Recent progress on BSM and dark matter searches in CUORE

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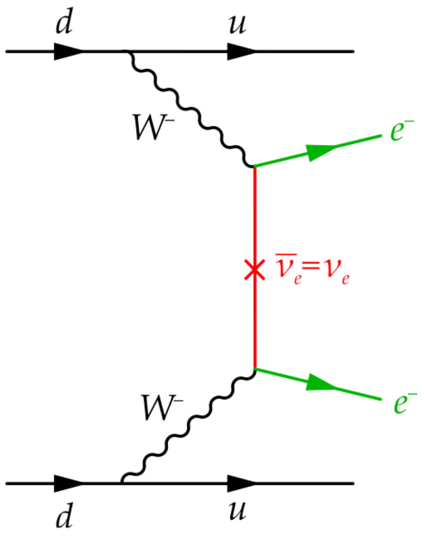
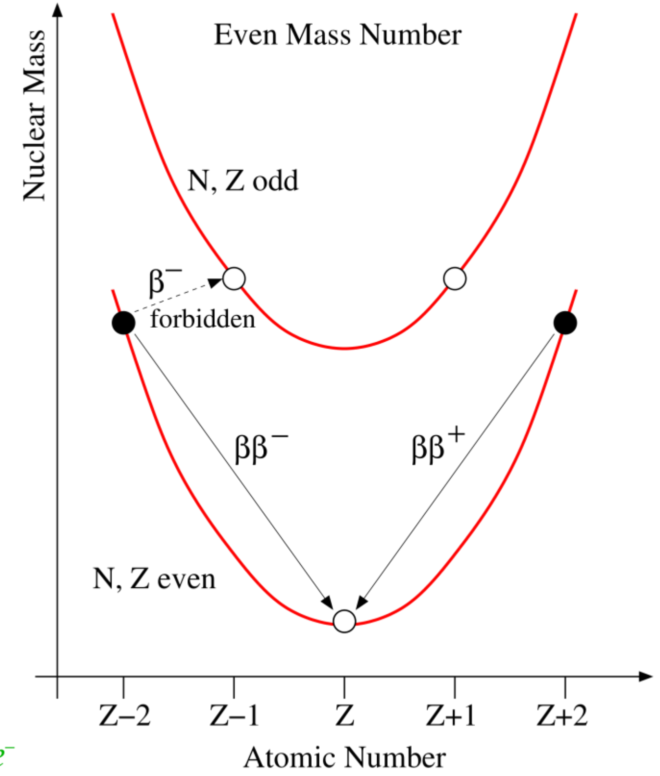
Double beta decay

- $2\nu\beta\beta$
  - Same mass number (A), changes the nuclear charge (Z) by two units
    - 2nd order weak transition, allowed by the Standard Model
  - Decay to the intermediate nucleus is forbidden
  - Detected in 11 nuclei

- $0\nu\beta\beta$
  - Violates lepton number conservation (Δ L = 2)
  - Matter-antimatter asymmetry
  - Majorana particles
  - New mechanism of mass generation

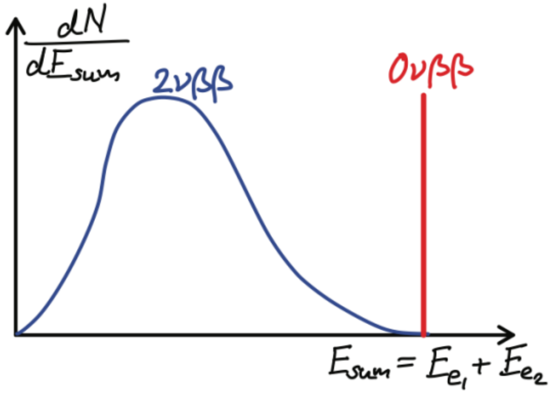
$$ {}_{Z-2}^{A}X \rightarrow {}_{Z}^{A}Y + 2\,e^{-} + 2\overline{\nu}_{e} $$

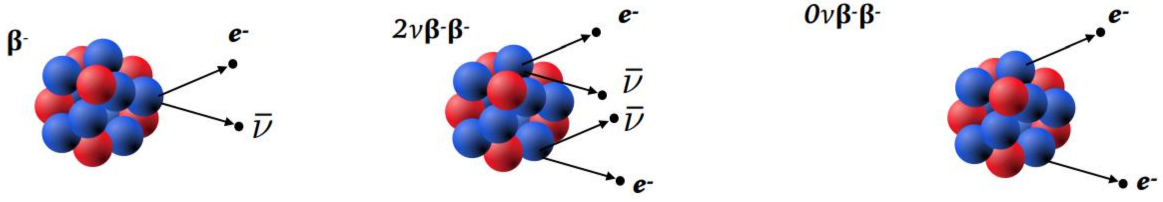




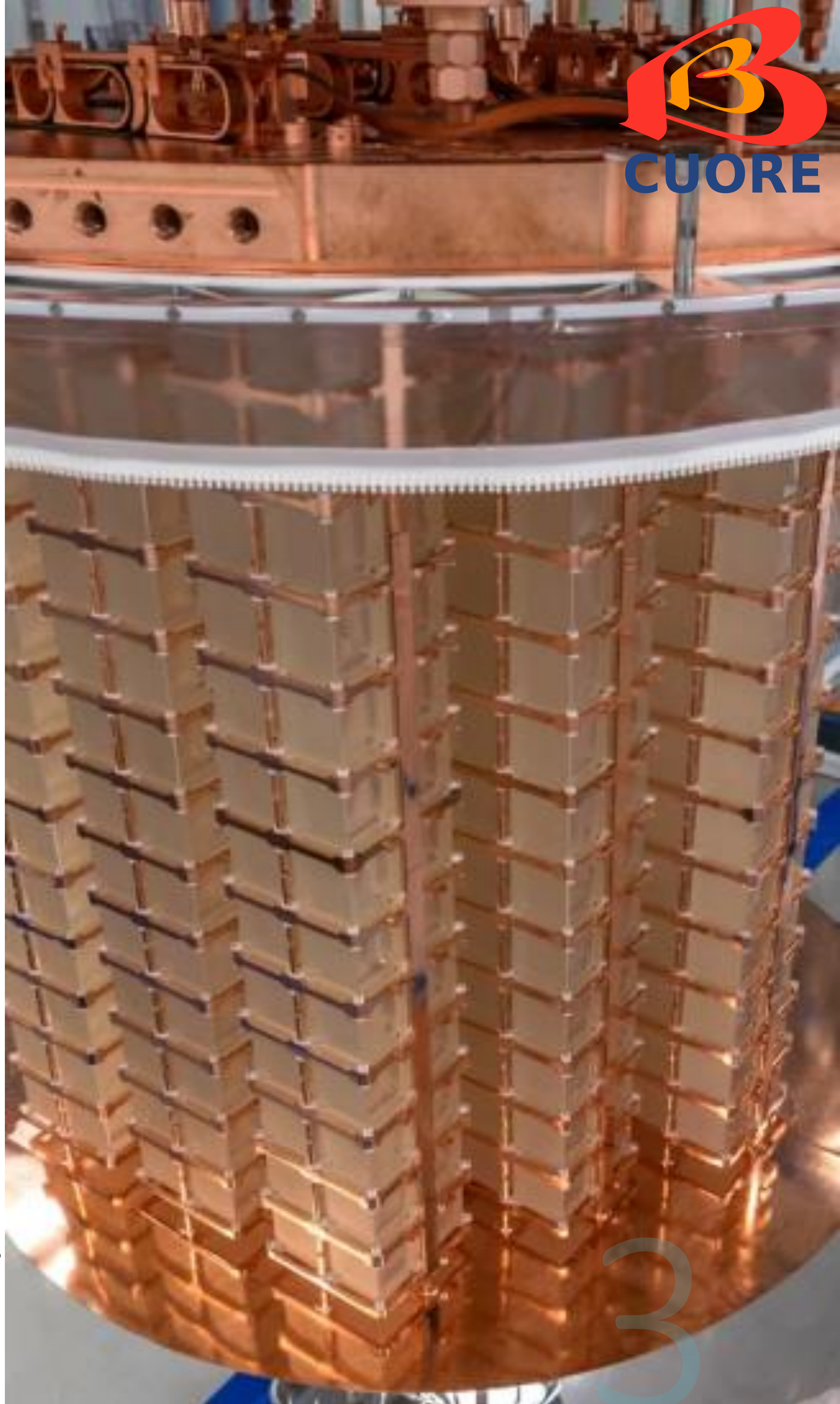
Double beta decay searches

- High $Q_{\beta\beta}$ (less background due γ and β)
  - ~2528 keV for ^{130}Te
- High natural isotopic abundance
  - 34.2% for ^{130}Te
  - 31.7% for ^{128}Te
- Long exposure: 742kg of TeO_2 for 2.8 years
- Excellent energy resolution
- Low background rate





Array of closely packed 988 TeO_2 crystals arranged in 19 towers
206 kg of ^{130}Te, 188kg of ^{128}Te, 5.3 kg of ^{123}Te, 0.5 kg of ^{120}Te



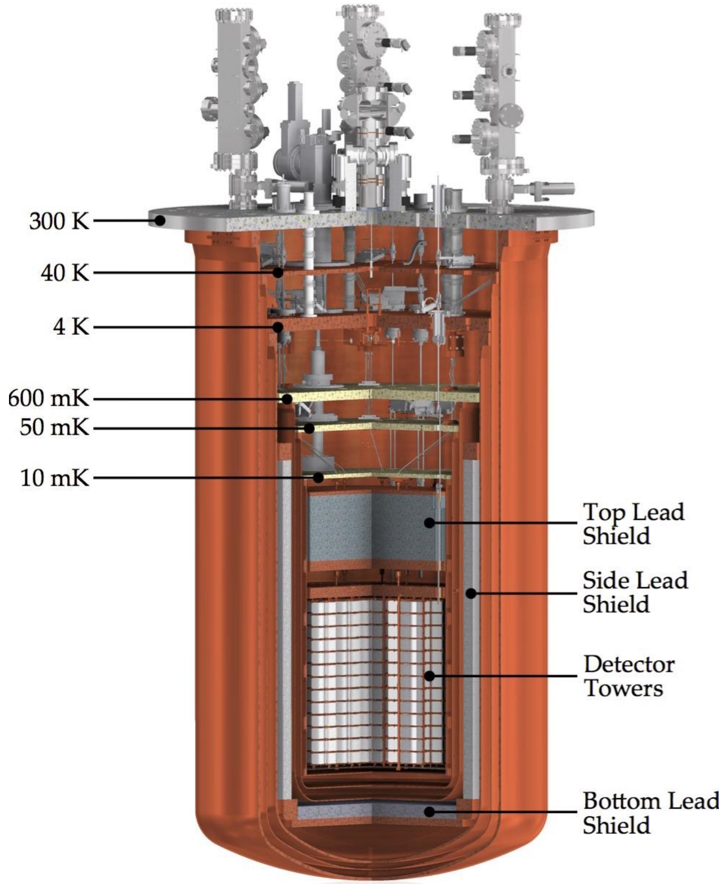
The CUORE experiment

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

Cryogenic experiment at tonne scale, using $^{nat}TeO_2$ thermal detectors
➡ located at Laboratori Nazionali del Gran Sasso (Italy)

Search for rare evens and/or physics beyond the Standard Model

- Search of 0νββ decay of ^{130}Te ⟶ Majorana nature of neutrinos
- Measurement of 2νββ decay of ^{130}Te and study of backgrounds
- Study of other rare decays of Te isotopes
  - ^{130}Te decay to excited states
  - ^{123}Te EC decay
  - 0νββ decay of ^{128}Te
  - 0ν(β+EC) ^{120}Te decay
  - Majorons
- Low energy studies
  - WIMP
  - Solar axions



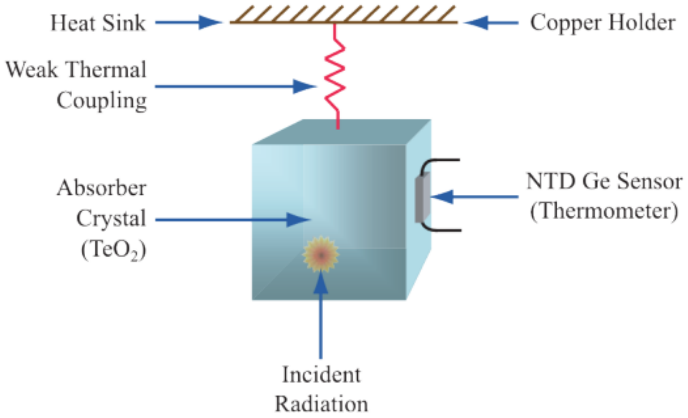
First cryogenic detector @tonne-scale exploiting bolometric technique

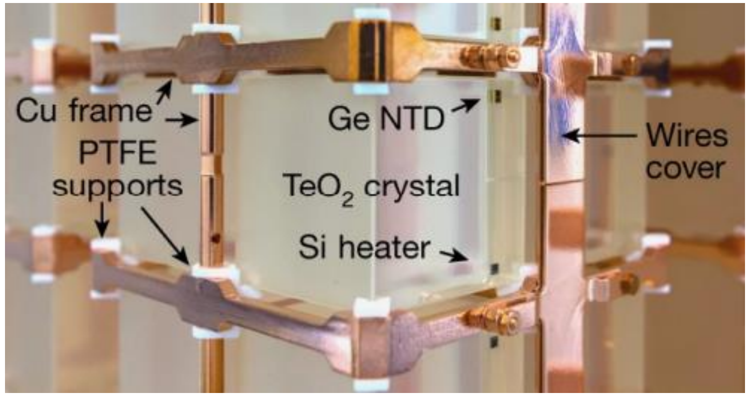
Adams D. et al. (CUORE collaboration), Nature 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

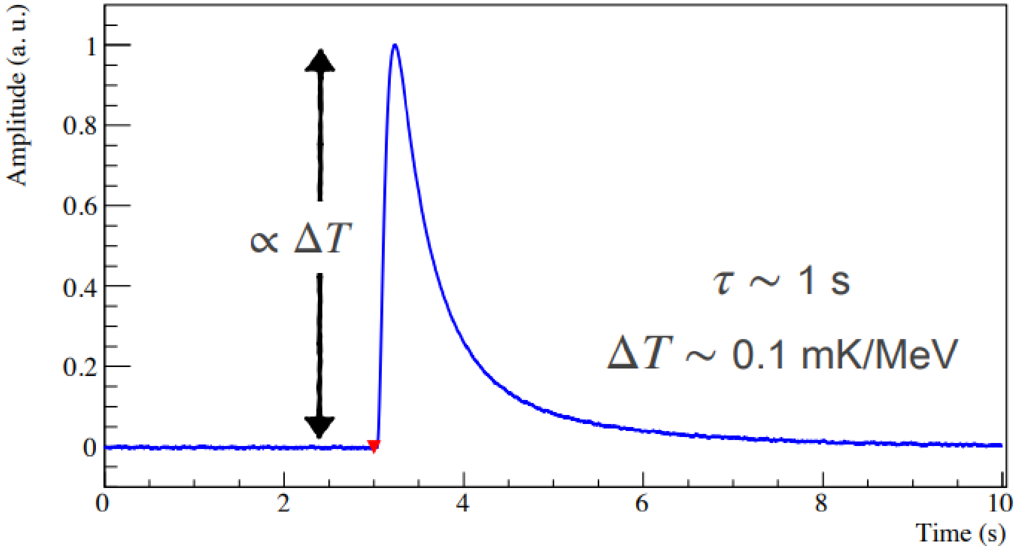
Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902, https://doi.org/10.1016/j.ppnp.2021.103902

The CUORE detectors

- Release energy converted into increase of temperature: $\Delta T \propto \Delta E / C$
- Low detector working temperature: $C \propto T^3$
- Decay time: $\tau \sim C/G$, G the thermal conductance of the heat bath to resptore the temperature after some energy deposit
- Signal readout with NTD-Ge sensors







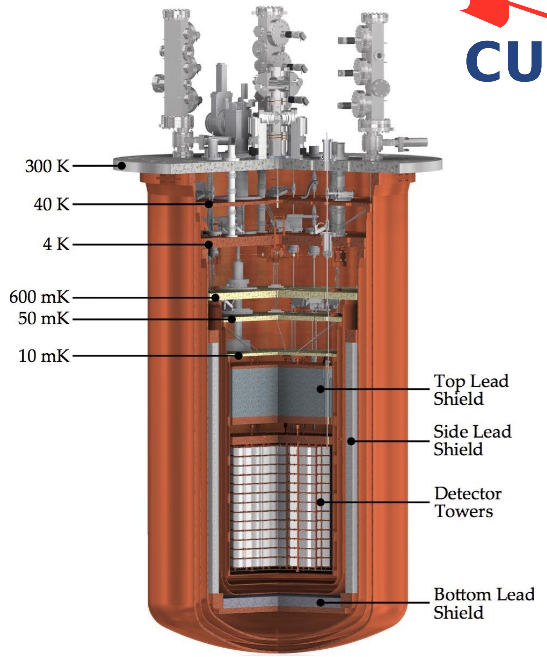
The CUORE challenge

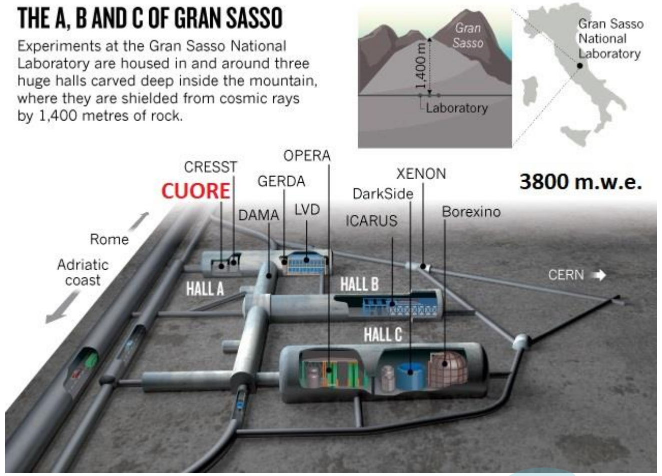
- Low temperature and low vibrations
  - TeO_2 detectors must be operated at stable low temperatures $\sim 10\ mK$
  - Multistage cryogen free (dry) cryostat → cooling systems: 5 pulse tubes and dilution units
    - Mass to be cooled < 4K: $\sim 15\ tons$ (IVC + Cu vessels + Roman Pb shield)

- Mechanical decoupling: isolated mechanically from outside
  - Reduce energy dissipations due to vibrations

- Low background
  - From detector: material screening and accurate selection to ensure radio purity + cleaning copper surface facing crystals + Roman and modern Pb shields + strict protocol for crystal growing
  - From outside: deep underground @LNGS + outer neutron shield (polyethylene + borid acid) + gamma shield (Pb)

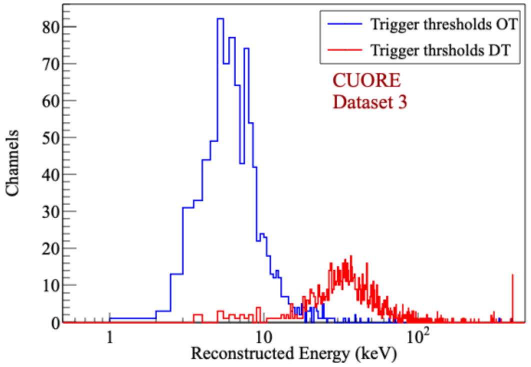
World leading cryostast in size and power!



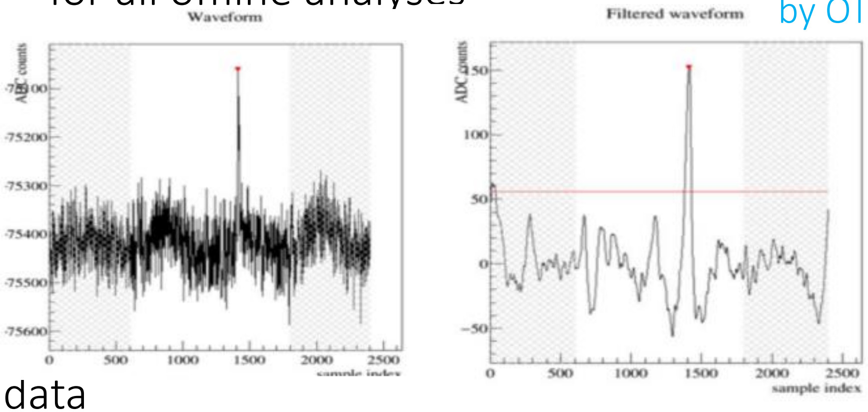


CUORE data processing

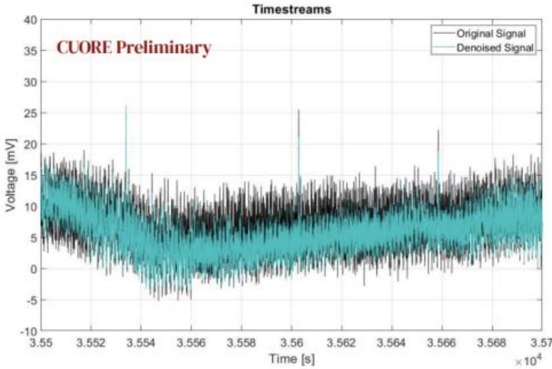
- Triggering pulses
  - Online Derivative Trigger (DT): threshold on the derivative of the data-stream ⟶ quality data monitoring
  - Offline Optimal Trigger (OT): identification of pulses in the filtered data-stream ⟶ for all offline analyses



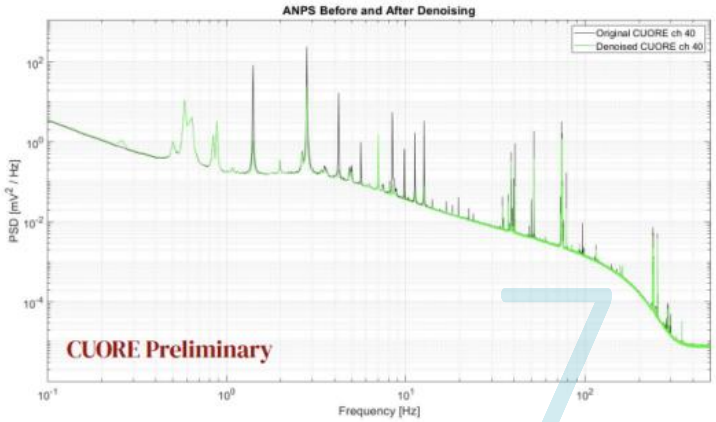
by OT



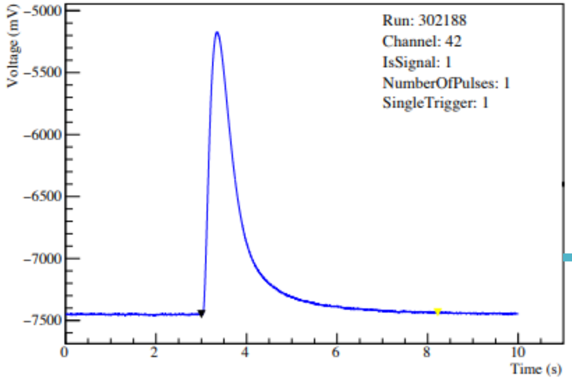
- Denoising the continuous data
  - Remove noise from each bolometric channel
  - Use of diagnostic devices to identify and measure noise sources: accelerometers, antennae, microphones
  - Ongoing



K. Vetter on going Ph.D. Thesis

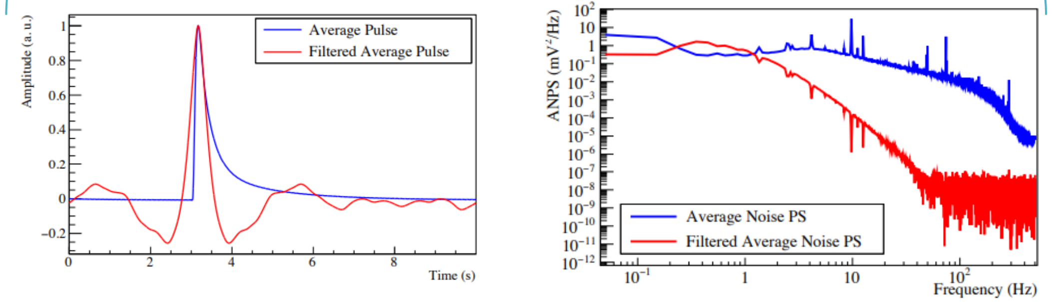


CUORE data processing

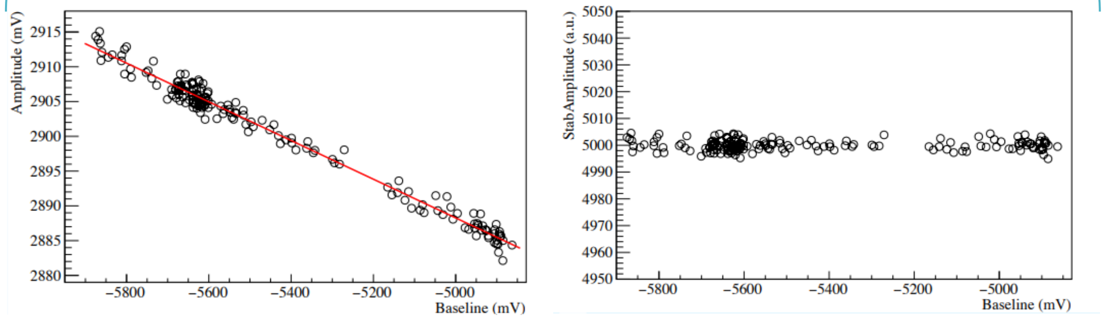


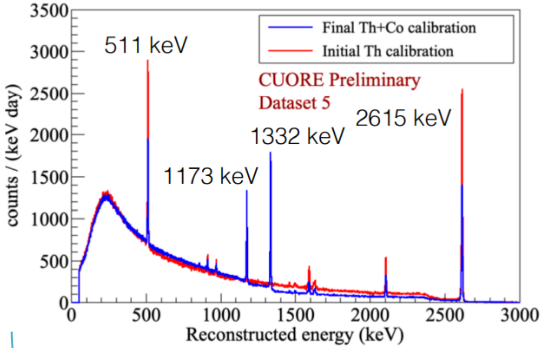
Amplitude Evaluation (a) → Thermal Gain Correction (b) → Energy Calibration (c) → Coincidence (d) → Quality Cuts (e)

(a)

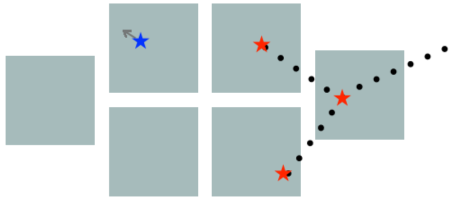


(b)

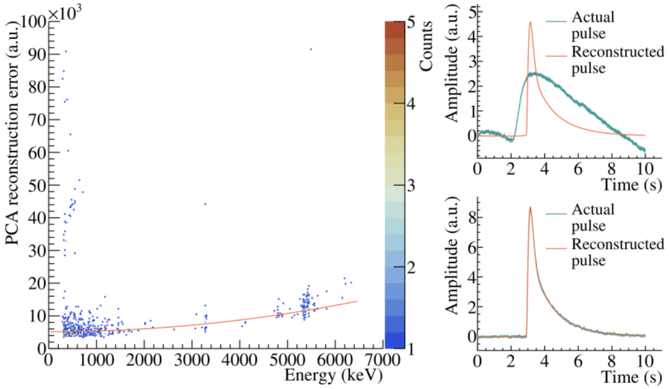




(c)



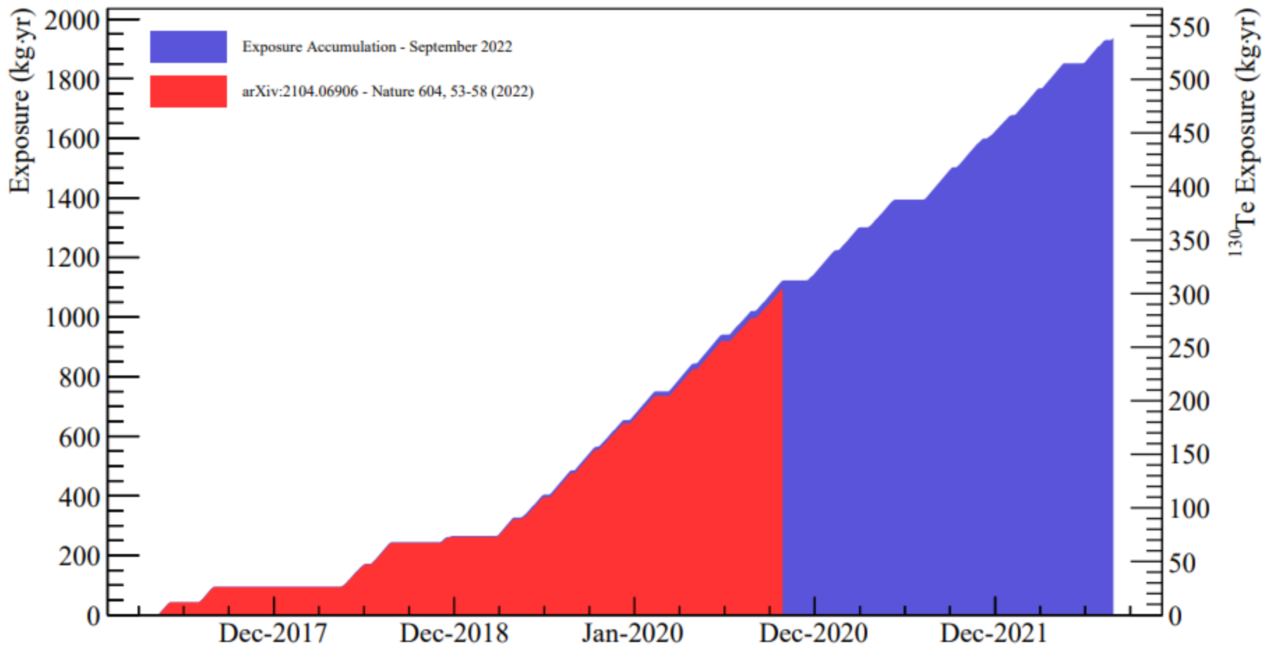
(d)

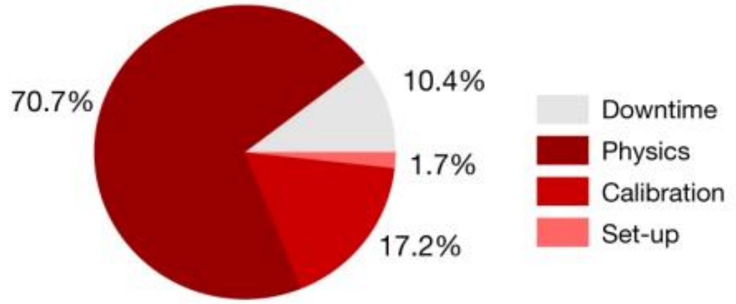


(e)

CUORE data taking

- Data taking started in Spring 2017: commissioning + optimization + operation
- Continuous data taking since early 2019
- Total uptime of $\sim 90\ \%$ C.I.
- Almost 2 ton.year exposure collected → $\sim 50\ kg.year/month$





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

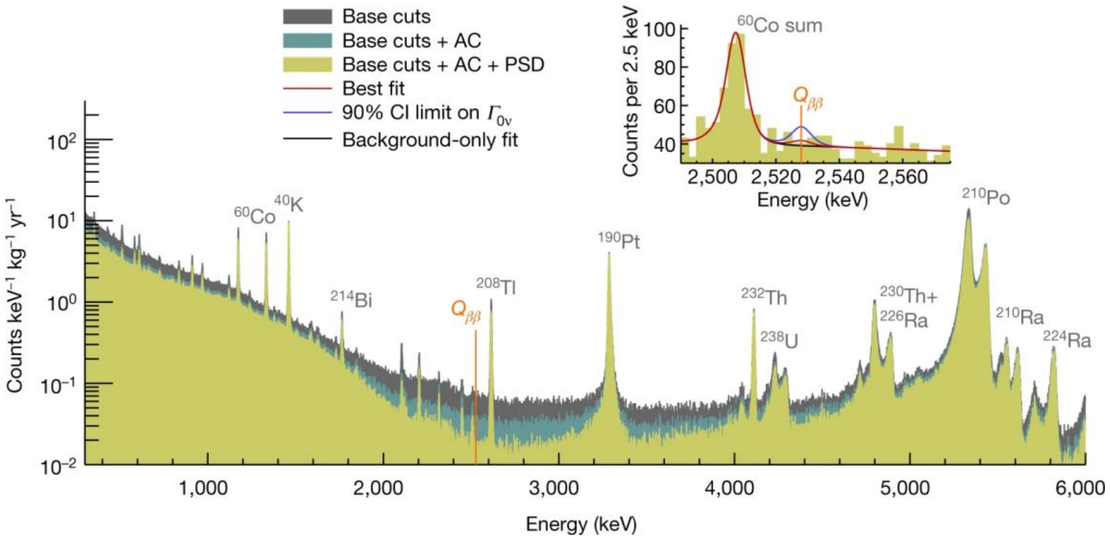
CUORE ^{130}Te $0\nu\beta\beta$ decay search

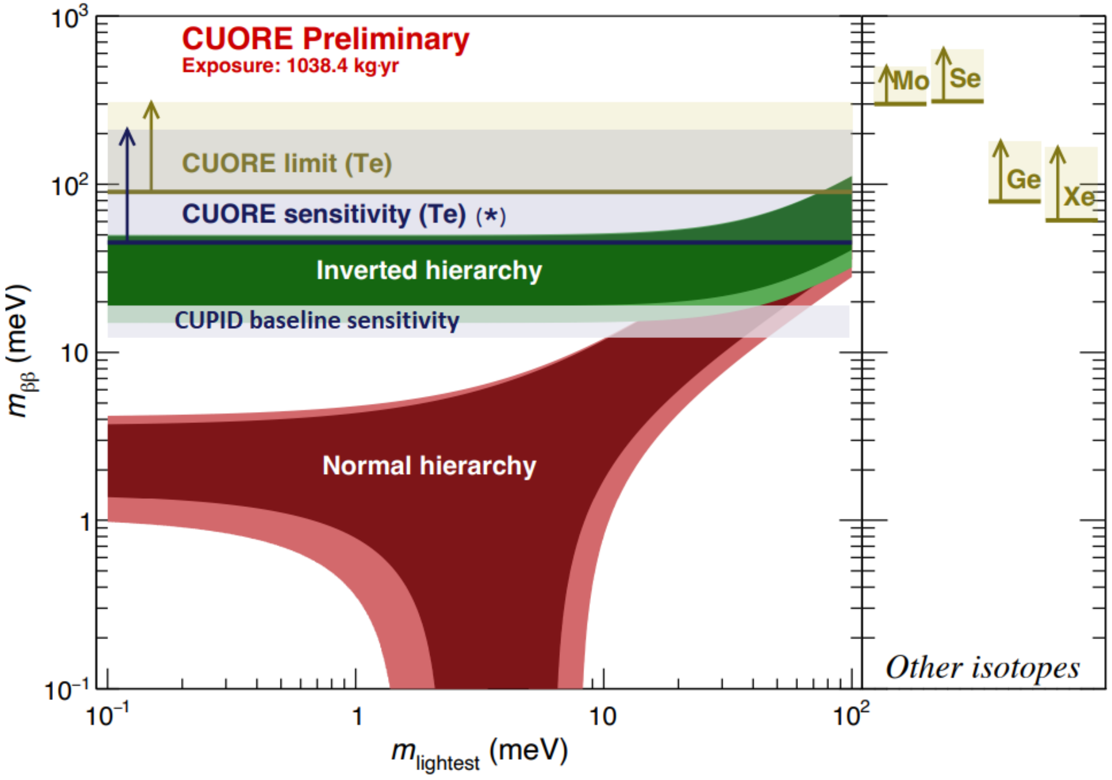
- Total exposure: 1038.4 kg.yr TeO_2, 288 kg.yr ^{130}Te
- $Q_{\beta\beta(^{130}Te)} = 2527.5\ keV$

$T^{0\nu}_{1/2}(^{130}Te) > 2.2 \times 10^{25}$ yr

ROI background index $\sim 1.49\ (4) \times 10^{-2}\ c/(keV.kg.yr)$
energy resolution $7.8\ (5)\ keV \rightarrow FWHM\ @\ Q_{\beta\beta}$

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



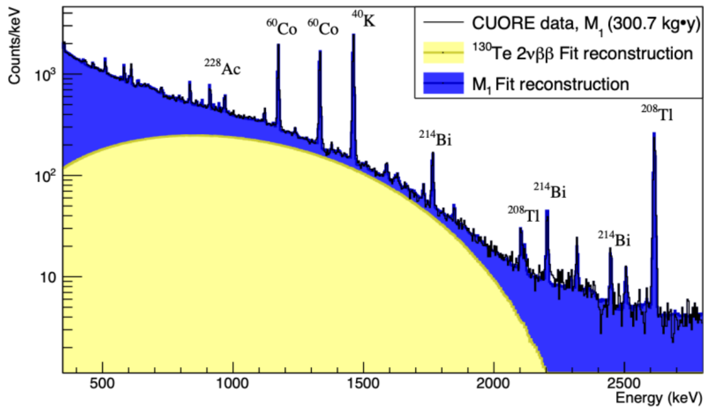


NATURE (2022)!

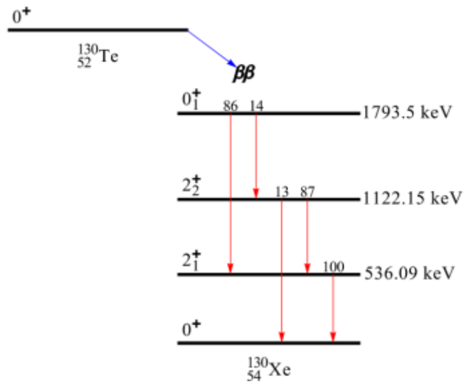
Adams D. et al. (CUORE collaboration), Nature 604 (2022) 7904, 53-58, https://www.nature.com/articles/s41586-022-04497-4

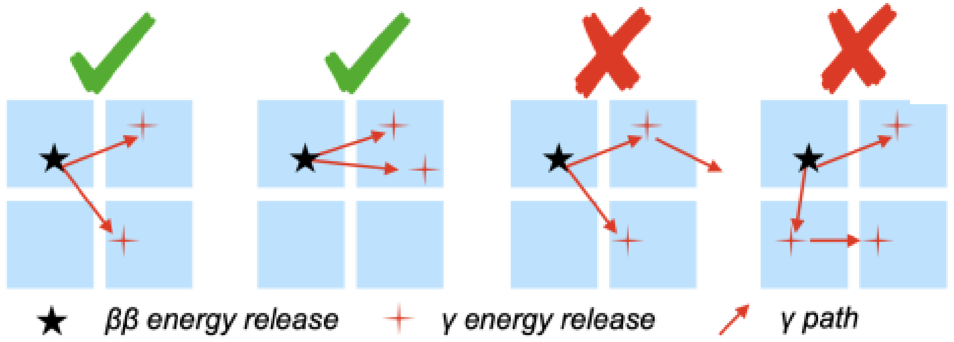
CUORE ^{130}Te ββ decays

- ^{130}Te 2νββ half-life measurement
  - Monte Carlo reconstruction of the CUORE background
  - Major background sources identified using
    - Coincidence analysis
    - Gamma peaks
    - Alpha peaks
    - Radio-assay measurements
    - Neutron activation
  - Most precise result to date: $T_{1/2}^{2\nu}(^{130}\mathrm{Te}) = 7.71^{+0.08}_{-0.06}(stat)^{+0.12}_{-0.15}(syst.) \times 10^{20}\ yr.$



- ^{130}Te ββ to first 0+ excitd state of ^{130}Xe
  - Multi-site signatures from βs and γs
  - Analysis on fully contained decays with coincident M2 and M3 events
  - 372.5 kg.yr of TeO_2
  - $T_{1/2}^{0\nu}(^{130}\mathrm{Te}) > 5.9 \times 10^{24}\ yr$
  - $T_{1/2}^{2\nu}(^{130}\mathrm{Te}) > 1.3 \times 10^{24}\ yr$





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

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

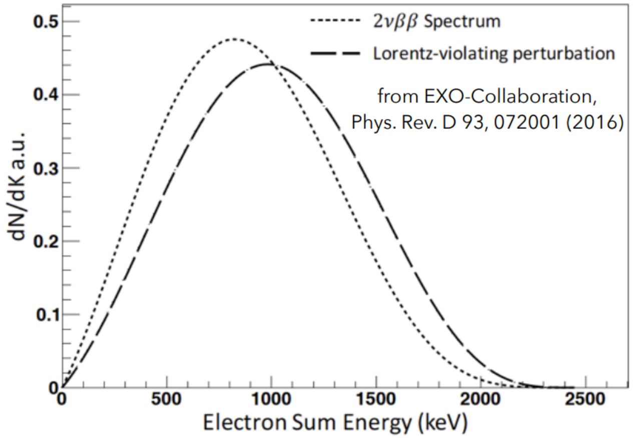
CUORE CPT violation search in 2νββ

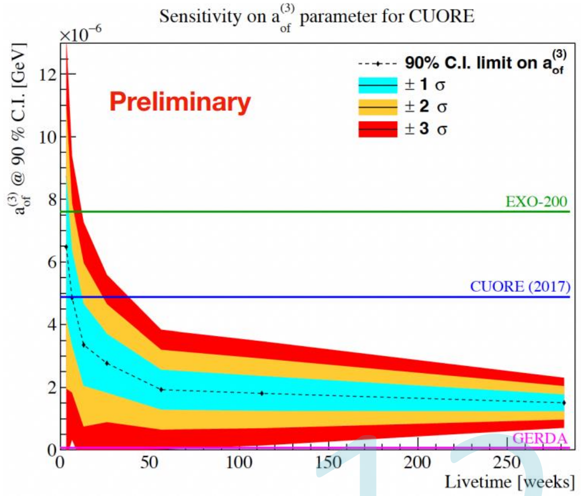
- Standard Model is invariant under Lorentz transformations $\longrightarrow$ CPT invariance
- Standard Model Extensions includes Lorentz violating operators which also violates CPT
- Effect of CPT breaking operator: modification in the decay spectrum of 2νββ due to modification in the phase space properties

$$\frac{d\Gamma}{dK} = \frac{d\Gamma_0}{dK} + \frac{d(\delta\Gamma)}{dK} \qquad with\ K = \overbrace{(T_1 + T_2)}^{\text{Sum of the kinect energy of the two emitted electrons}}/m_e$$

$$\frac{d\Gamma_0}{dK} \approx \zeta'(K^5 + 10K^4 + 40K^3 + 60K^2 + 30K)\underbrace{(Q_{\beta\beta} - K)^5}_{\text{SM 2νββ}}$$

$$\frac{d(\delta\Gamma)}{dK} \approx \zeta'(K^5 + 10K^4 + 40K^3 + 60K^2 + 30K)\underbrace{10\mathring{a}^3_{of}}_{\text{Parameter of interest}}\underbrace{(Q_{\beta\beta} - K)^4}_{\text{CPT violating term}}$$



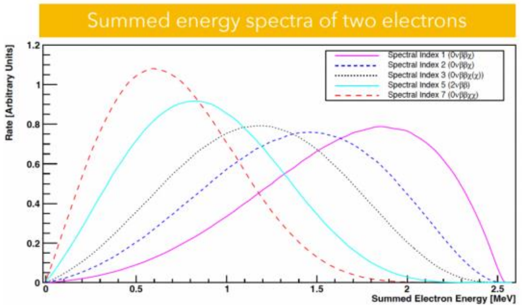


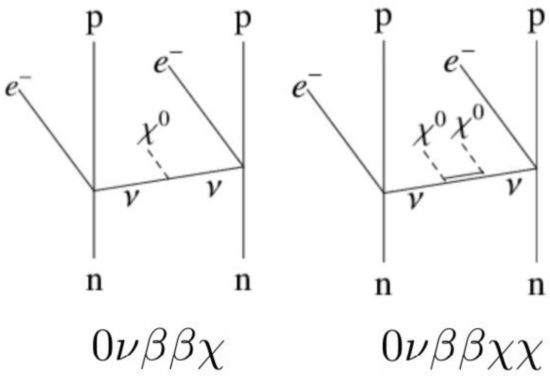
Irene Nutini's PhD Thesis (2019)

Work under development -> we are upgrading the *background model*

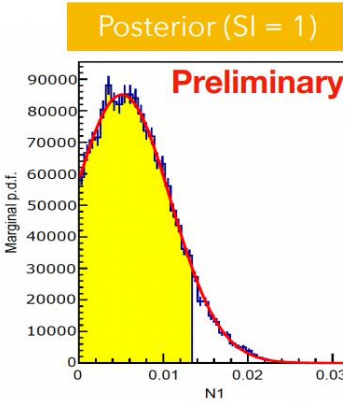
CUORE 0νββ with Majoron emission

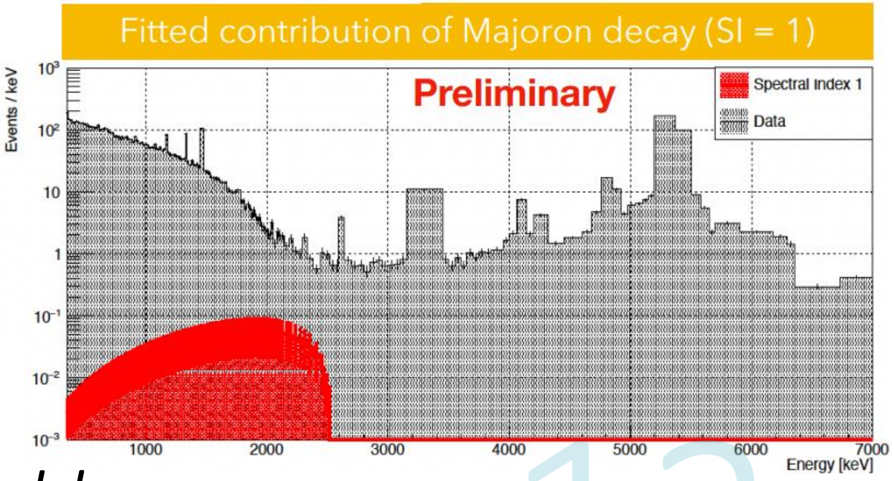
- Proposed models predict emission of 1 or 2 neutral bosons (Majoron) in 0νββ
- Experimental signature: continuous energy spectrum of the total electron energy depending on the considered model





- Background model fit with a given spectral index from a Majoron emission model
- Bayesian fit of the spectrum from data with signal+background model → set an upper limit on the coupling constants g_α
  - 387.5 kg.yr used for TeO2: updated ongoing



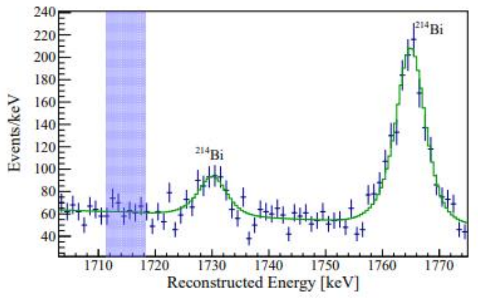


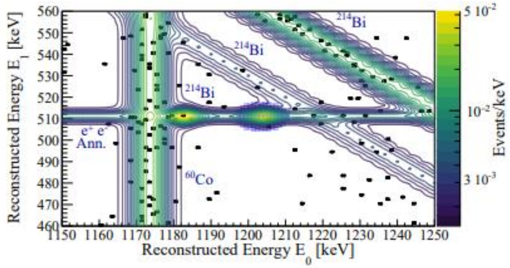
Work under development -> we are upgrading the *background model*

Christopher J. Davis' PhD Thesis (2019)

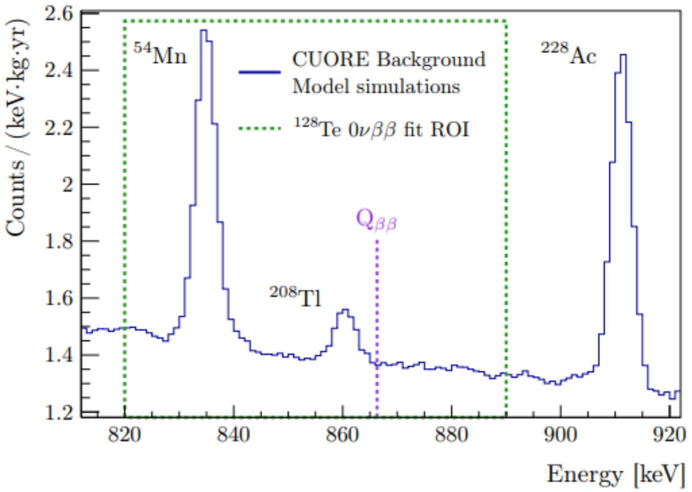
CUORE ^{120,128}Te decays

- ^{120}Te 0νβ⁺EC decay
  - $Q_{\beta\beta}$= 1714.8 keV
  - Natural abundance: 0.09 %
  - $^{120}Te + e^- \longrightarrow {}^{120}Sn + X + 2\gamma_{511}$
  - Multi-site signature: M1, M2 and M3 events
  - 355.7 kg.yr TeO2, 31.75 kg.yr ^{120}Te
  - $T^{0\nu}_{1/2}(^{120}\mathrm{Te}) > 2.9 \times 10^{22}\ yr$ at 90% C.I.
  - One order of magnitude better than previous results





- ^{128}Te 0νββ decay
  - $Q_{\beta\beta}$= 866.7 keV
  - Natural abundance: 31.74 %
  - 309.33 kg.yr, 78.56 kg.yr ^{128}Te
  - $T^{0\nu}_{1/2}\ (^{128}\mathrm{Te}) > 3.6 \times 10^{24}\ yr$ at 90% C.I.
  - 30x better than previous results

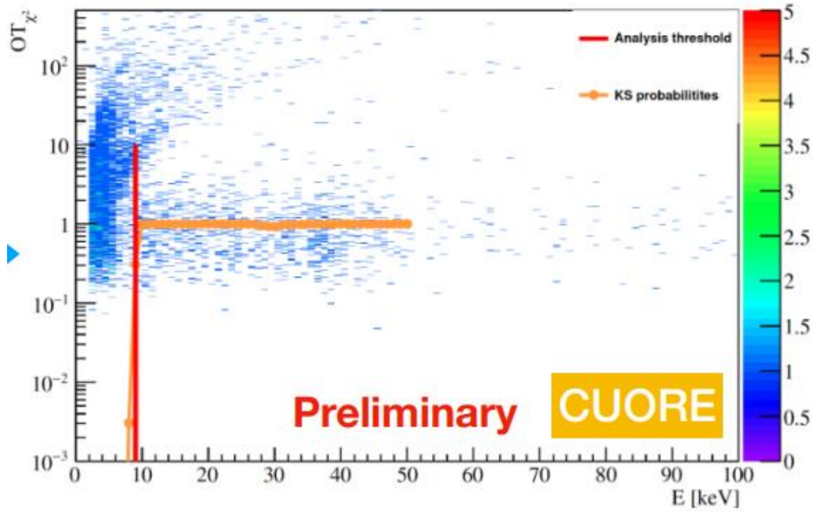


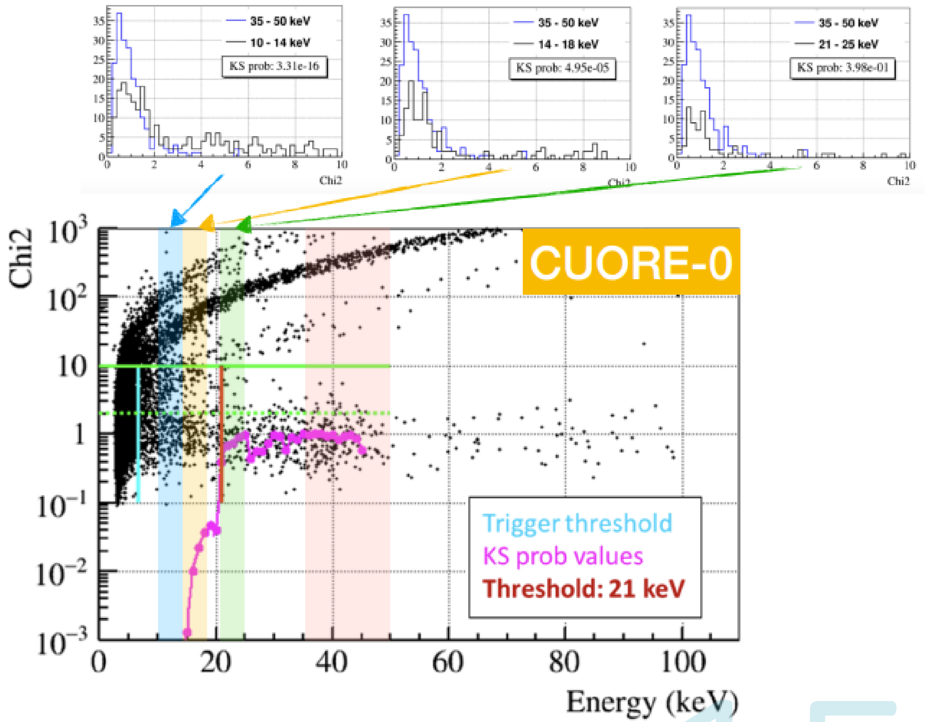
Adams D. et al. (CUORE collaboration), Phys.Rev.C 105:065504, https://doi.org/10.1103/PhysRevC.105.065504

Adams D. et al. (CUORE collaboration), arXiv:2205.03132, https://doi.org/10.48550/arXiv.2205.03132

The CUORE low energy analysis

- Cuts are optimized for CUORE ROI. Tools need to be optimized for low energy analysis
- Near trigger threshold we need to discard events that could contribute to the spectrum
- Noise contributions: tower vibrations + electronic spikes + sharp baseline jumps
- Pulse Shape Discriminaton (PSD)
  - Main variable is $OT\chi^2$
    - It is the χ^2 from the fit of the pulse under test with a template drawn from the average pulse of the considered channel
    - Real signal events: $OT\chi^2 \sim 1$
- Analysis threshold algorithm
  - CUORE-0 used a Kolmogorov-Smirnov (KS) algorithm
  - We are testing new methods



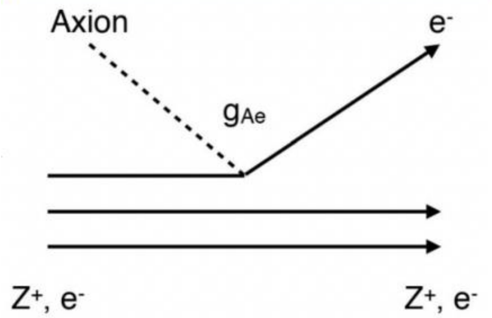


Adams D. et al. (CUORE collaboration), 2017, https://link.springer.com/article/10.1140/epjc/s10052-017-5433-1

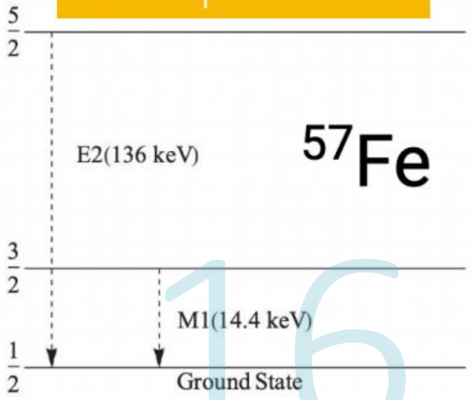
CUORE solar axions search

- Solar axions emitted by de-excitation of the first ^{57}Fe level (thermally populated in the core of the Sun)
- Can be detected in TeO_2 crystals through axio-electric effect
  - Signature: peak @ 14.4 keV
  - Analysis sensitive to $g_{Ae} \times g_{AN}^{eff}$ coupling constant
  - Working in progress
    - But analysis already developed and validate in past CCVR
- Can also be detected in TeO_2 crystals through Bragg-Primakov conversion
  - Axion couples to the crystal lattice charge though a virtual photon
  - Sun-CUORE angle dependence: only produces a photon if Bragg's condition is satisfied
  - Signature: counting rate x time over single day ⟶ analyze time-correlation method
  - Analysis sensitive to $g_{A\gamma\gamma} \times g_{AN}^{eff}$ coupling constant

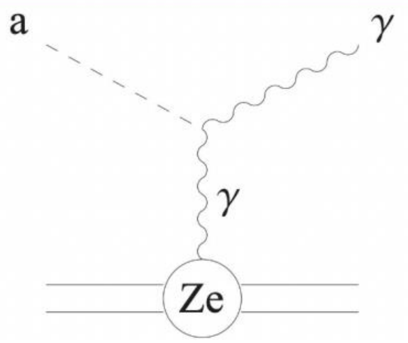
Detection: axio-electric effect

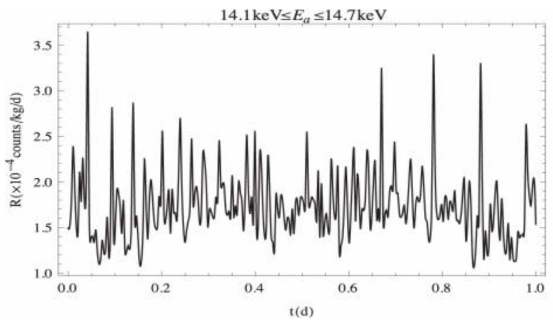


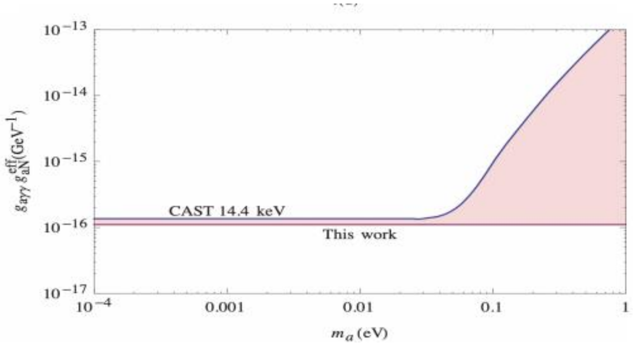
Axion production



Detection: Inverse-Coherent Bragg-Primakov Conversion

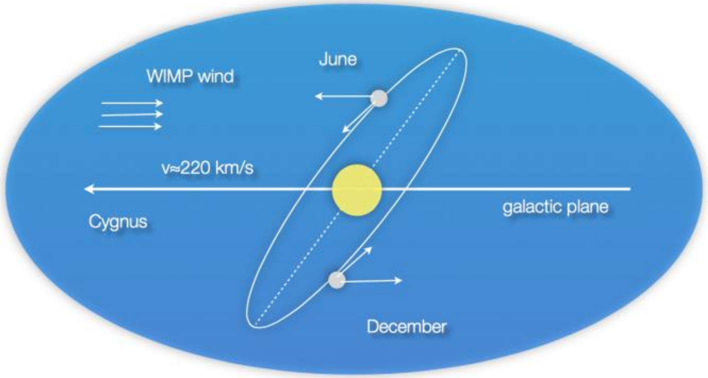


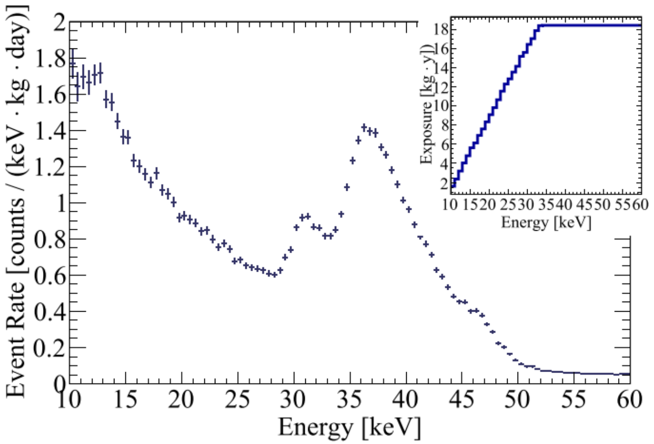




CUORE WIMP modulation

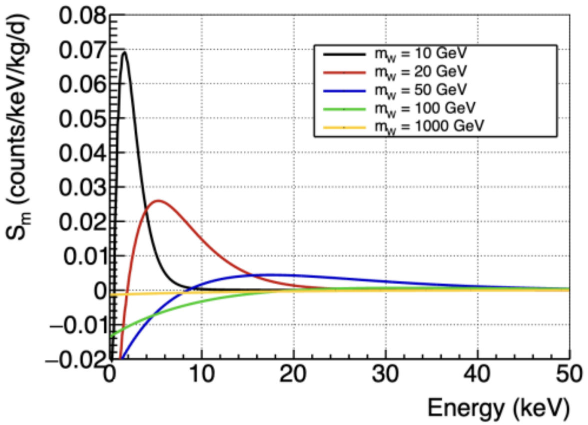
- TeO_2 combines heavy Te and light O nuclei: enhances the sensitivity to low WIMP masses
- Exploit CUORE-0 result to estimate CUORE sensitivity
  - Background rate and analysis threshold





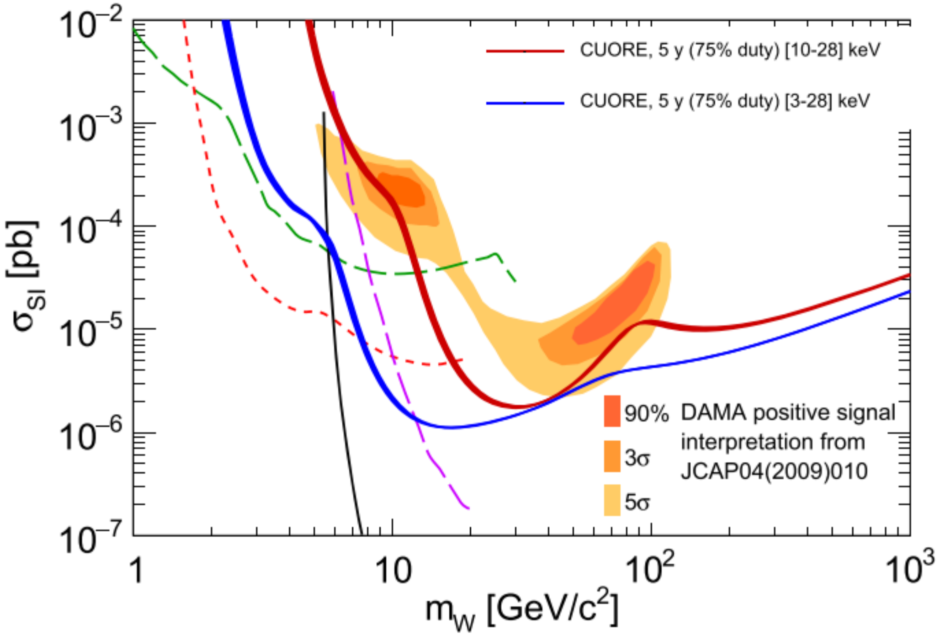
- ROI: [10,28] keV
- Peak at 30.5 keV not present anymore

$$\frac{dR_W}{dE}(E,t) = S_0(E) + S_m(E)\cos[\omega(t-t_0)]$$



CUORE WIMP modulation

- Scan (m_W, σ_{SI}) parameter space
  - Fit energy spectrum to signal+background and determine best-fit background coefficients
  - Use these background coefficients to generate 100 toy-MC simulations
  - For each toy-MC maximum the likelihood is computed
  - Experimental sensitivity is computed as the parameter space for which 90% experiments prefer modulation hypothesis compared to the null one



Analysis on going!

Alduino C. et al. (CUORE collaboration), 2017, https://link.springer.com/article/10.1140/epjc/s10052-017-5433-1

Conclusion

- CUORE is running in stable conditions
  - Started in 2017: comissioning + optimization + operation
  - Stable data-taking since 2019
- Developed tools needed for BSM and DM searches
  - Trigger and analysis tresholds
- Developed and validated a set of BSM and DM searches
  - CPT violation
  - Majorons
  - Axions and WIMPs
- Work in progress to use the full available statistics

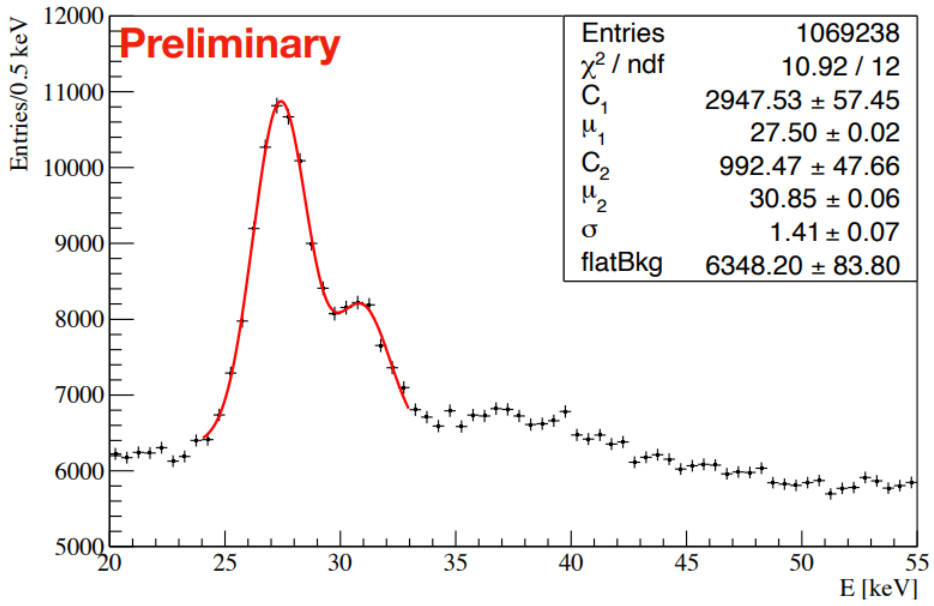
More results coming soon!

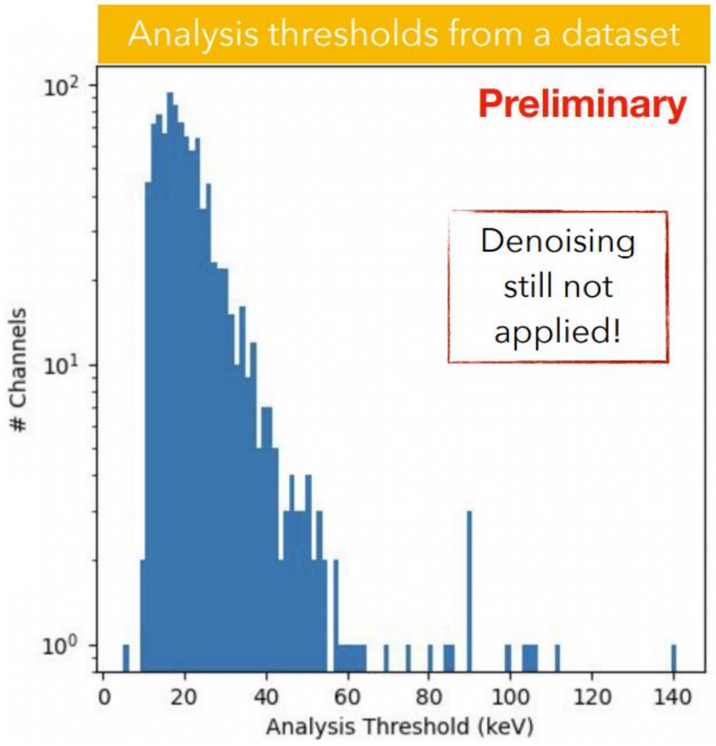
The CUORE collaboration

> 110 scientists
27 institutions in 4 countries

The CUORE low energy calibration

- X-rays from Te can be produced due γ interactions
- X-rays can escape and be measured by adjacent crystals
- 8 K shell peaks from Te





CUORE CPT violation search in 2νββ

- Background model: fits of simulated spectra from different contributions + measured energy spectrum
- 2νββ CPT violating term included in the background model fit
- Sensitivity study: for each given exposure, a set of toy-MC spectra are generated according to background only hypothesis
  - Fit with signal+background is performed for each toy-MC
  - Likelihood marginalized over all nuisances
  - Decay rate related to CPT violating term evaluated with 90% C.I. ⟶ exclusion sensitivity obtained for each parameter of interest
  - Distribution sensitivity obtained from set of toy-MC to obtain sensitivity with 1 and 2 sigma bands
- Analysis of physics data: bayesian fit from data with signal+background model ⟶ upper limit evaluation
  - Exposure of 86.3 kg.yr
  - Update analysis with refined background model and full available statistics ongoing