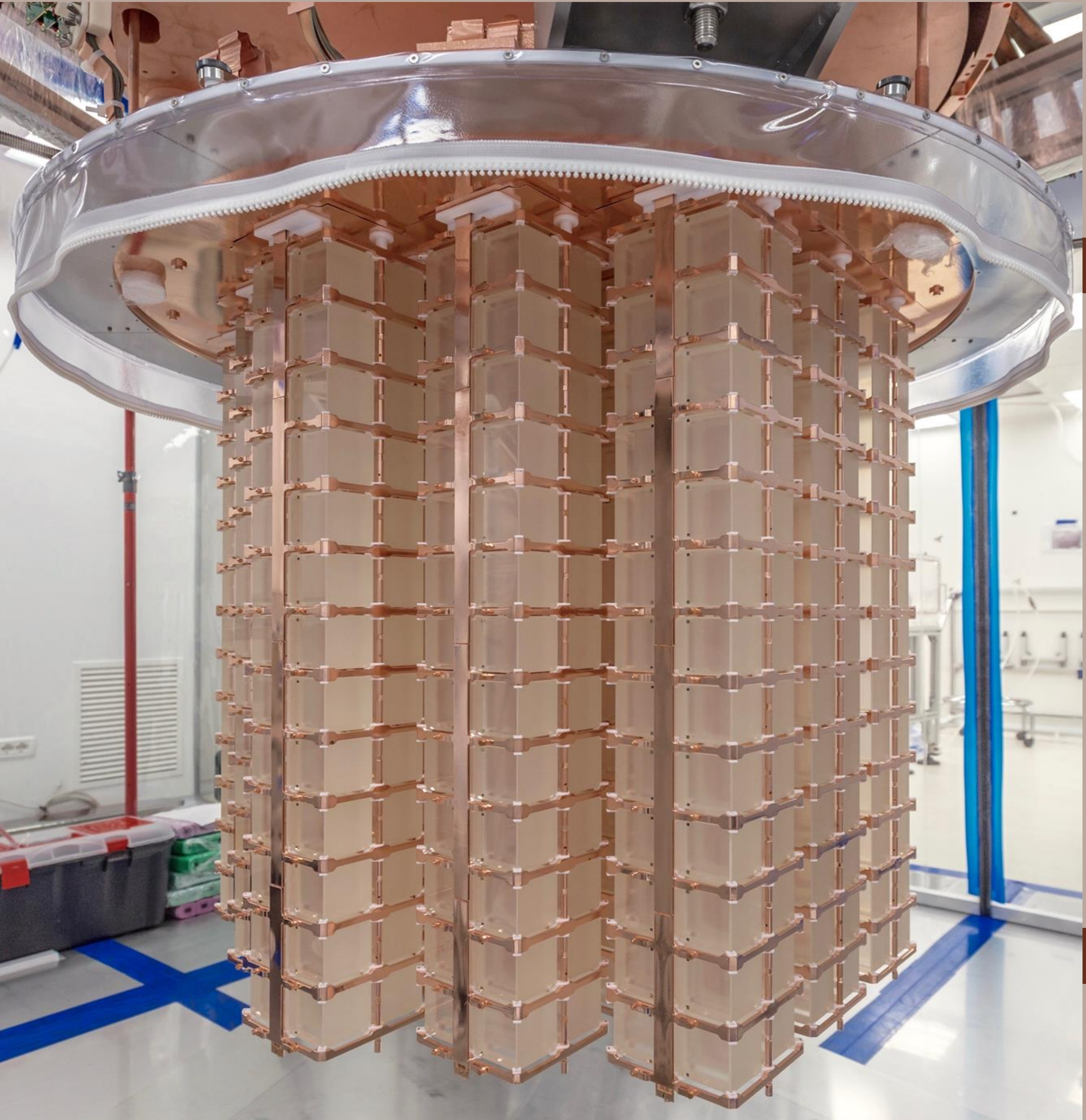


# LATEST RESULTS FROM CUORE

Vivek Sharma

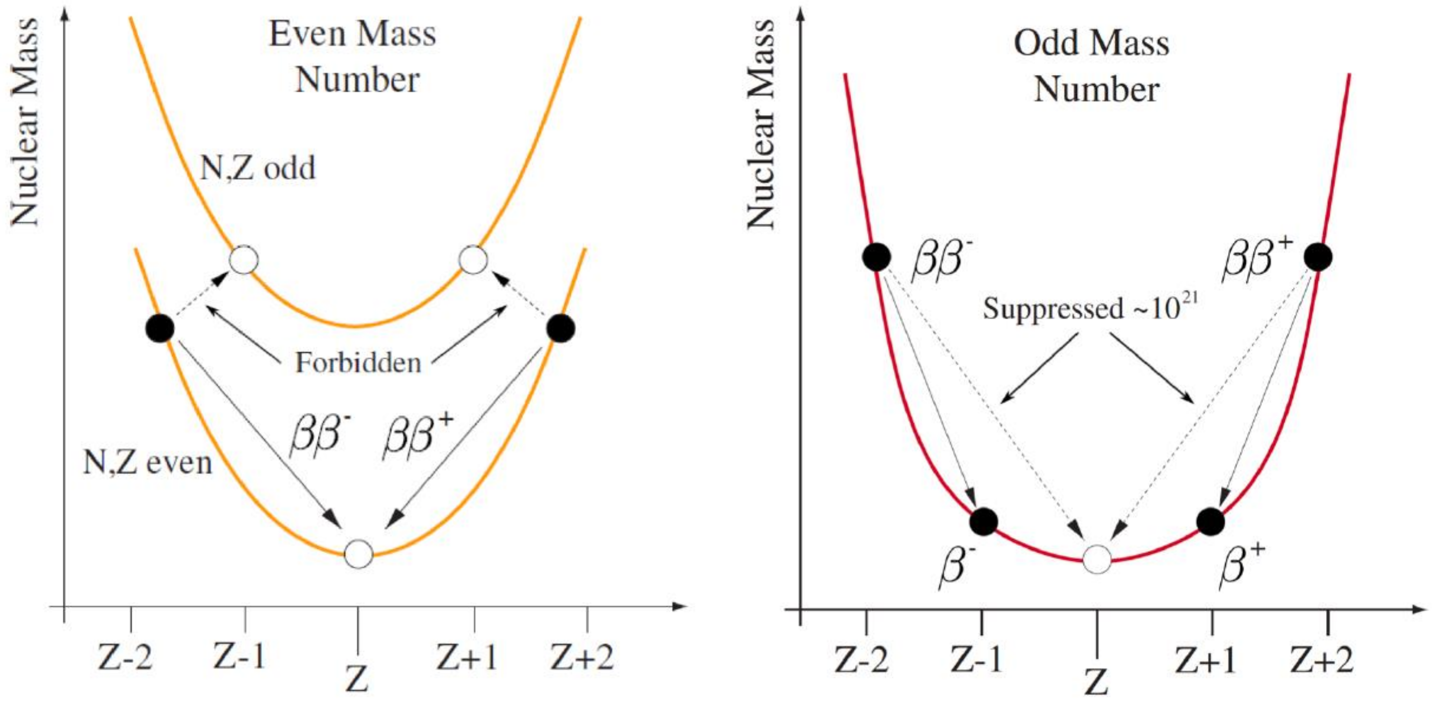
06/26/2023

PASCOS 2023

# 2ν DOUBLE BETA DECAY

- Standard model 2nd order weak transition, extremely rare (half life of $10^{19}$-$10^{22}$ yr)
- Observable when beta decay is kinematically forbidden

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

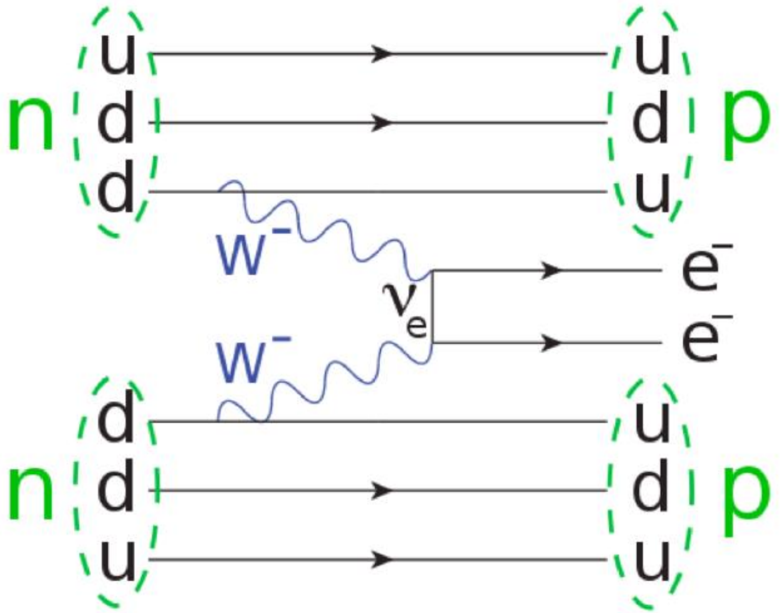


# NEUTRINOLESS DOUBLE BETA DECAY

CUORE

- Beyond the Standard Model phenomenon, can occur if neutrinos are Majorana particles
- Lepton number violating process
- Potentially impact understanding of origins of matter/anti-matter asymmetry
- Constrains neutrino mass hierarchy, scale (model dependent)

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




Light neutrino exchange model

# NEUTRINOLESS DOUBLE BETA DECAY

CUORE

- Experimental observable is **decay rate**
  - Depends on effective Majorana mass **($m_{\beta\beta}$)**
  - Directly related to absolute neutrino mass scale
- The decay rate also depends on various nuclear and atomic effects.
- Limit on ($m_{\beta\beta}$) can help rule out Inverted Hierarchy (model dependent)

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{< m_{\beta\beta} >^2}{m_e^2}$$

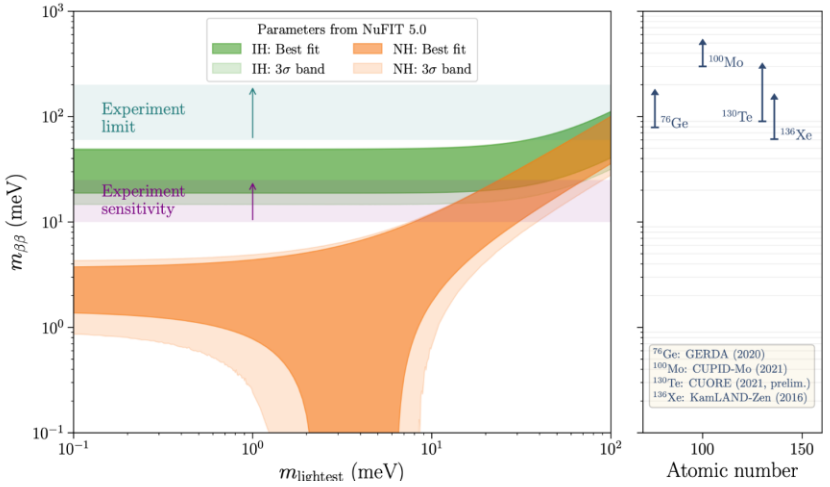
Effective Majorana mass

Majorana phases

$$m_{\beta\beta} = |\sum_{i=1}^{3} |U_{ei}|^2 m_i e^{i\alpha_i}|$$

PMNS matrix

Individual neutrino masses

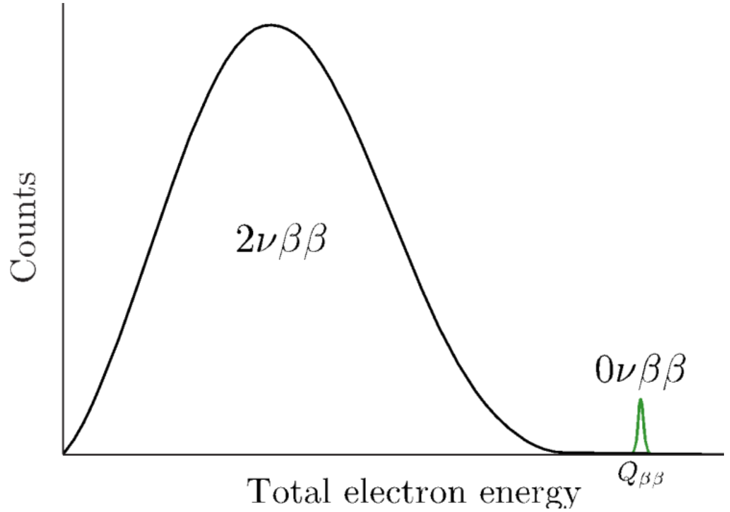



https://github.com/toej93/LobsterPlot

# DETECTION CHALLENGES

CUORE

- $0\nu\beta\beta$ signal is the summed electron energy at Q-value
  - **Exceptional resolution** essential to differentiate between the $0\nu\beta\beta$ and $2\nu\beta\beta$ spectra
  - **High Q-value** for practically observable half-life and avoiding gamma-ray backgrounds
- Very **low background** required for a detectable signal, going underground is necessary
- **Exposure** needs to be maximized
  - Large detector mass
  - Efficient duty cycle to lengthen livetime
- **Choice of isotope** should be compatible with detector technique




$$T^{0\nu}_{1/2} \propto Q^{-5}$$

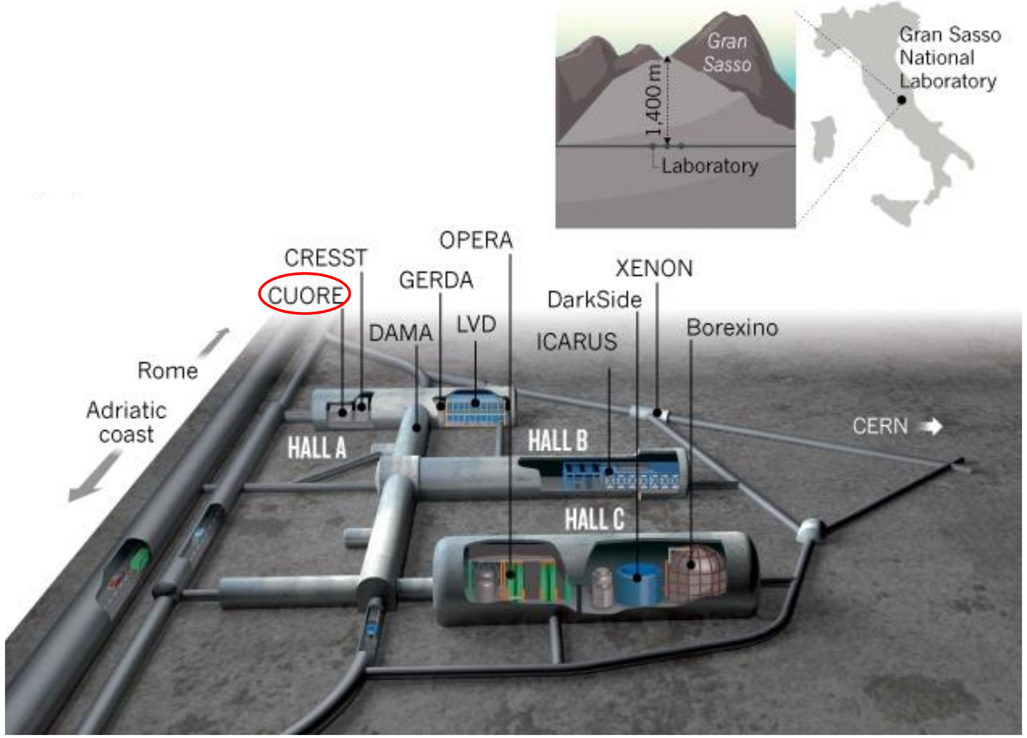
$$T^{0\nu}_{1/2}(1\sigma) = ln(2)\frac{a\epsilon N_A \eta}{W}\sqrt{\frac{mt}{b\Delta E}}$$

1-sigma sensitivity

- $a$: Isotopic abundance
- $\epsilon$: Efficiency
- $N_A \eta$: Number of nuclei per molecule
- $W$: Molar Mass
- $m$: Detector mass
- $t$: Livetime
- $b$: Bkg rate/ energy/mass
- $\Delta E$: Energy Resolution

# CUORE

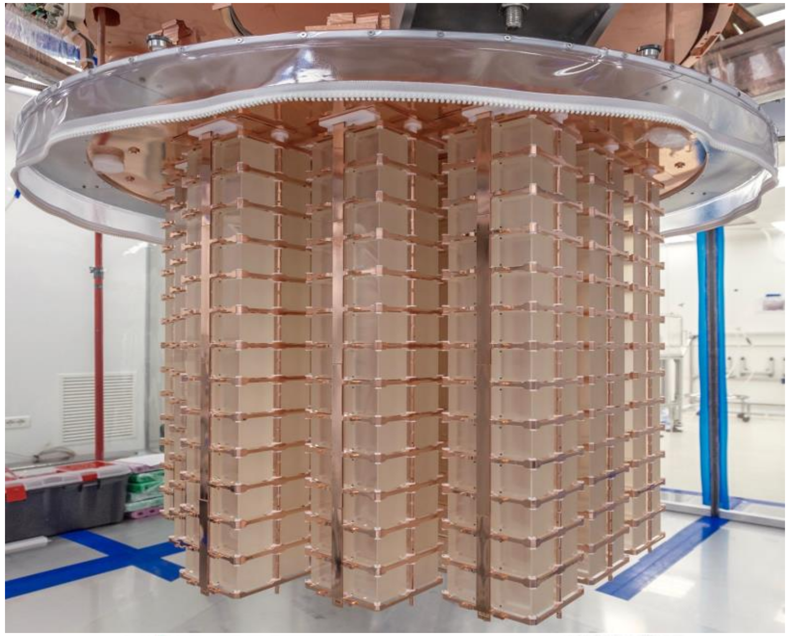
- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- Located at Hall A of Gran Sasso National Laboratory
- **Low Background**: **3600 m.w.e** of overburden, muon rate 6 orders of magnitude less than surface, extensive shielding
- **High Q-value:** $^{130}Te$ has a ββ Q-value of 2527.5 keV
- **Exceptional resolution:** Operation at ~11 mK, resolution of ~8 keV at 2615 keV
- **Exposure:** 742 kg $TeO_2$, 206 kg $^{130}Te$ (34% natural abundance)

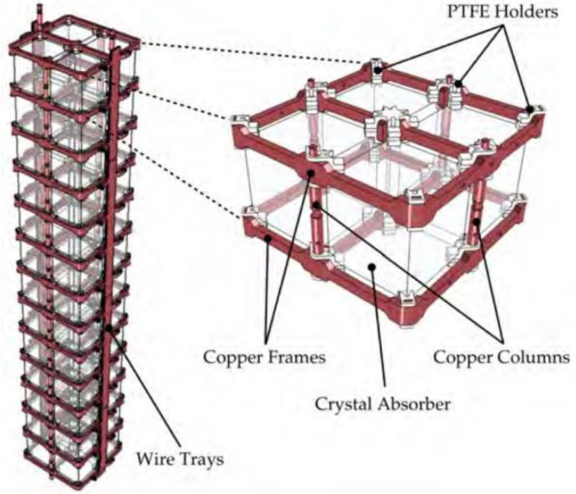



Images courtesy of LNGS: https://www.lngs.infn.it/en

# CUORE CONSTRUCTION

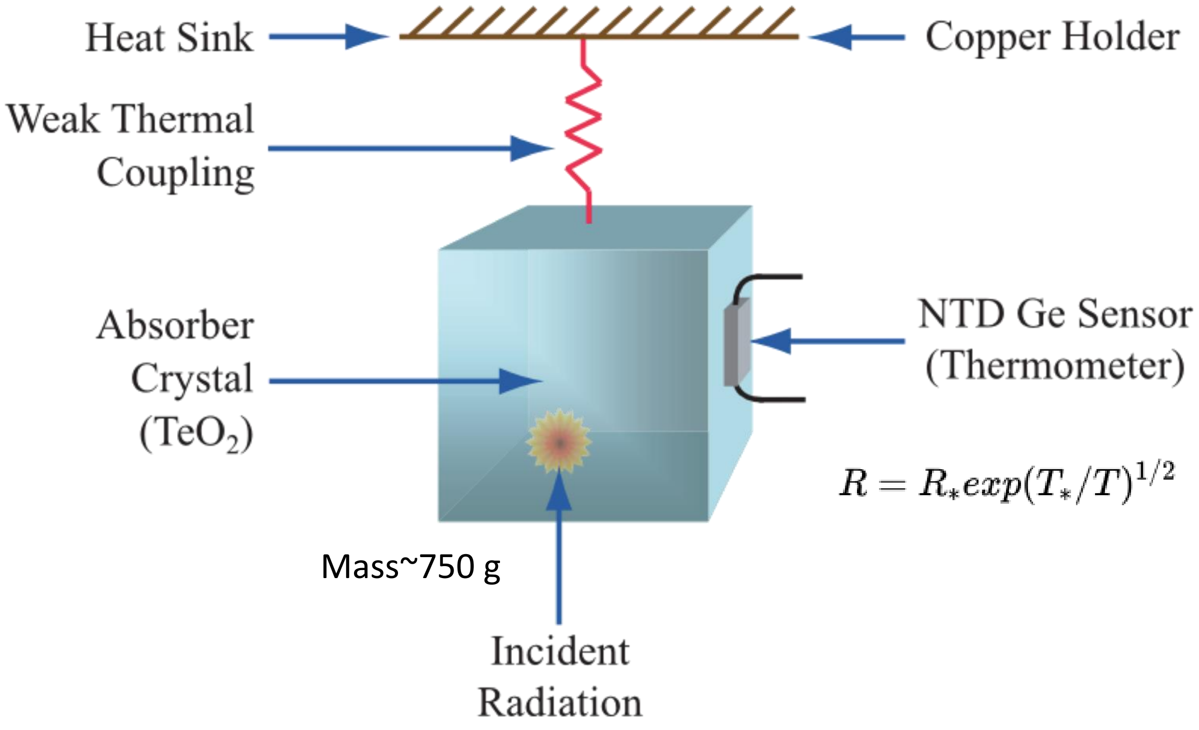
- 988 natural $TeO_2$ crystals
  - Total mass: 742 kg
  - $^{130}Te$ mass: 206 kg
  - 5x5x5 $cm^3$, arranged in 19 towers
- Housed in copper frame and held in place by PTFE spacers
  - Copper linked to thermal bath
  - PTFE spacers are also weak thermal links and contract more at low temperatures
- Tightly spaced crystals allow for coincidences to be exploited for background reduction





# DETECTION PRINCIPLE

- 988 $TeO_2$ crystals operated as bolometers; energy deposited is registered as temperature change
  - Read out by a NTD (**Neutron Transmutation Doped**) Ge thermometer
- Signal strength and detector resolution depend strongly on temperature (Debye's Law)
  - $C \propto T^3$
  - Detector operated at **~11 mK**
- In CUORE, we observe an average resolution of **~8 keV FWHM at 2615 keV**†



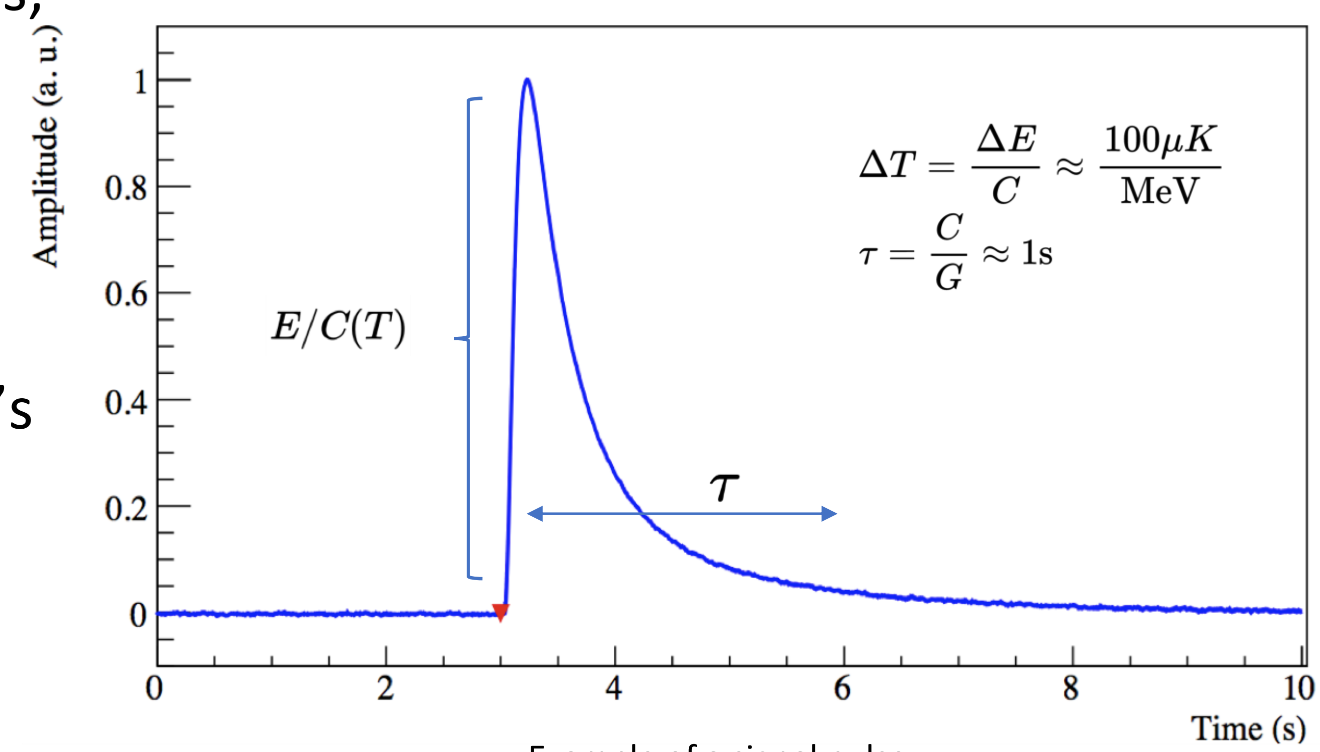

Schematic of a CUORE bolometer.
(cuore-lngs.infn.it)

†CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

# DETECTION PRINCIPLE

CUORE

- 988 $TeO_2$ crystals operated as bolometers; energy deposited is registered as temperature change
  - Read out by a NTD (**Neutron Transmutation Doped**) Ge thermometer
- Signal strength and detector resolution depend strongly on temperature (Debye's Law)
  - $C \propto T^3$
  - Detector operated at **~11 mK**
- In CUORE, we observe an average resolution of **~8 keV FWHM at 2615 keV**†

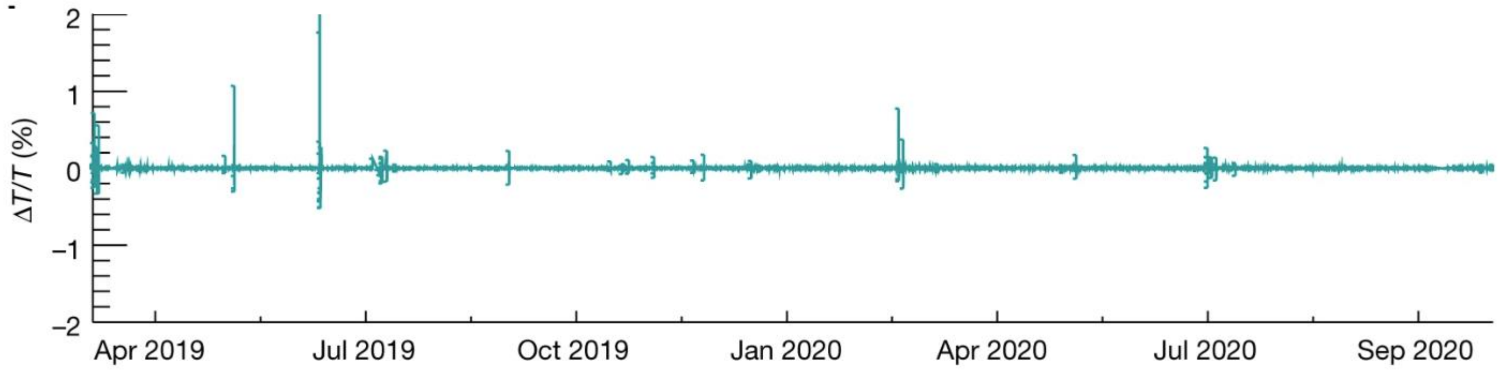



Example of a signal pulse

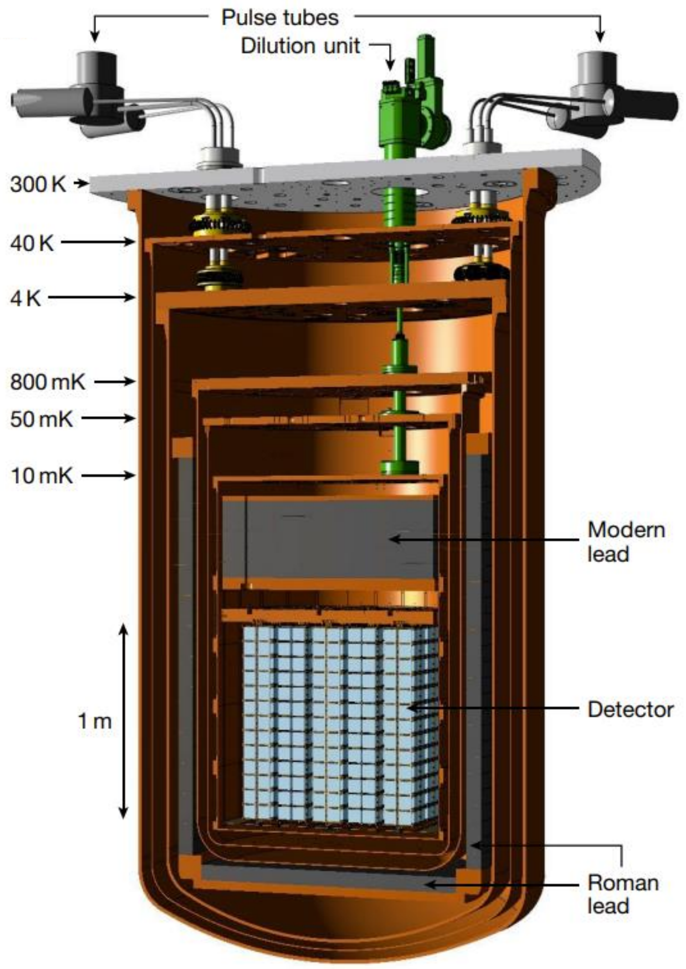
†CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

# CRYOGENICS

- Operating temperature of 11 mK is achieved via multistage cryogen-free dilution refrigerator
  - Pre-cooling performed by pulse tube cryocoolers
  - Multistage design shields from thermal radiation
- Cooling power of 4 µW at 11 mK
  - Experimental volume of 1 $m^3$ and payload of 1.5 tonne
  - Demonstrated stability over years of data taking




CUORE relative temperature fluctuation over time*

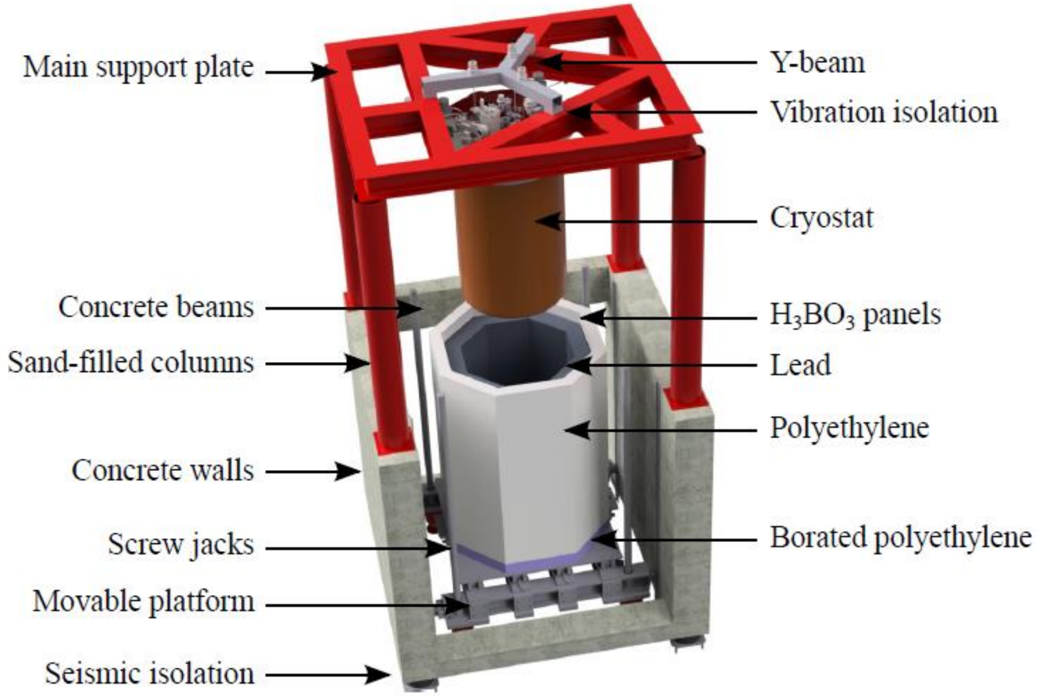



The CUORE cryostat*

*CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

# SHIELDING

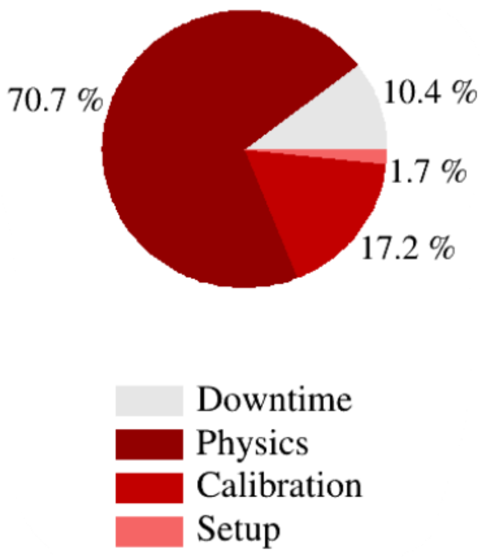
- Experimental setup is externally shielded from radiation by multiple layers
- Neutron background:
  - Lateral 18 cm polyethylene layer with 2 cm thick $H_3BO_3$ panels
  - 20 cm thick borated polyethylene at the bottom
- Gamma background:
  - 25 cm thick lead laterally and at the bottom

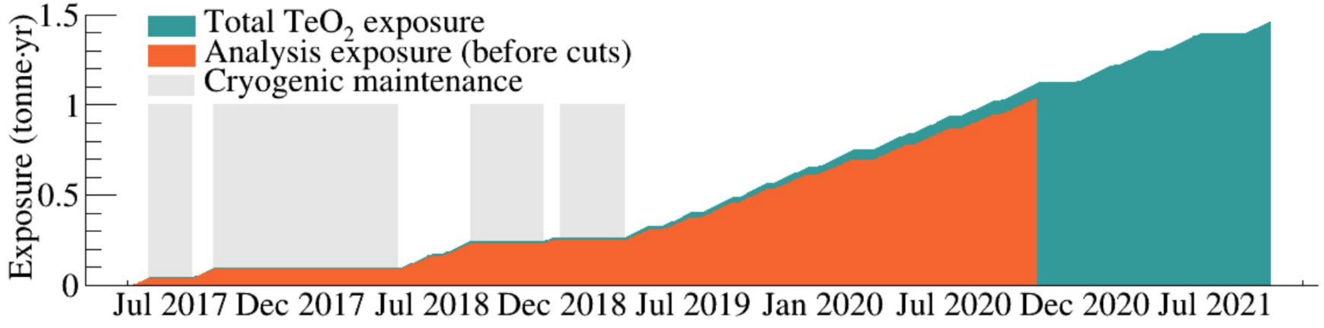



External structure of CUORE

# CUORE DATA TAKING

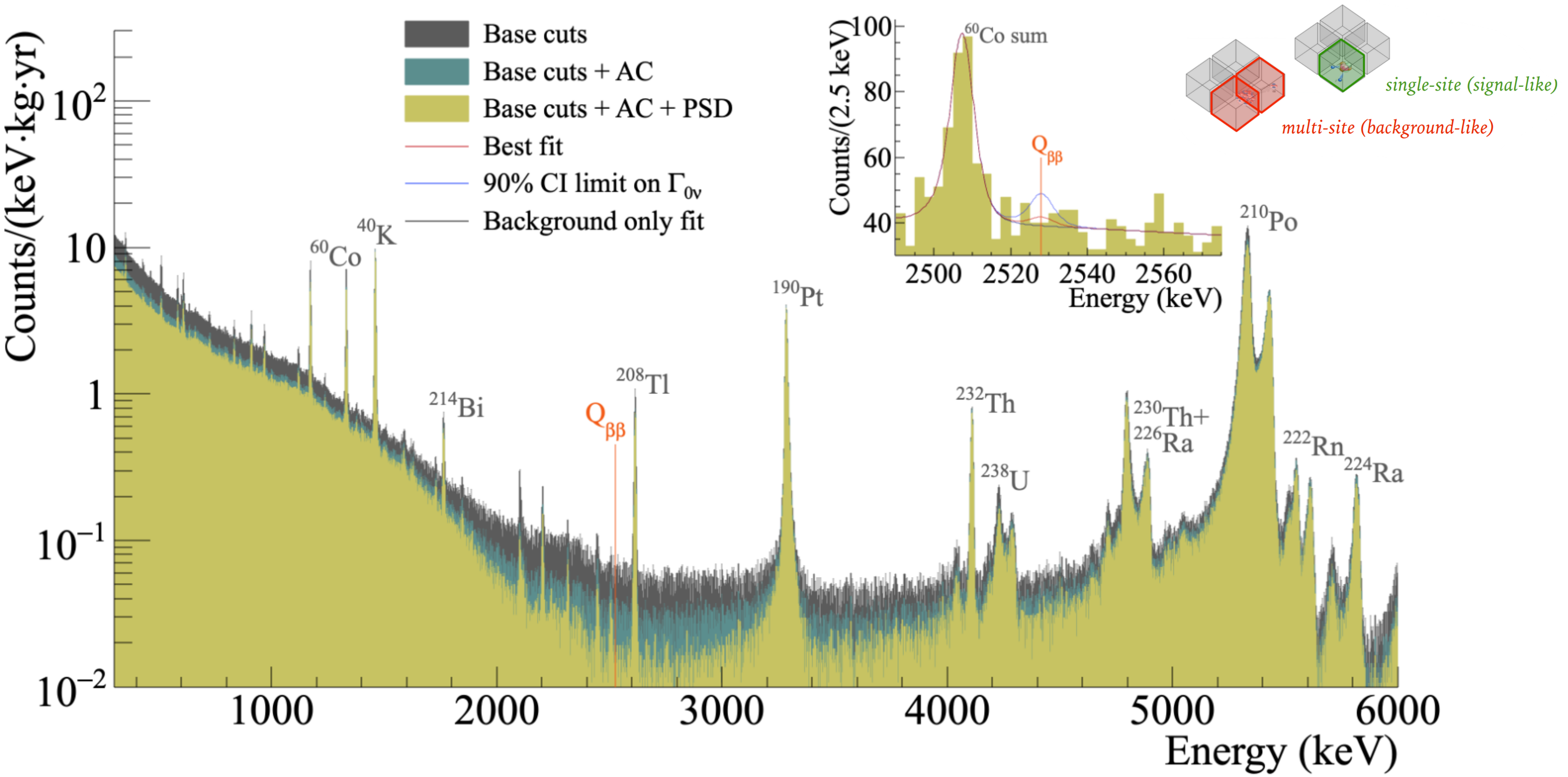
- Data taking began in 2017
  - Software and hardware optimizations since have improved stability of data taking
- Steady data taking since 2019 with 90% uptime
- Smooth transition to remote detector monitoring after pandemic lockdown
- 0νββ results for 1038 kg.yr exposure reported in Nature*



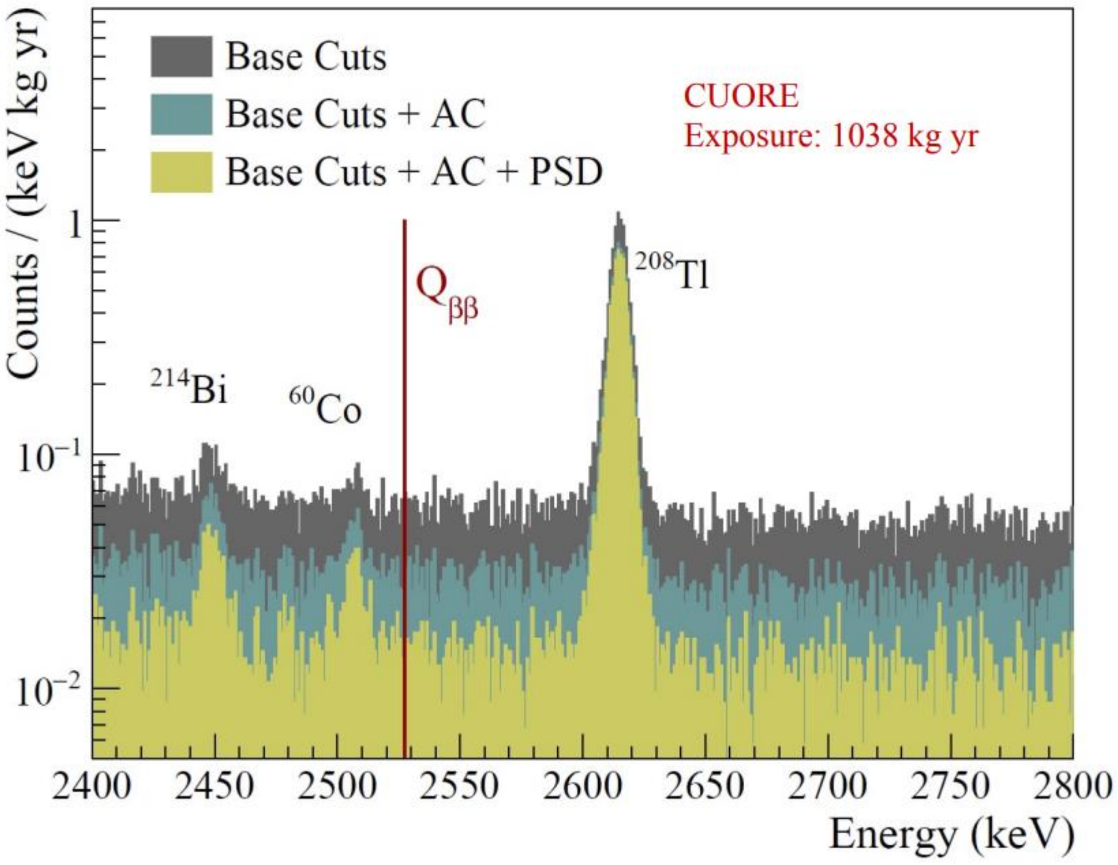

*CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

# 1 TONNE-YR DATA RELEASE



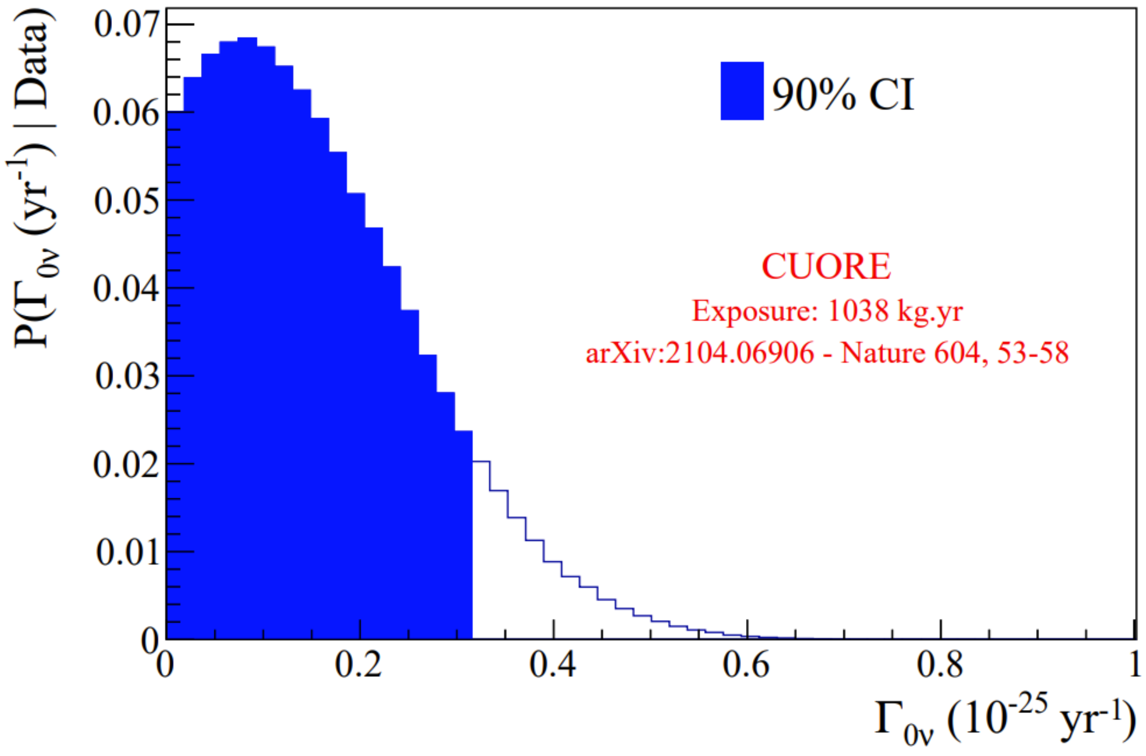
# BACKGROUND IN ROI

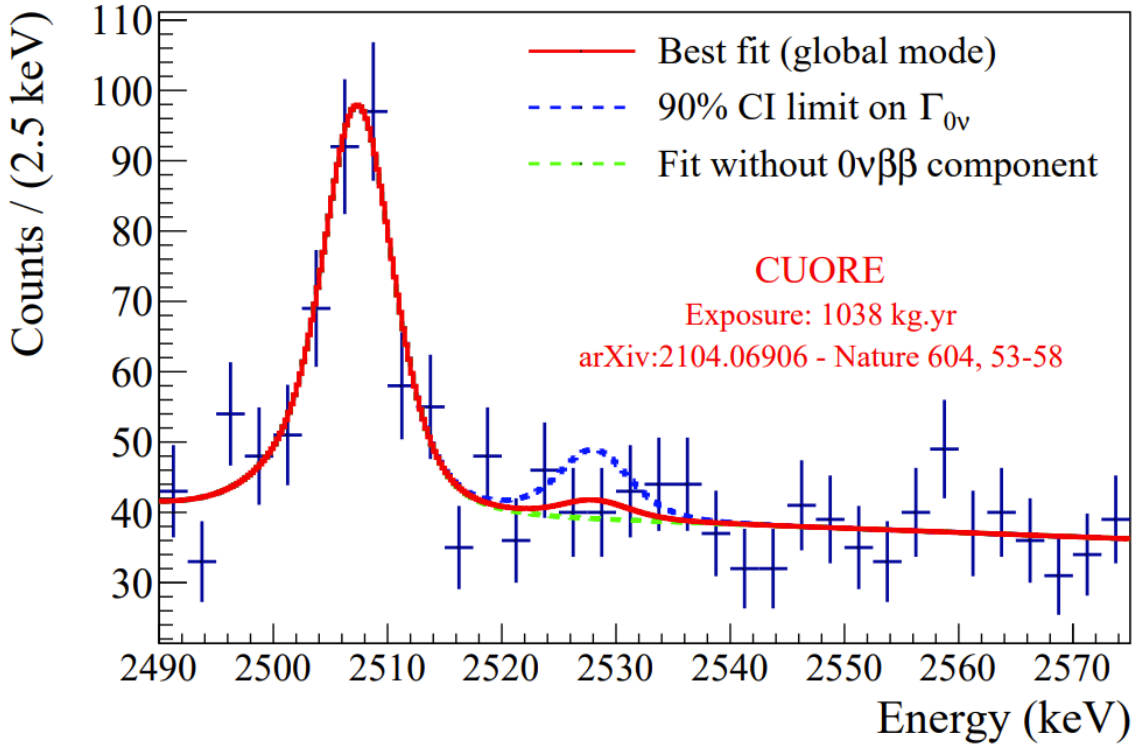
- Alpha region:
  - Flat background in [2650, 3100] keV
  - 1.40(2) x $10^{-2}$ counts/(keV kg yr)*
- $Q_{\beta\beta}$ region
  - Flat background + $^{60}Co$ peak in [2490, 2575] keV
  - 1.49(4) x $10^{-2}$ counts/(keV kg yr)*
- Background dominated by degraded alpha energy depositions (90%)




*CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

# FIT RESULTS




$$T^{0\nu}_{1/2} > 2.2 \times 10^{25} \mathrm{yr} (90\% \text{ C.I.})$$

$$b = 1.49(4) \times 10^{-2} \text{counts}/(\text{keV kg yr})$$

*CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

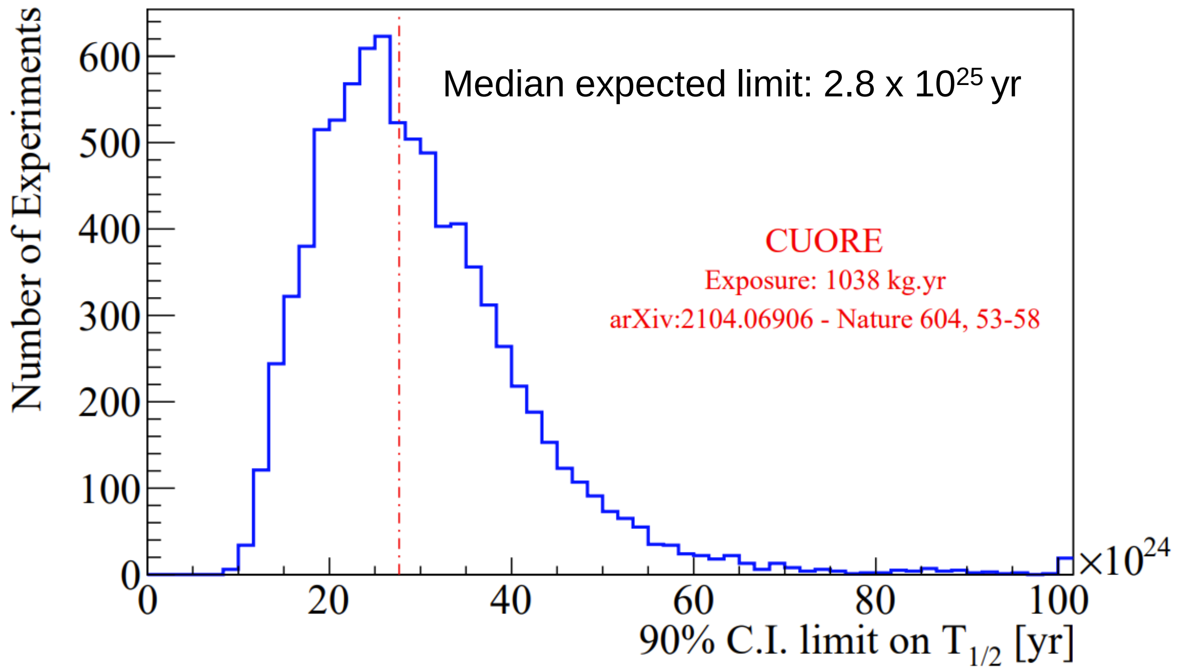
# SENSITIVITY

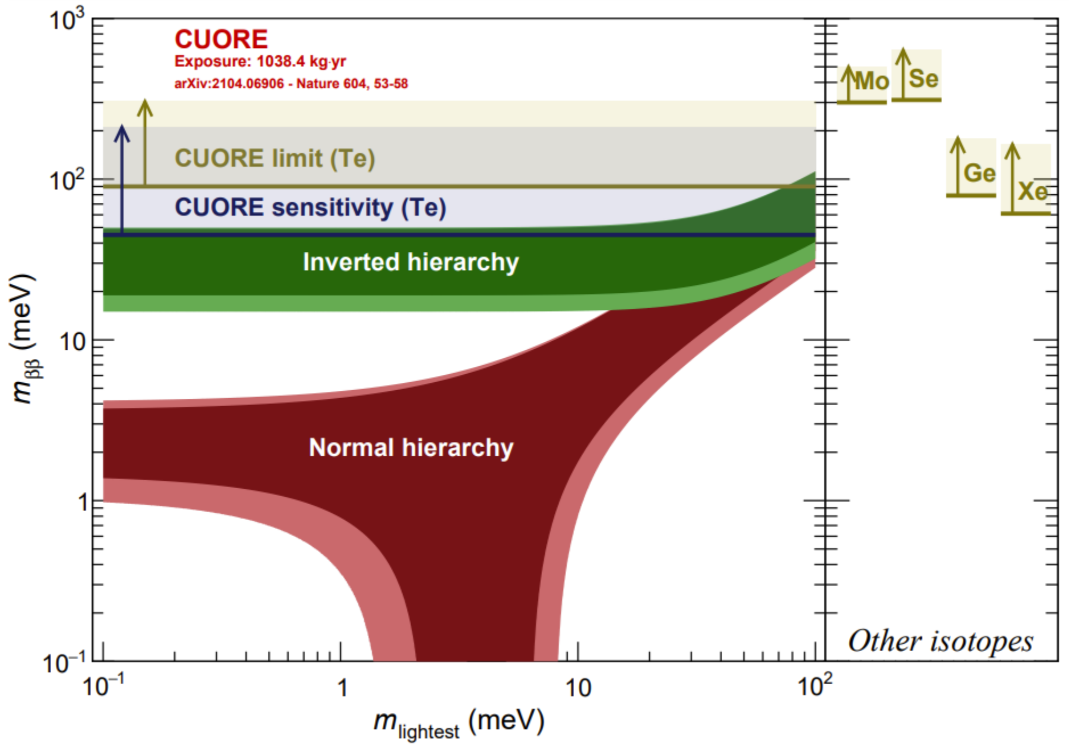
- Median exclusion sensitivity: 2.8 x $10^{25}$ yr
  - $10^4$ toy experiments with background only hypothesis
  - Background and $^{60}$Co event rate from fit to data
- $m_{\beta\beta}$ < 90 – 305 meV
  - Light Majorana neutrino exchange model
  - Range depends on nuclear matrix elements

**$m_{\beta\beta}$ result** :
Cuore collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

**Limits on other isotopes:**
GERDA Collaboration, Phys. Rev. Lett. 125, 252502 (2020) https://doi.org/10.1103/PhysRevLett.125.252502
CUORE Collaboration, Eur. Phys. J. C (2017) 77: 532 https://doi.org/10.1140/epjc/s10052-017-5098-9
CUPID-Mo Collaboration https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.181802
CUPID-0 Collaboration, Phys. Rev. Lett. 123, 032501 (2019) https://doi.org/10.1103/PhysRevLett.123.032501
KamLAND-Zen Collaboration, Phys. Rev. Lett. 117, 082503 (2016)
https://doi.org/10.1103/PhysRevLett.117.082503

**Oscillation parameters:**
Esteban, I. et al., J. High En. Phys. 2020 (178) https://doi.org/10.1007/JHEP09(2020)178

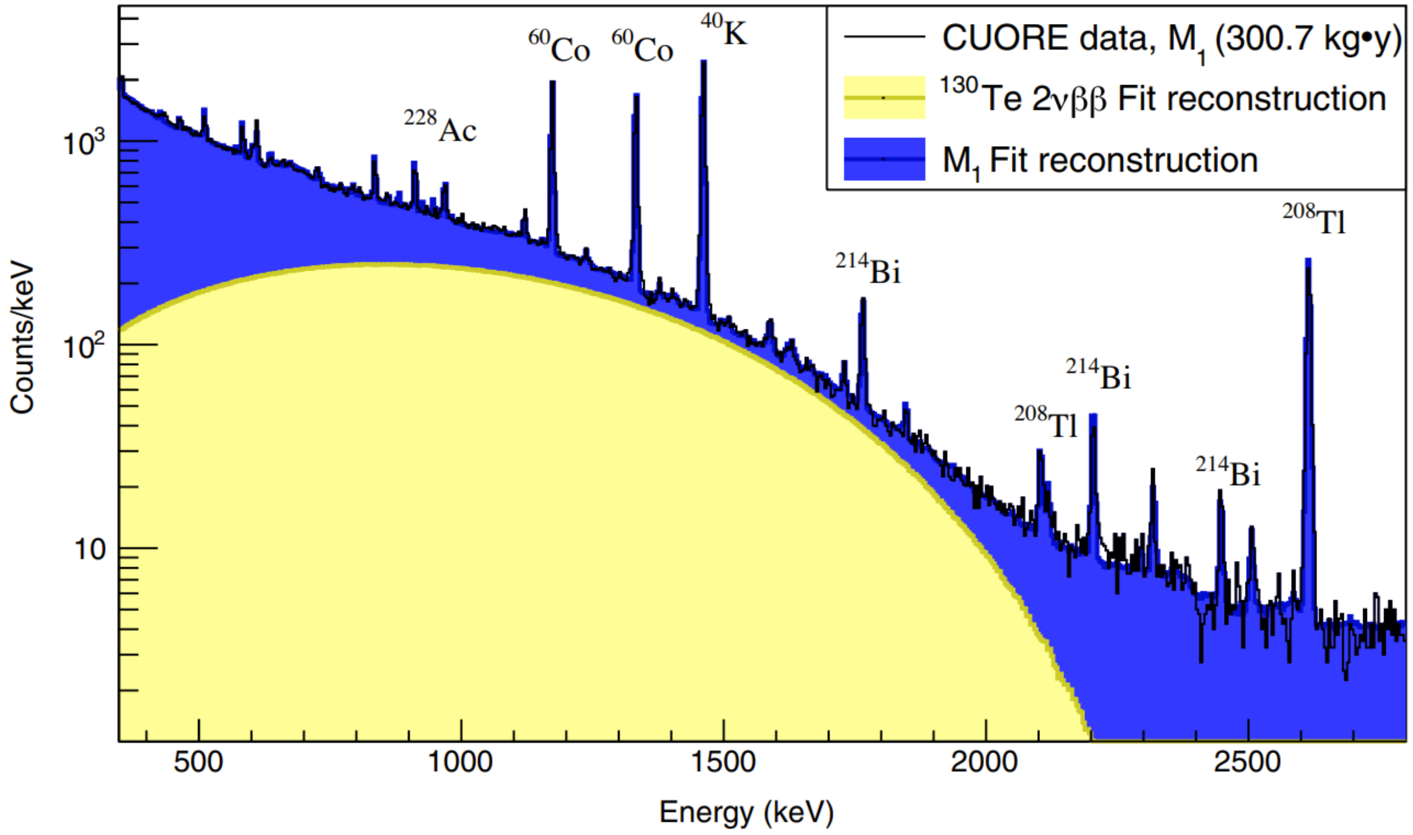


# DOUBLE BETA DECAY RESULTS

CUORE

- Double beta decay simulated in Geant4 with CUORE geometry and detector response
- Spectrum reconstructed by simultaneous fit of data with 62 MC simulated sources (2νββ + surface and bulk contaminations + muons)
  - MCMC Bayesian approach
  - Uniform prior for sources except muons
- For 900-2000 keV, more than 50% counts are 2νββ events




$$T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.12}_{-0.15}(\text{syst.}) \times 10^{20} yr$$

D. Q. Adams et al.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.171801

# Conclusion

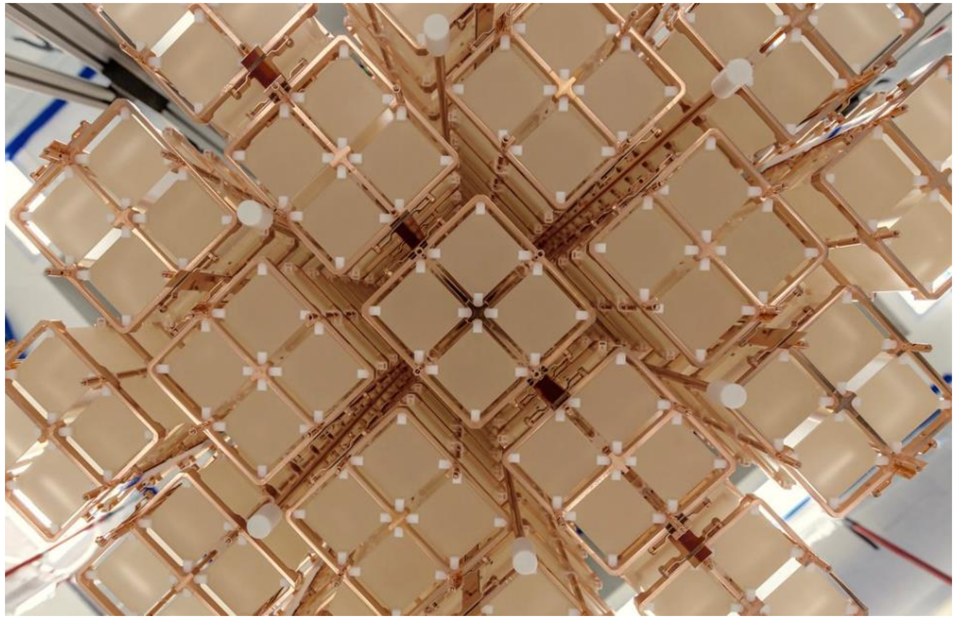
- CUORE has achieved 1 tonne year of exposure and continues stable data taking
- No evidence of $0\nu\beta\beta$ decay with 1038 kg.yr of data
  - Bayesian 90% C.I. limit*

$$T^{0\nu}_{1/2} > 2.2 \times 10^{25}\mathrm{yr}(90\%\ \mathrm{C.I.})$$

  - Effective Majorana mass upper limit: 90-305 meV
- $2\nu\beta\beta$ half-life measurement with 300.7 kg.yr of data†

$$T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(\mathrm{stat.})^{+0.12}_{-0.15}(\mathrm{syst.}) \times 10^{20} yr$$

- Stay tuned for higher exposure results!



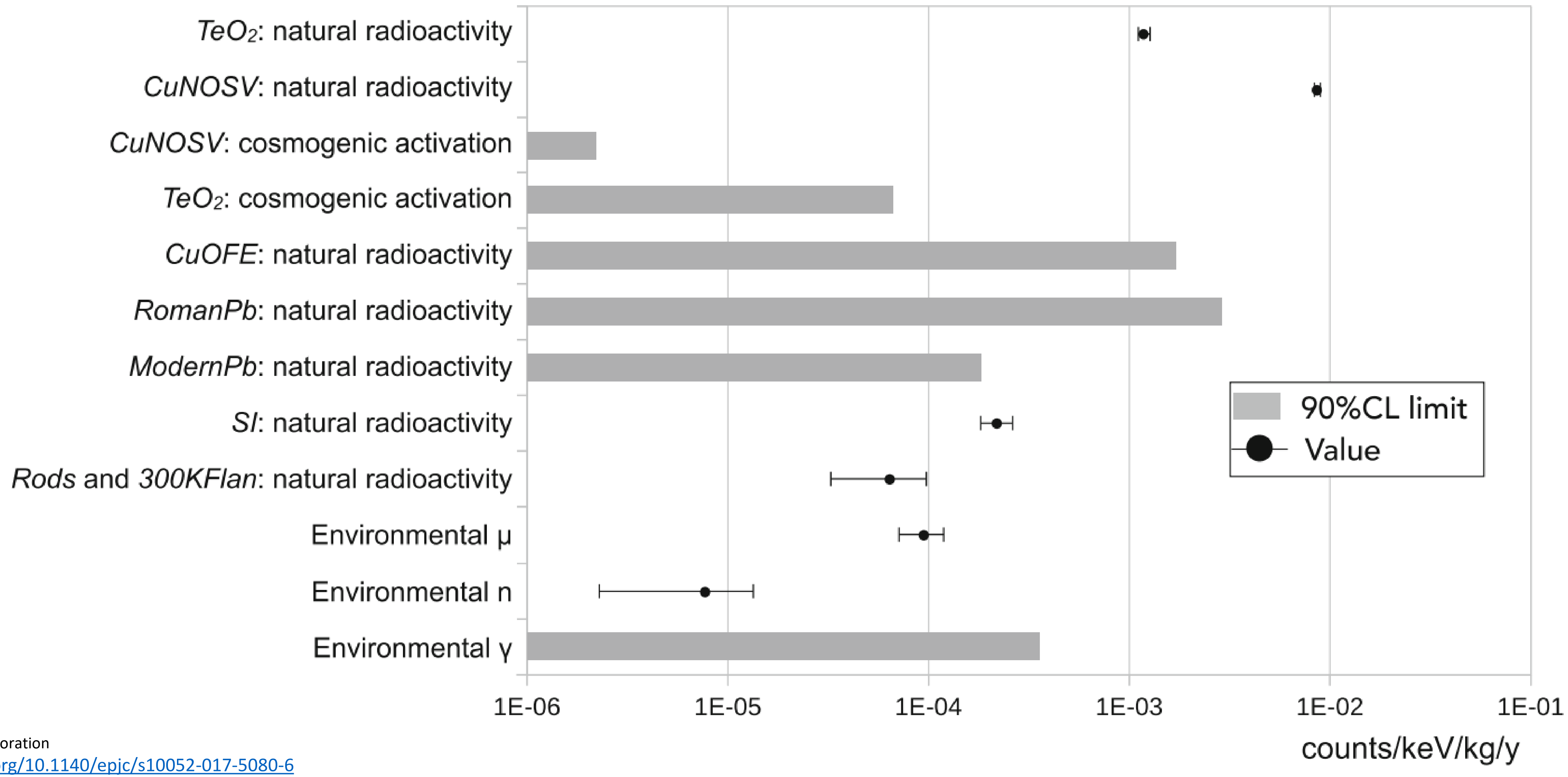
*CUORE collaboration
https://www.nature.com/articles/s41586-022-04497-4.pdf

†D. Q. Adams et al.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.171801

# EXTRA SLIDES

# BACKGROUND BUDGET

CUORE




*CUORE collaboration
https://doi.org/10.1140/epjc/s10052-017-5080-6

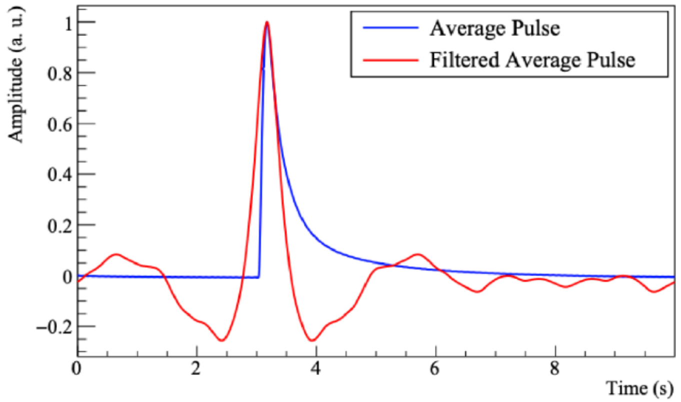
# CUORE DATA PROCESSING

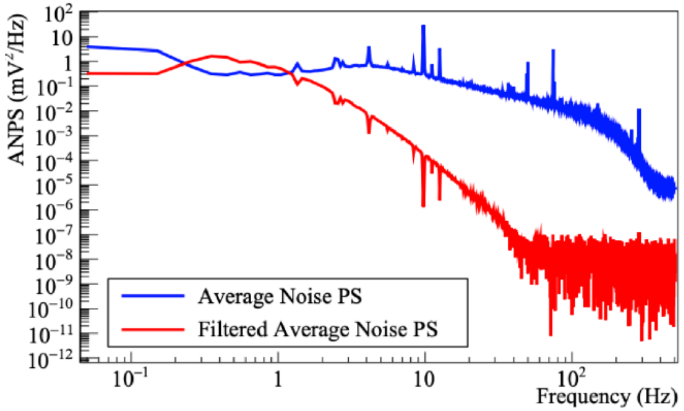
- Amplitude Evaluation
  - Using Optimum waveform filter to estimate amplitude of pulse

$$H(\omega_k) = h\frac{s^*(\omega_k)}{N(\omega_k)}e^{-J\omega_k i_M}.$$

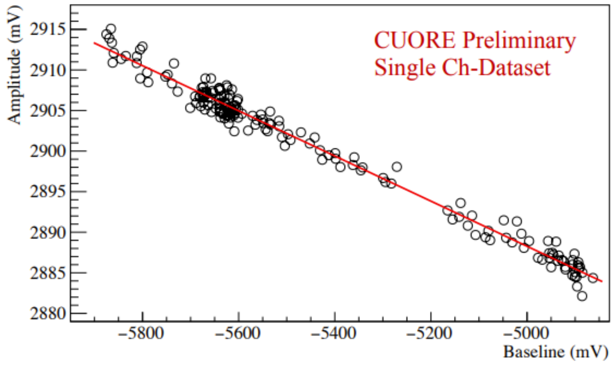
$s^*(\omega_k)$ → Average Pulse

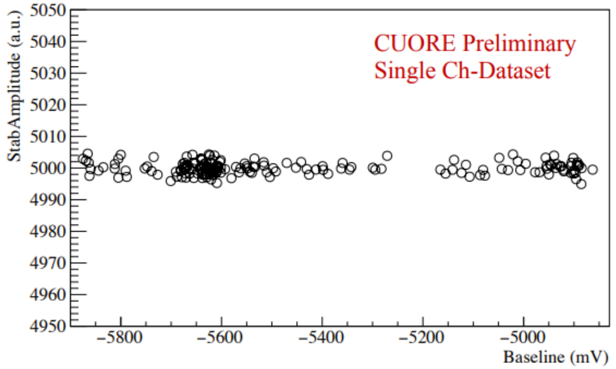
$N(\omega_k)$ → Average Noise



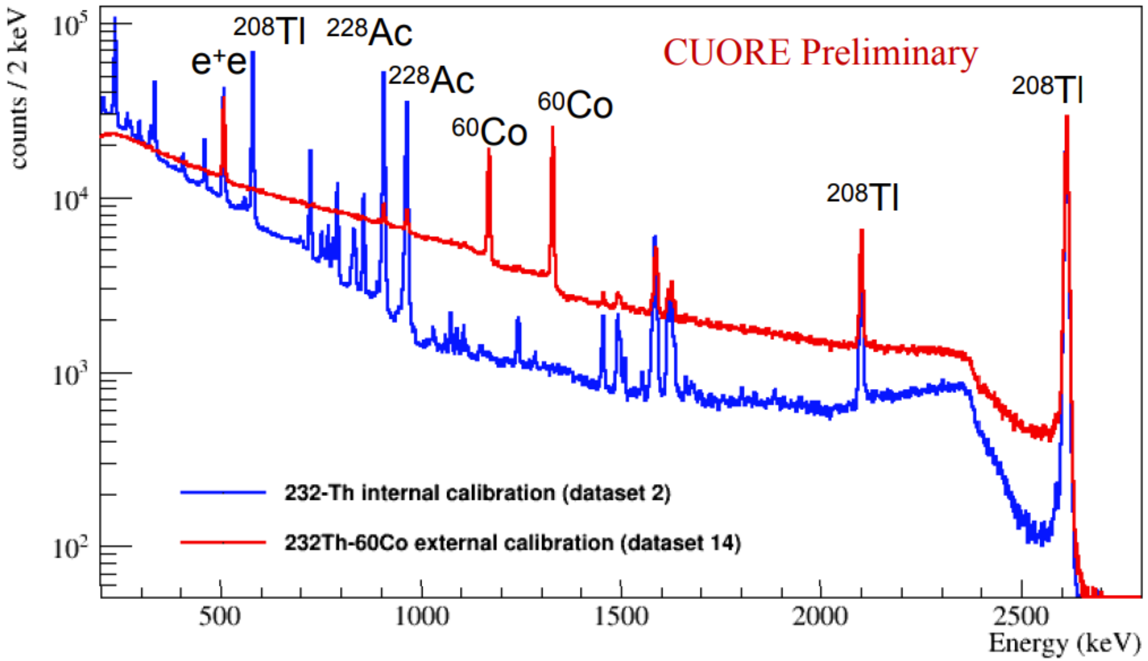

- Gain Stabilization
  - Eliminating gain dependence on temperature using periodically injected pulses



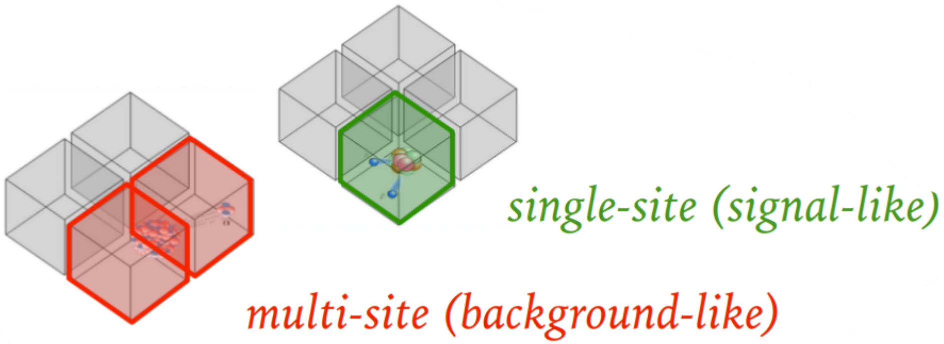



# CUORE DATA PROCESSING

- Calibration
  - First 3 datasets used internal $^{232}Th$ source
  - Later datasets calibrated with external $^{232}Th$-$^{60}Co$ source

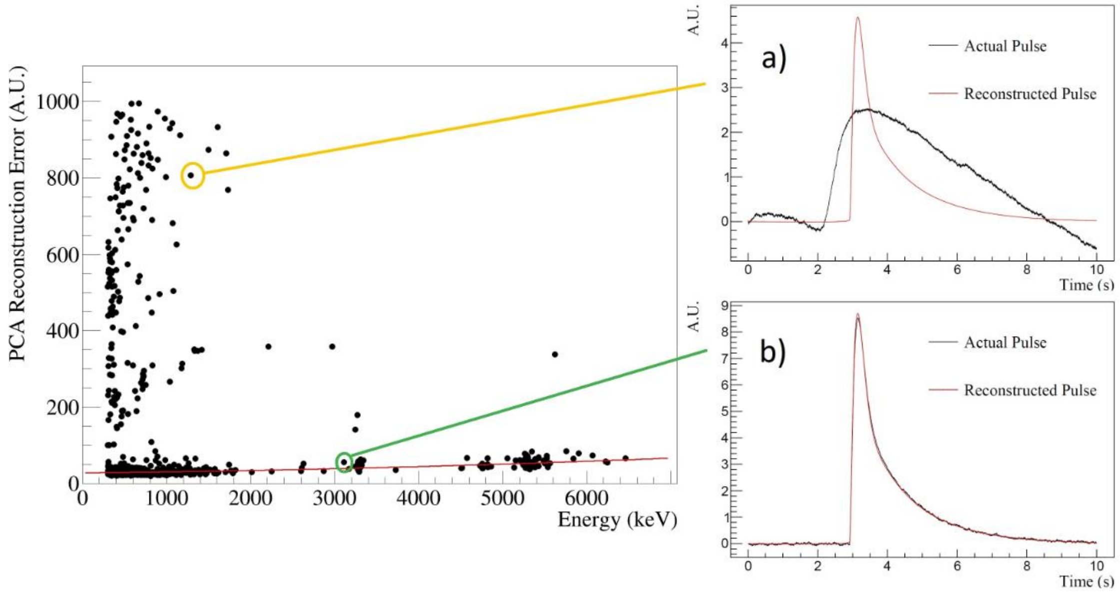



- Coincidences
  - 88% of 0νββ events occur in a single crystal
  - Applying anti-coincidence veto

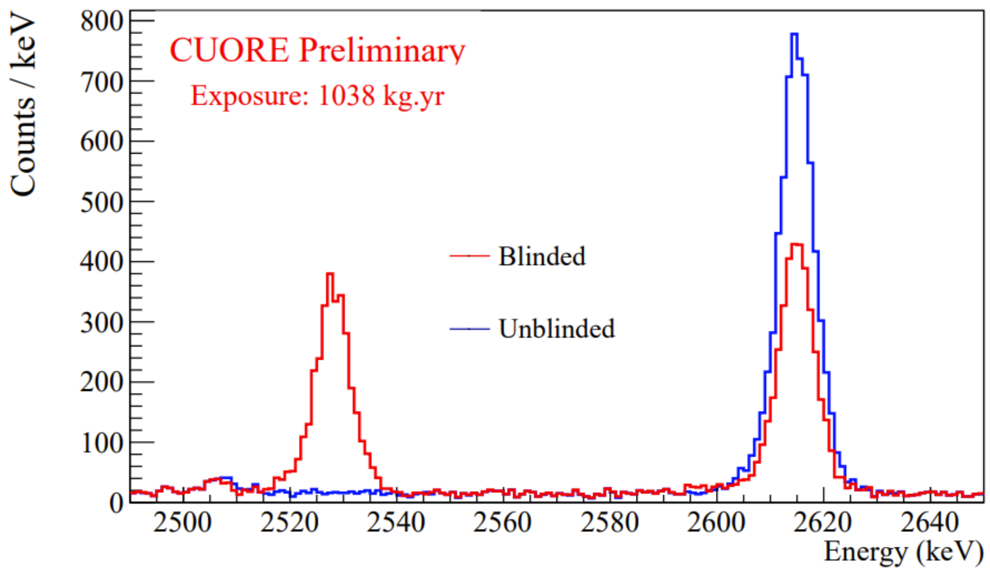


# CUORE DATA PROCESSING

- Pulse Shape Discrimination
  - Using PCA (Principal Component Analysis) to eliminate pulses with a non-physical shape

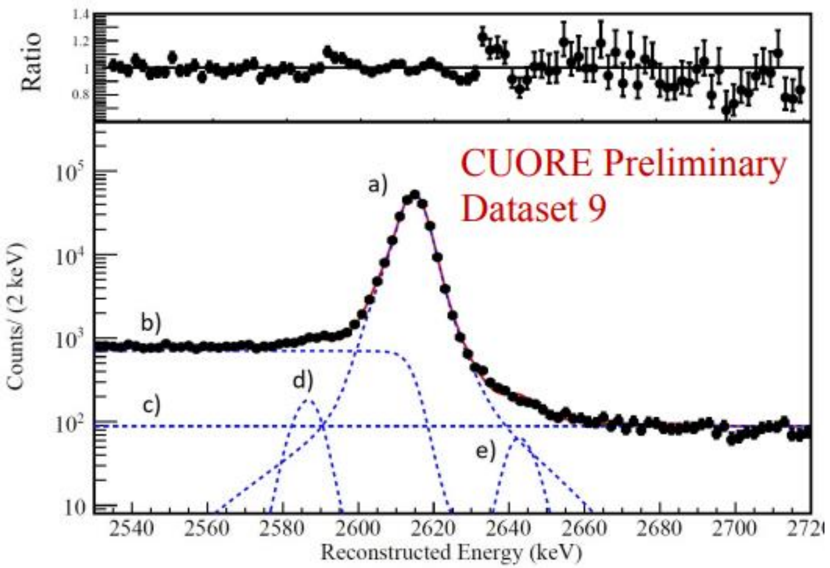


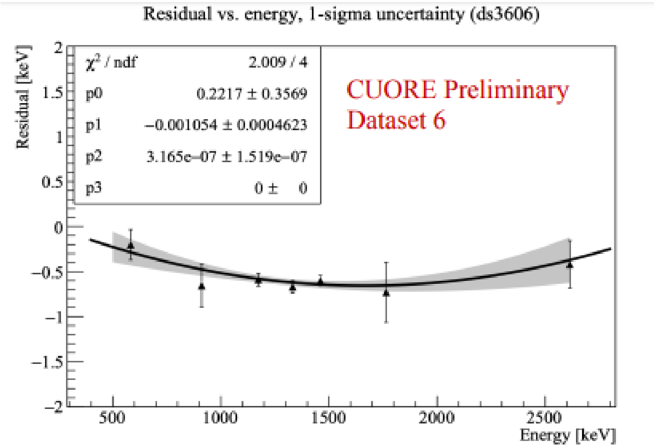

- Data Blinding
  - Blind ROI using events from $^{208}$Tl peak for high level analysis

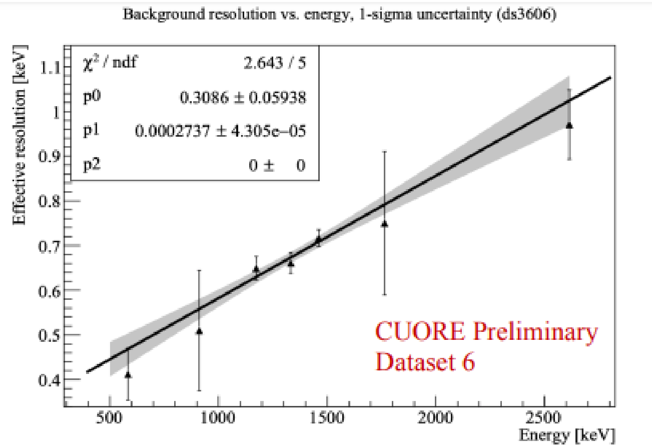


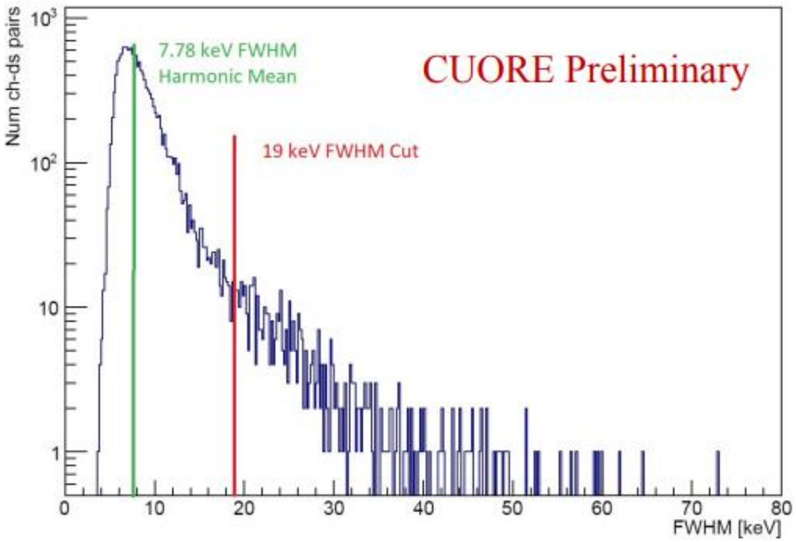
# CUORE DETECTOR RESPONSE

- Fit 2615 keV calibration peak for each channel
  - 3-Gaussian signal peak
  - Compton background
  - Flat background
  - 30 keV X-ray escape peak
  - 30 keV X-ray sum peak
- Scale detector response from 2615 keV calibration fit to peaks in physics data



# CUORE UPGRADE WITH PARTICLE IDENTIFICATION

CUPID

- Next generation $0\nu\beta\beta$ decay search.
  - Scintillating bolometer technology.
  - Extremely good energy resolution, flexible choice of isotope.
- CUPID builds on CUORE, the largest bolometric array ever built.
  - Established and well understood infrastructure and environment.
  - CUORE has demonstrated stable and reliable operation over multiple years of exposure.
- Particle identification with scintillating $Li_2MoO_4$ bolometers has been demonstrated in the CUPID-Mo pilot experiment.*
  - Isotopic enrichment and crystals growth has been demonstrated and can be done at scale.*
- Background index goal of $<10^{-4}$ counts/(keV·kg·yr).
  - Data driven based on CUORE, CUPID-0, and CUPID-Mo experiments.*
- Probe the full Inverted Hierarchy region down to $m_{\beta\beta}<12$ meV ($3\sigma$, favorable NME).
  - Using only 240 kg of $^{100}Mo$.
- Next-next generation CUPID-1T capable of probing into Normal Hierarchy, or multiple isotope precision measurements in Inverted Hierarchy.

*https://cupid.lngs.infn.it/doku.php?id=cupid_pub:start, arXiv:1907.09376

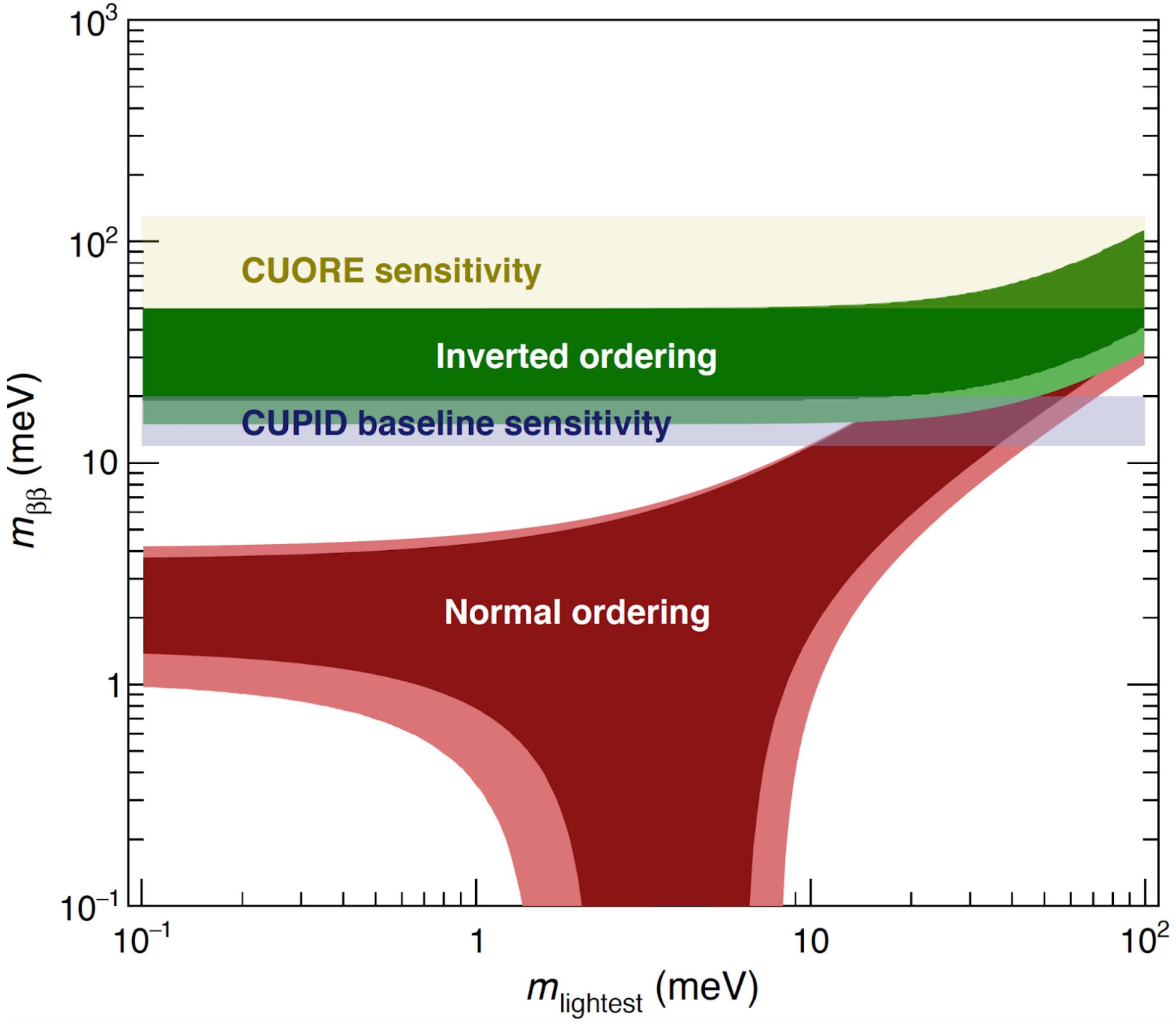
# CUORE UPGRADE WITH PARTICLE IDENTIFICATION

- Will operate in the same cryostat that currently houses CUORE
- Goal: Fully probe the "Inverted Hierarchy" region. Improve sensitivity to $m_{\beta\beta}$ by factor of ~5 relative to CUORE

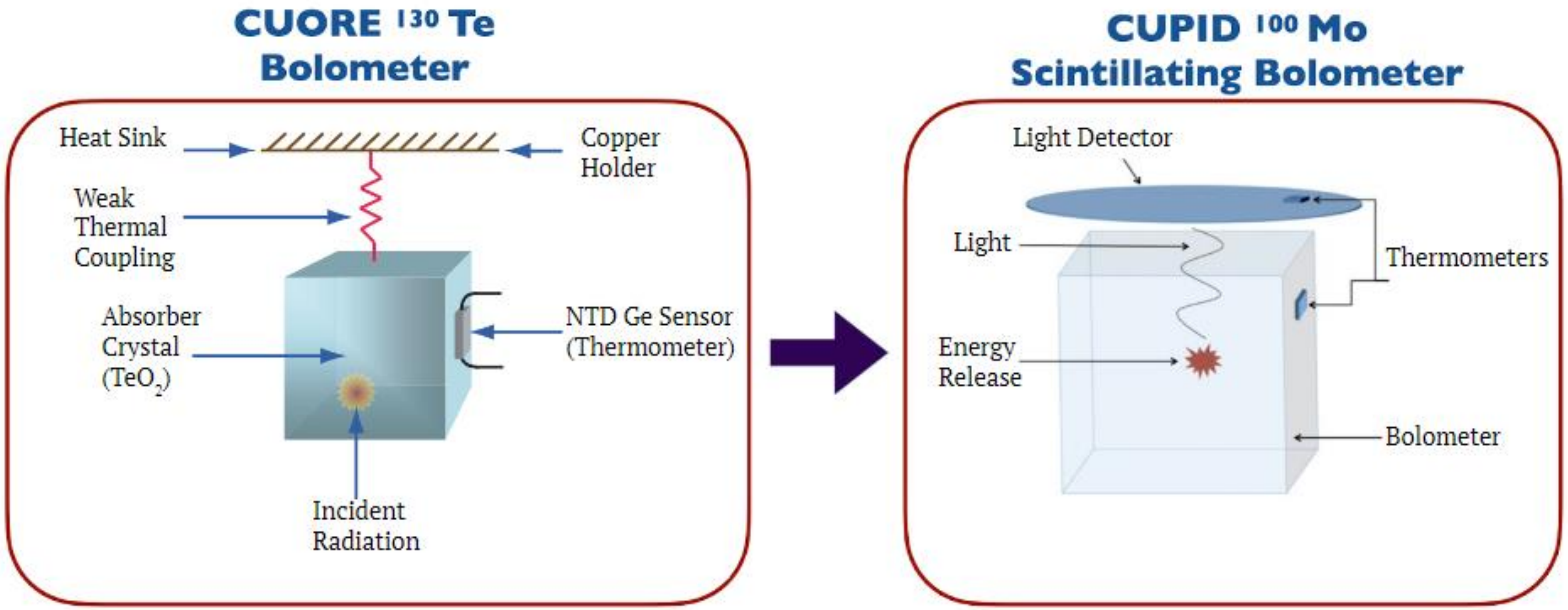
Improved Sensitivity from Background Reduction

Particle identification

- Muon veto
- Increased Q value for reduced γ/β backgrounds



# CUPID Technology




- $Q_{\beta\beta}$ = 2527 keV < 2615 keV peak
- Measure only heat
- No particle ID

- $Q_{\beta\beta}$= 3034 keV: Most β/γ backgrounds reduced
- Measure both heat + light
- Particle ID to actively discriminate **α** particles