New results from CUORE and prospects for CUPID

Giovanni Benato for the CUORE and CUPID collaborations

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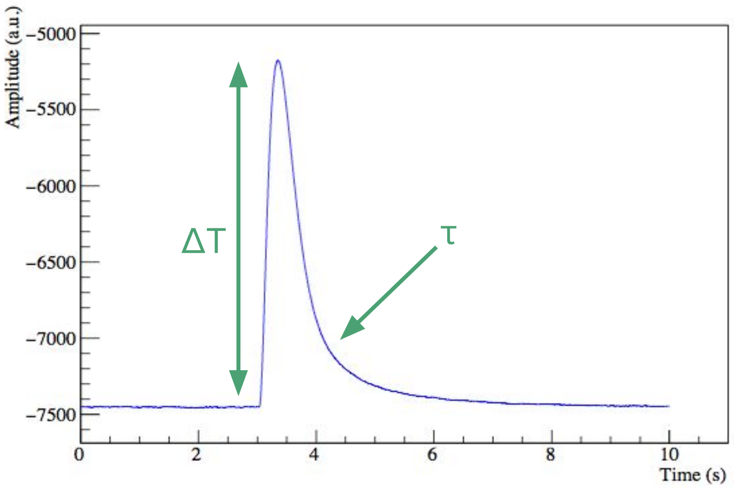
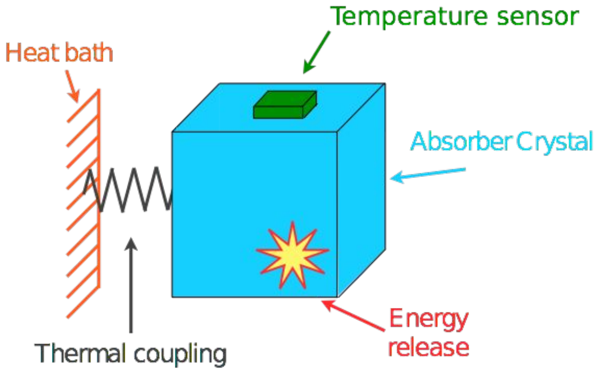
The bolometric technique

- Low heat capacity @ T ~ 10 mK
- Excellent energy resolution (~0.2% FWHM)
- Detector agnostic to origin of energy deposition
- Detector response of O(1) sec if readout with e.g. Neutron Transmutation Doped (NTD) Ge sensors

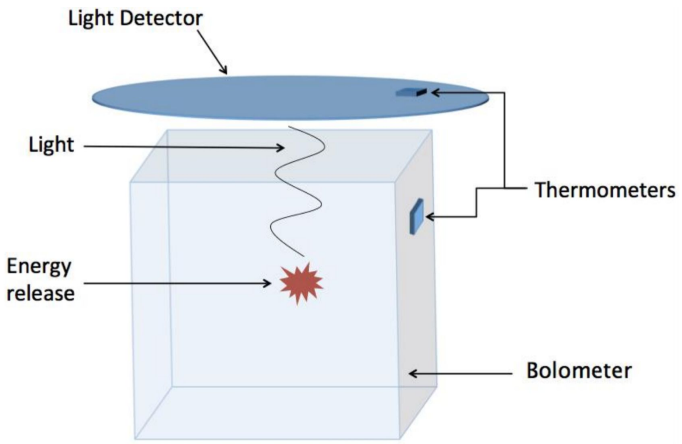


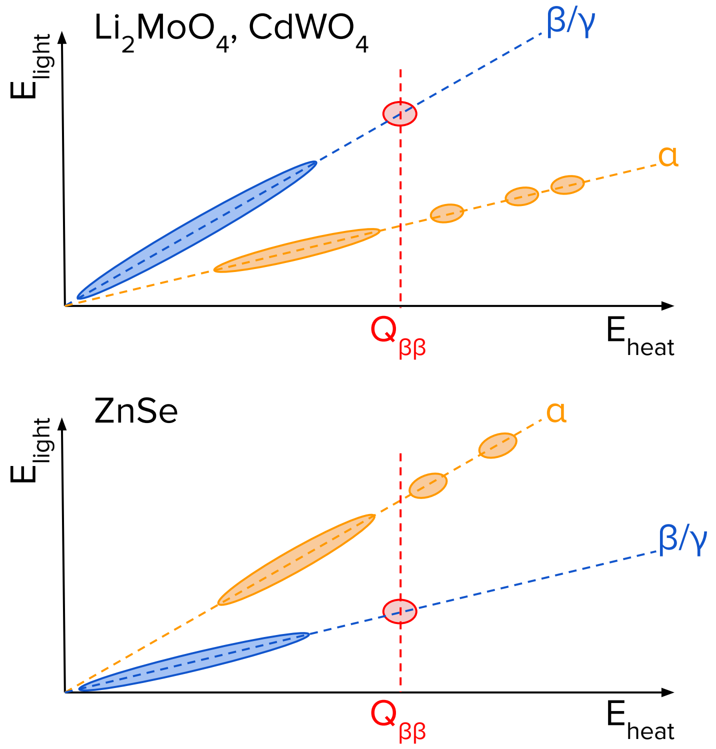


Simplified thermal model

- Crystal heat capacity: C
- Conductivity of coupling to thermal bath: G
- Signal amplitude ∝ $\Delta T = E_{dep} / C$
- Decay constant: $\tau = G / C$

Background suppression via Particle IDentification (PID)

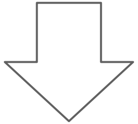




- Main background: surface α events
- Couple main crystal with secondary bolometer reading the scintillation (or Cherenkov) light
- Exploit different light yield (LY) of α vs β/γ to actively suppress background
- Typical light detector: thin Ge wafer coupled to thermometer (NTD, TES, KID, MMC)

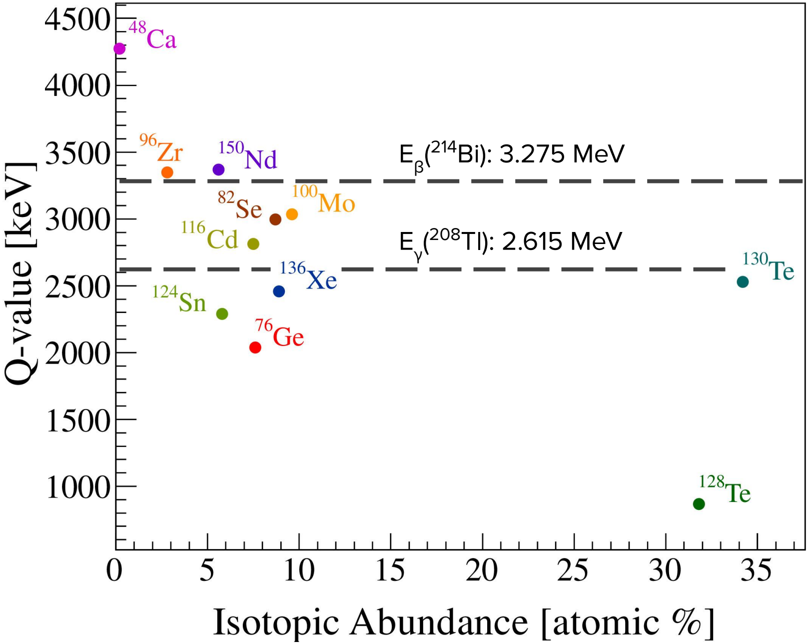
Isotope choice for bolometric experiment

- High isotopic abundance
- Enrichment possible at reasonable cost?
- $Q_{\beta\beta}$ above end point of β or γ radiation?
- Scintillating crystal available?
- Large scale crystal production possible?

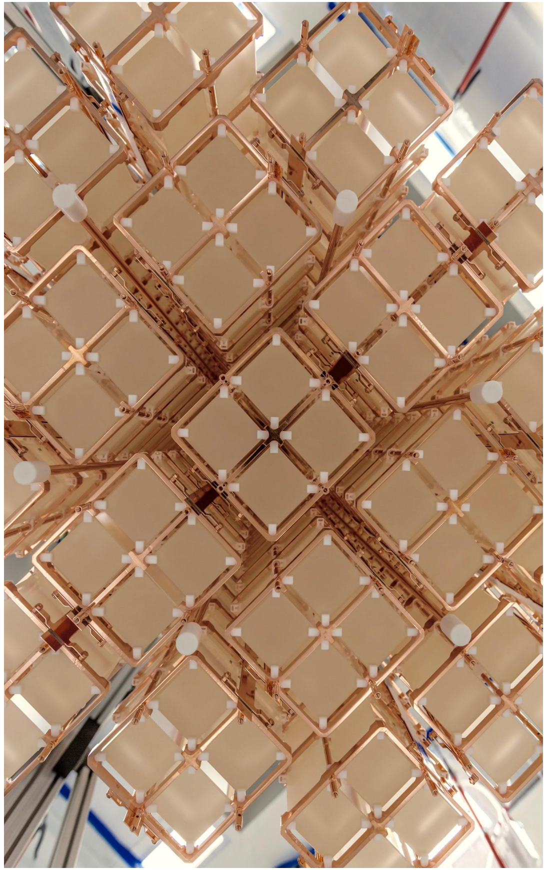


Advantages of bolometric approach

- Detectors and infrastructure are decoupled. Same cryogenic infrastructure re-usable with different isotopes and/or crystals
- Perfect for test of discovery or precision measurements



The CUORE experiment



The CUORE experiment

CUORE: the Cryogenic Underground Observatory for Rare Events

- 988 TeO_2 crystals with natural Te composition
  ➔ **742 kg total mass**, 206 kg ^{130}Te mass
- $Q_{\beta\beta}(^{130}Te) = 2527.5$ keV ➔ Above most natural γ background
- Located in [Hall A of the Gran Sasso National Lab]
- Background goal: 10^{-2} counts/keV/kg/yr at $Q_{\beta\beta}$
- Sensitivity goal on $T^{0\nu}_{1/2} = 9 \cdot 10^{25}$ yr with 5 yr of live time

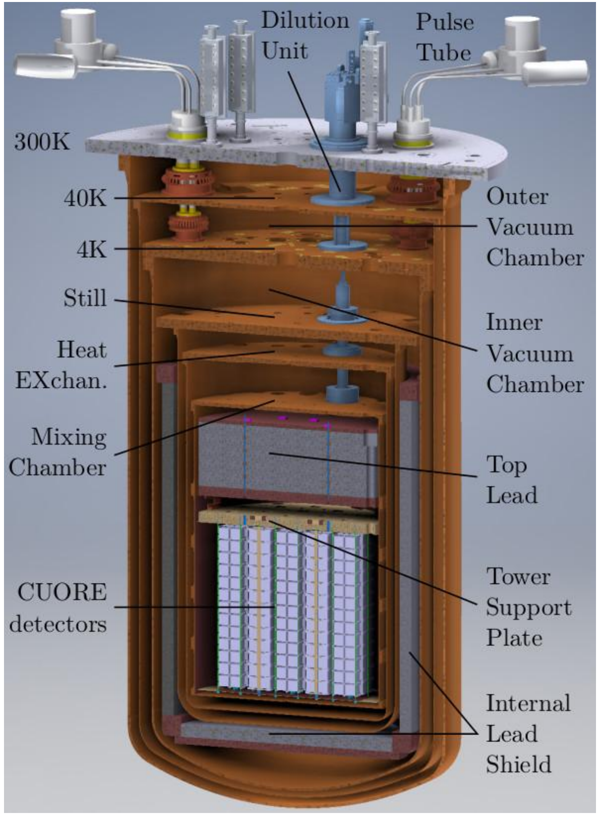
CUORE infrastructure

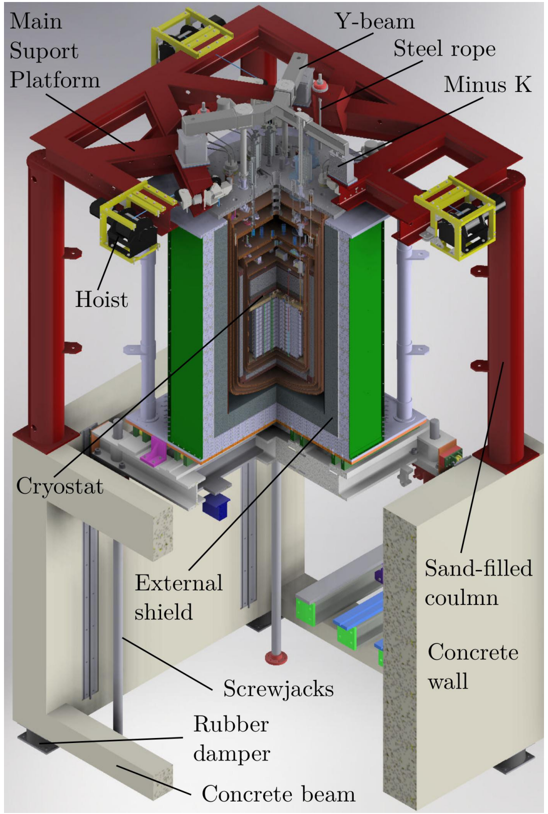
The coldest cubic meter in the known Universe

- Multistage cryogen-free cryostat
- Cooling systems: fast cooling system, Pulse Tubes (PTs), and Dilution Unit (DU)
- ~15 tons @ < 4 K
- ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancelling

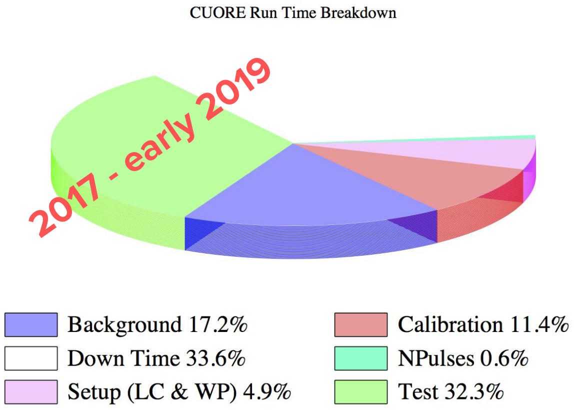
CUORE (passive) shielding

- Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels + polyethylene

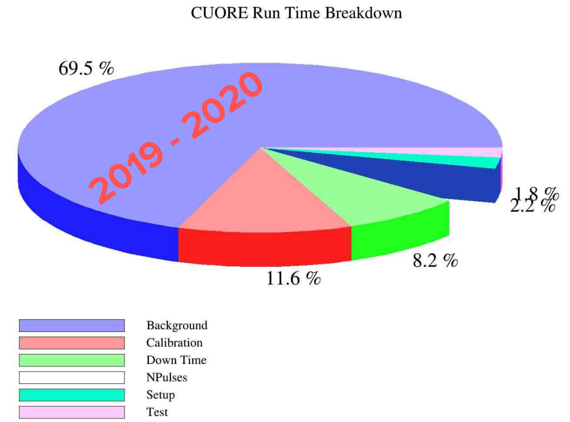


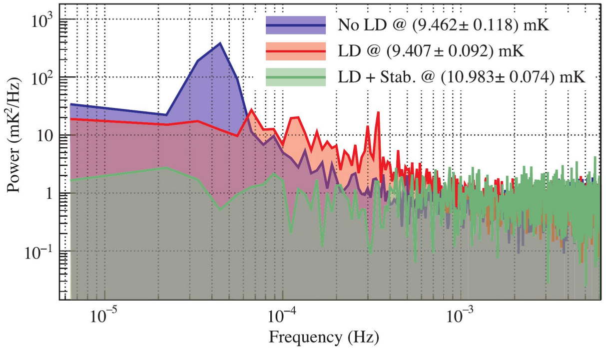


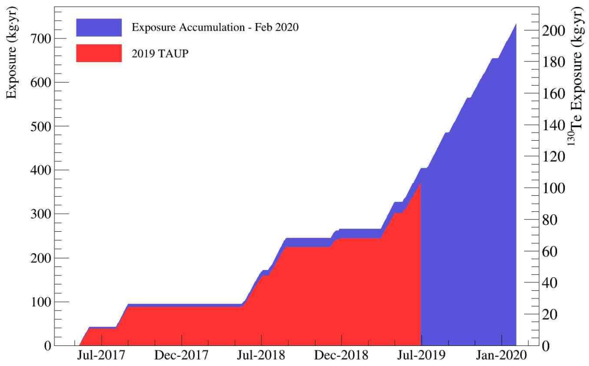
Optimization of the CUORE operations



- Upgrade of calibration system (2018)
- Major cryogenic maintenance (early 2019)
- Installed linear drives to control the pulse tube (PT) motorhead frequency
- Implemented PT active noise cancellation via phase tuning
- Optimized procedure for load curve, working point and temperature scan
- Improved data processing and analysis techniques

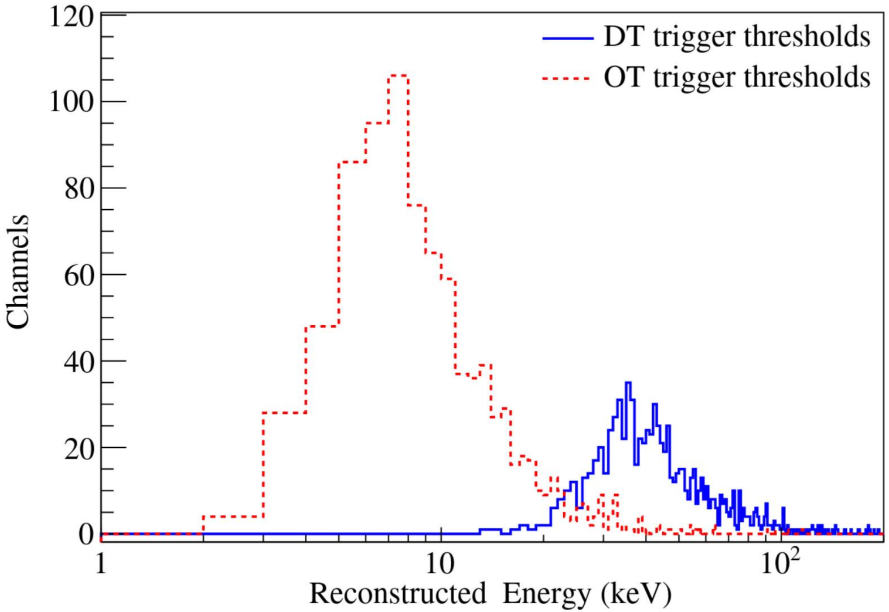




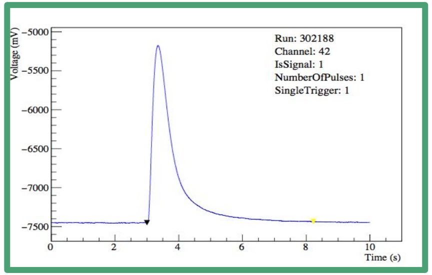


Optimum Trigger

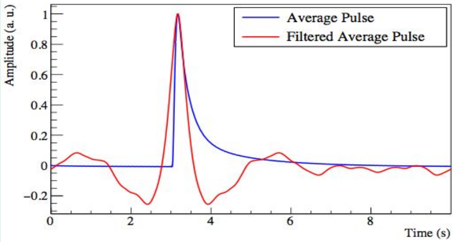
- Identifies physical signals using the full information contained in the signal pulse, not only on the signal rise
- Disentangles low energy signal from noise events ➡ Lower threshold
- Applied for offline retriggering of continuous data
- Threshold at 90% trigger efficiency reduced by a factor ~5 with respect to the “standard” derivative trigger

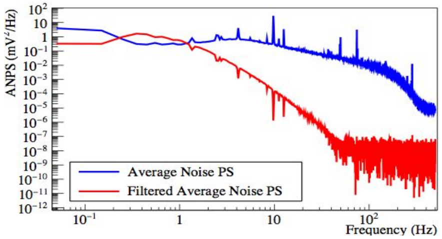


CUORE data processing

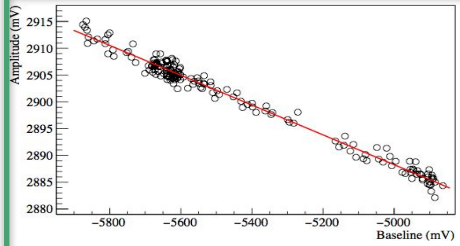


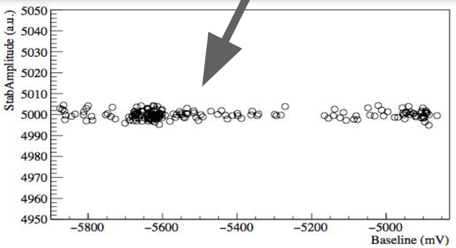
Optimum Filter → Gain Correction → Energy Calibration → Coincidences



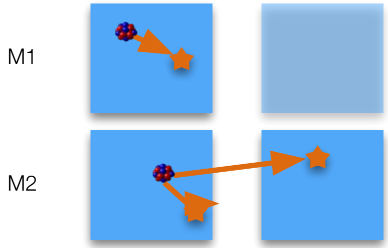


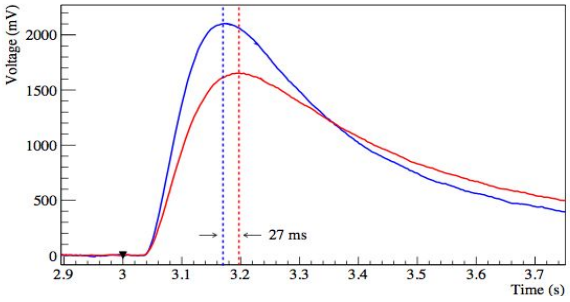
Matched filter that maximizes the signal-to-noise ratio



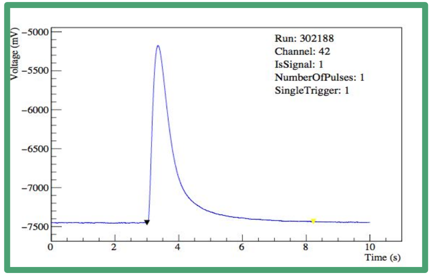


Heater pulses for thermal gain stabilization

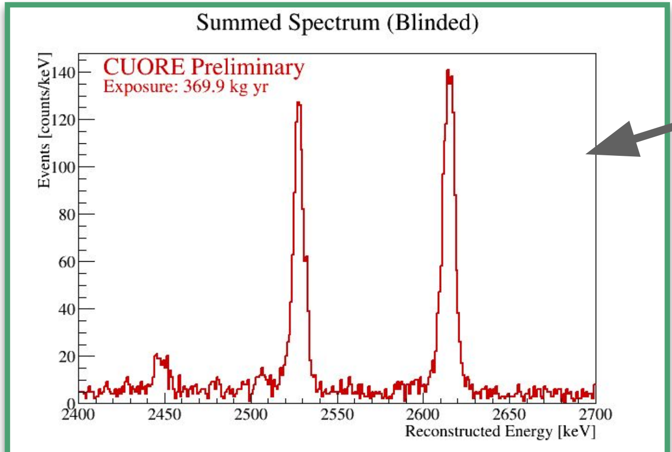




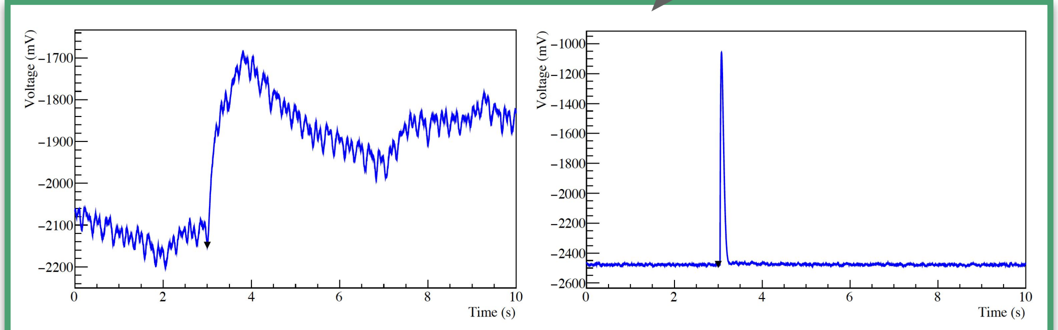
CUORE data processing



Optimum Filter → Gain Correction → Energy Calibration → Coincidences → PSA → ROI blinding → Data quality selection → Unblinding



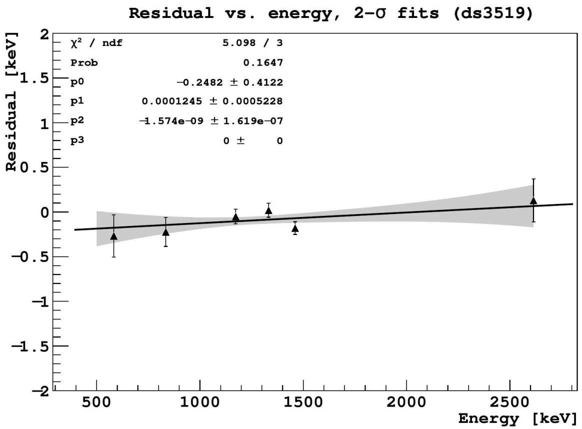
Quality cuts optimization on blinded data

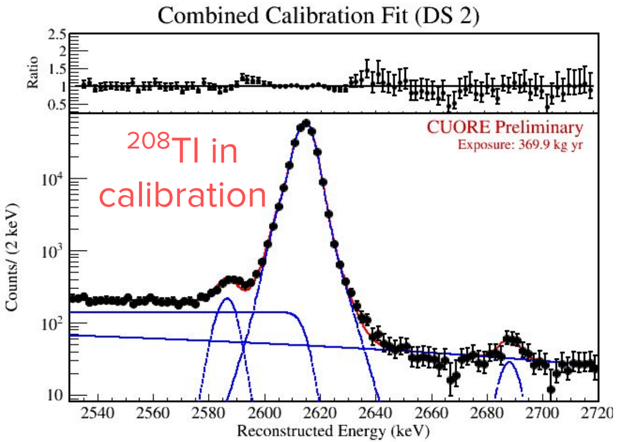


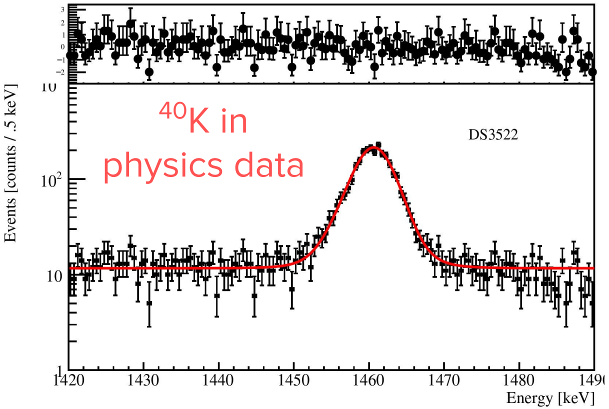
Reject non-physical pulses

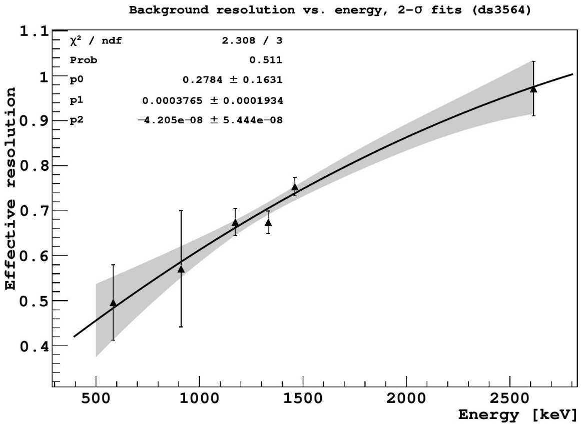
Lineshape

- Fit ^{208}Tl line at 2615 keV in calibration data to precisely model peak shape
- Fit γ lines in physics data keeping lineshape function fixed, and extract position and FWHM
- Fit bias vs energy, and FWHM vs energy
- Bias and FWHM uncertainties treated as systematics for the 0νββ decay analysis



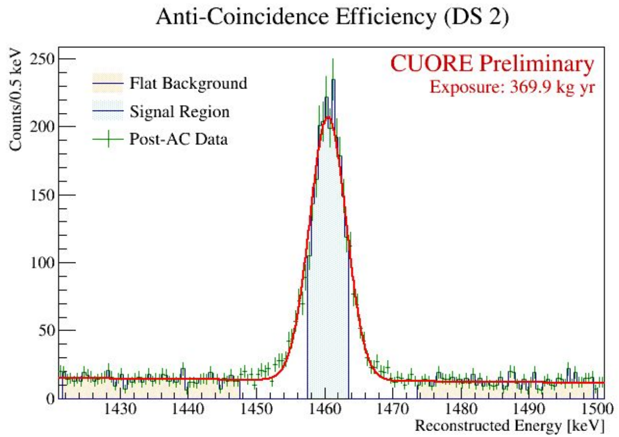


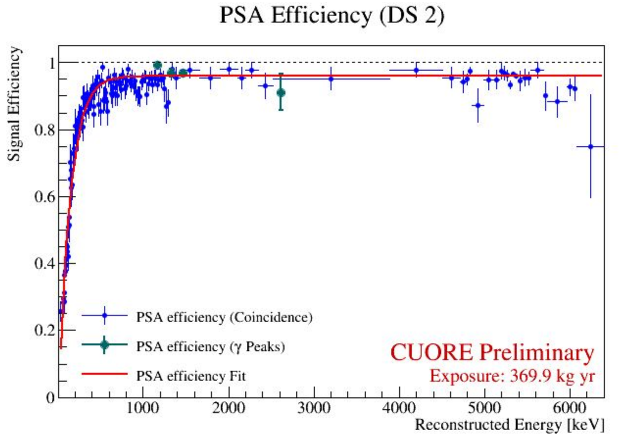




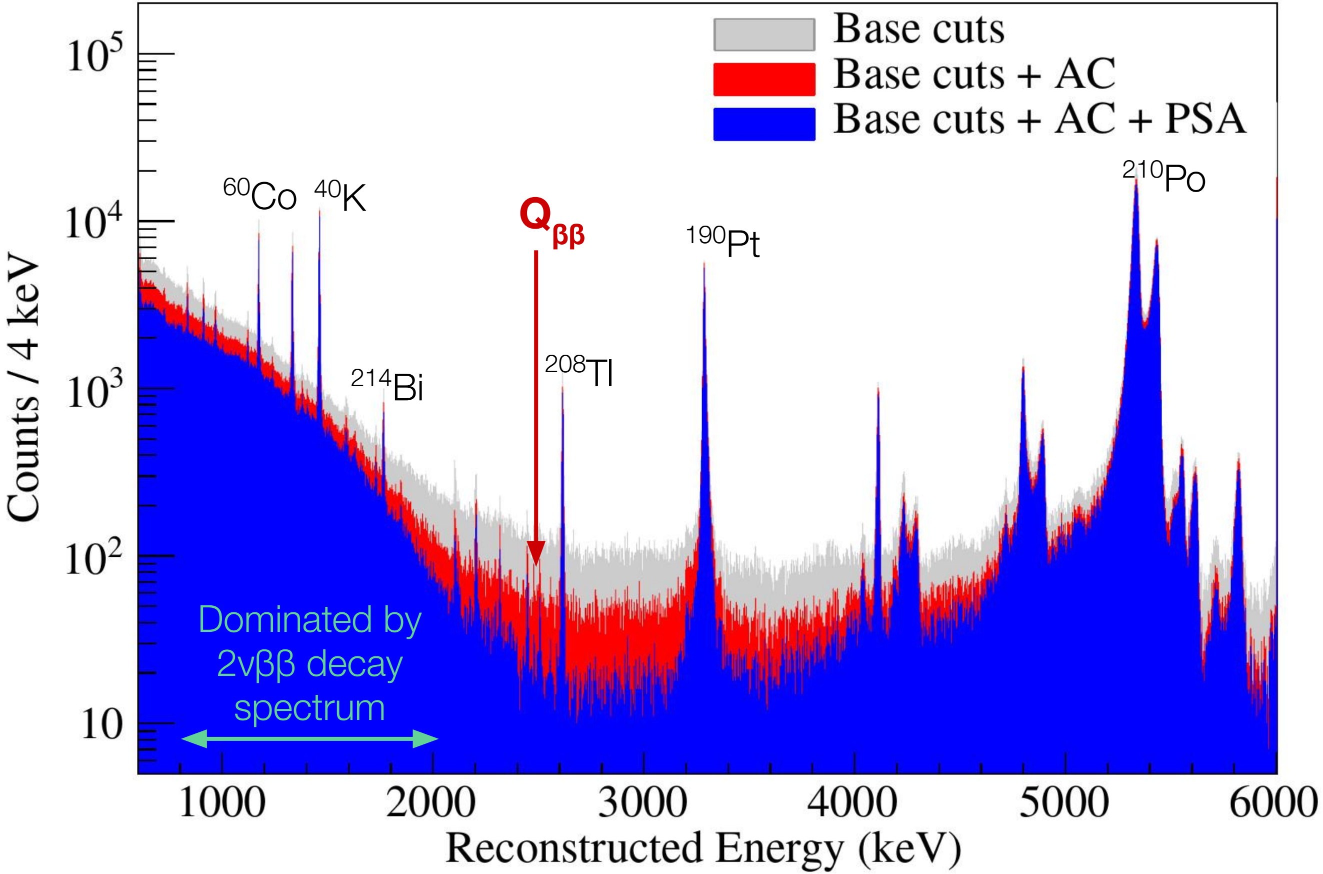
Efficiencies

Containment efficiency	Evaluated with MC simulations	88.35(9) %
Reconstruction efficiency	Comprises: ➔ trigger ➔ event reconstruction ➔ pile-up identification	95.802(3) %
Anti-coincidence efficiency	Quantifies the probability of properly identifying a single-crystal event	98.7(1) %
Pulse-shape analysis efficiency	Fraction of events passing a multi-dimensional cut on 6 pulse-shape variables	92.6(1) %





CUORE physics spectrum



Statistical approach to 0νββ decay search

Bayes theorem: $P\left(\vec{\theta}|\vec{E}\right) = \dfrac{\mathcal{L}\left(\vec{E}|\vec{\theta}\right)\cdot\pi\left(\vec{\theta}\right)}{\int_\Omega \mathcal{L}\left(\vec{E}|\vec{\theta}\right)\cdot\pi\left(\vec{\theta}\right)d\vec{\theta}}$

Signal component

Background components

Likelihood: $\mathcal{L}\left(\vec{E}|\vec{\theta}\right) = \prod_{dataset}\prod_{channel}\left[\dfrac{e^{-\lambda}\lambda^n}{n!}\prod_{event\ i}\left(\dfrac{s}{\lambda}pdf_{0\nu\beta\beta}\left(E_i|\vec{\theta}\right)+\dfrac{c}{\lambda}pdf_{^{60}Co}\left(E_i|\vec{\theta}\right)+\dfrac{b}{\lambda}\dfrac{1}{\Delta E}\right)\right]$

Expectation value: $\lambda=s+c+b$

Width of fit region: ΔE

Systematics implemented as nuisance parameters

Parameter	Dependence	Method
Analysis efficiency I	Dataset	Gaussian
Analysis efficiency II	Global	Flat in [0.993, 1.007] range
Energy bias	Dataset	Fit residuals of peaks in physics spectrum from literature values with 2nd order polynomial
Energy resolution	Dataset	Fit ratio of FWHM in physics and calibration data with 2nd order polynomial
$Q_{\beta\beta}$	Global	Gaussian, 2527.518(13) keV
^{130}Te isotopic fraction	Global	Gaussian, 34.1668(16)%

0νββ search results

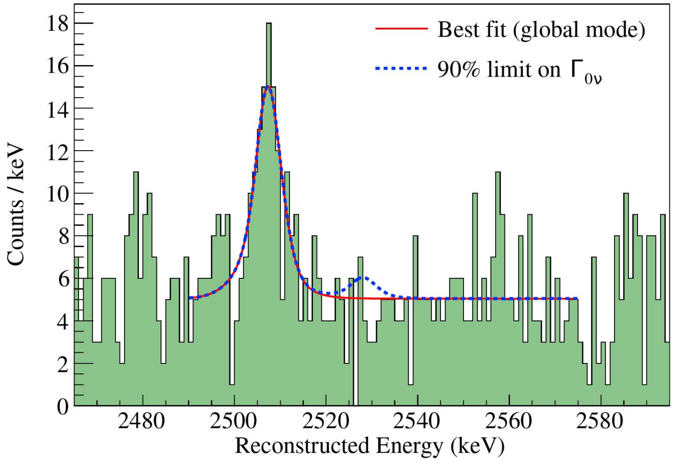
- Background index (BI) is a dataset dependent parameter
- Fit performed using BAT
- From bkg-only fit: **BI = (1.38±0.07) · 10^{-2} counts/(keV·kg·yr)**

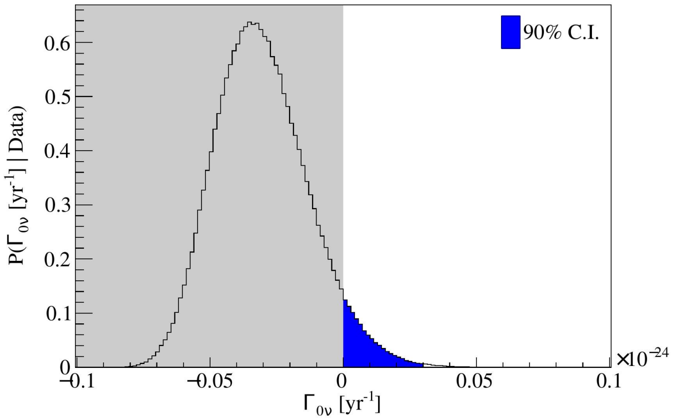
Sensitivity

- Generate toy-MC data using bkg-only model, fit them with the signal+bkg model, extract 90% c.i. Limit on $T_{1/2}^{0\nu}$
- Median exclusion sensitivity: **$T_{1/2}^{0\nu}$ = 1.7 · 10^{25} yr**

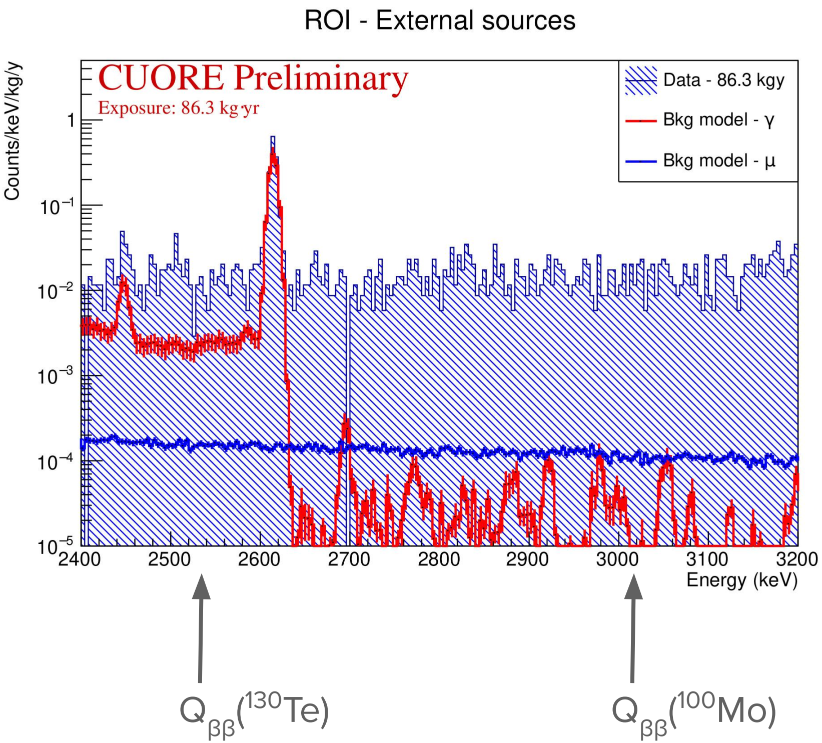
Results

- Best fit at $\Gamma_{0\nu}$ = 0 yr^{-1}
- **$T_{1/2}^{0\nu}$ > 3.2 · 10^{25} yr @ 90% c.i.**
  ➜ 3% probability of getting a stronger limit
- Systematics affect limit by 0.4%
- Assuming light neutrino exchange: **$m_{\beta\beta}$ < 75 - 350 meV**
- More infos: arXiv:1912.10966



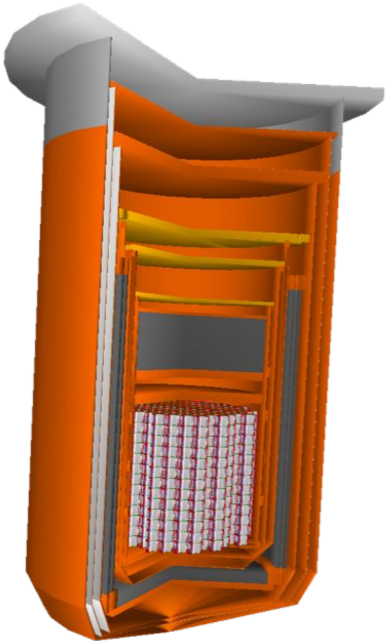


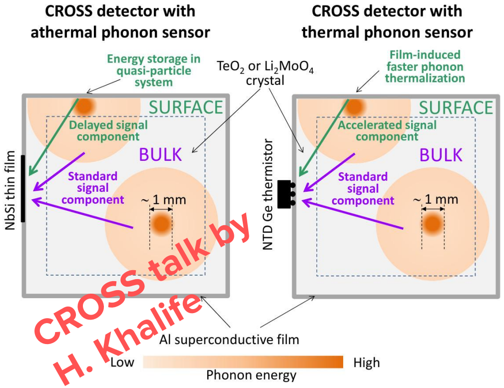
Lessons learned from CUORE



- Most measured background is due to α particles (U/Th contaminations close to TeO_2 crystals)
  ➔ α/β discrimination is required
- A $Q_{\beta\beta}$ > 2.6 MeV would automatically reduce the remaining non-α background by one order of magnitude
- Muons are the dominant contribution
  ➔ active muon veto

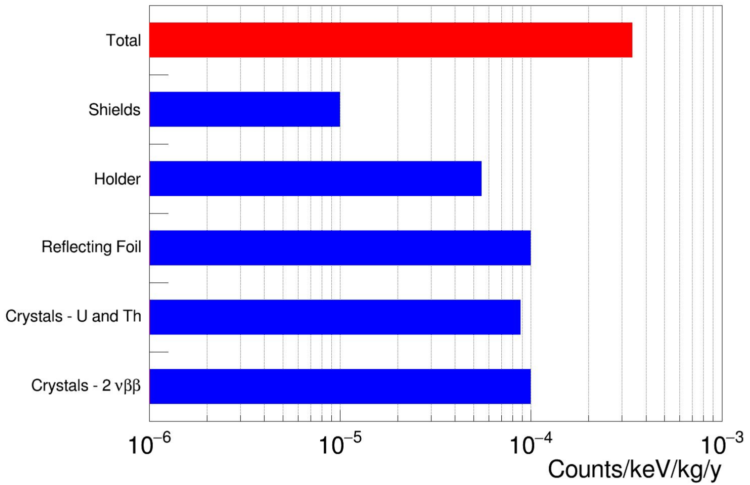
CUPID: CUORE Upgrade with Particle Identification





CUPID goals and background projection

- Crystals:
  - U/Th bulk → from CUPID-Mo
  - U/Th surface → from CUORE bkg-model
  - $2\nu\beta\beta$ pile-up ($T_{1/2}^{2\nu} = 7.1\times10^{18}$ yr)
- Crystal holders
  - U/Th surface → CUPID-0 bkg-model
- Cryogenic infrastructure and shielding
  - U/Th bulk → CUORE bkg-model
- Muons → Cut by muon veto

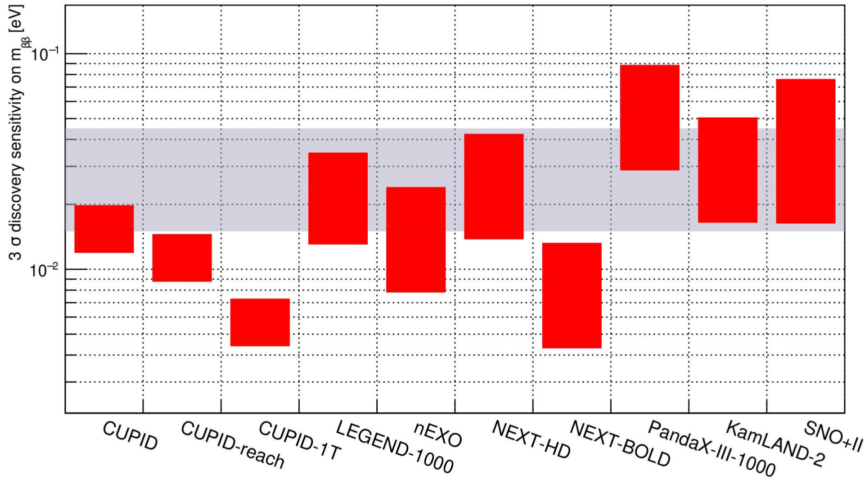


Goals

- ~1500 $Li_2{}^{100}MoO_4$ scintillating crystals (~250 kg of ^{100}Mo)
- Goal FWHM: 5 keV at $Q_{\beta\beta}$
- α rejection via PID
- Goal background: 10^{-4} counts/keV/kg/yr
- Discovery sensitivity: $T^{0\nu}_{1/2} = 10^{27}$ yr

CUPID physics goal

- CUPID pre-CDR: very conservative
  - Exactly what we could start building today. No improvement assumed!
- CUPID reach: assume improvement at reach before construction
  - Improved signal timing with TES on LD
  - Improved radiopurity
  - Zero-bkg condition: $2{\cdot}10^{-5}$ counts/keV/kg/yr
- CUPID 1 ton: new 4x larger cryostat
  - 1 ton of ^{100}Mo, plus possibly other isotopes
  - BI: $5{\cdot}10^{-6}$ counts/keV/kg/yr



Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

THANK YOU!

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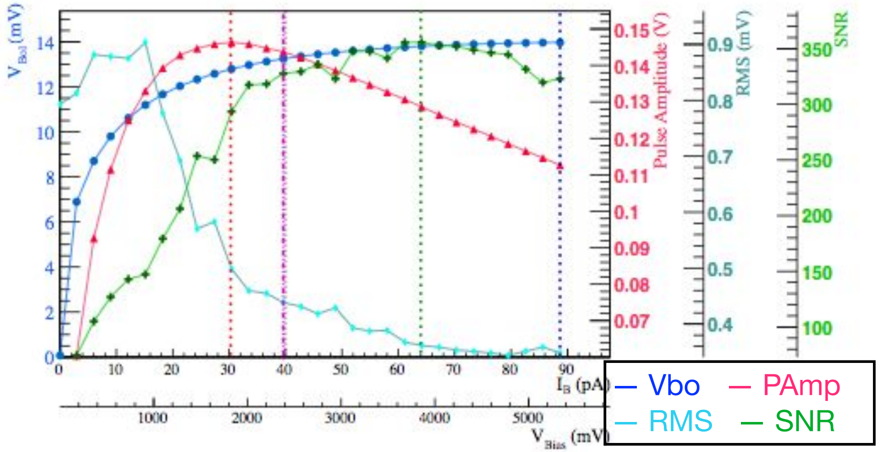
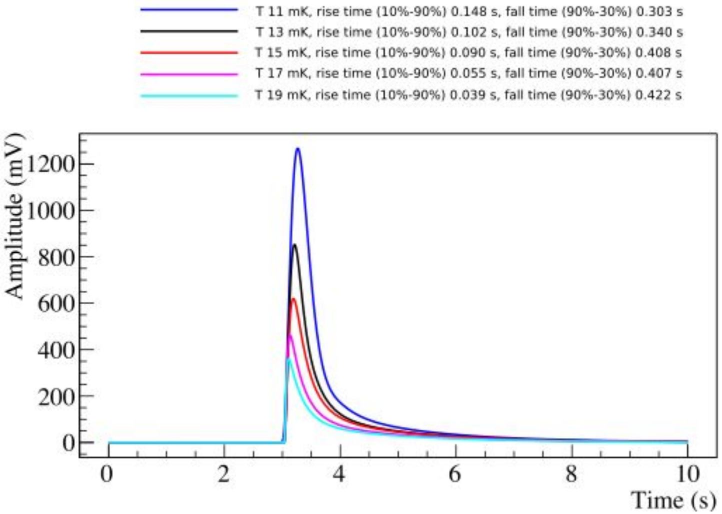
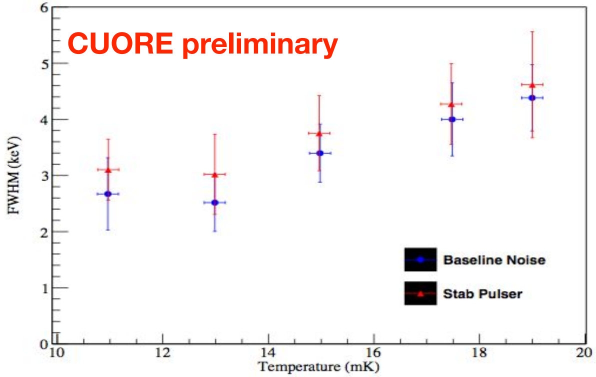
Fellini
Fellowship for Innovation at INFN

Backup: load curves, working point & temperature scans

- Achieve high quality detector readout with a good signal-to-noise ratio
- Dedicated procedures and algorithms to automate the load curve measurement and the working point identification at each T_{base}.

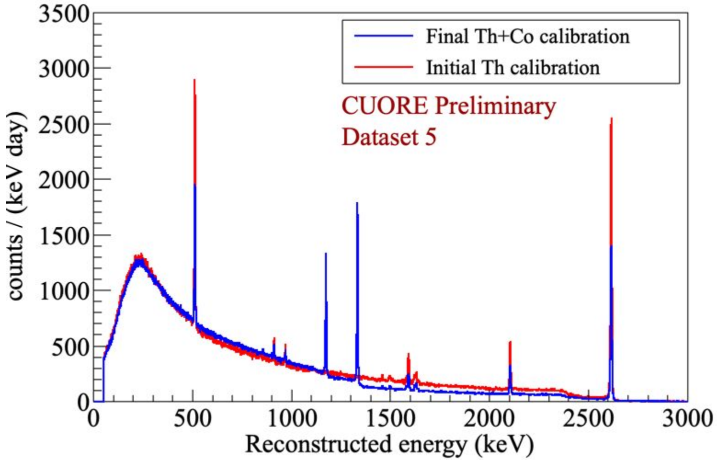


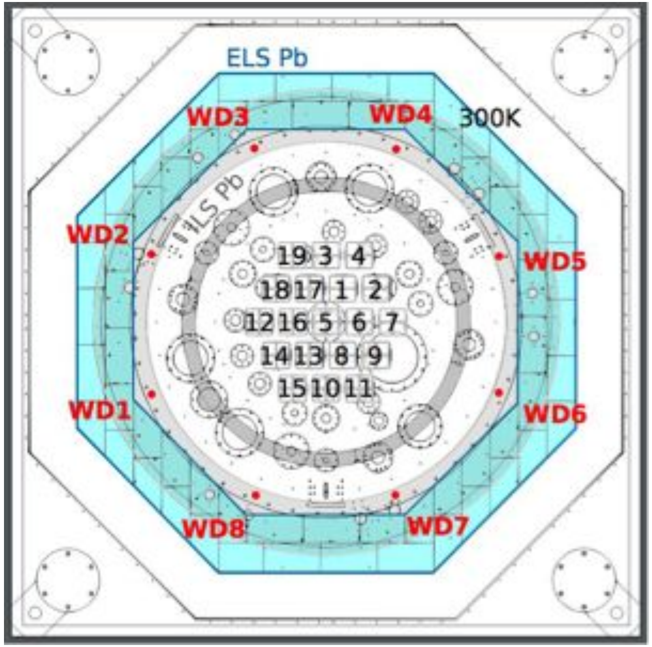




Backup: external detector calibration system (EDCS)

- Internal calibration system: ^{232}Th sources inserted between crystals at 10 mK
  ➔ Complicated and delicate procedure that interferes with the cryogenic system operation
- External calibration system: mixed $^{232}Th+^{60}Co$ sources inserted between cryostat and external lead shielding.





Backup: effective parameters

Number of datasets	7
Number of valid calorimeters (min-max)	900-954
TeO_2 exposure	372.5 kg·yr
FWHM at 2615 keV in calibration data	7.73(3) keV
FWHM at $Q_{\beta\beta}$ in physics data	7.0(4) keV
Reconstruction efficiency	95.802(3)%
Anticoincidence efficiency	98.7(1)%
PSA efficiency	92.6(1)%
Total analysis efficiency	87.5(2)%
Containment efficiency	88.35(9)%