13th INTERNATIONAL SPRING SEMINAR ON NUCLEAR PHYSICS

Perspectives and Challenges in Nuclear Structure after 70 Years of Shell Model

SANT'ANGELO D'ISCHIA, MAY 15-20, 2022

Latest results from the CUORE experiment

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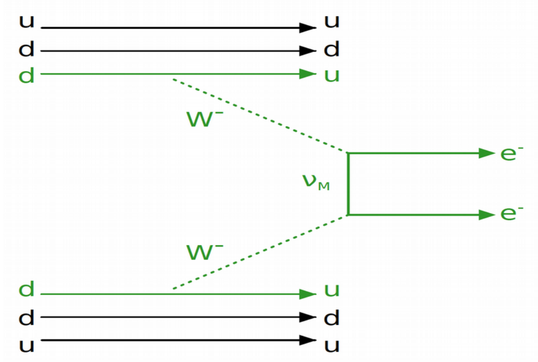
on behalf of the CUORE collaboration

Double beta decay: second order nuclear process, alternative to beta decay when forbidden by negative mass difference for some even-even nuclei

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

2nd order SM process, observed on nuclei with $T_{1/2}$ ~ $10^{18\text{-}24}$ years

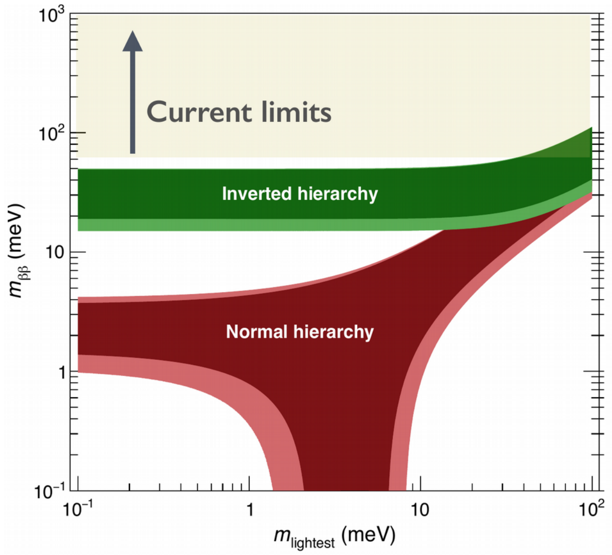
$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$



→ SM forbidden, lepton number violation
→ **if** observed, **then** neutrino is a Majorana particle
→ underlying mechanism can give insight into BSM physics:

- light neutrino mass scale and hierarchy
- heavy, sterile neutrinos

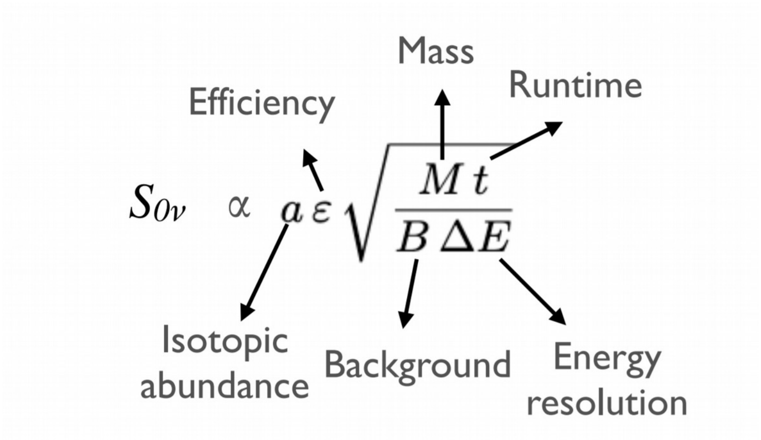
Effective neutrino mass $m_{\beta\beta}$:
- measures the intensity of the new-physics involved in the process
- compares different isotopes

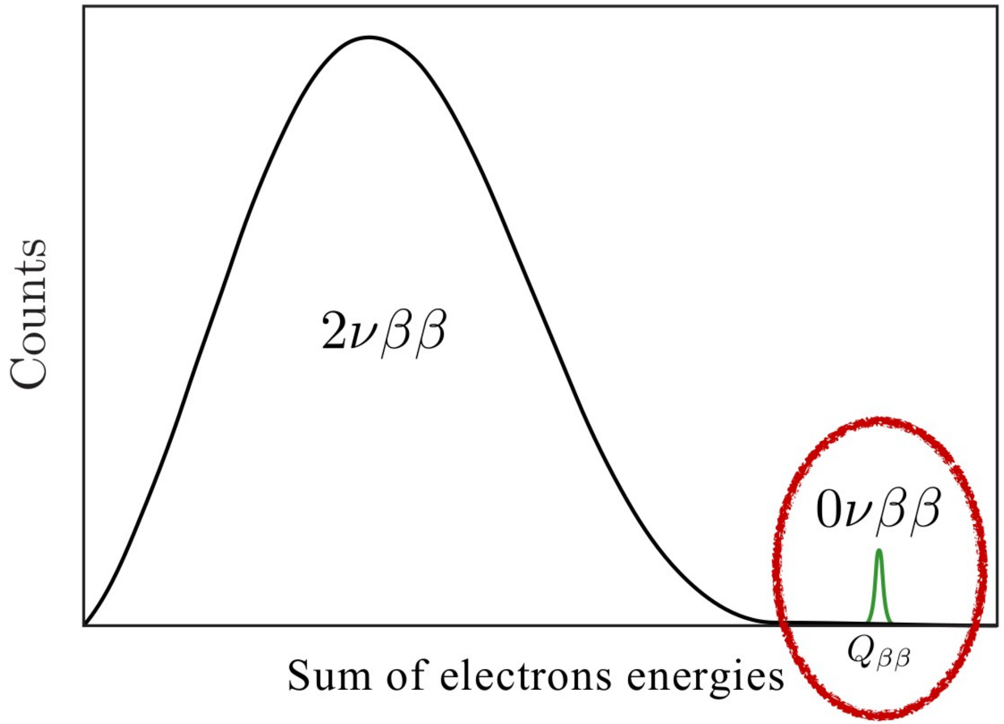


Searching for $0\nu\beta\beta$

Searching for a peak at the Q value of the decay

Sensitivity in presence of background:





Resolution and background play an important role in sensitivity

> 110 scientists

27 Institutions

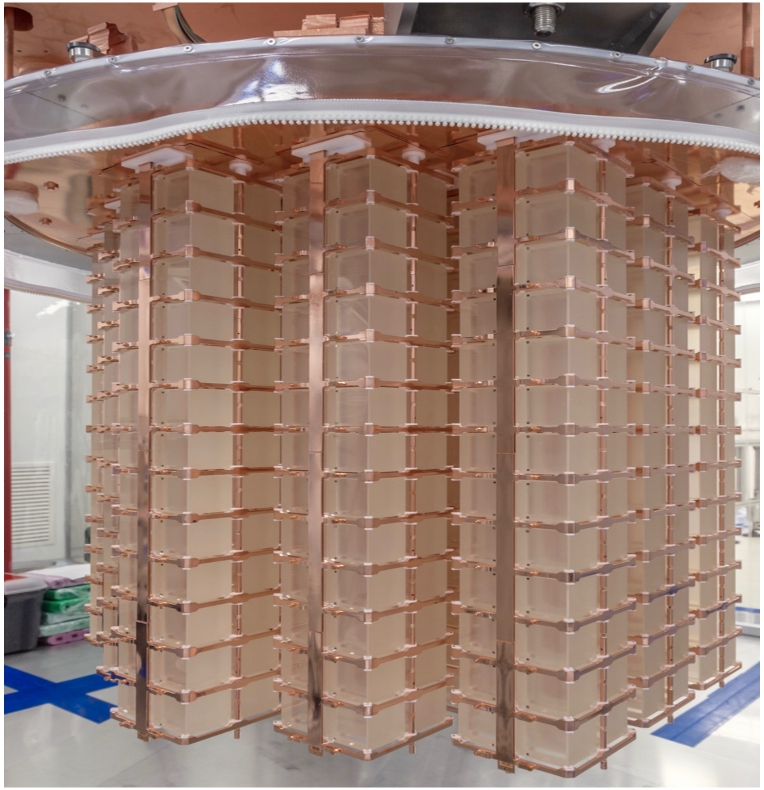
4 countries

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

Main goal: search for 0νββ decay of ^{130}Te

Design:

- closely packed modular array of 988 natural TeO_2 crystals arranged in 19 towers
- Large mass: 742 kg of TeO_2 ,206 kg of ^{130}Te
- Low background goal: 10^{-2} cts/(keV kg yr)
  - → high granularity
  - → deep underground location (LNGS, Italy) @3600 mwe
  - → strict radio-purity controls on materials and assembly
  - → passive shielding
- Energy resolution: Goal of 5 keV FWHM at $Q_{\beta\beta}$
- High efficiency and duty cycle

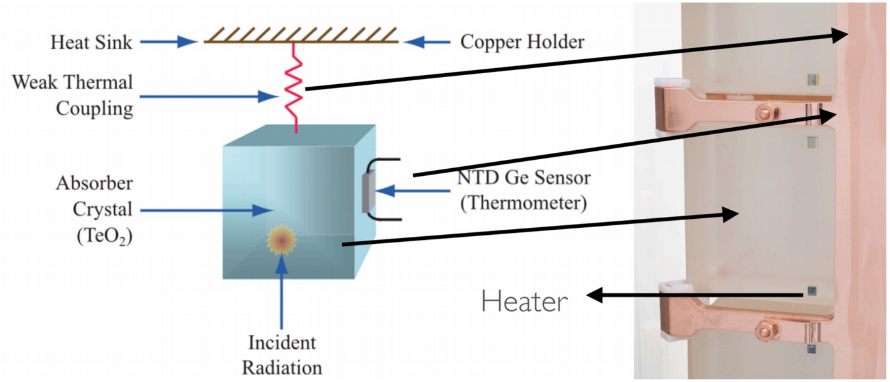


Sensitivity:

$T^{0\nu}_{1/2}$ ~ 9 x 10^{25} yrs (90% C.L) in 5 yrs

$m_{\beta\beta}$ < 50-130 meV

Experimental technique: low temperature detectors



Low temperature detectors:

- macroscopic (hundreds of grams) crystals instrumented with thermistors operated @10 mK → low thermal capacity

- energy deposition in absorber == source detected as temperature variation

- large active mass and efficiency per unit cost

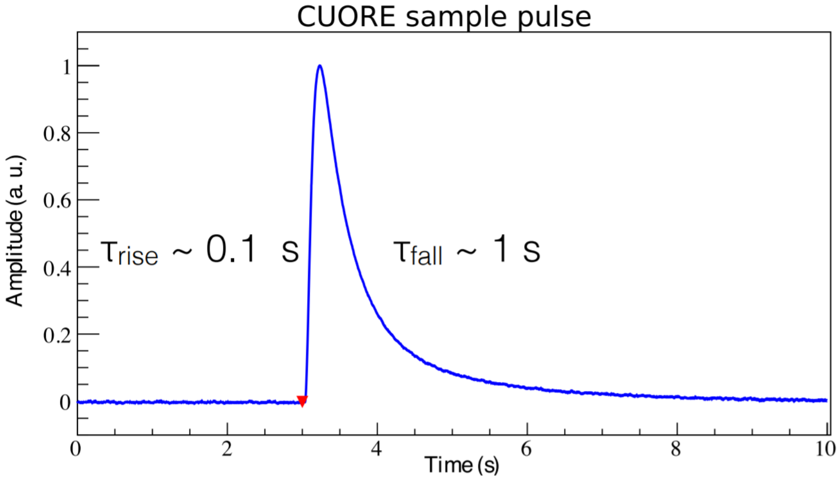
- fully active sensitive volume, no dead-layer → simple response function → high energy resolution, clear signature

Each detector:

→ Absorber: 5x5x5 cm^3 TeO_2 crystal

→ Sensor: Ge neutron transmutation doped (NTD) thermistor

→ Heater: Gain calibration



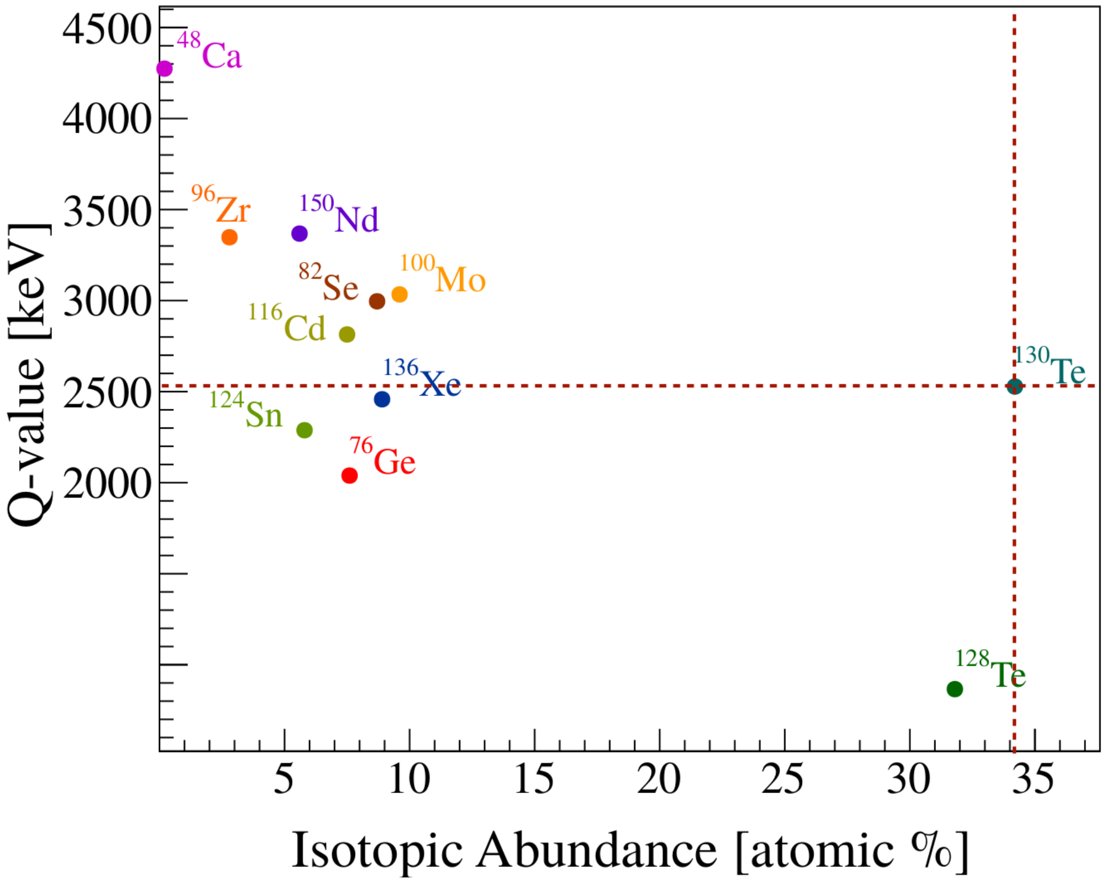
- Excellent energy resolution (~0.2% ΔE/E FWHM)

- Detector response independent of particle type

- Flexibility in 0νββ candidate choice

Isotope choice

- 34 % natural isotopic abundance
- $Q_{\beta\beta}$ (2528 keV)
  - → Above most γ natural radioactivity
  - → Background from 2νββ ~1/Q^5
- Isotope within the absorber
- Reproducible growth of high quality TeO_2 crystals with low contamination



CUORE Cryostat

- Ton-scale infrastructure cooled down by a custom built cryogen-free structure: 5 pulse tubes + 3He/4He Dilution Refrigerator

- Almost 1.5 t of material cooled at operational T ~ 10 mK, stable over years

- Background level goal of 10^{-2} counts/(keV kg yr):

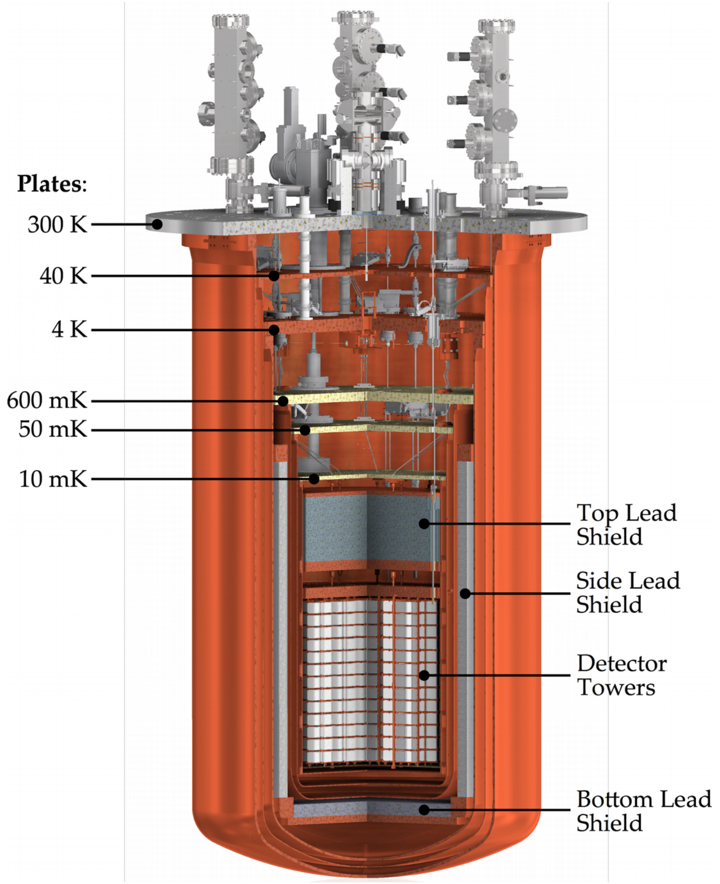
  → low-radioactivity materials choice, strict cleaning and assembling protocols

  → Roman ^{210}Pb-depleted + modern lead shields

  → Neutrons shield: external polyethylene layer with boric acid panels

- Energy resolution < 8 keV FWHM at ^{130}Te $Q_{\beta\beta}$:

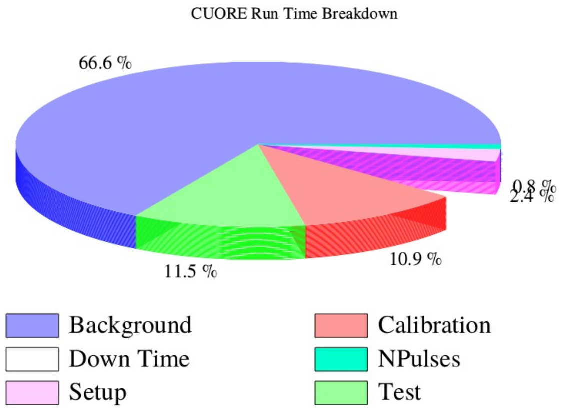
  → Minimization of vibrational noise: external support structure mechanically decouples the detectors from the cryostat



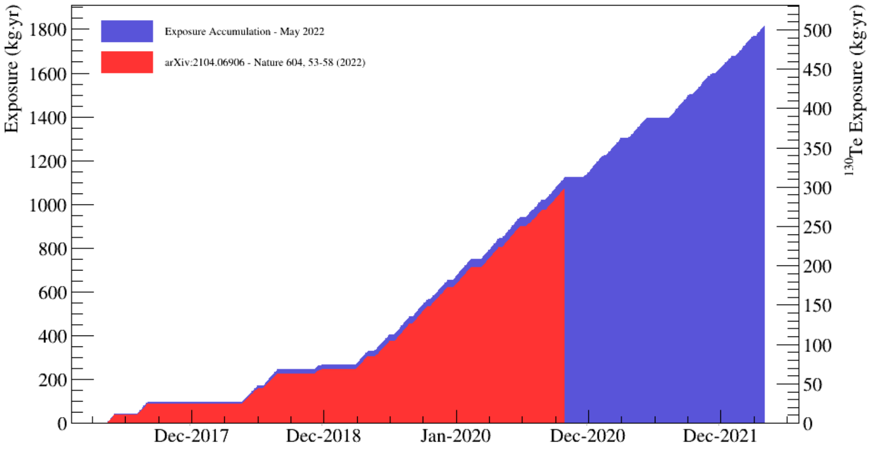
Data Taking

- Data taking organization: runs (physics, calibration, test,…)
- 1 Dataset (40 - 60 days) = initial calibration runs + physics runs + final calibration runs
- 2017 - beginning of 2019: mostly devoted to cryogenic interventions and detector optimizations
- After detector upgrades, continues data taking with low downtime
- 17 datasets completed, each dataset ~1 month long (> 1600 kg yr data collected)
- 15 datasets analyzed (1038.4 kg.yr)

- **Continue to take data**

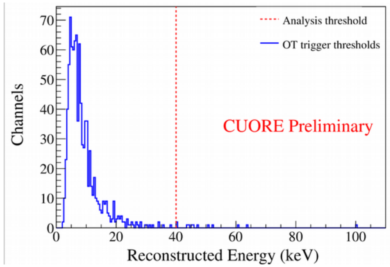


Stability of operation for ton-scale cryogenic detector is a fundamental milestone for future generation experiments (CUPID)

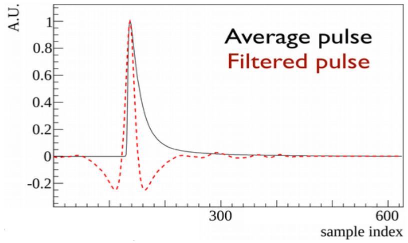


Event reconstruction

1. Trigger of continuous data stream

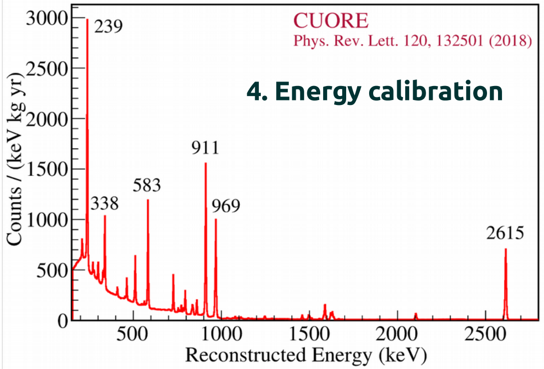


2. Amplitude evaluation with Optimum Filter

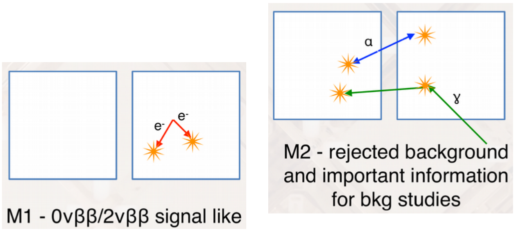


3. Thermal gain stabilization vs. baseline temperature

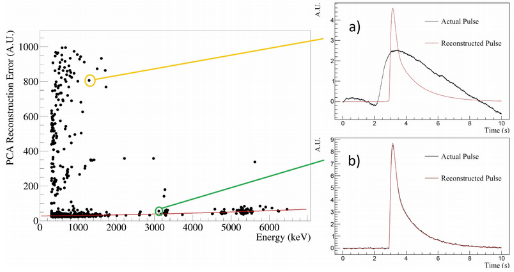
4. Energy calibration



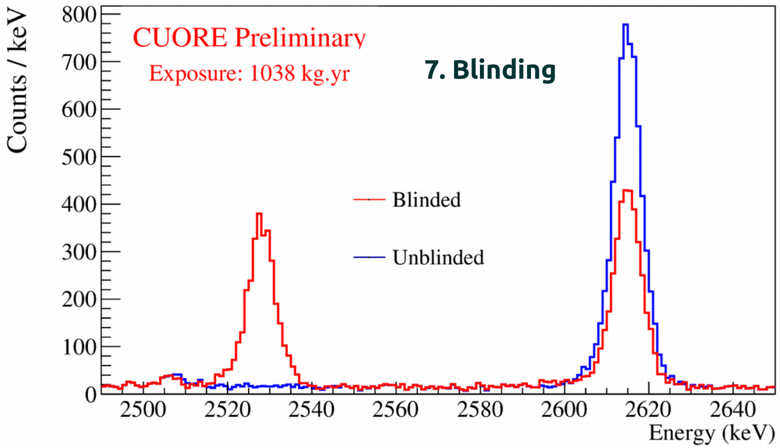
5. Event multiplicity selection



6. Pulse shape cut



7. Blinding



Spectrum: all datasets

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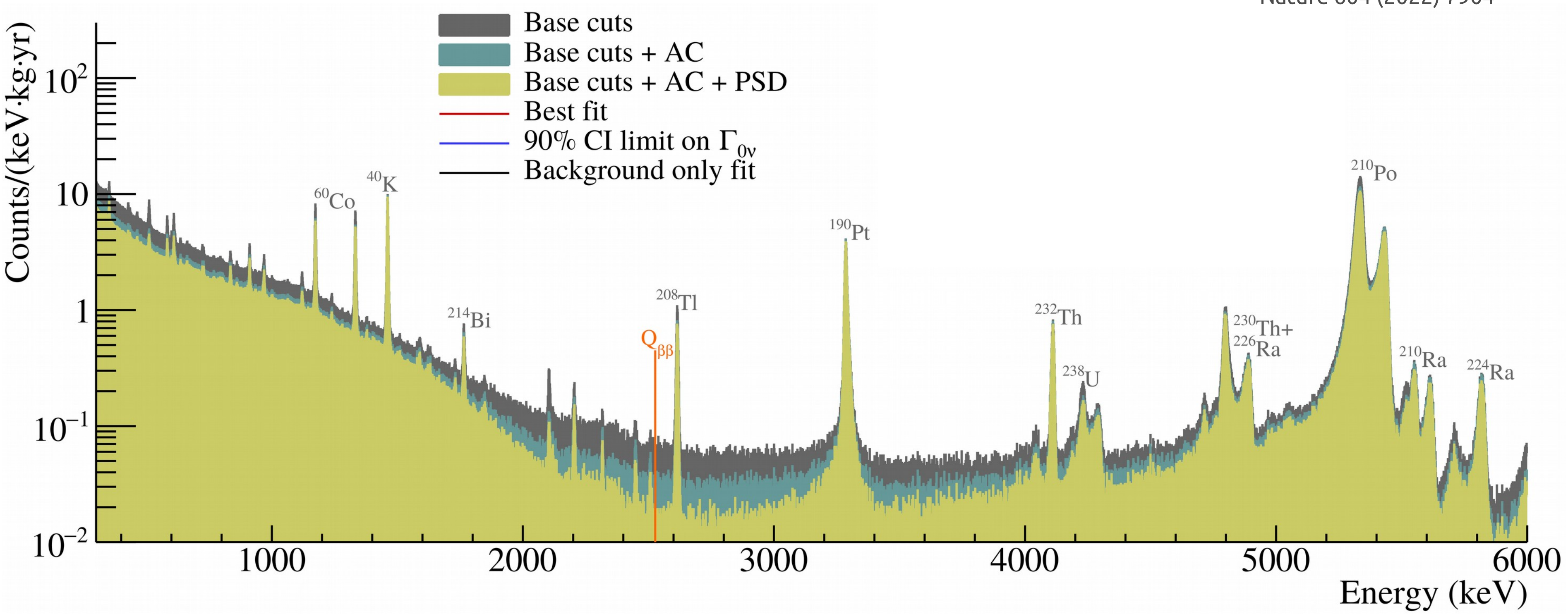
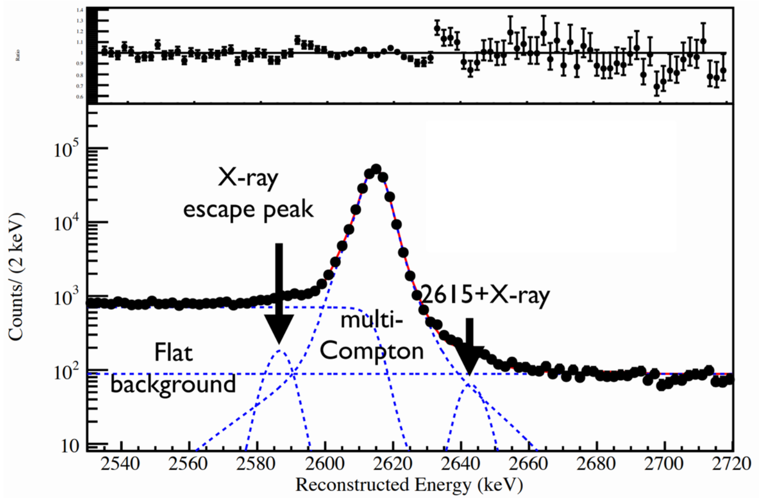


Gamma background region	Alpha background region

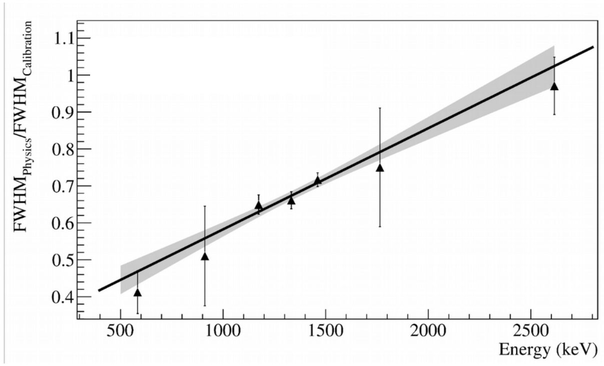
Detector response function

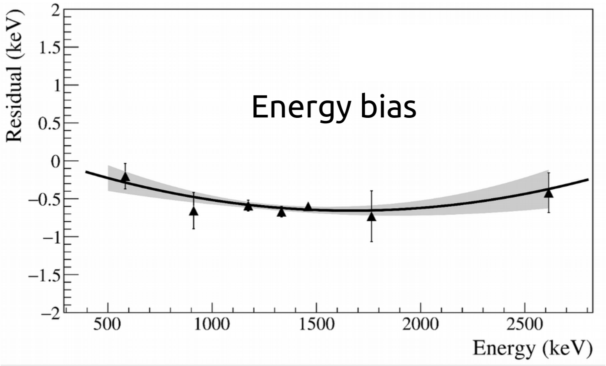
Line shape response function

- 2615 keV calibration gamma line is used to model the detector response to monochromatic electron-like energy deposition
- Model = 3 gaussians (signal) + X-ray escape + flat background + multi-compton shoulder
- Signal parameters are defined on channel/dataset basis
- Exposure-weighted average FWHM: 7.78(3) keV



Response scaling





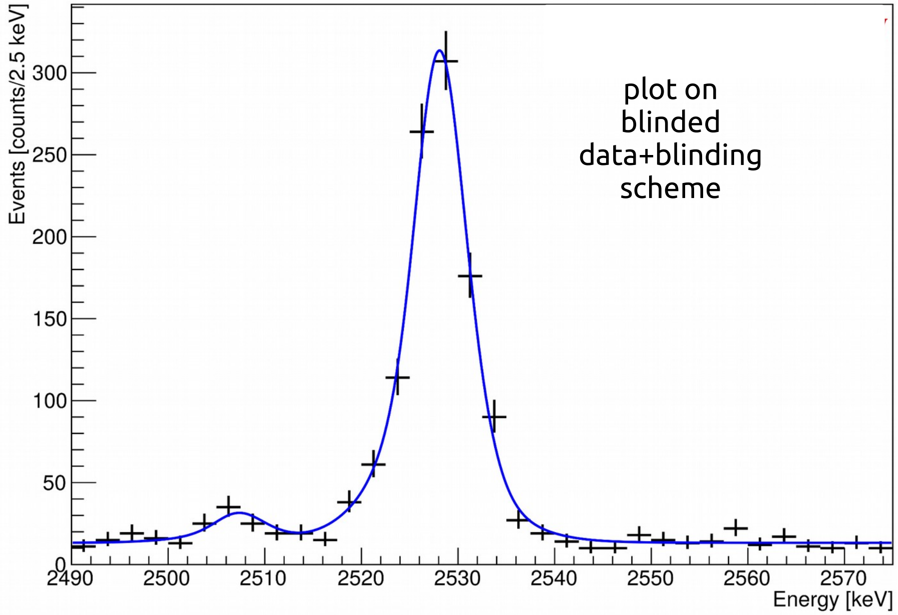
- Signal parameters are scaled to ROI energy by fitting peaks in the background spectrum - **FWHM = 7.8(5)** keV
- Signal parameters fixed in the final fit to ROI
- Uncertainty in the scaling included as nuisance parameters in systematics fit
- Line shape also used to estimate energy scaling bias (< 0.7 keV @$Q_{\beta\beta}$)

Cuts efficiency

Channel/run	Reconstruction	→ trigger → energy reconstruction → pile-up rejection	Heater pulses	96.418(2) %
Channel/dataset	Anti-coincidence	Probability of identifying single-site event	^{40}K gamma line @1460 keV	99.3(1) %
	Pulse-shape discrimination	Probability of keeping a physical event	Multiple gamma lines in background spectrum	96.4(2) %
	Total analysis			**92.4(2) %**
	Containment	Geometry and electrons interaction	MC	**88.35(9) %**

Fit Details

- Unbinned Bayesian fit over all datasets
- Bayesian Analysis Toolkit (BAT)
- Fit region [2490,2575] keV
- Systematics implented as nuisance parameters



Fit Parameters

→ $0\nu\beta\beta$ decay rate @ 2527.518 keV

→ ^{60}Co sum peak amplitude

→ Background index

→ Background slope

Systematics:

→ Analysis efficiencies

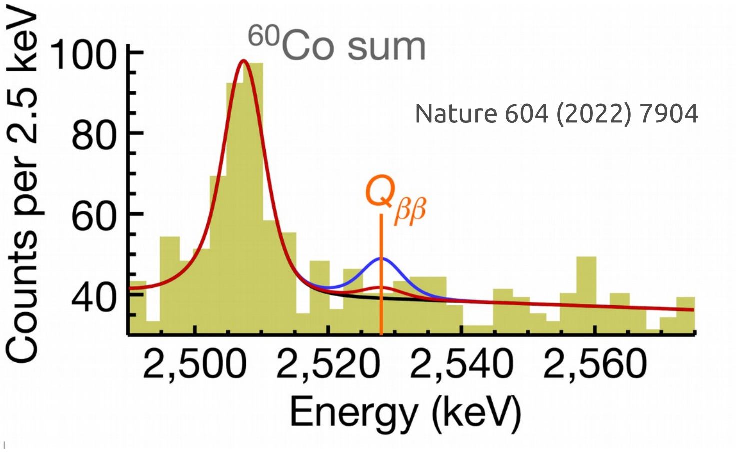
→ Containment efficiency

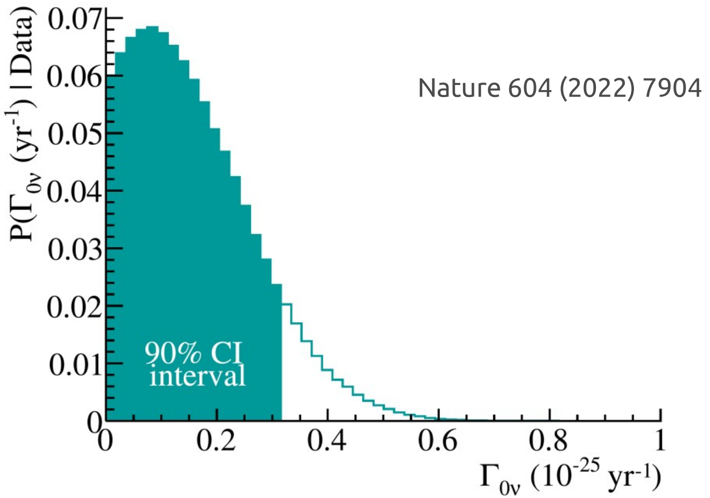
→ Energy resolution

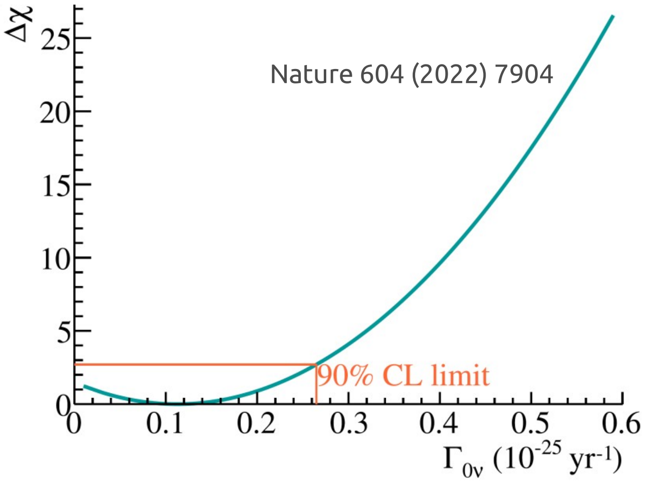
→ Energy scale

→ $Q_{\beta\beta}$

→ ^{130}Te abundance







- No evidence of $0\nu\beta\beta$

- Best fit rate: **$(0.9\pm1.4)\times10^{-26}$ yr^{-1}**

- Background index =**$1.49(4)\times10^{-2}$ cts/keV/kg/yr**

- **$T^{0\nu}_{1/2}$> 2.2 x 10^{25} yr at 90% C.I**

(numbers from Bayesian analysis)

Sensitivity

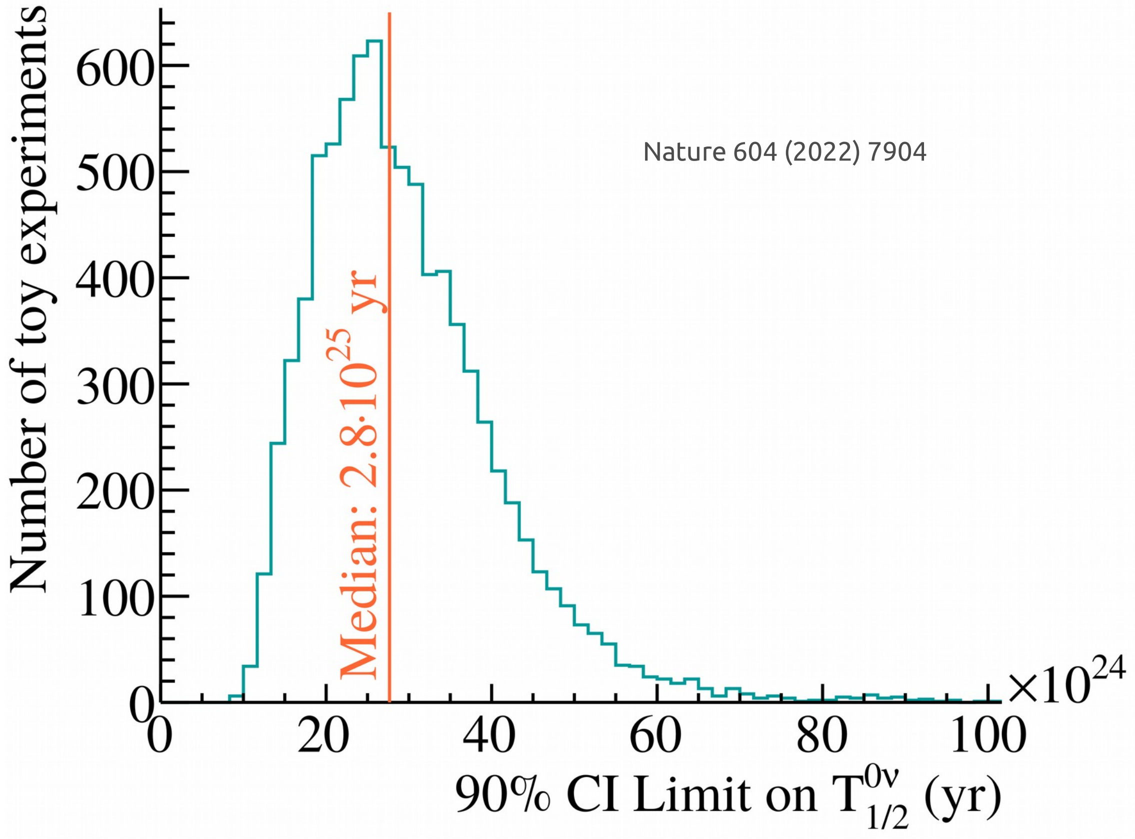
- Sensitivity calculated by generating 10k toy experiments assuming no signal

  → Toys generated using linear background and ^{60}Co components

  → Fit with signal + background

- Median expected **$T^{0\nu}_{1/2}$= 2.8 x 10^{25} yr at 90% C.I**

- Probability of getting a stronger limit is 72%



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Limit on effective neutrino mass

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

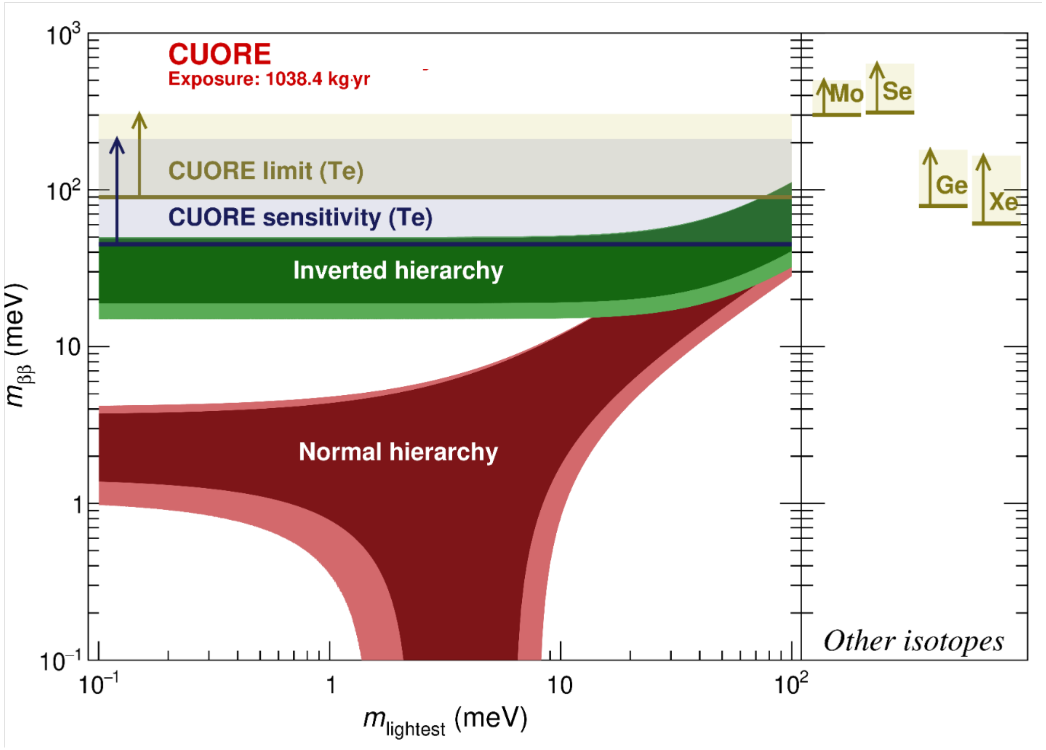
- Assuming light neutrino exchange:

$$\mathbf{m_{\beta\beta} < 90 - 305\ meV}$$

- Range dominated by uncertainties in NME

- Target sensitivity in 5 yr data taking:

$$\mathbf{m_{\beta\beta} < 50 - 130\ meV}$$



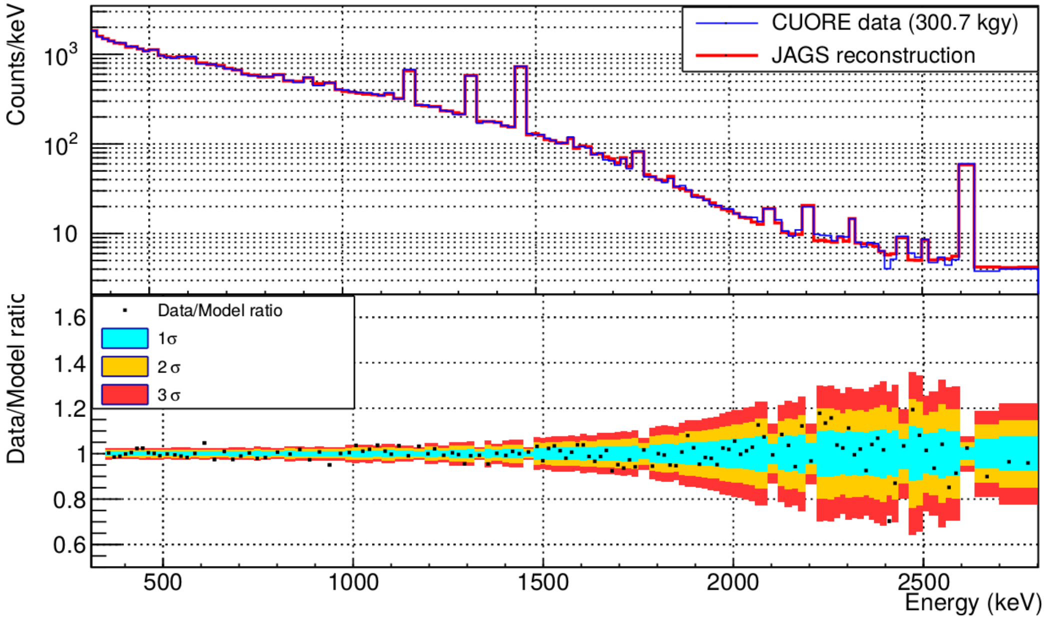
^{130}Te $2\nu\beta\beta$ decay & CUORE background model

- $2\nu\beta\beta$ decay has a continuum spectrum from 0 keV to $Q_{\beta\beta}$

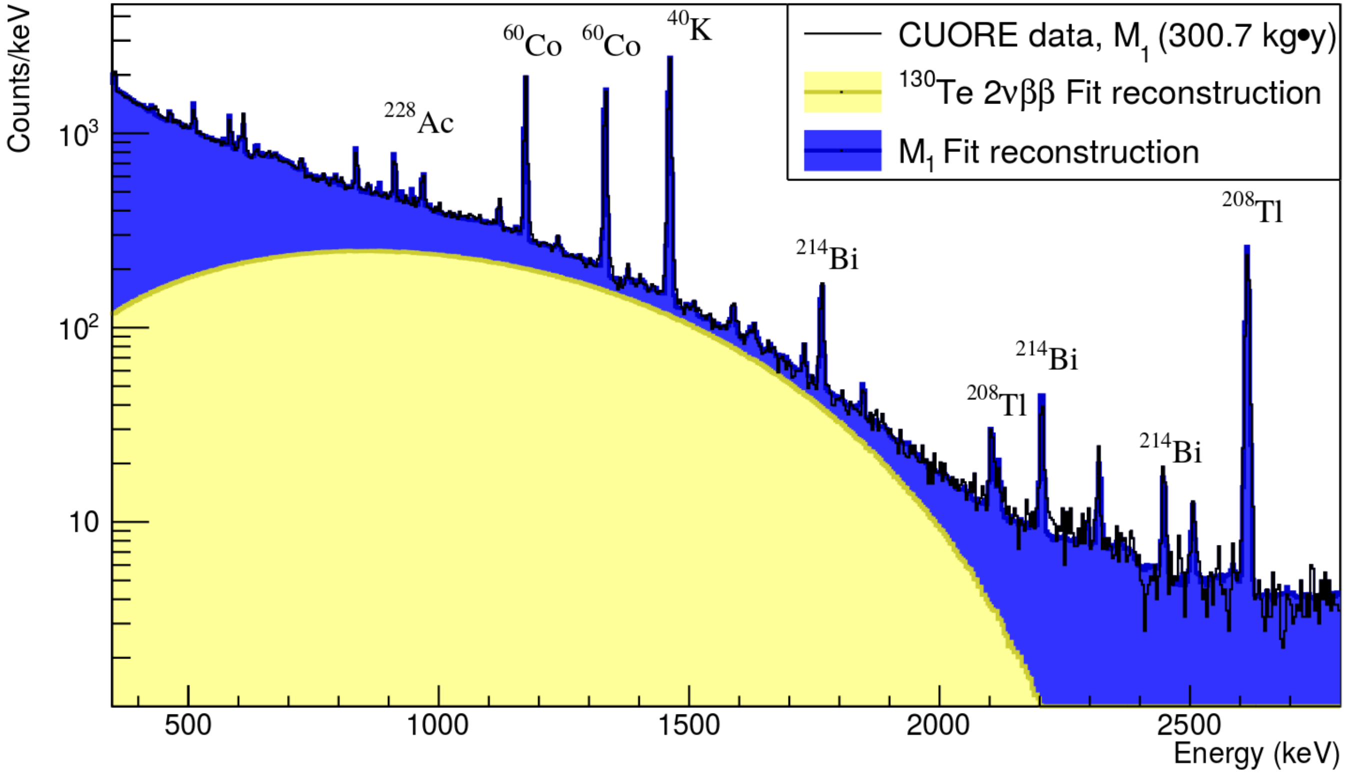
- $2\nu\beta\beta$ contribution to the CUORE spectrum can be disentangled through the Background Model fit

- CUORE background model: 60 radioactive contaminants + muons + $2\nu\beta\beta$

- $2\nu\beta\beta$ rate extracted from MC multi dimensional fit (M1, M2, M2sum) of gamma region with 60+ components (Geant4 simulated contaminations) including $2\nu\beta\beta$



^{130}Te $2\nu\beta\beta$ decay



Most precise measurement of ^{130}Te $2\nu\beta\beta$ decay half-life to date obtained with of 300.7 kg·yr exposure dataset

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

Phys. Rev. Lett., 126:171801,2021

CUORE science program

- Other recently published high level analysis:
  - ^{130}Te 0ν and 2ν to excited states (10.1140/epjc/s10052-021-09317-z)
- Upcoming papers (short term):
  - ^{120}Te 0ν
  - ^{128}Te 0ν
  - Full-spectrum Background Model → input to CUPID background budget
- Long term plan:
  - ***Data taking to be continued until 3 ton*yr exposure is collected (expected end 2024)***
  - ^{130}Te 0ν with improved topological analysis (M1 + M2)
  - ^{120}Te 0ν and 2ν
  - ^{128}Te 0ν and 2ν
  - ^{130}Te 0ν combined ground state and excited states, with topological analysis (final publication)
  - High-multiplicity BSM processes (tri-nucleon decay, electron decay, etc…)
  - Low energy:
    - DM direct detection
    - Axion searches
    - Sensitivity to neutrino coherent scattering (galactic SN detection)

Conclusion

Experimental technique:

→ Currently the largest solid state and low temperature detector for the search of $0\nu\beta\beta$

→ Array of 988 crystals of natural TeO_2 crystals for total active mass of 742 kg (206 kg of ^{130}Te)

→ Operated in one of the largest DU-based cryostats in the world @10 mK

Operation and data taking:

→ data-taking ongoing since 2017

→ from January 2019 → 93% duty cycle

→ 1 tonne-yr exposure collected and analysed

→ stability of operation for ton-scale cryogenic detector: fundamental milestone for future upgrades (CUPID)

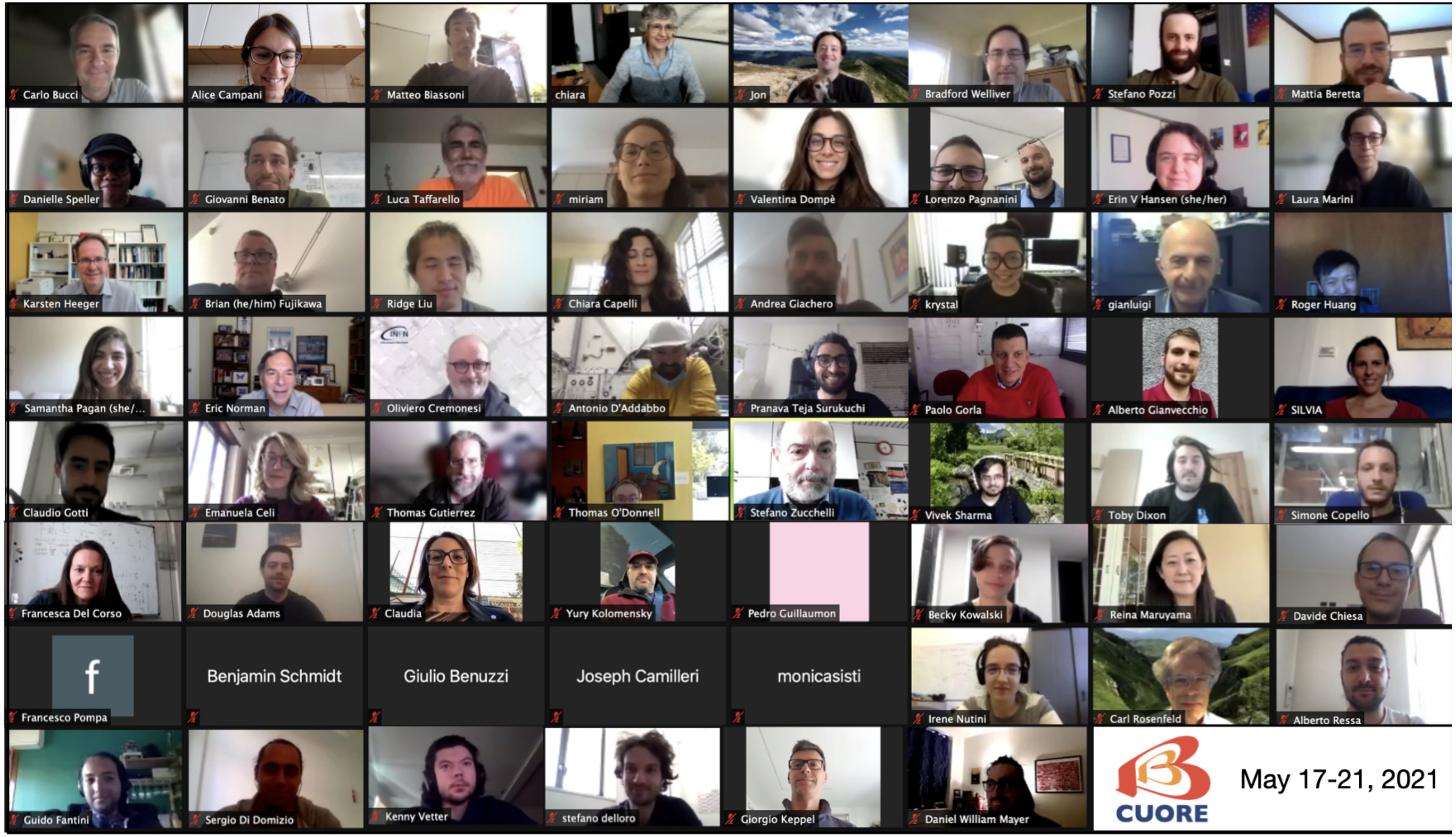
Latest physics results:

→ most sensitive search for $0\nu\beta\beta$ in ^{130}Te: $T_{1/2} > 2.2\text{x}10^{25}$ yr with median sensitivity $2.8\text{x}10^{25}$ yr

→ most accurate and precise measurement of ^{130}Te half life through $2\nu\beta\beta$

→ many more results to come: updated $0\nu\beta\beta$ every new tonne-yr of exposure, decays to excited states, low energy processes, fundamental symmetries violations, etc.

Thank you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