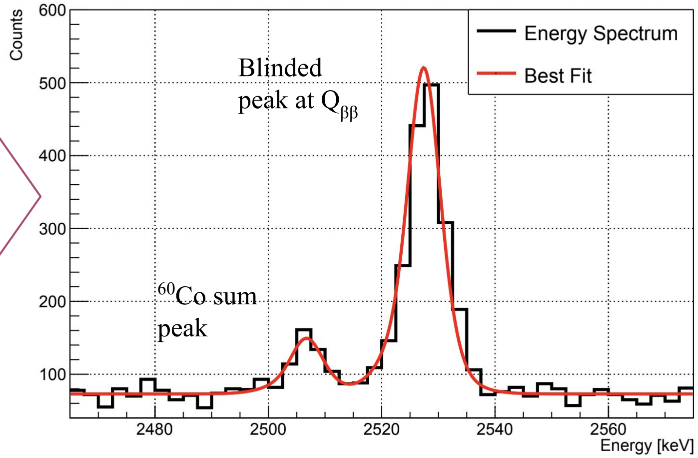
→ **FWHM at $Q_{\beta\beta}$** : $7.525^{+1.45}_{-1.15}$ keV (*exposure weighted*)

**Blinded fit**

Bayesian *(and Frequentist)* Analysis using BAT software

Definition of ROI and fit model:

- Unbinned fit in ROI: [2465, 2575] keV
- Likelihood model (S+B): flat-continuum (BI) ds-dependent, posited peak for 0νββ and $\Gamma_{0\nu}$ global, 60Co-sum peak (initial rate + position) global, ch-ds dependent parameters (FWHM, energy bias)

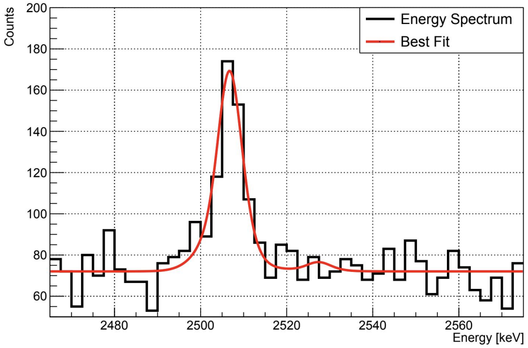


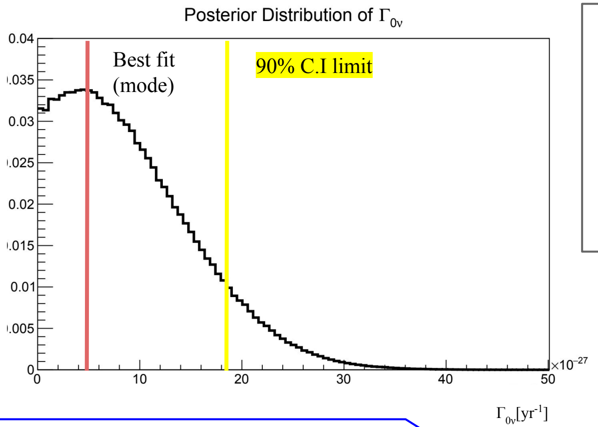
# $^{130}$Te 0νββ decay search

**0νββ peak search on unblinded data:**

Fit of the unblinded data
Systematics: include nuisance parameters (efficiencies, energy bias, resolution scaling..)

No evidence of signal at $Q_{\beta\beta}$ in ROI. Posterior of $\Gamma_{0\nu}$ → Extract an upper limit on $\Gamma_{0\nu}$





**$T_{0\nu}^{1/2}$ ($^{130}$Te) > 3.8 x $10^{25}$ yr**

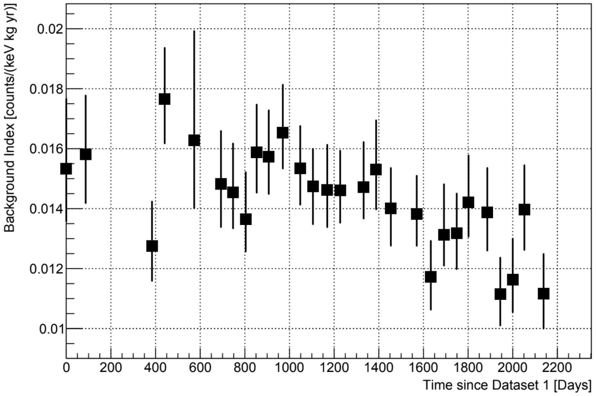
(90%C.I. including syst.)

(new most stringent limit for $^{130}$Te)

Frequentist limit: $T_{1/2} > 3.7 \cdot 10^{25}$ yr (90% C.L.)

**Evaluating the background index in ROI**

Fit ROI of unblinded data with bkg-only hypothesis
BI ~ (1.42 ± 0.02) x $10^{-2}$cts/(keV kg yr)
[*avg, exposure weighted*]

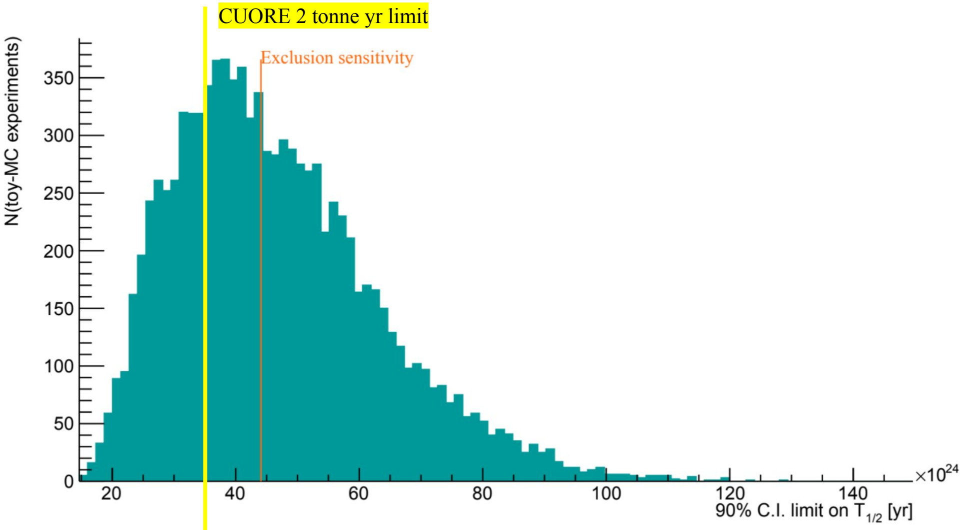


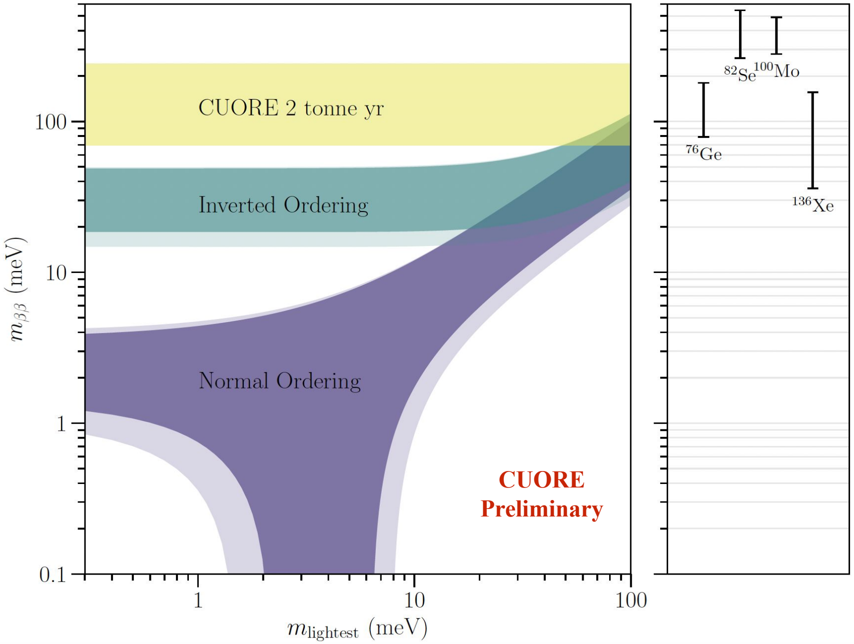
# $^{130}$Te 0νββ decay search

New CUORE 0νββ $^{130}$Te decay $T_{1/2}$ limit with 2 tonne year exposure

Compare with 2 tonne yr sensitivity:
$S_{0\nu}^{1/2}$ ($^{130}$Te) = $4.4 \times 10^{25}$ yr;
Probability to get a more stringent limit given the current sensitivity: 66.6%

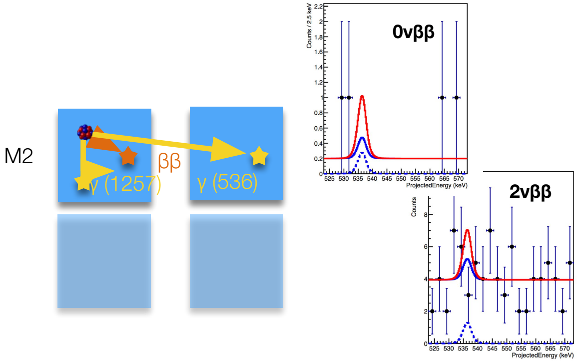
Limit on the effective Majorana mass, assuming light Majorana neutrino-exchange: $m_{\beta\beta} < 70\text{-}240$ meV





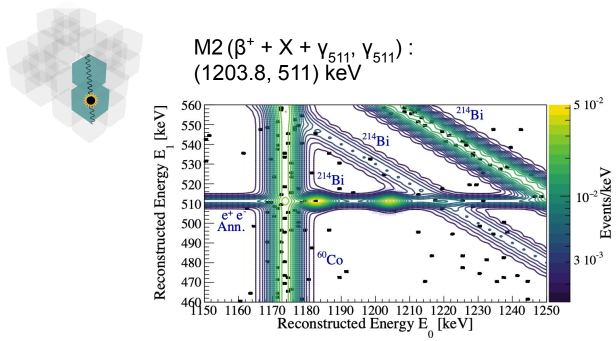
# Not only 0νββ decay search

## $^{130}$Te ββ to excited states



Adams D. et al. (CUORE collaboration), Eur. Phys. J. C (2021) 81:567 https://doi.org/10.1140/epjc/s10052-021-09317-z

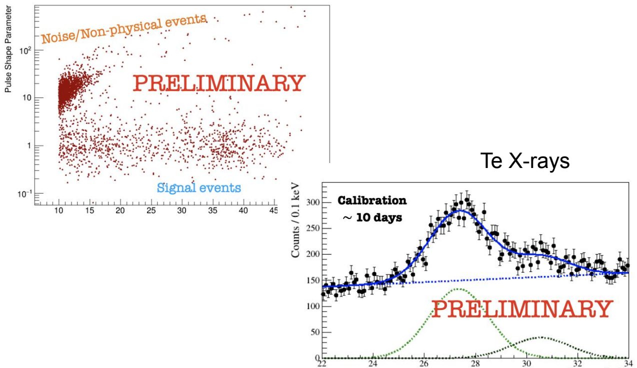
## $^{120}$Te 0νβ+EC decay



M2 $(\beta^+ + X + \gamma_{511}, \gamma_{511})$ : (1203.8, 511) keV

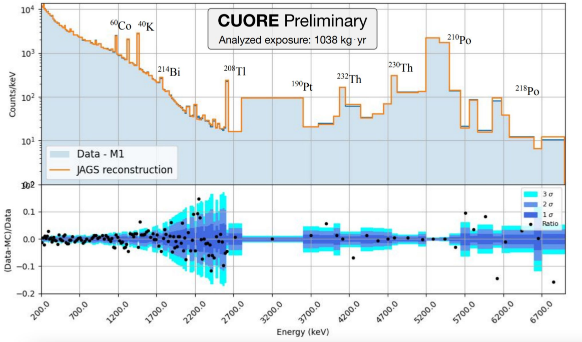
D. Q. Adams *et al.* (CUORE Collaboration), Phys. Rev. C 105, 065504 (2022), https://doi.org/10.1103/PhysRevC.105.065504

## Low energy studies - *ongoing*



LowE poster - Taup2023

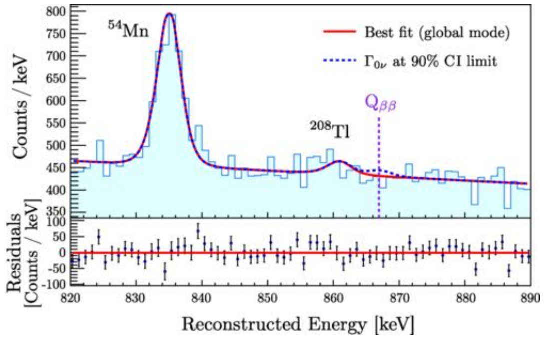
## Background model & 2νββ measurement - *ongoing*



BM Talk - Taup 2023

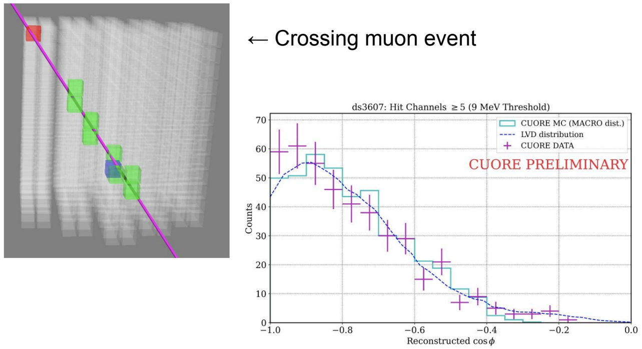
Paper in preparation

## $^{128}$Te 0νββ decay



D. Q. Adams *et al.* (CUORE Collaboration), Phys. Rev. Lett. 129, 222501 (2022), https://doi.org/10.1103/PhysRevLett.129.222501

## Multi-crystal studies: muon tracks reconstruction - *ongoing*



← Crossing muon event

Muons talk - DNP2023

# CUORE: what's next

## CUORE phase-I (current)

Run up to mid-2025
Reach > 3 tonne yr TeO2, 1 tonne yr $^{130}$Te exposure (*largest ever collected for $^{130}$Te*)

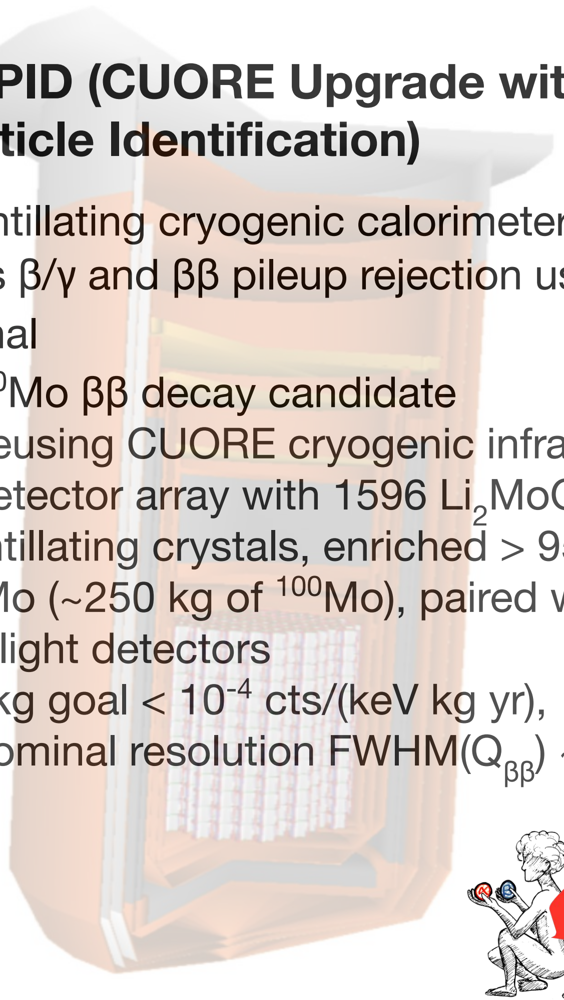
Room for multiple rare events searches with high statistic, optimal energy resolution and low background

## CUORE phase-II

Cryogenic interventions to improve noise and push towards low energy studies

Plan to resume data-taking in 2026

## CUPID (CUORE Upgrade with Particle Identification)



Scintillating cryogenic calorimeters: α vs β/γ and ββ pileup rejection using light signal

- $^{100}$Mo ββ decay candidate
- Reusing CUORE cryogenic infrastructure
- Detector array with 1596 $Li_2MoO_4$ scintillating crystals, enriched > 95% in $^{100}$Mo (~250 kg of $^{100}$Mo), paired with Ge-light detectors
- Bkg goal < $10^{-4}$ cts/(keV kg yr),
- Nominal resolution FWHM($Q_{\beta\beta}$) ~ 5 keV

# Conclusion

- CUORE demonstrates the feasibility of a tonne-scale experiment employing cryogenic calorimeters at 10 mK, for the search of the 0νββ decay and rare events
- CUORE data-taking is proceeding with > 90% uptime. A raw exposure of more than 2.5 tonne yr achieved as of today!

- CUORE released today new physics results of $^{130}$Te 0νββ decay search, utilising 2 tonne yr $TeO_2$ data!
- CUORE has a rich science program of searches for rare decays of different Te isotopes, low energy studies and multi-crystal studies.

- The CUORE data taking is currently underway to collect up to more than 3 tonne yr $TeO_2$ exposure.
- CUORE paves the road to the CUPID project (CUORE Upgrade with Particle IDentification) for next generation tonne-scale cryogenic calorimeters for 0νββ decay searches

# Thank you on behalf of the CUORE collaboration

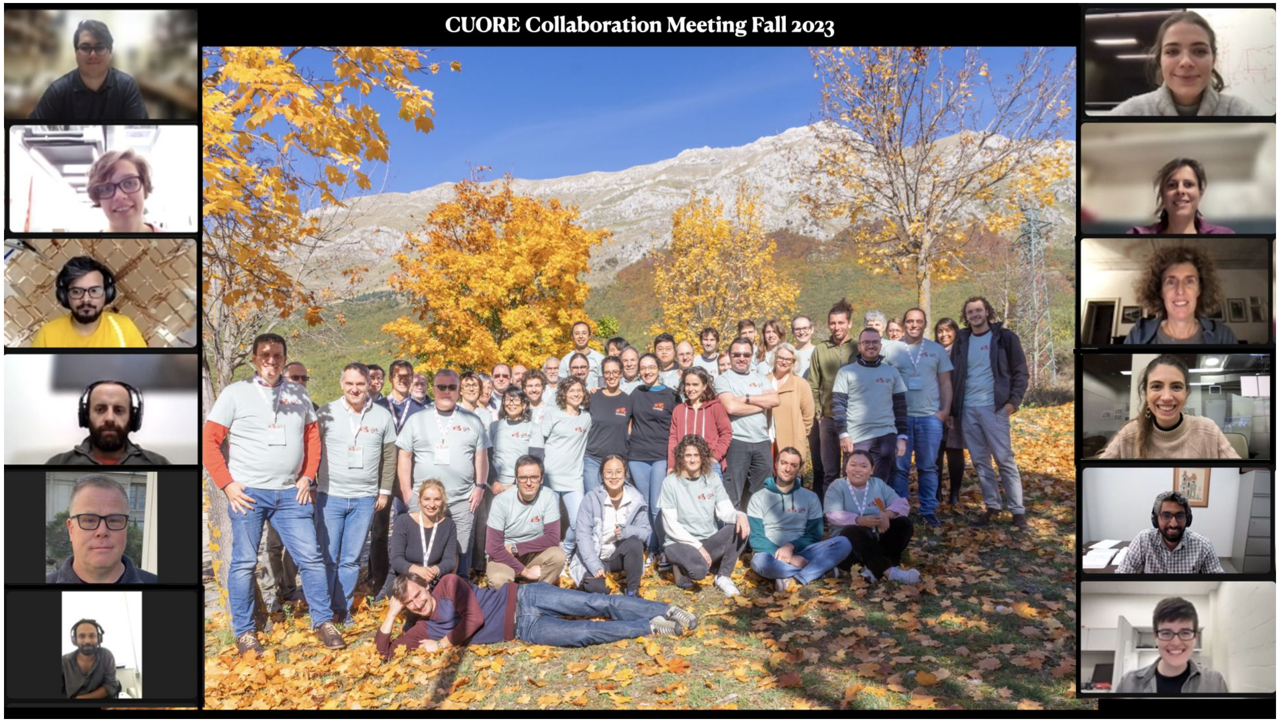
INFN
Istituto Nazionale di Fisica Nucleare

CSNSM
CENTRE DE SCIENCES NUCLÉAIRES ET DE SCIENCES DE LA MATIÈRE

SINAP

Yale

UCLA



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UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE
SOL PER NOCTEM

UNIVERSITAS STUDII PADUANI
MCCXXII

ALMA MATER STUDIORUM
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# Backup

# Acknowledgements

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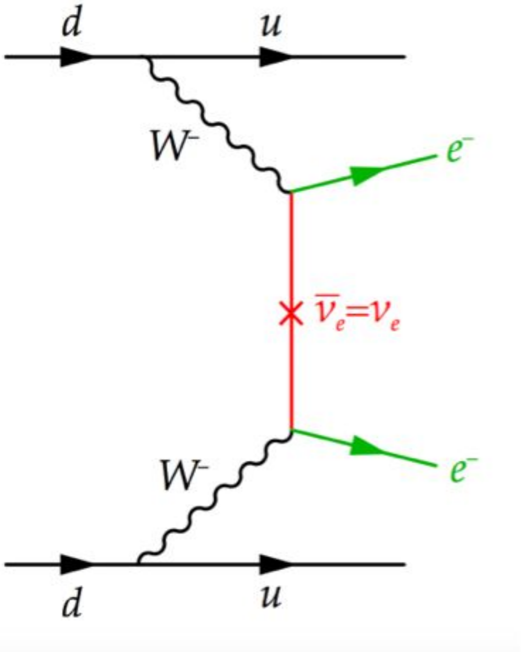
# 0νββ decay and inference on neutrino mass

*The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange*



The parent nucleus emits a pair of virtual W bosons. The W exchange a Majorana neutrino to produce the outgoing electrons. The exchanged neutrino can be seen as emitted (in association with an electron) with almost total positive helicity. For a massive Majorana neutrino, it has a small, O(m/E), negative helicity component which is absorbed in the other vertex by the Standard Model electroweak current.

From the decay rate it is possible to infer the effective neutrino mass

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

**Phase space integral**
$G(Q_{\beta\beta},Z) \sim Q_{\beta\beta}^5$

**Nuclear matrix element**
(NME)

**Effective neutrino mass term**

# 0νββ decay and inference on neutrino mass

*The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange*

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

**Effective neutrino mass term** $|m_{\beta\beta}|^2$

Neutrino mass matrix Mν can be decomposed as $M_\nu = U\ \mathrm{diag}(m_1, m_2, m_3)\ U^t$

where $m_i>0$ are the masses of the neutrinos and U is the PMNS mixing matrix.

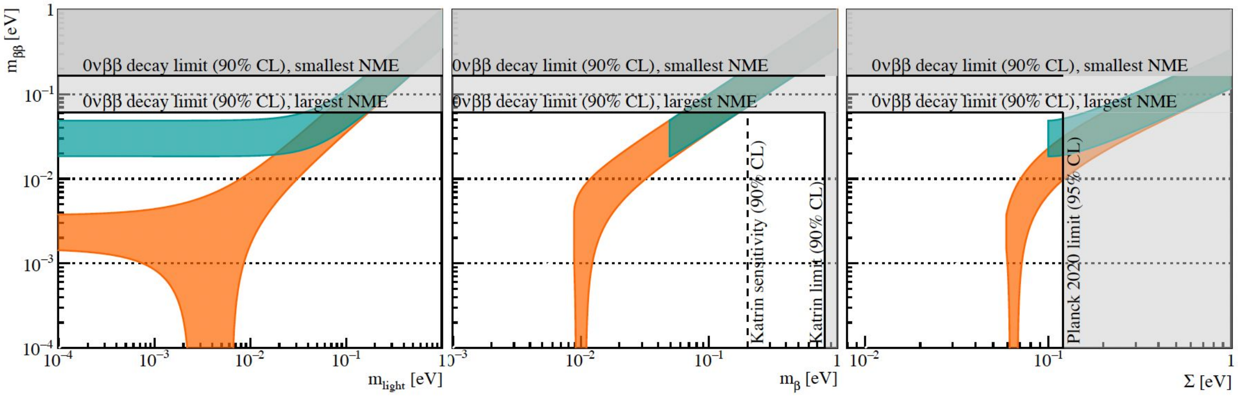
Define the effective Majorana mass $m_{\beta\beta}$ where $\phi_i$ are called Majorana phases and cannot be probed by oscillation experiments.

$m_{\beta\beta}$ is the ee-element of the mass matrix $|(M_\nu)_{ee}|$

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} |U^2_{\mathrm{ei}}|\ e^{i\varphi_{\mathrm{i}}}\ m_{\mathrm{i}}\right|$$

*Rev. Mod. Phys.* **95**, 025002; https://doi.org/10.1103/RevModPhys.95.025002

0νββ is directly connected to neutrino oscillations phenomenology, and that it also provides direct information on the absolute neutrino mass scale, as cosmology and decay experiments do.



# 0νββ decay and inference on neutrino mass

*The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange*

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

**Nuclear Matrix Elements**

Factoring out the hadron coupling gA wrt to just the **nuclear many-body part** and to light neutrino exchange

$$|M_{nucl}|^2 = g_A^4|M^{0\nu}_{light}|^2$$

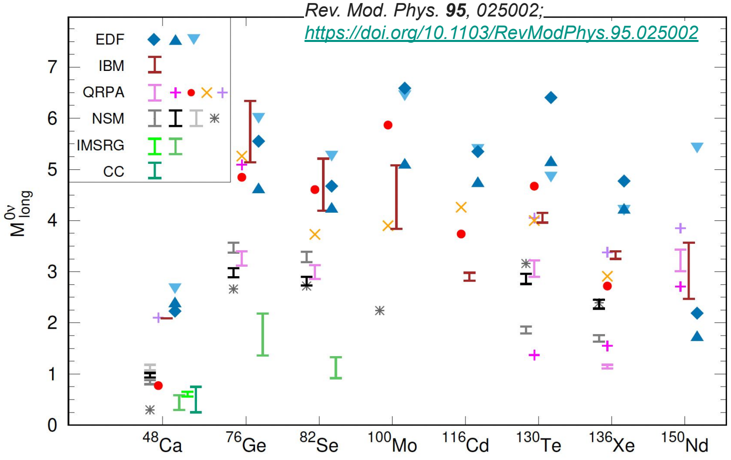
All nuclear methods used to study 0νββ decay make a significant effort to describe with high quality the structure of the initial and final nuclei and the relative long and short-term interactions among nucleons. Models: *Shell model, QRPA, EDF theory, IBM, Ab-initio methods*

$$M^{0\nu}_{light} = M^{0\nu}_{long} + M^{0\nu}_{short}$$

The variation of the NME about a factor three for a given isotope, highlights the uncertainties introduced by the approximate solutions of the nuclear many-body problem.

Current strong effort to improve the nuclear models for multiple isotopes and quantify the NMEs theoretical uncertainties

Rev. Mod. Phys. **95**, 025002; https://doi.org/10.1103/RevModPhys.95.025002



# 0νββ decay and inference on neutrino mass

*The standard neutrinoless double-beta decay mechanism: light Majorana neutrino exchange*

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q_{\beta\beta}, Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

**Nuclear Matrix Elements**

Factoring out the **hadron coupling gA** wrt to just the nuclear many-body part and to light neutrino exchange

$$|M_{nucl}|^2 = g_A^4|M^{0\nu}_{light}|^2$$

The “gA quenching" is a potential source of uncertainty in 0νββ-decay NMEs.
Most calculations systematically overestimate β-decay Gamow–Teller matrix elements. This implies the need of a correction, by quenching the value of the axial coupling $g_A$ ($g_A' = q\ g_A$ with q ~0.7-0.8).

Very recently decay β-decay has been studied with the ab initio methods. These calculations suggest that the overprediction of matrix elements is more likely related to the GT β-decay operator than to gA.

# Experimental sensitivity

The number of observable 0νββ decays is limited by the fluctuations of the background counts around $Q_{\beta\beta}$ (region of interest, ROI)

'Finite background'

$$S_{0\nu} \propto \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta \cdot B}}$$

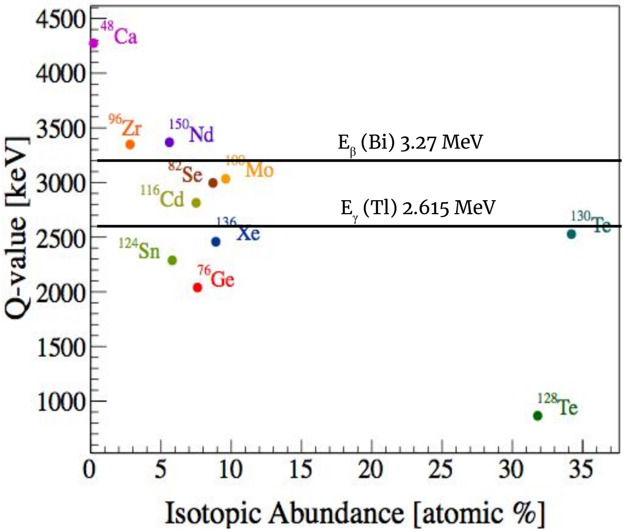
'Zero background' $(B \cdot \Delta \cdot M \cdot T) << 1$

$$S_{0\nu} \propto \eta \cdot \epsilon \cdot M \cdot T$$

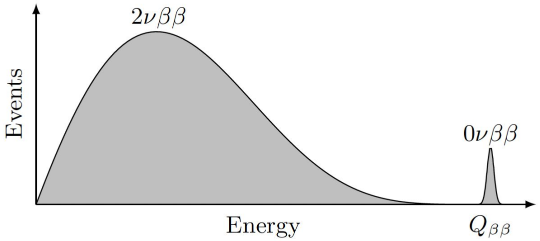
Ingredients for 0νββ decay experiments

*Isotope choice*
- High isotope natural abundance or enrichment, η
- High Q-value, $Q_{\beta\beta}$

*Exposure*
- Large active mass (M) detector
- Long live-time (T)

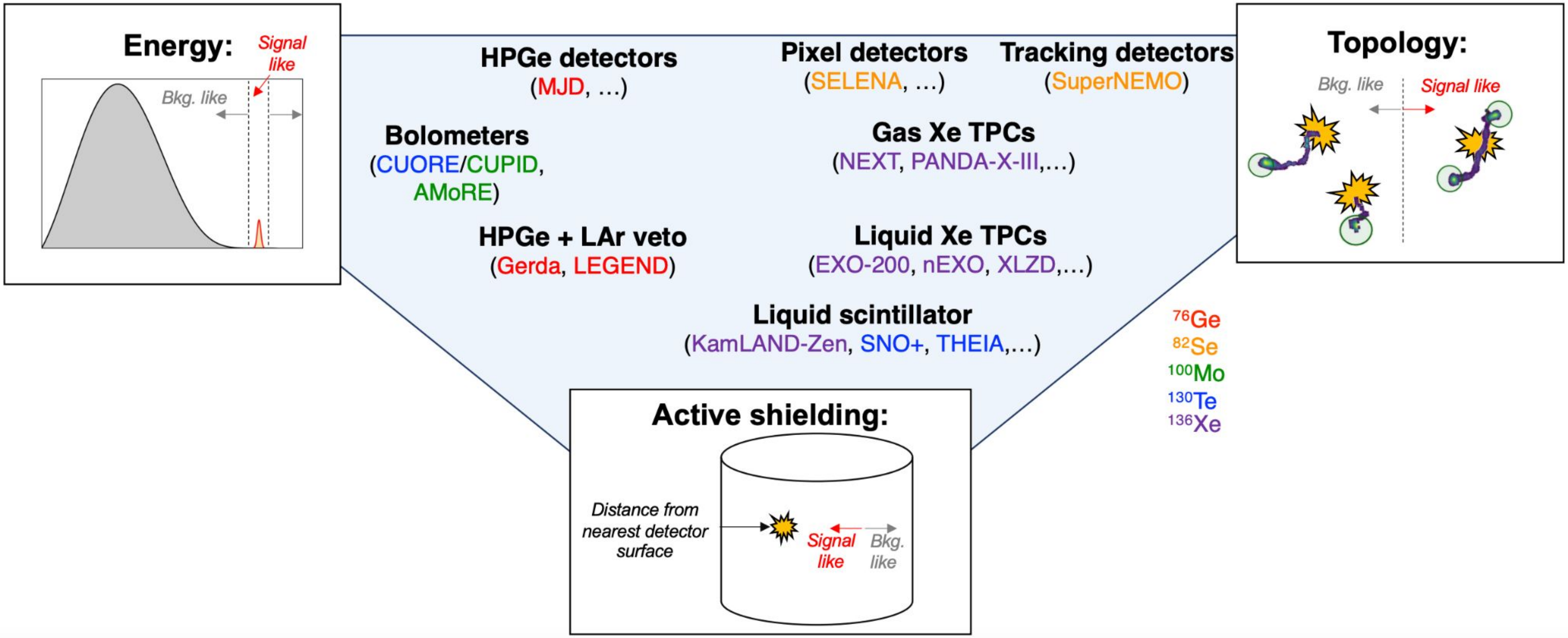


*Detection technology*
- Good detection efficiency (ε): ββ source embedded into the absorber
- Excellent energy resolution (Δ)
- Low backgrounds (B)



# 0νββ experimental landscape

Different detection approaches and background suppression techniques



**HPGe detectors**
(MJD, …)

**Pixel detectors**
(SELENA, …)

**Tracking detectors**
(SuperNEMO)

**Bolometers**
(CUORE/CUPID, AMoRE)

**Gas Xe TPCs**
(NEXT, PANDA-X-III,…)

**HPGe + LAr veto**
(Gerda, LEGEND)

**Liquid Xe TPCs**
(EXO-200, nEXO, XLZD,…)

**Liquid scintillator**
(KamLAND-Zen, SNO+, THEIA,…)

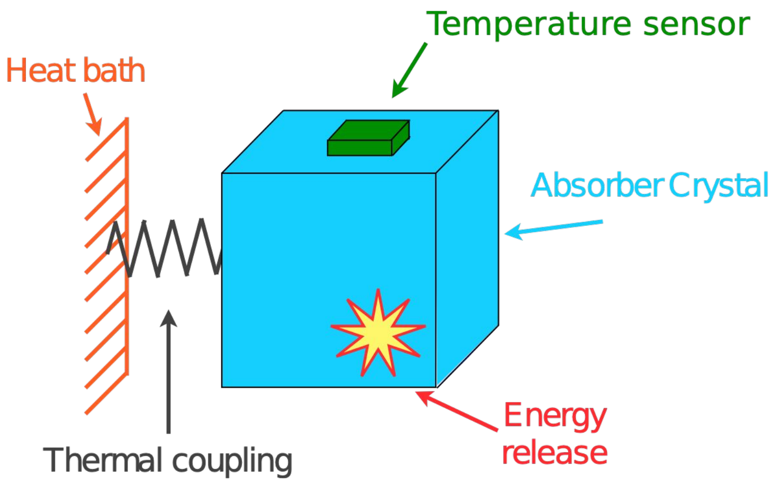
$^{76}$Ge
$^{82}$Se
$^{100}$Mo
$^{130}$Te
$^{136}$Xe

*ββ decay review - D.Moore (TAUP2023)*

# Low temperature detectors

**Cryogenics calorimeters**. An absorber crystal is connected to an ‘heat bath’ at ~few mK. It is instrumented with a sensor measuring the temperature variation in the crystal induced by a small energy release (~keV/MeV). The deposited energy is converted into phonons - heat.

- Absorber at T~ 10 mK
- Energy deposition in the absorber ($E_{dep}$): particles scattering on electrons and nuclei → production of athermal phonons → energy degradation → thermal phonons/heat → ΔT
- Phonon sensor - NTD thermistor: large resistance variation with T (ΔR) → generation of an electrical pulse signal with amplitude proportional to the energy of the excess phonons

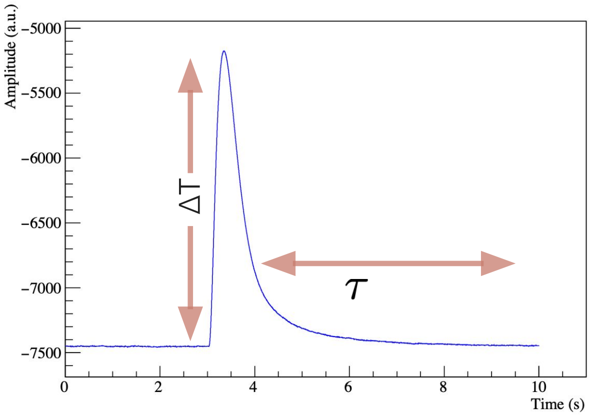


Simplified thermal model:

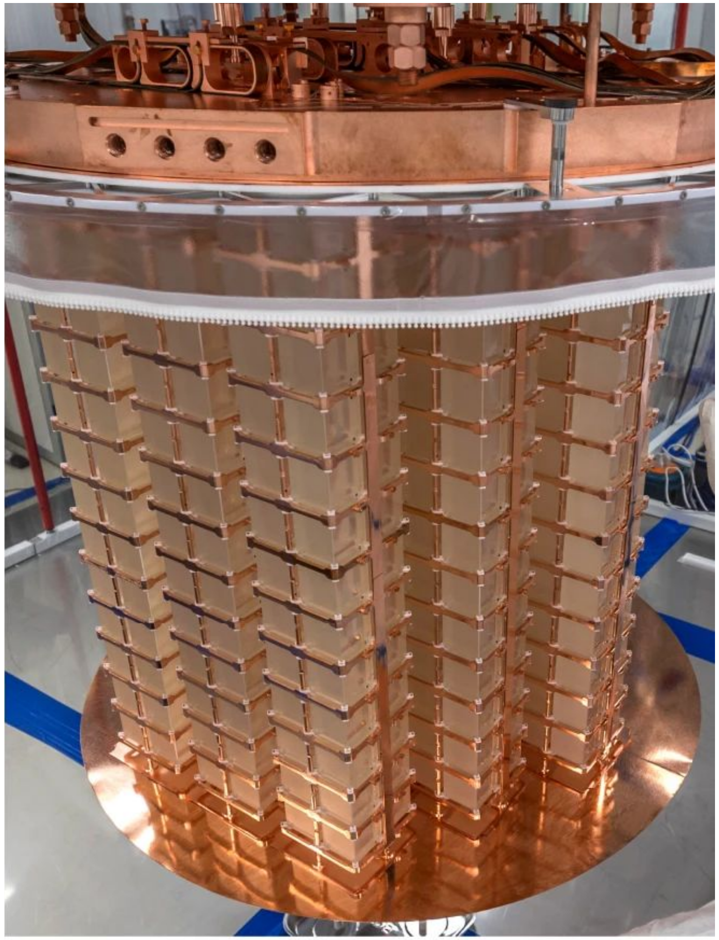
One thermal capacity C (crystal)
One thermal link G (btw crystal/heat bath)

$$\Delta T \propto \frac{E_{dep}}{C}$$

$$\tau = \frac{G}{C}$$



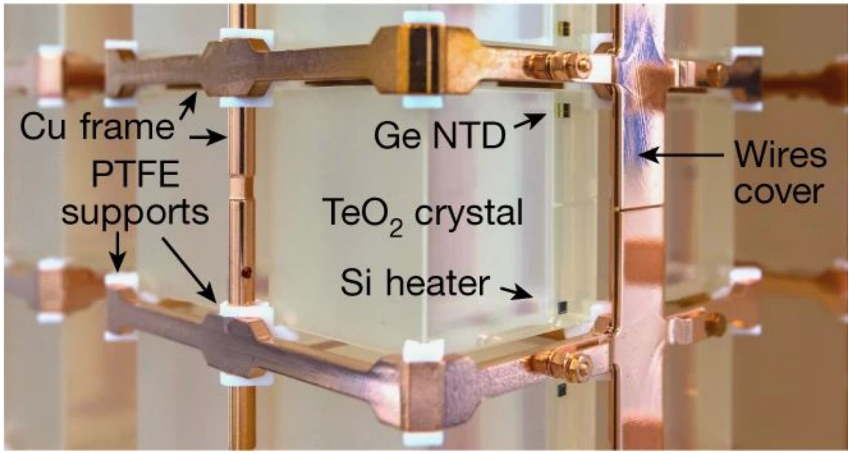
# The CUORE detectors



Array of closely packed **988 $TeO_2$ crystals arranged in 19 towers**

High Mass of $TeO_2$: **742 kg**

**206 kg of $^{130}$Te, 188 kg of $^{128}$Te, 0.5 kg of $^{120}$Te**



@10 mK

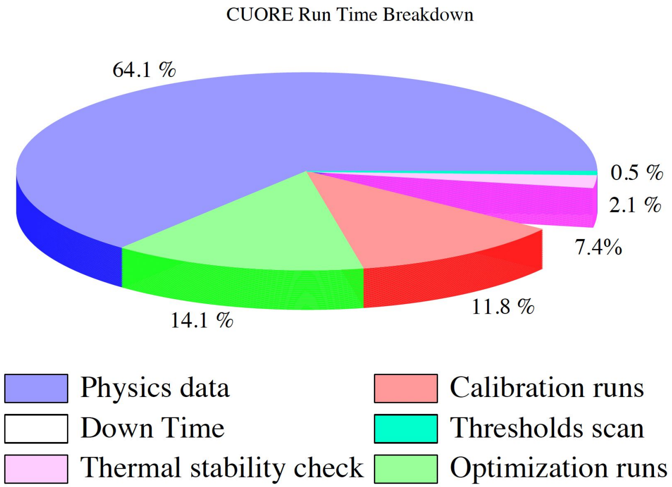
$\Delta T_{crystal}$ ~ 100 μK/MeV ; $\Delta V_{NTD}$ ~ 400 μV/MeV

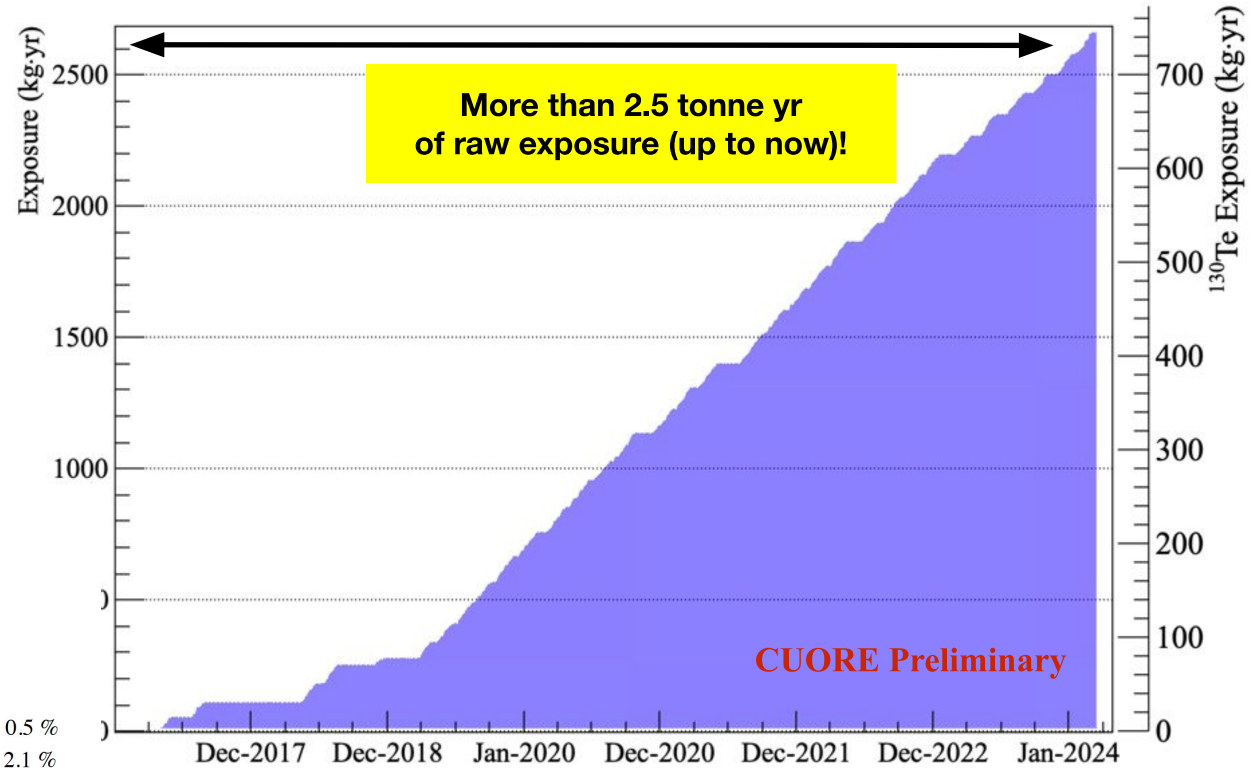
Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

Alduino C. et al. (CUORE collaboration), J. Inst. 11(07), P07009, (2016) https://doi.org/10.1088/1748-0221/11/07/p07009

# CUORE data-taking

- Data taking started in Spring 2017: detector commissioning and optimisation in 2017-2018
- **Continuous physics data taking since early 2019**, at operating temperature 11-15 mK. **Uptime ~90%.** Data taking rate ~50 kg yr/month



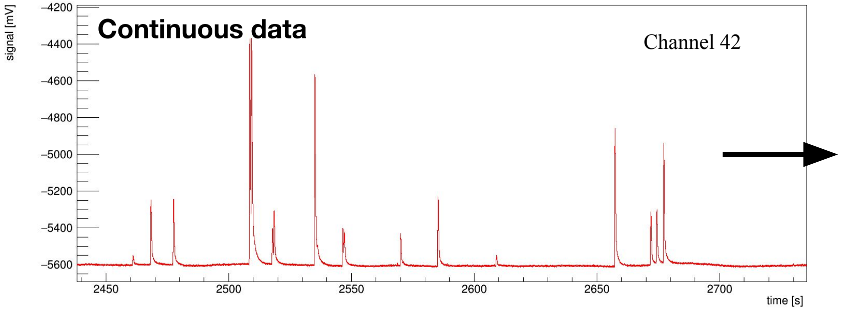


**More than 2.5 tonne yr of raw exposure (up to now)!**

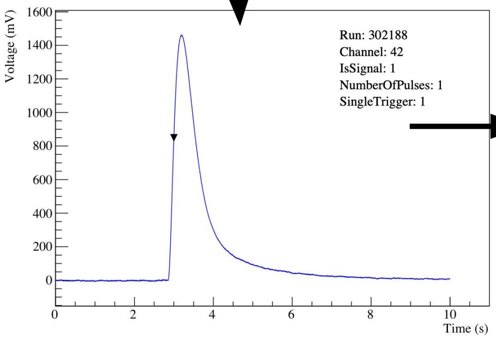
**CUORE Preliminary**

# CUORE data production chain

**From single detectors waveform data stream**



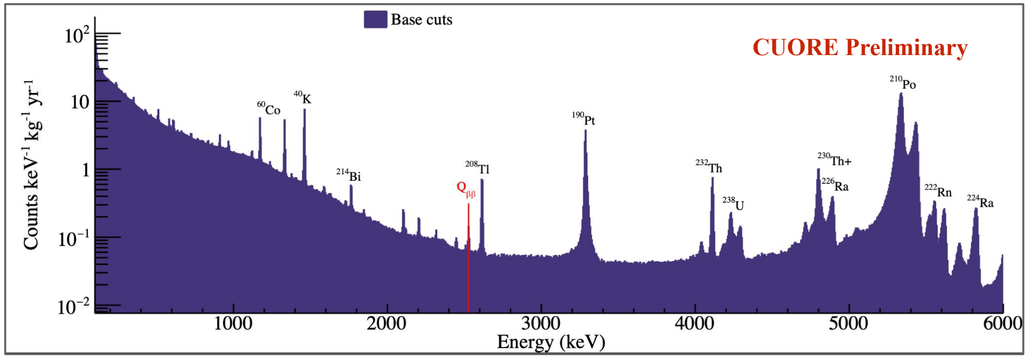
Denoising → Optimum trigger



**Event: physics pulse**

Optimum Filter → Gain Correction → Energy Calibration → Coincidences → PCA

**To a cumulative energy spectrum**



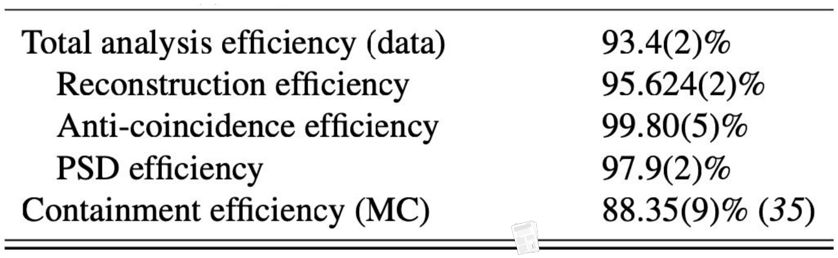
# CUORE performance

**CUORE 2 TonneYr release (this result)**

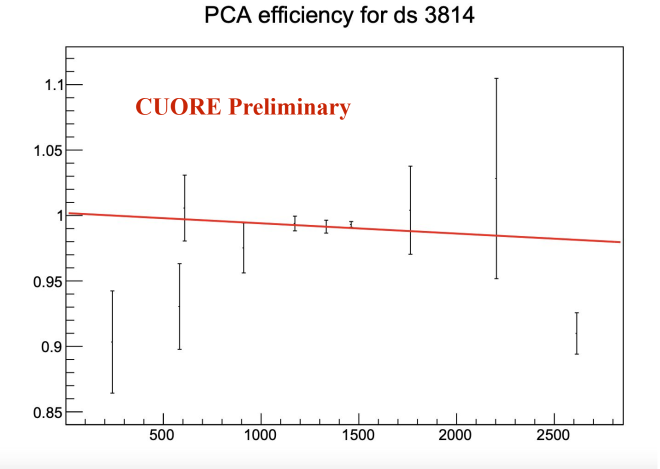
Quality cuts: identify single site events corresponding to single particle-like pulses

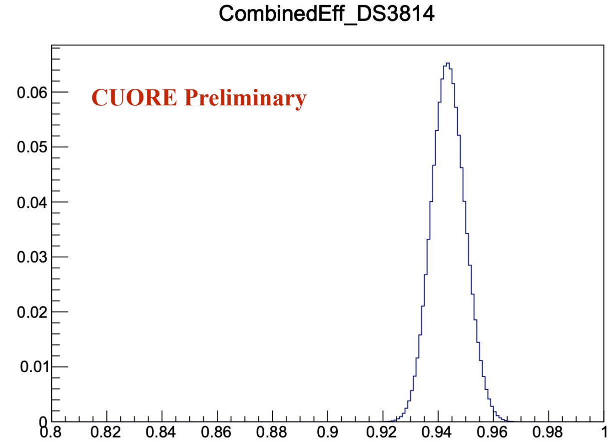
- BaseCuts: @ch-ds level → exposure weighted average @ds-level
- Anti-coincidence (M1): @ds-level → posterior distribution at ds-level
- PCA: @ds-level → posterior distribution at ds-level (evaluated from 500 keV to 5 MeV) for M1 and M2 events

→ Total combined efficiency for each ds: distribution fed as prior for the 0νββ fit



| | |
|---|---|
| Total analysis efficiency (data) | 93.4(2)% |
| Reconstruction efficiency | 95.624(2)% |
| Anti-coincidence efficiency | 99.80(5)% |
| PSD efficiency | 97.9(2)% |
| Containment efficiency (MC) | 88.35(9)% (35) |


PCA efficiency for ds 3814

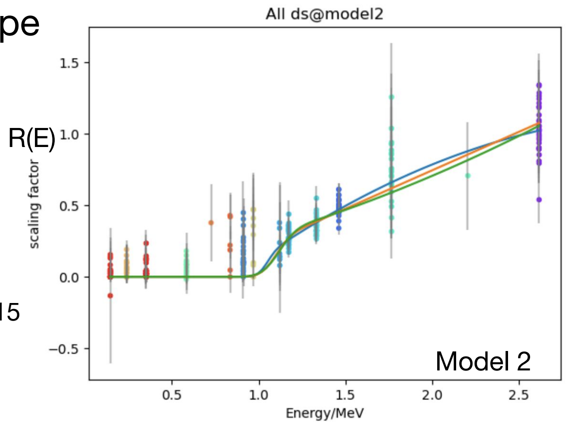

CombinedEff_DS3814

# $^{130}$Te 0νββ decay search

**Physics data: resolution study**

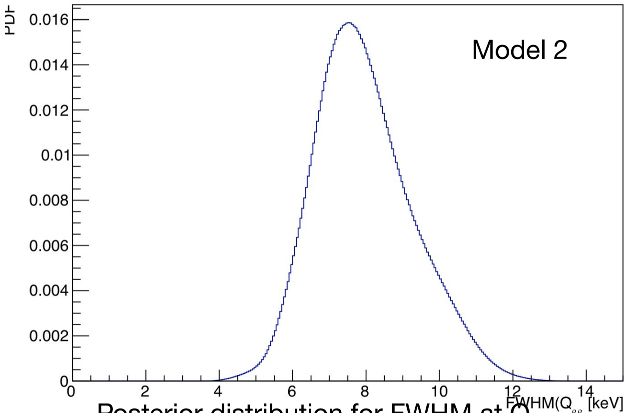
**Resolution scaling:**

1. Fit background physics peaks with lineshape model, and extract σ(E)
2. Model σ vs E dependence:
   - Model 0 (used for prev. releases): $\sigma(E) = R(E)^*\sigma_{2615}$, $R(E) = \mathrm{pol1}(E)$
   - Model 1 (new): Linear dependence wrt $\sigma_{2615}$ $\sigma(E) = R(E)^*\sigma_{2615}$, $R(E) \sim$ erf & sqrt(pol1)
   - Model 2 (new - official!): Include 'baseline resolution' ('intrinsic' σ), quadratic sum $\sigma(E) = \mathrm{sqrt}[\sigma^2_{\mathrm{bkg,base}} + R(E)^*(\sigma^2_{2615} - \sigma^2_{\mathrm{cal,base}})]$, $R(E) \sim$ erf & pol2 ($a E^2 + b E$) with 0 intercept



New model for R(E)
$R(E) = \phi(E)(\mathrm{Tail}(E)) + (1 - \phi(E))h$

$\phi(E)$ erf function, Tail(E) tail fitting polinomial



Posterior distribution for FWHM at $Q_{\beta\beta}$

→ Official energy resolution and bias (Model 2)

Exposure-weighted FWHM @Qbb: 7.525 +1.45 -1.15 keV

Exposure-weighted Bias @Qbb: 0.515 +0.04 -0.3 keV

# $^{130}$Te 0νββ decay search

**0νββ peak search on unblinded data:**

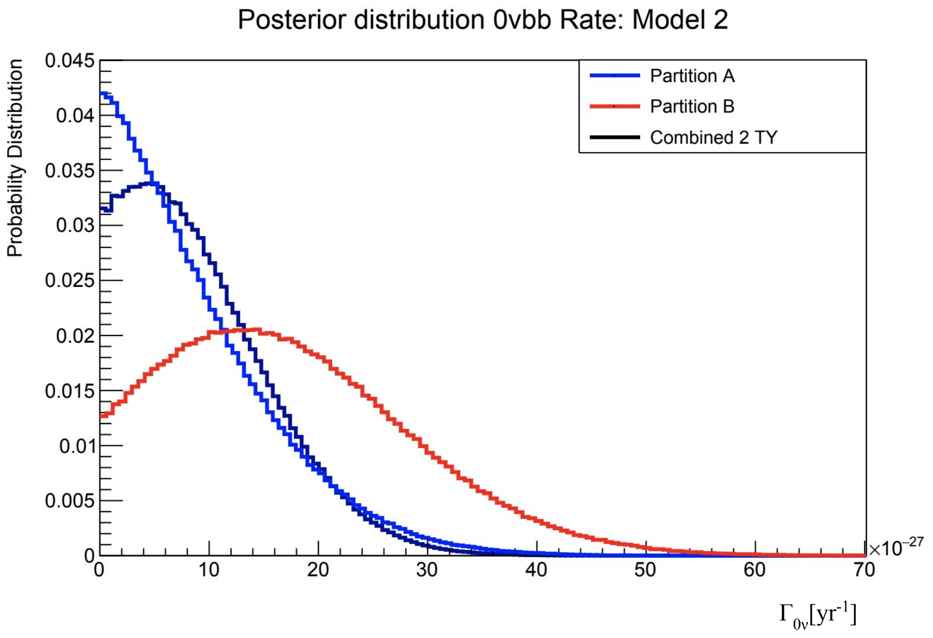
Unbinned extended likelihood

$$\mathcal{L} = \prod_{\text{DS, C}} \frac{e^{-\lambda}\lambda^{n}}{n!} \prod_{i} \left[ \frac{s}{\lambda} f_{0\nu}(E_i|\vec{\theta}_{0\nu}) + \frac{c}{\lambda} f_{\text{Co}}(E_i|\vec{\theta}_{\text{Co}}) + \frac{b}{\lambda \Delta E} \right]$$

Subdivide 2TY data in two partitions on 1 tonne yr each

- Fit of the ROI of each partition
- Combine posteriors of $\Gamma_{0\nu}$

| | Partition A | Partition B | Total |
|---|---|---|---|
| nDS | 14 | 14 | 28 |
| nDS 1st TY | 8 | 7 | 15 |
| nDS 2nd TY | 6 | 7 | 13 |
| Exposure [kg yr] | 1010.14 | 1028.82 | 2038.96 |
| Eff-Weighted Exposure [kg yr] | 941.78 | 959.87 | 1901.65 |
| 1st TY Exp [kg yr] | 542.46 | 487.73 | 1030.19 |
| 2nd TY Exp [kg yr] | 467.68 | 541.09 | 1008.77 |
| Partition A:<br>3802,3803,3805,3806,3808,3811,3815,3817,3819,3820,3823,3826,3827,3828 | | | |
| Partition B:<br>3801,3804,3807,3809,3810,3812,3813,3814,3816,3818,3821,3822,3824,3825 | | | |



# $^{130}$Te 0νββ decay search

**0νββ peak search on unblinded data:**

**Bayesian fit**: MCMC sampler

Bayesian limit:

<u>Reso Model 1</u>

Best fit rate $\Gamma_{0\nu} = 4.3^{+7.1}_{-4.3} \times 10^{-27}$ yr$^{-1}$

90% C.I. Limit $\Gamma_{0\nu} < 1.9 \times 10^{-26}$ yr$^{-1}$

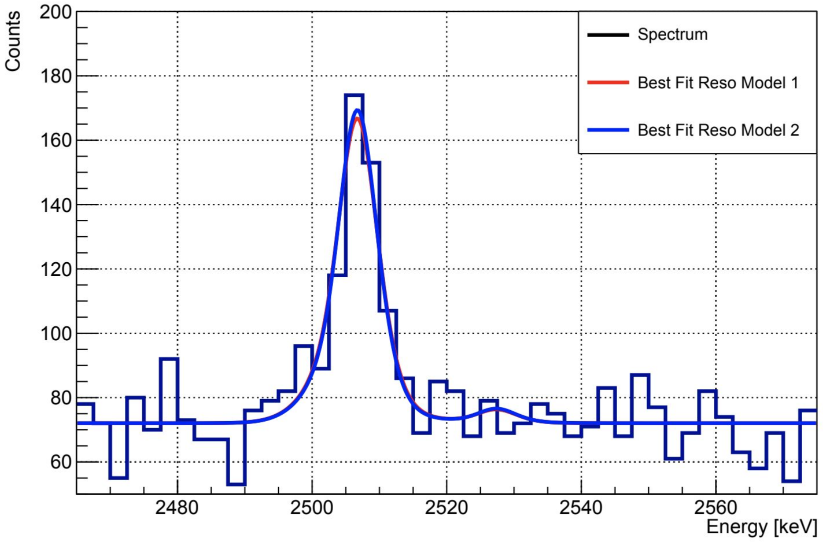
$T_{1/2} > 3.7 \times 10^{25}$ yr (90% C.I.)

<u>Reso Model 2 (official)</u>

Best fit rate $\Gamma_{0\nu} = 4.5^{+6.9}_{-4.5} \times 10^{-27}$ yr$^{-1}$

90% C.I Limit $\Gamma_{0\nu} < 1.8 \times 10^{-26}$ yr$^{-1}$

$T_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)



# $^{130}$Te 0νββ decay search

**0νββ peak search on unblinded data:**

**Frequentist fit**: Rolke method (background dominated ROI)

Frequentist limit:

Model 1 →

$\Gamma_{0\nu} < 1.9 \times 10^{-26}\ \mathrm{yr}^{-1}$ (90% C.L.)

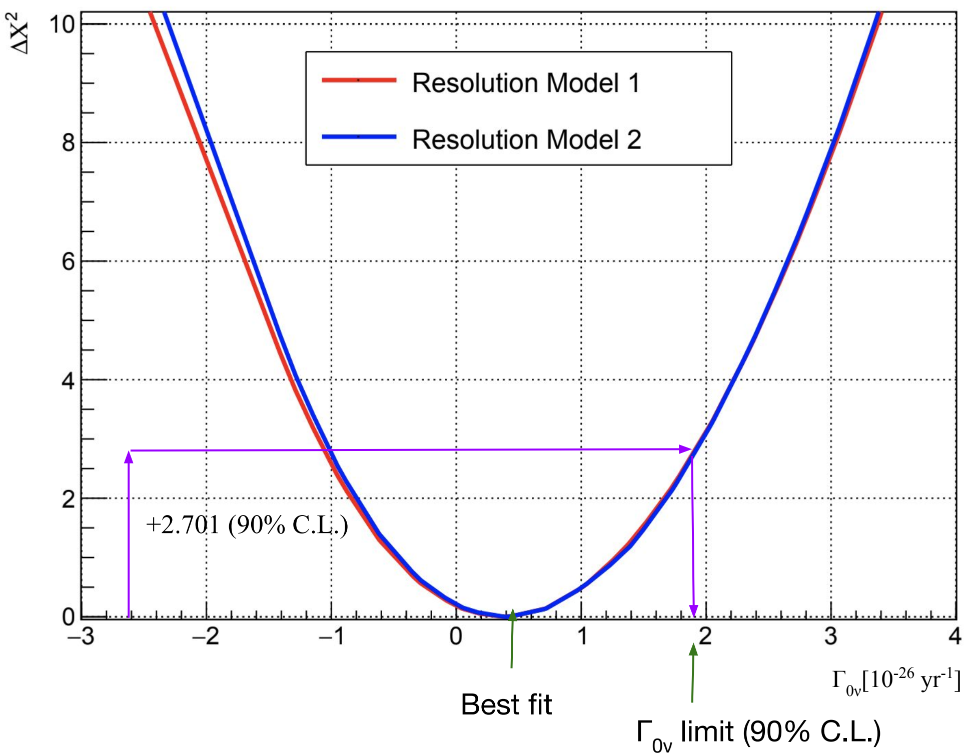
$T_{1/2} > 3.7 \cdot 10^{25}$ yr (90% C.L.)

Model 2 (official) →

$\Gamma_{0\nu} < 1.9 \times 10^{-26}\ \mathrm{yr}^{-1}$ (90% C.L.)

$T_{1/2} > 3.7 \cdot 10^{25}$ yr (90% C.L.)

Profiled Likelihood (-2LogL)

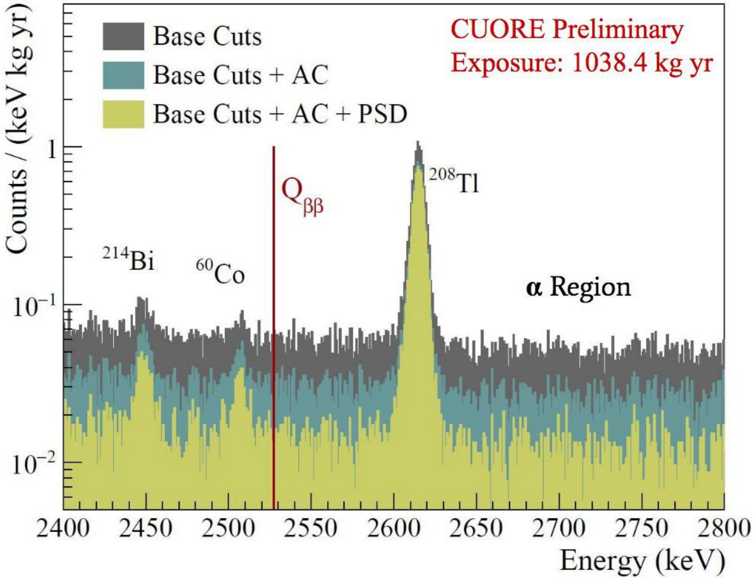


# $^{130}$Te 0vββ decay search

**0vββ peak search on unblinded data:**

CUORE $TeO_2$ detectors background in ROI:

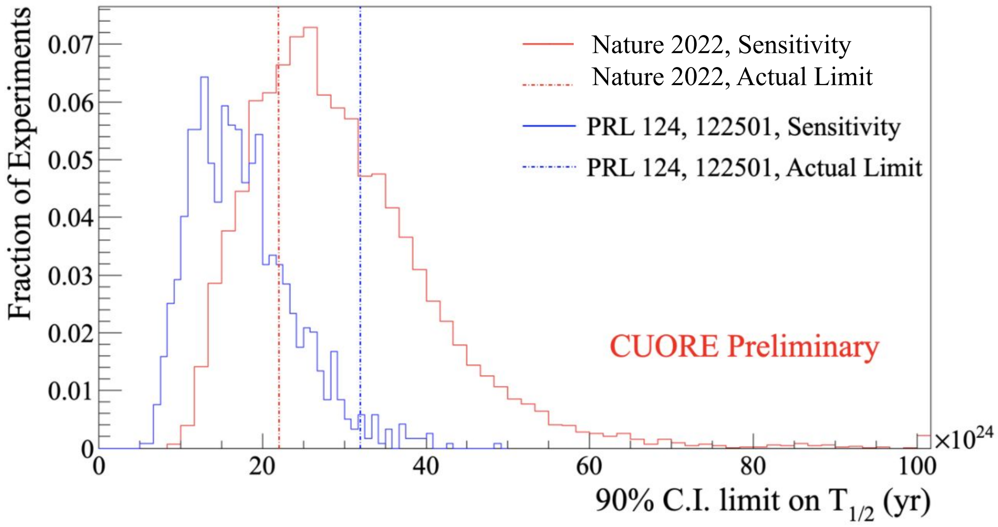
- **Degraded α particles**, produced from radioactive decays close to the detectors or on their surface, which deposit part of their energy in the detectors - ~90% contribution
- Multi-Compton of γ emitted by the $^{232}$Th/$^{238}$U chains and cosmic muons - <10% contribution



# $^{130}$Te 0νββ decay search

**Exclusion sensitivity for 0νββ decay and CUORE results:**

- PRL 2020 (372.5 kg yr TeO2): $T_{0\nu}^{1/2}$ ($^{130}$Te) > $3.2 \times 10^{25}$ yr; $S_{0\nu}^{1/2}$ ($^{130}$Te) = $1.7 \times 10^{25}$ yr; Probability to get a more stringent limit given the current sensitivity: 3%; $m_{\beta\beta}$ < 75 - 350 meV
- Nature 2022 (1038.4 kg yr $TeO_2$): $T_{0\nu}^{1/2}$ ($^{130}$Te) > $2.2 \times 10^{25}$ yr; $S_{0\nu}^{1/2}$ ($^{130}$Te) = $2.8 \times 10^{25}$ yr; Probability to get a more stringent limit given the current sensitivity: 72%; $m_{\beta\beta}$ < 90 - 305 meV

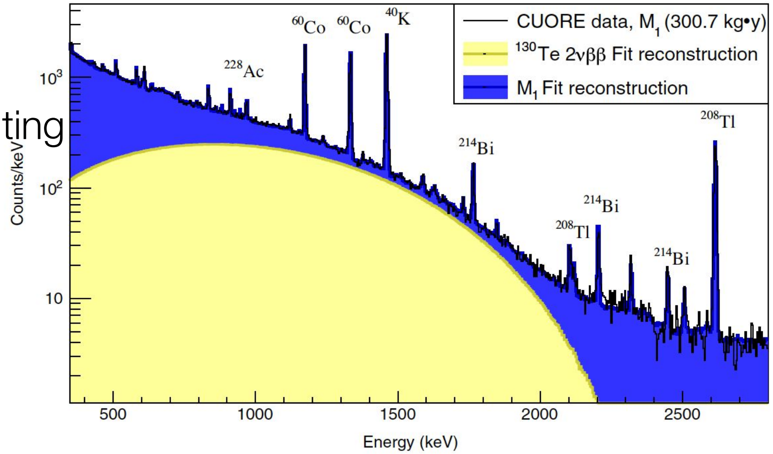


Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 124, 122501, (2020), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501

Adams D. et al. (CUORE collaboration), *Nature* 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

# $^{130}$Te ββ decay

## $^{130}$Te 2νββ half-life measurement



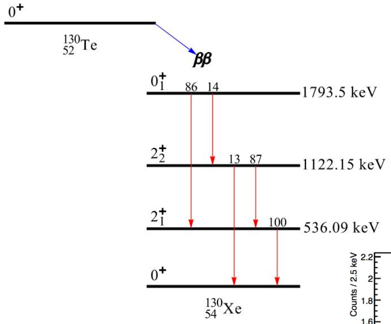
Monte Carlo reconstruction of the CUORE background, profiting from a segmented detector.

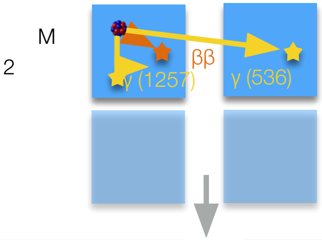
Most precise measurement of $T_{2\nu}^{1/2}$ ($^{130}$Te):

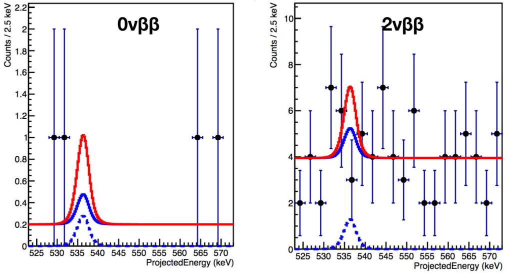
$$T_{2\nu}^{1/2}\,(^{130}\mathrm{Te}) = [0.76\,^{+0.09}_{-0.07}(\mathrm{stat})\,^{+0.14}_{-0.17}(\mathrm{syst})] \times 10^{20}\ \mathrm{yr}$$

Adams D. et al. (CUORE collaboration), Phys. Rev. Lett. 126, 171801 (2021)
https://doi.org/10.1103/PhysRevLett.126.171801
https://doi.org/10.1103/PhysRevLett.131.249902

## $^{130}$Te ββ to first 0+ excited state of $^{130}$Xe







Cascade of de-excitation γs in coincidence with βs

- Multi-site signatures
- Analysis of only fully contained events

Half-life limits @90%C.I.

**0νββ: $(T^{1/2})^{0\nu}_{0+} > 5.9 \times 10^{24}$ yr**

**2νββ: $(T^{1/2})^{2\nu}_{0+} > 1.3 \times 10^{24}$ yr**

Exposure:
372.5 kg·yr $TeO_2$,
103.6 kg·yr $^{130}$Te

Adams D. et al. (CUORE collaboration), Eur. Phys. J. C (2021) 81:567
https://doi.org/10.1140/epjc/s10052-021-09317-z

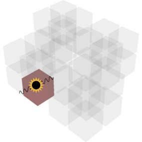
# Decays of other Te isotopes

### $^{120}$Te 0νβ$^+$EC decay

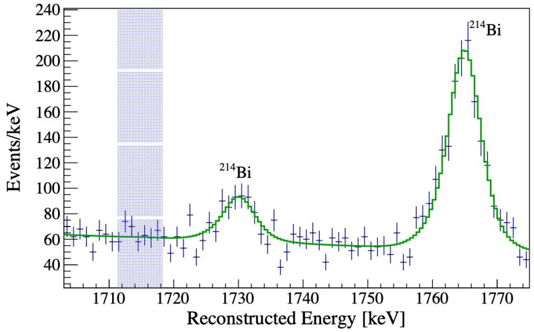
Q$_{\beta\beta}$= 1714.8 keV, natural abundance: 0.09%
Clear signature from e+e- annihilation and $^{120}$Sn de-excitation via X-ray/Auger electrons emission
Half-life limit @90%C.I.

**$T_{0\nu}^{1/2}$ ($^{120}$Te) > 2.9 × $10^{22}$ yr**

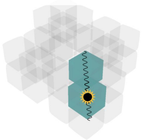
Exposure: 355.7 kg·yr TeO$_2$, 0.2405 kg·yr $^{120}$Te



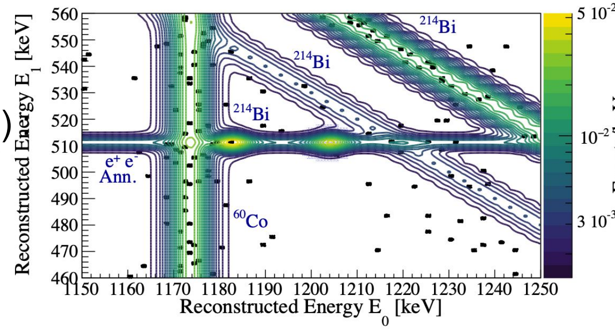
M1
$\beta^+ + X + 2\,\gamma_{511}$:
1714.8 keV



*See CUORE poster P0209 (A.Campani)*



M2
$(\beta^+ + X + \gamma_{511}, \gamma_{511})$
(1203.8, 511) keV



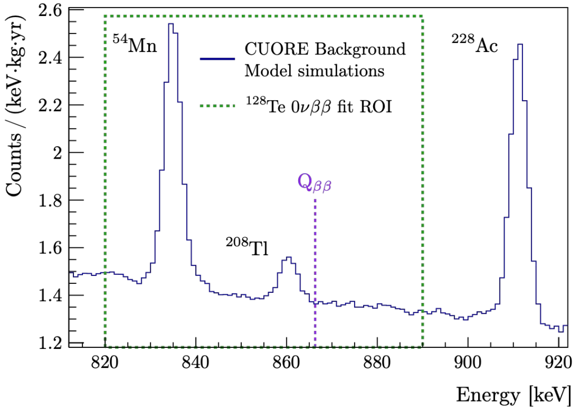
D. Q. Adams *et al.* (CUORE Collaboration), Phys. Rev. C 105, 065504 (2022), https://doi.org/10.1103/PhysRevC.105.065504

### $^{128}$Te 0νββ decay

Q$_{\beta\beta}$= 866.7 keV, natural abundance: 31.74%
Half-life limit @90%C.I.

**$T_{0\nu}^{1/2}$ ($^{128}$Te) > 3.6 × $10^{24}$ yr**

Improved limit of over a factor 30 wrt to previous direct search results, and exceeded the results from geochemical experiments



D. Q. Adams *et al.* (CUORE Collaboration), Phys. Rev. Lett. 129, 222501 (2022), https://doi.org/10.1103/PhysRevLett.129.222501

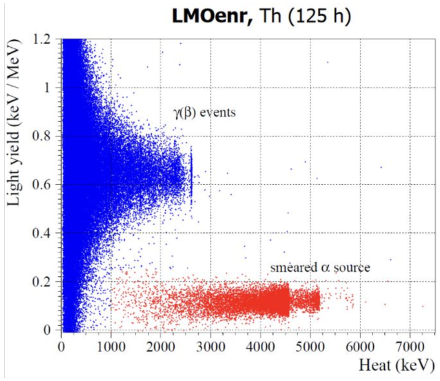
Exposure:
309.33 kg·yr TeO$_2$,
78.56 kg·yr $^{128}$Te

# The CUPID experiment

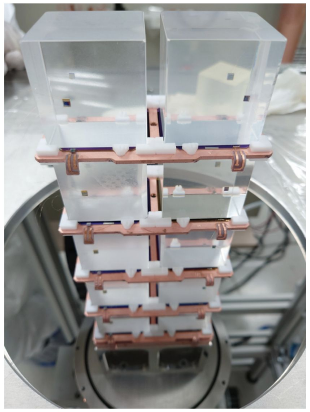
**CUPID: CUORE Upgrade with Particle IDentification**

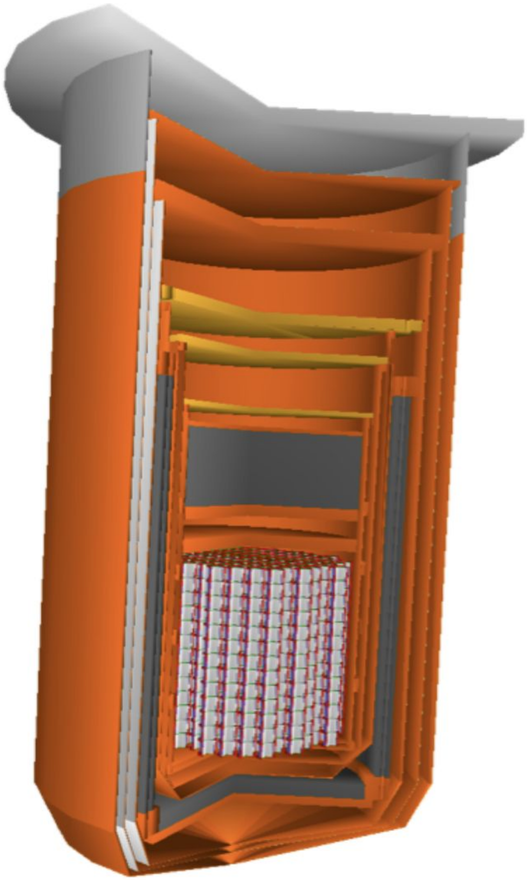
$Li_2{}^{100}MoO_4$ scintillating cryogenic crystals (CUPID-Mo, successful proof of concept)

- **readout of both heat and scintillation light**
- alpha-particle and ββ pileup rejection using light signal
- **$^{100}$Mo ββ decay candidate: $Q_{\beta\beta}$ ~3034 keV**



- Reusing CUORE cryogenic infrastructure @LNGS (Italy)
- Detector array with 1596 $Li_2MoO_4$ scintillating crystals, enriched > 95% in $^{100}$Mo (~250 kg of $^{100}$Mo), paired with Ge-light detectors
- Bkg goal < $10^{-4}$ cts/(keV kg yr),
- Nominal resolution FWHM($Q_{\beta\beta}$) ~ 5 keV
- Status:
  - CUPID tower design demonstrators in progress
  - Conceptual design in progress, projected 3σ discovery sensitivity $m_{\beta\beta}$=12-20 meV ($T_{1/2}$ = 1 x $10^{27}$ yr)





CUPID updates (C.Nones) @TAUP2023