Latest Results from the CUORE Experiment

Direct Dark Matter Detection

RICAP 2024

Samantha Pagan on behalf of the CUORE Collaboration

CUORE collaboration and acknowledgments

The CUORE Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN); the National Science Foundation under Grant Nos. NSF-PHY-0605119, NSF-PHY-0500337, NSF-PHY-0855314, NSF-PHY-0902171, NSF-PHY-0969852, NSF-PHY-1307204, NSF-PHY-1314881, NSF-PHY-1401832, and NSF-PHY-1913374; Yale University, Johns Hopkins University, and University of Pittsburgh. This material is also based upon work supported by the US Department of Energy (DOE) Office of Science under Contract Nos. DE-AC02-05CH11231 and DE-AC52-07NA27344; by the DOE Office of Science, Office of Nuclear Physics under Contract Nos.DE-FG02-08ER41551, DE-FG03-00ER41138, DE- SC0012654, DE-SC0020423, DE-SC0019316. This research used resources of the National Energy Research Scientific Computing Center (NERSC)This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER, and CUPID-0 Collaborations. The authors acknowledge Advanced Research Computing at Virginia Tech for providing computational resources and technical support that have contributed to the results reported.

CUORE

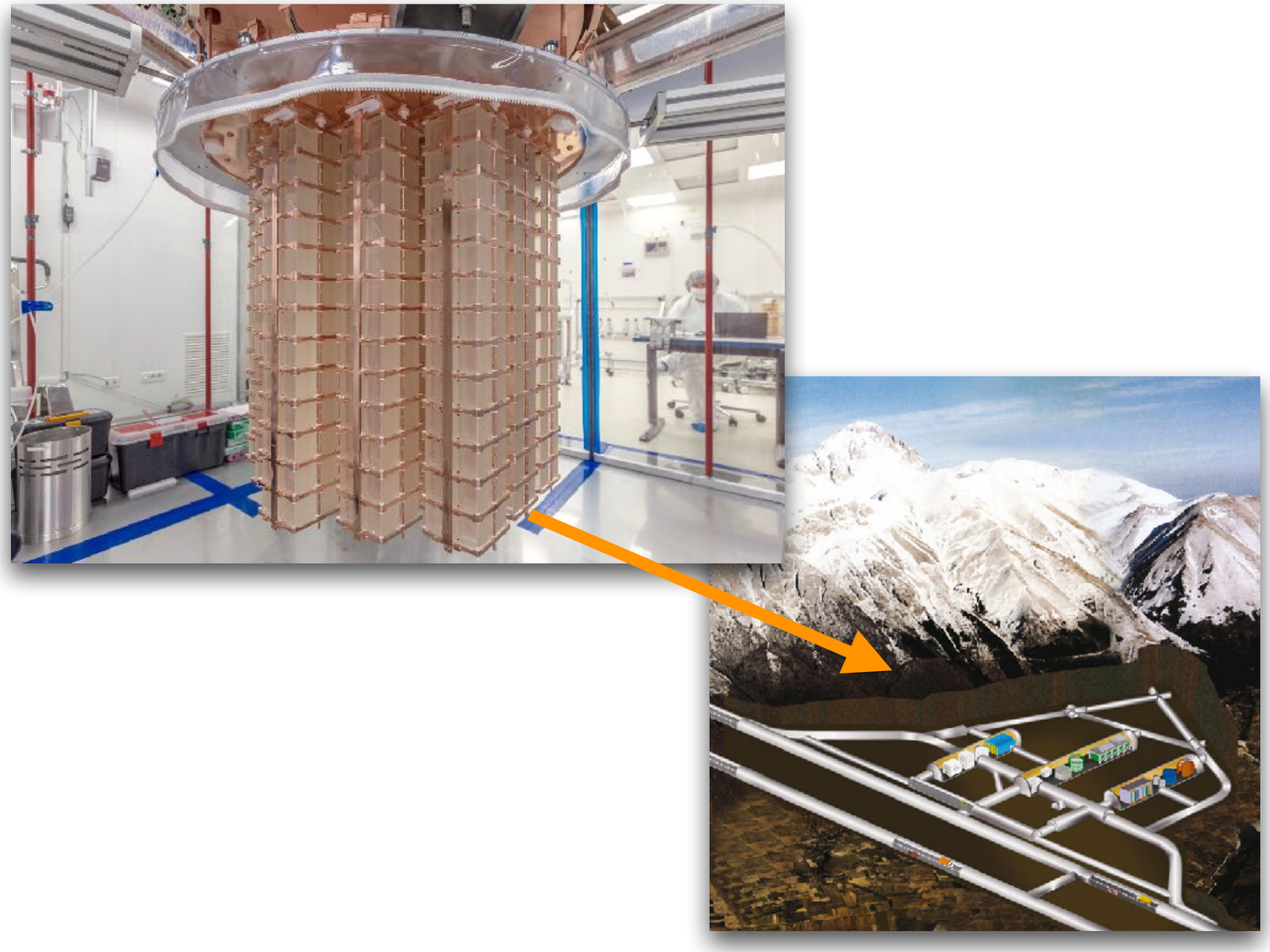
The **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents

Science Program: Neutrinoless double-beta decay, double-beta decay, decay studies, beyond the standard model searches

Located at LNGS Gran Sasso National Laboratory (~3600 m.w.e.)

988 TeO_2 crystal cryogenic calorimeters

Began collecting data in 2017, stably taking data since 2019



CUORE

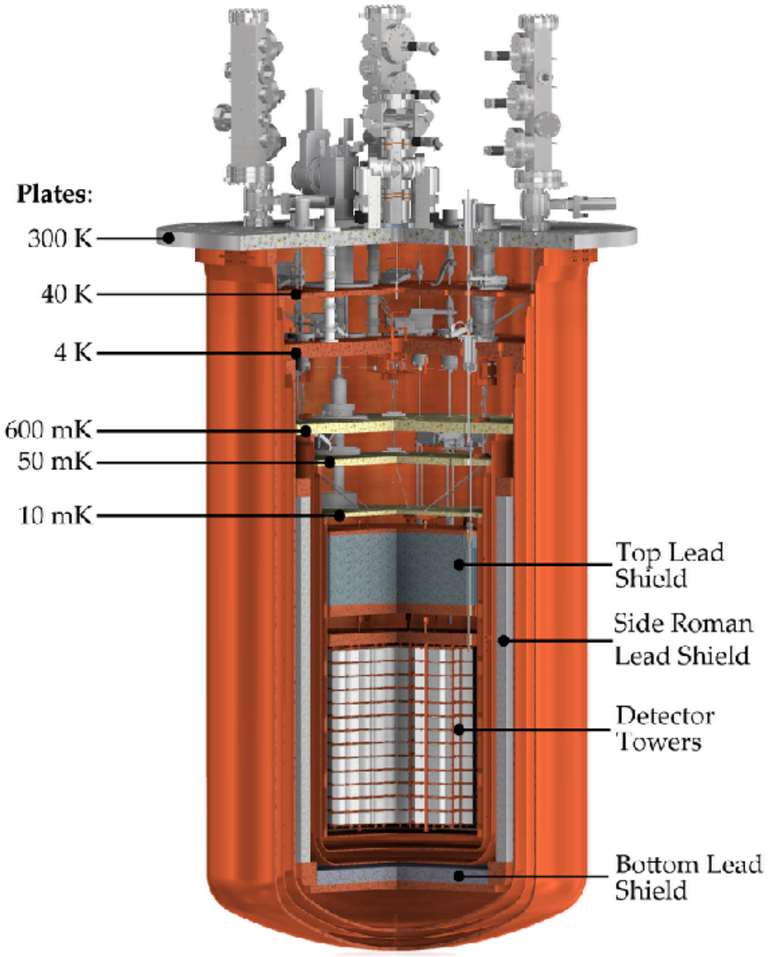
Modern lead on top of detectors and side Roman lead shielding

Custom dilution refrigerator, nested vessels, and pulse tubes, with vibration mitigation

Operated at ~10 mK

19 towers with 13 floors of 4 crystals each

Natural TeO_2 crystals
$5\times5\times5$ cm^3, 750 g each



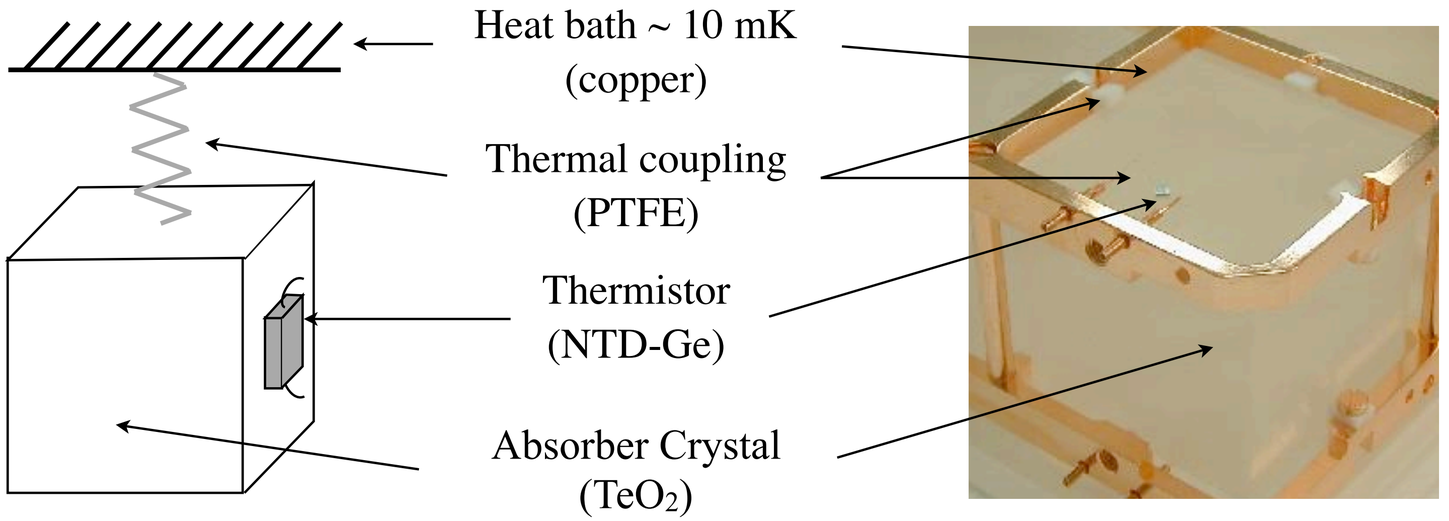
CUORE Cryostat

Cryogenic calorimeters: operating principle

Particle interaction increase crystal temperature

Thermal coupling to 10 mK heat bath

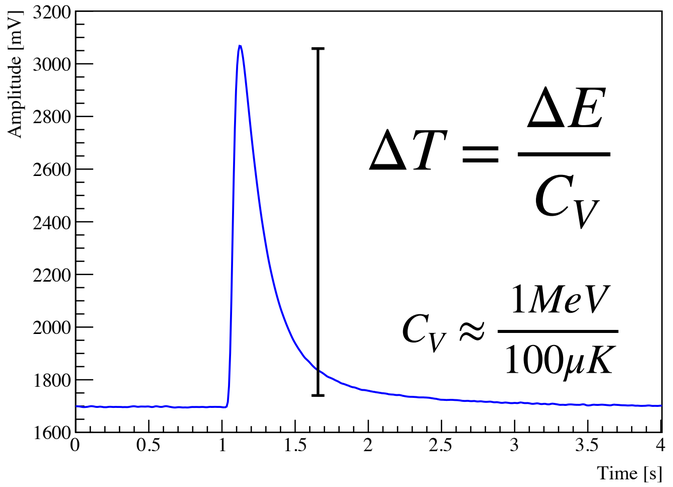
Neutron Transmutation Doped (NTD) Ge thermistors



$$C_V(T) \propto T^3$$

$$R(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$$

E. E. Haller, J. Appl. Phys. 77, 2857-2878 (1995)



CUORE data taking: 2 tonne·yr (2TY)

TeO_2 exposure

~86 kg·yr

Alduino, C et al. (CUORE Collaboration), *Phys. Rev. Lett.* **120**, 132501 (2018)

~300 kg·yr

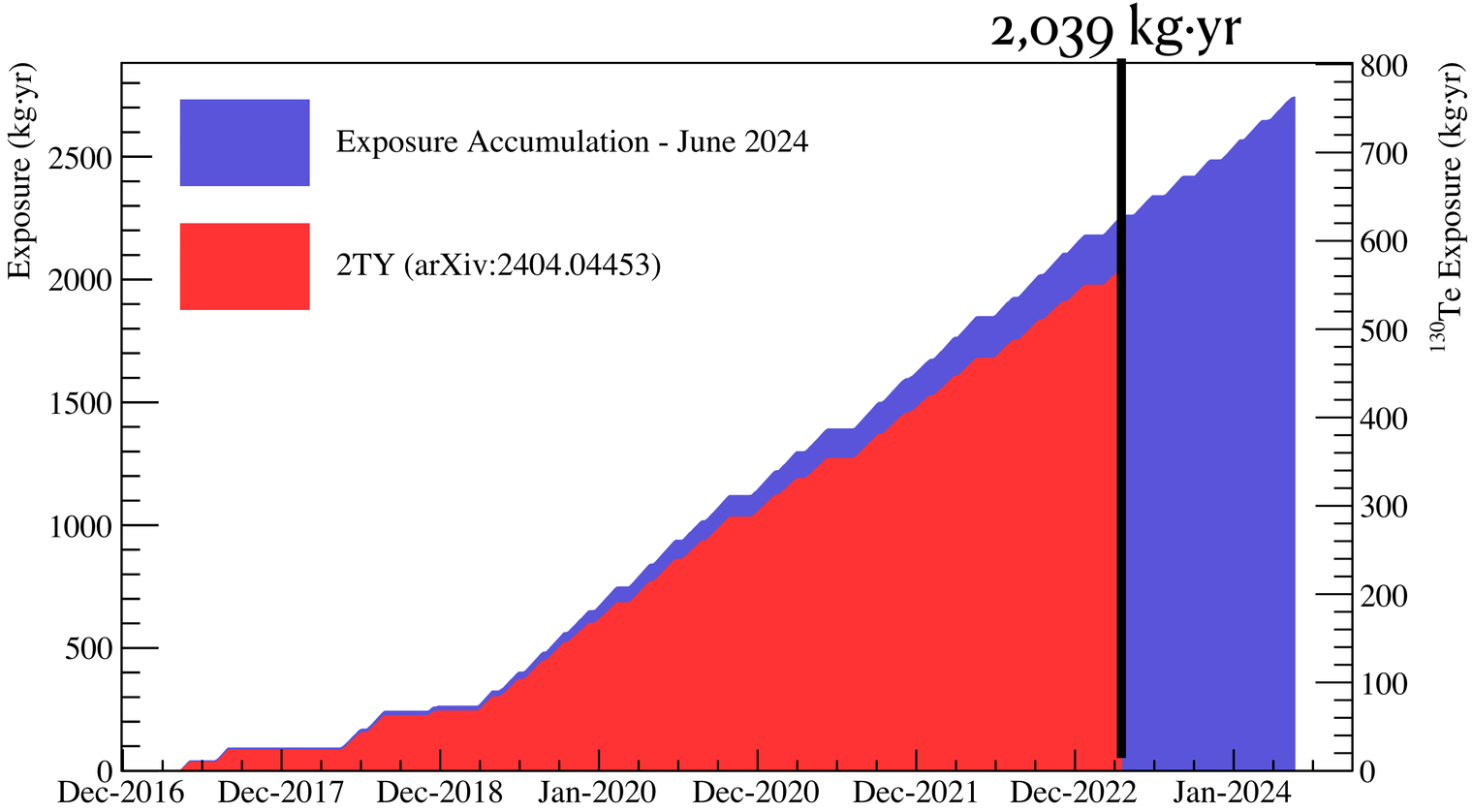
Adams, D.Q. et al. (CUORE Collaboration), Phys. Rev. Lett. **124**, 122501 (2020)

~1,000 kg·yr

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

~2,000 kg·yr

Adams, D.Q. et al. (CUORE Collaboration), *arXiv:2404.04453* (2024)

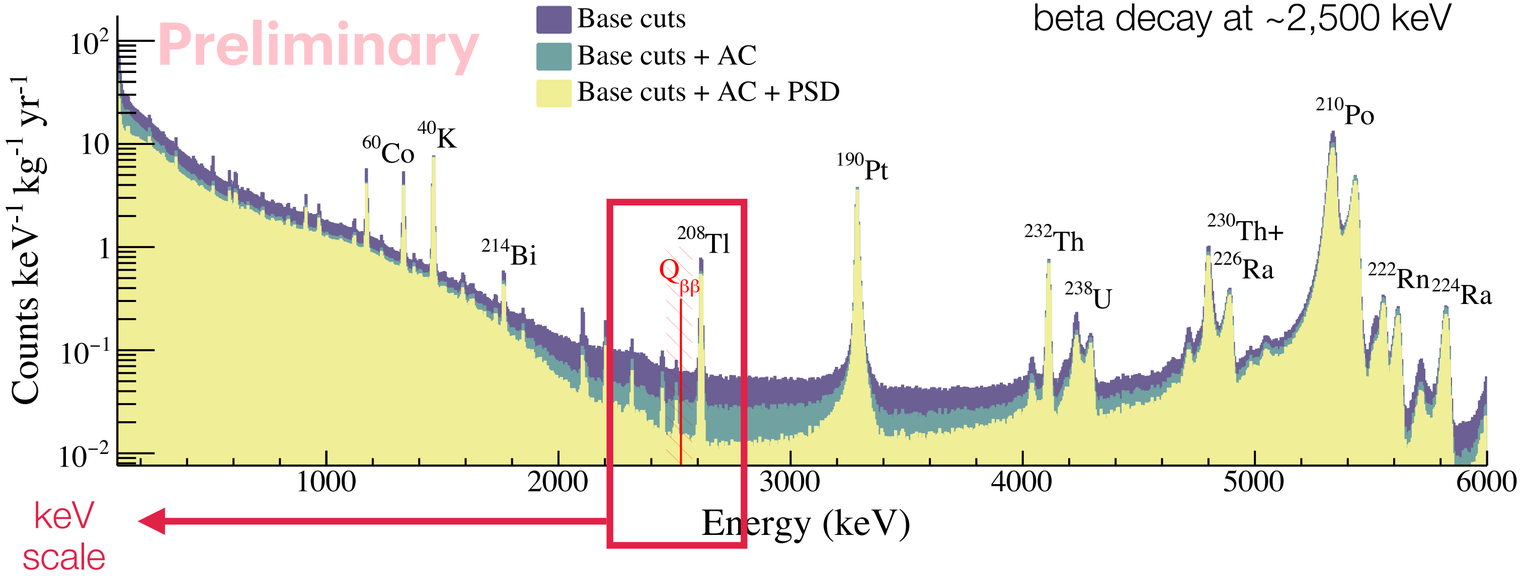


Data taking is divided into ~1.5 months long datasets

CUORE 2TY energy spectrum

Adams, D.Q. et al. (CUORE Collaboration), *arXiv:2404.04453* (2024)

Search for neutrinoless double beta decay at ~2,500 keV

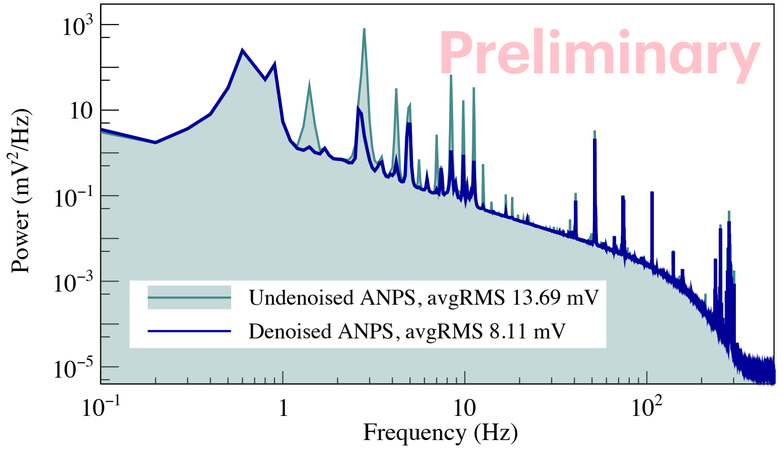


2039.0 kg·yr TeO_2 (567.0 kg·yr ^{130}Te)

2 TY Improvements

De-noising using auxiliary devices

Vetter, K. J. et al. *arXiv:2311.01131* (2024)

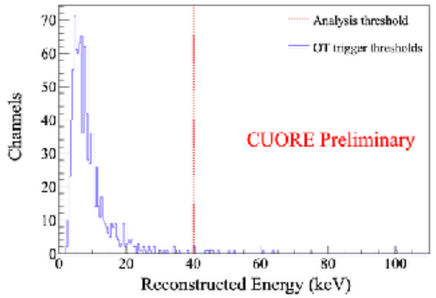


Updates to multiple analysis methods and addition of low energy variables

CUORE analysis chain

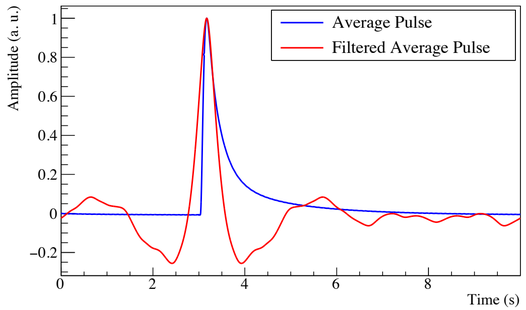
1. Triggering

Data is continuously saved and can be re-triggered offline



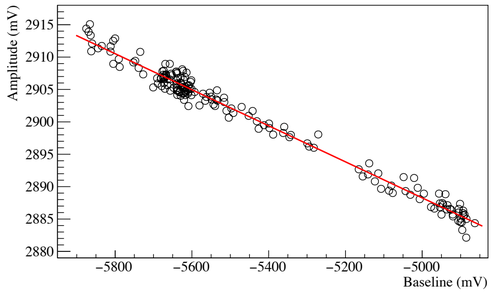
2. Amplitude Evaluation

Calculate the amplitude of pulses using an optimum filter, which maximizes signal to noise ratio



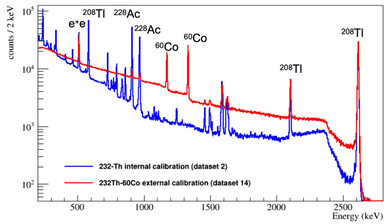
3. Gain Stabilization

Correct for calorimeter gain dependence on drifts in temperature



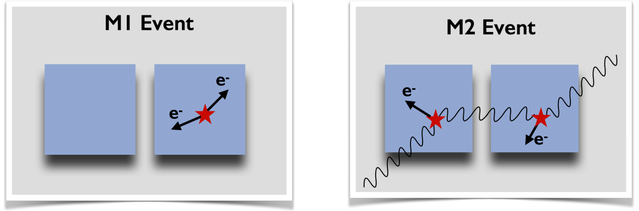
4. Energy Calibration

Calibrate calorimeters using known peaks



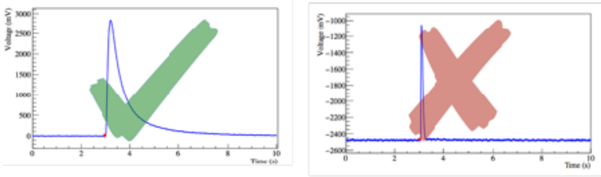
5. Building coincidence events

Differentiate events that occur in one or multiple crystals



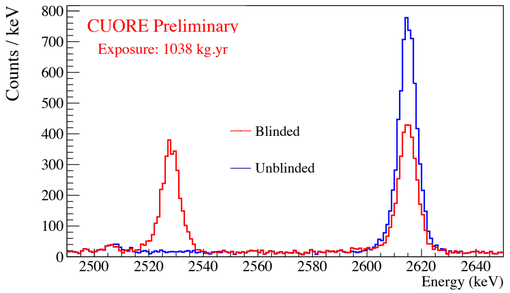
6. Pulse Shape Analysis

Save pulses with physical shapes



7. Peak Salting

Data blinding technique, that moves data from a nearby peak



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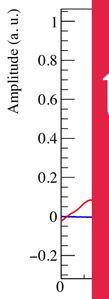

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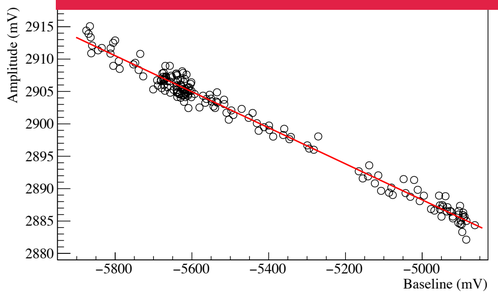

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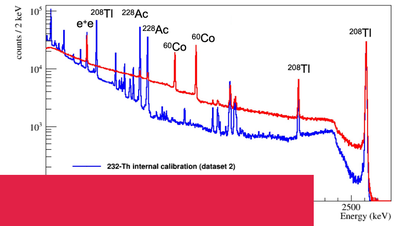
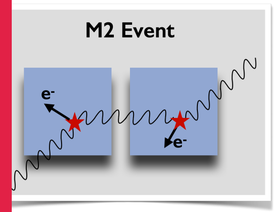
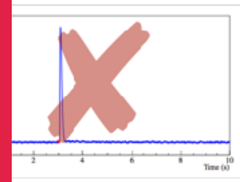


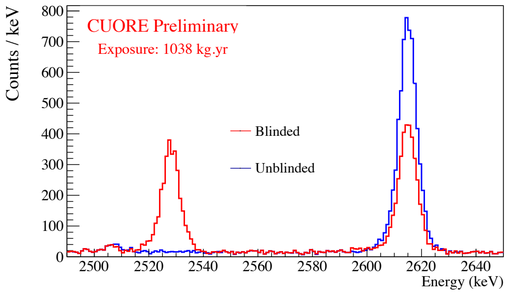




In the 2TY dataset, we built upon these techniques for keV-scale searches such as direct dark matter detection

7. Peak Salting

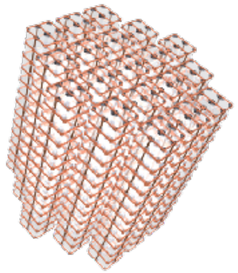
Data blinding technique, that moves data from a nearby peak



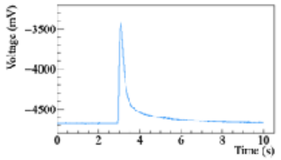
Tools for keV-scale searches

CUORE Data

- Optimized detector selections

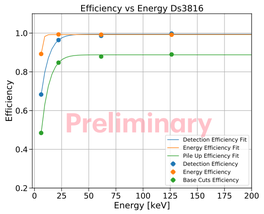


- Event level cuts



- New filters, de-noising

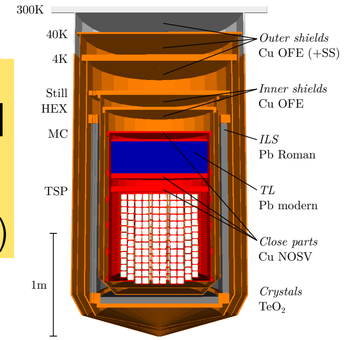
- Calibrations, efficiencies evaluations



Simulations

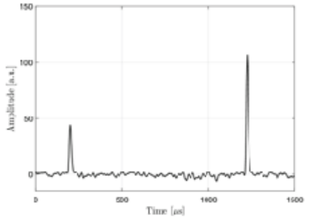
Monte Carlo Background Model

Adams, D.Q. et al. (CUORE Collaboration), *arXiv:2405.17937* (2024)



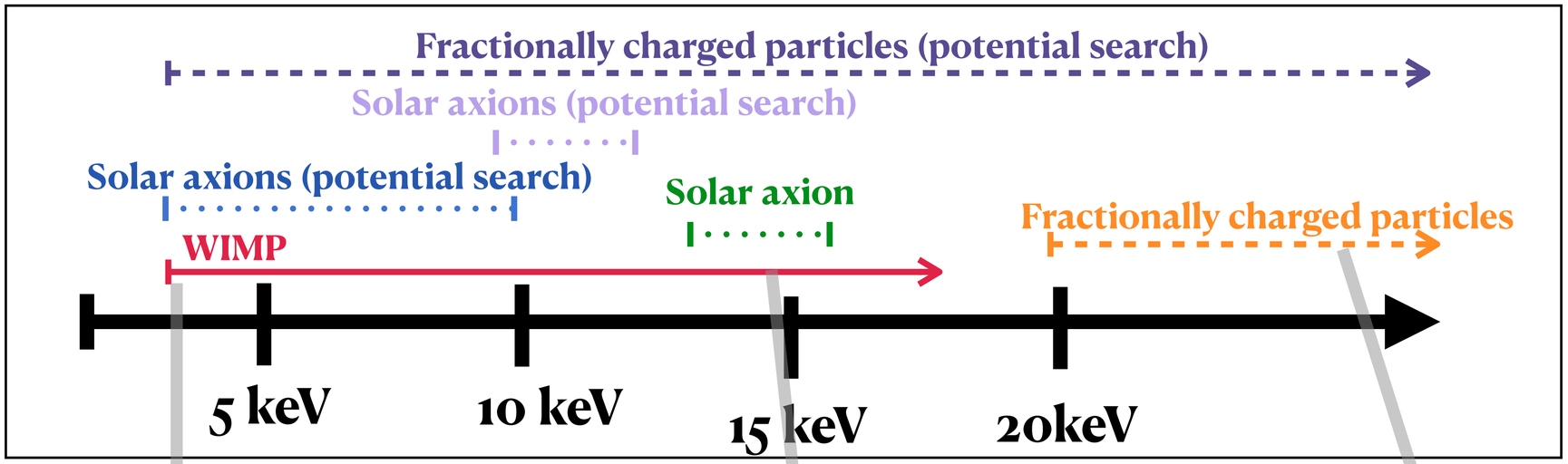
Mock Data Steam

Beretta, M., Biassoni, M., Gironi, L. *et al.* *Eur. Phys. J. Plus* **136**, 89 (2021)



Building upon: Low energy analysis techniques for CUORE. *Eur. Phys. J. C* **77**, 857 (2017).

Status of low energy analyses

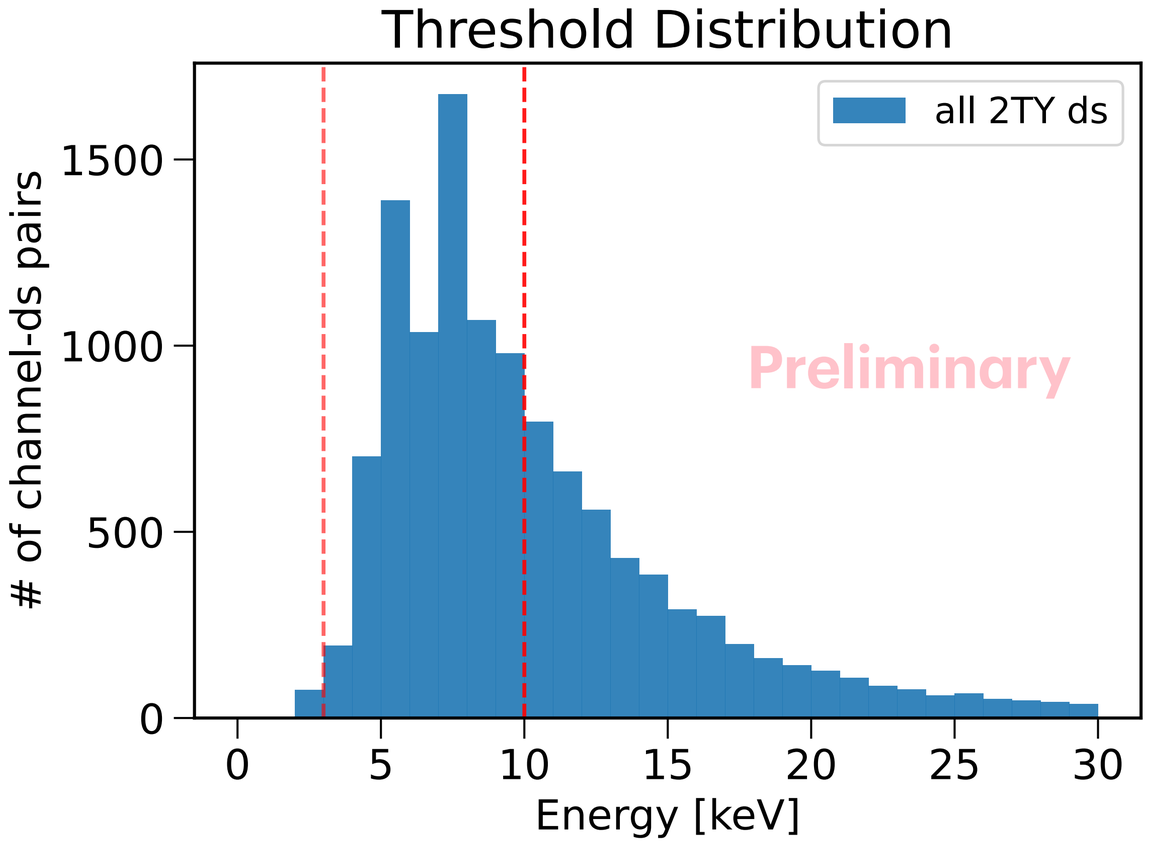


On 2TY data
In progress

On 2TY data
In progress

On 1TY data
Search for fractionally charged particles with CUORE. arXiv:2406.12380

Results of 2TY keV-scale processing



Thresholds of bolometer-dataset pairs in the 2TY dataset, method from [1]. Vertical lines at 3 keV and 10 keV.

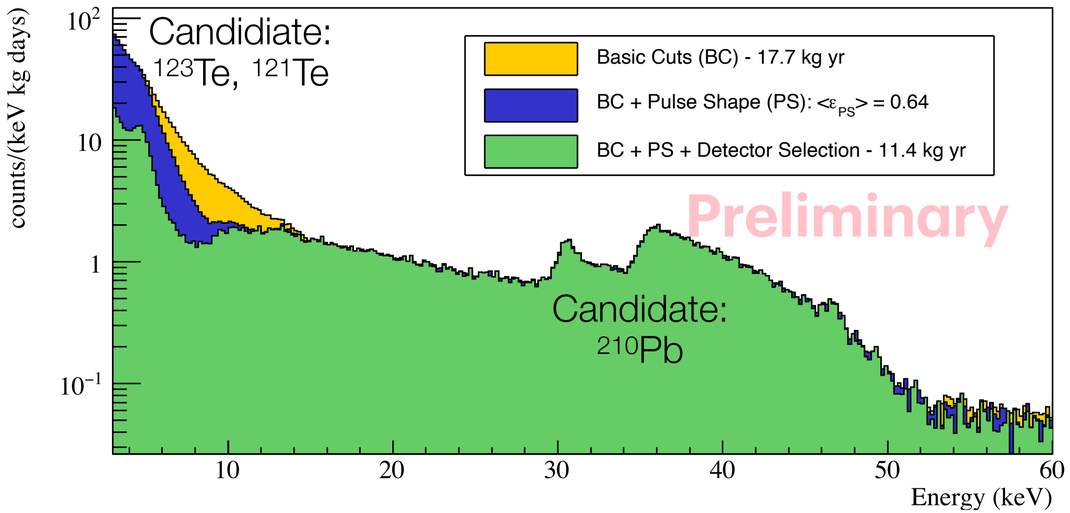
[1] S Di Domizio et al 2011 JINST 6 P02007

Preliminary

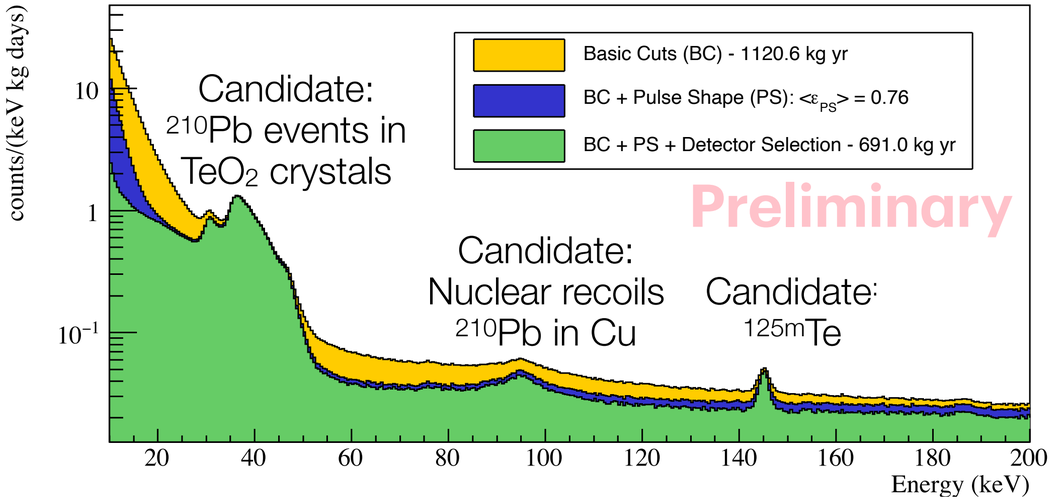
Optimized region of interest	[3,10] keV channels	[10,20] keV channels
Exposure of TeO_2	11.4 kg·yr	691.0 kg·yr
FWHM Baseline (noise resolution)	1.2 keV	2.5 keV
FWHM Energy resolution at 30 keV from Te x-rays	1.6 keV	2.7 keV

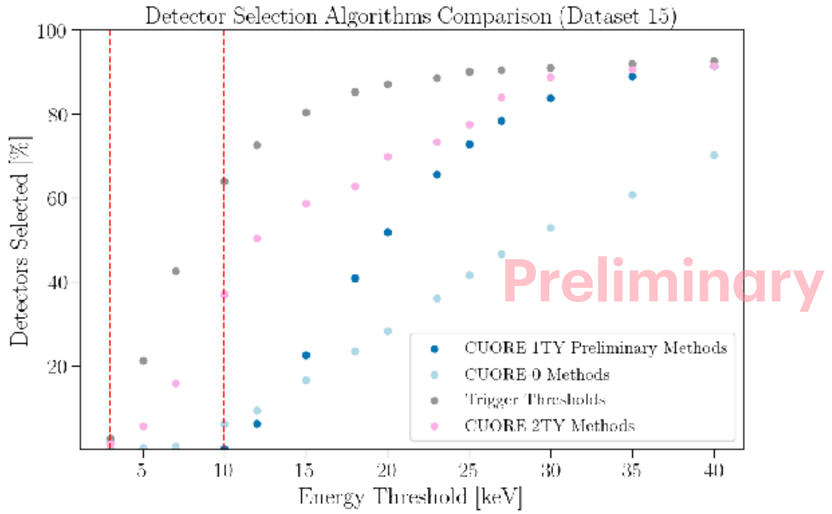
CUORE 2TY low energy spectrum

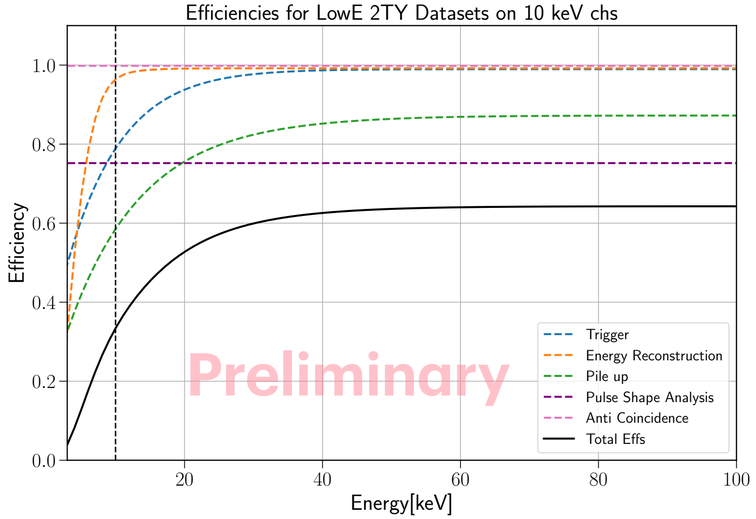
[3,10] keV dataset



[10,20] keV dataset





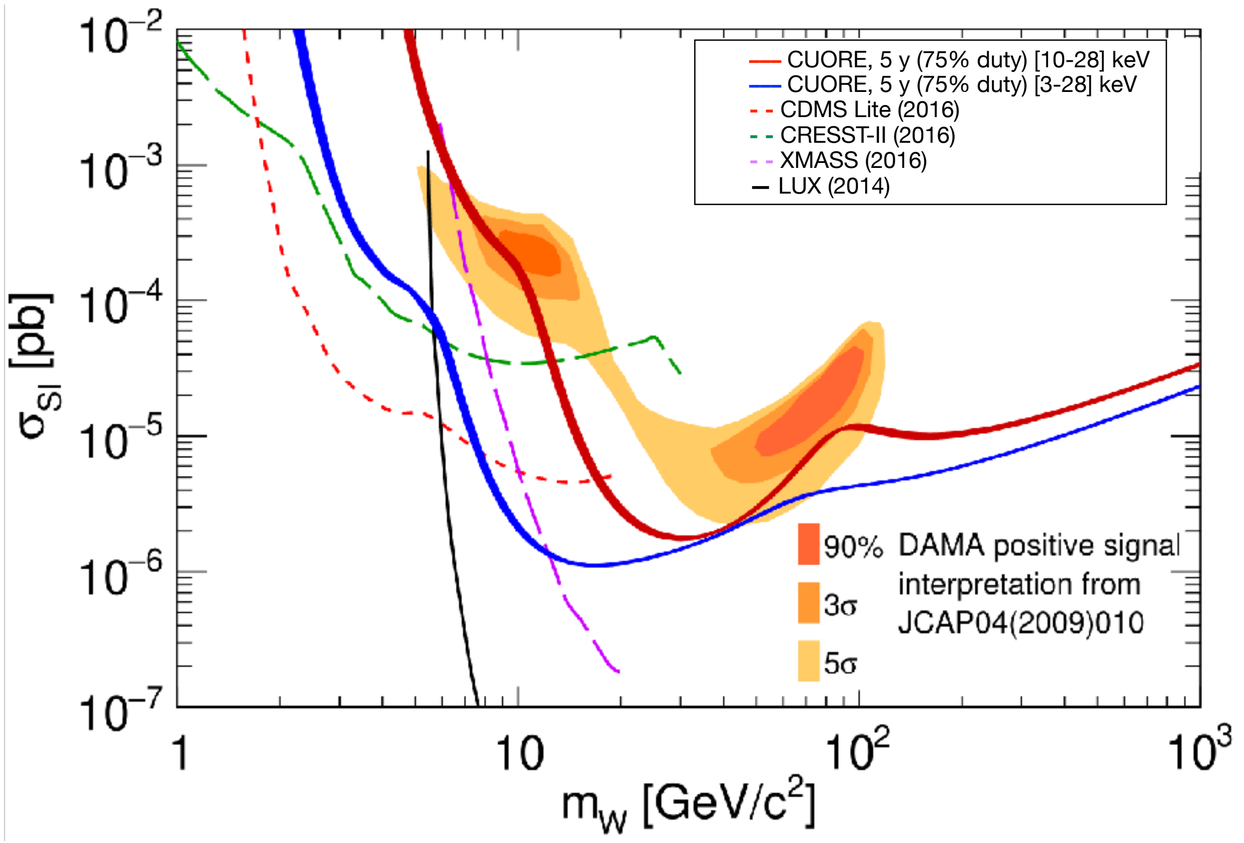


Low mass dark matter

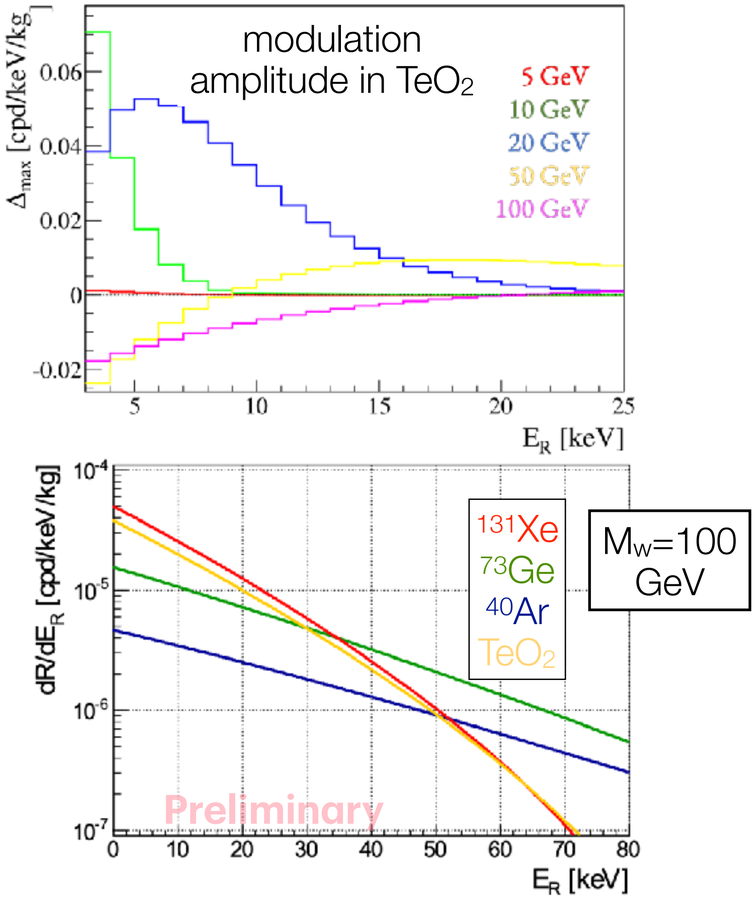
Weakly Interacting Massive Particles (WIMPs) Annual Modulation Search

TeO_2 target: combines high and low mass nuclei

Sensitivity estimated from CUORE's expected exposures using results from CUORE-0



Eur. Phys. J. C (2017) 77: 857



F. Alessandria et al JCAP01(2013)038

Solar axion-like particle searches

Search region of interest and production mechanism

g_{ae}

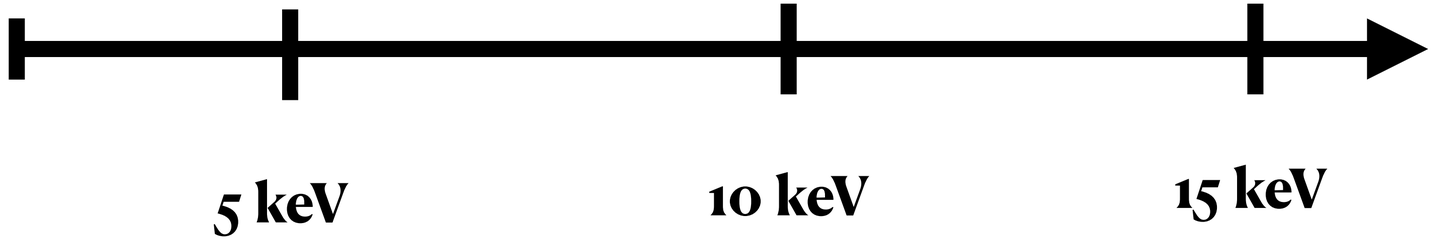
Fe atomic de-excitation

g_{aN}

^{57}Fe M1 nuclear transition

$g_{a\gamma}$

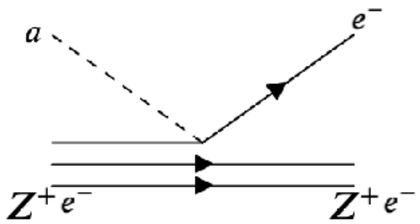
Blackbody photons Primakoff conversion



Detection in CUORE

Absorption

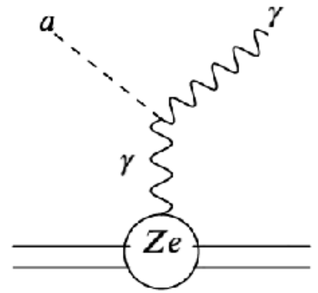
Axio-electric effect



g_{ae}

Time dependent conversion

Inverse Coherent Bragg-Primakoff conversion



$g_{a\gamma}$

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Search region of interest and production mechanism

g_{ae}

Fe atomic de-excitation

g_{aN}

^{57}Fe

M1 nuclear transition

$g_{a\gamma}$

Blackbody photons

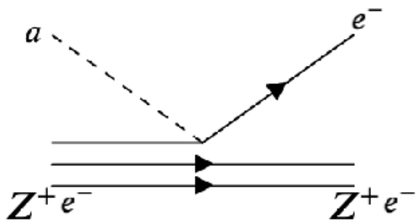
Primakoff conversion

5 keV 10 keV 15 keV

Detection in CUORE

Absorption

Axio-electric effect



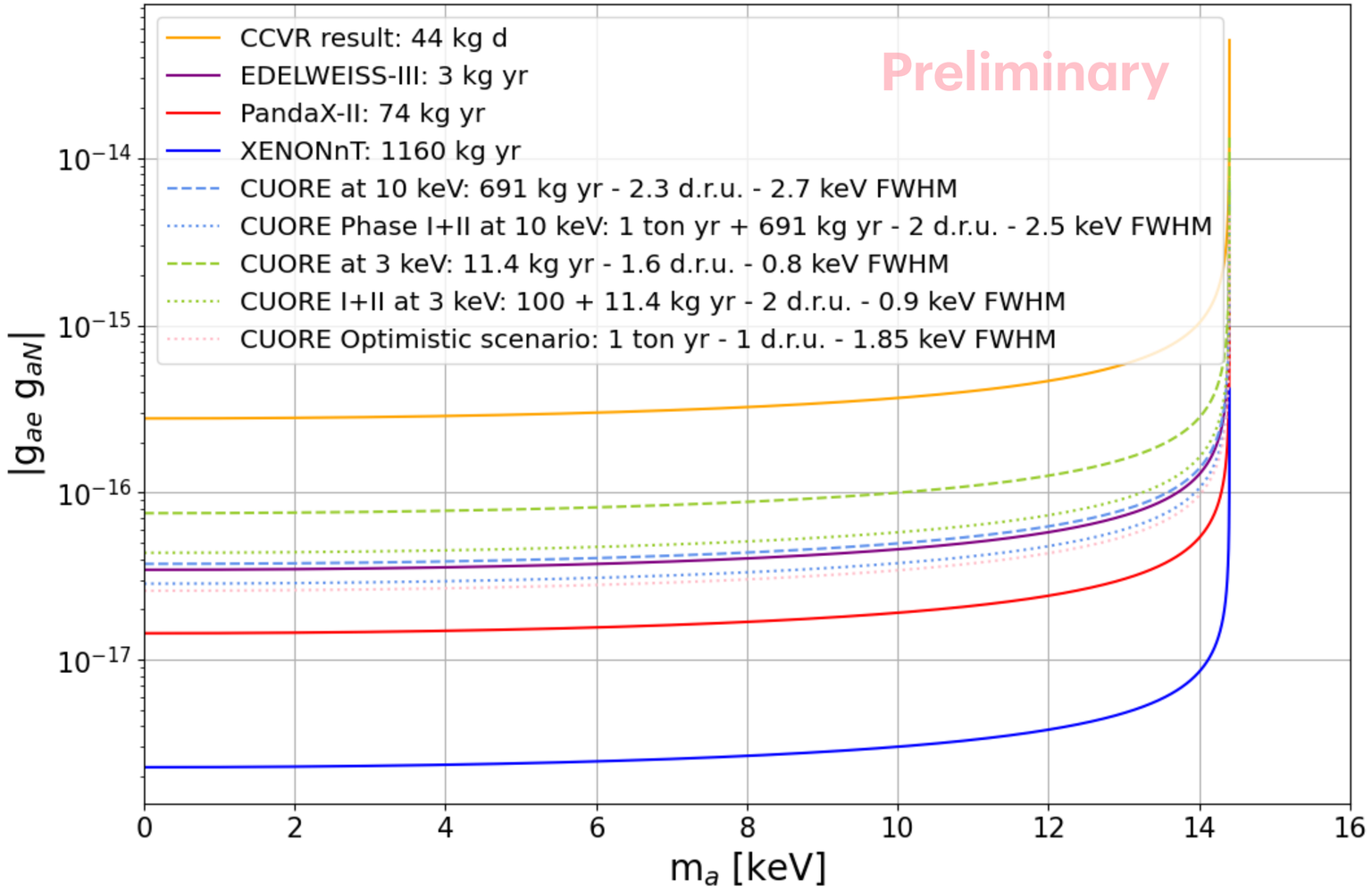
g_{ae}

Time dependent conversion

Inverse Coherent Bragg-Primakoff conversion

$g_{a\gamma}$

M1 solar axion search sensitivity



CUORE's sensitivity to the M1 solar axion search based on 2TY processing and findings

Included scenarios of upgrades to CUORE for future dedicated low energy runs

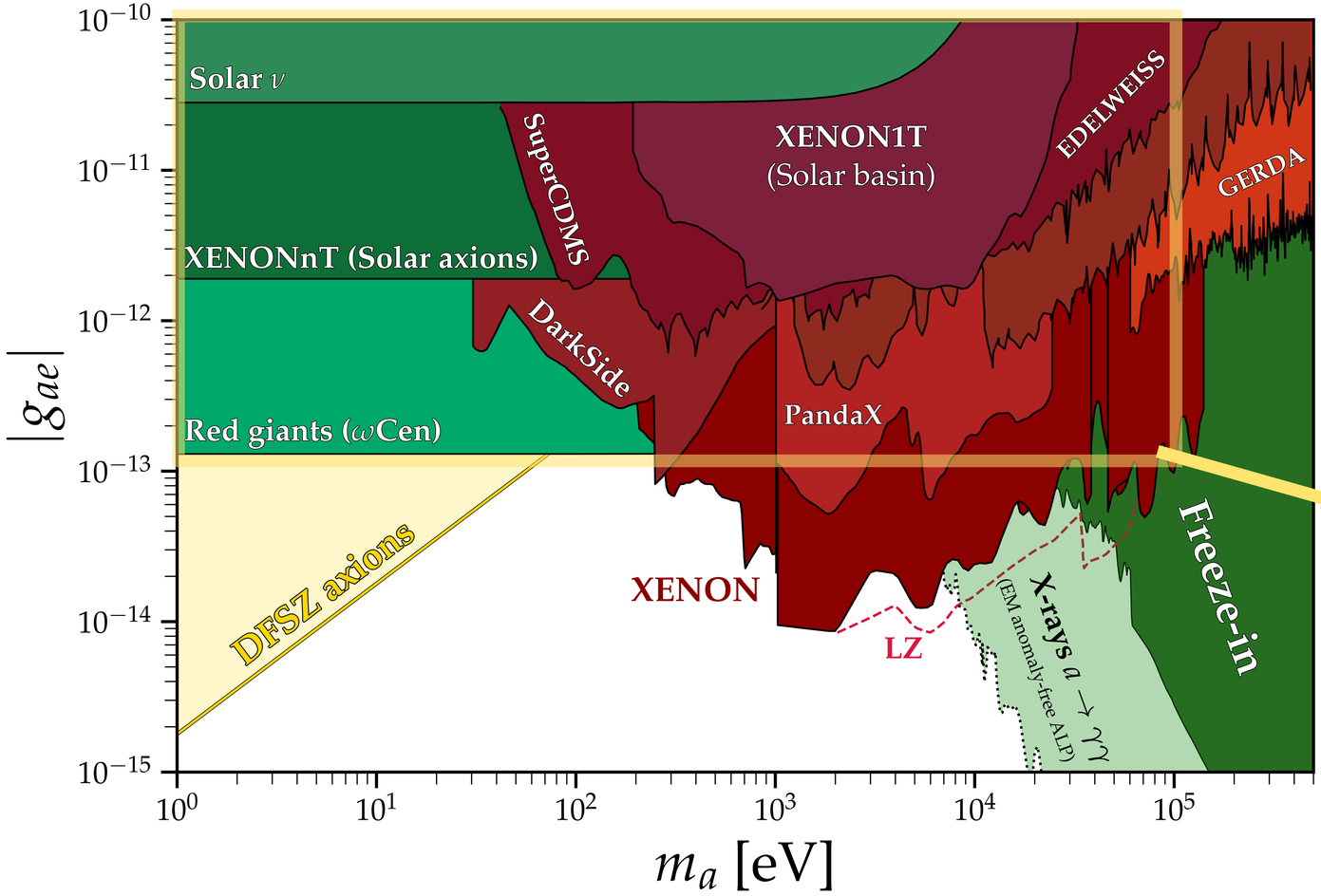
CCVR: JCAP05(2013)007

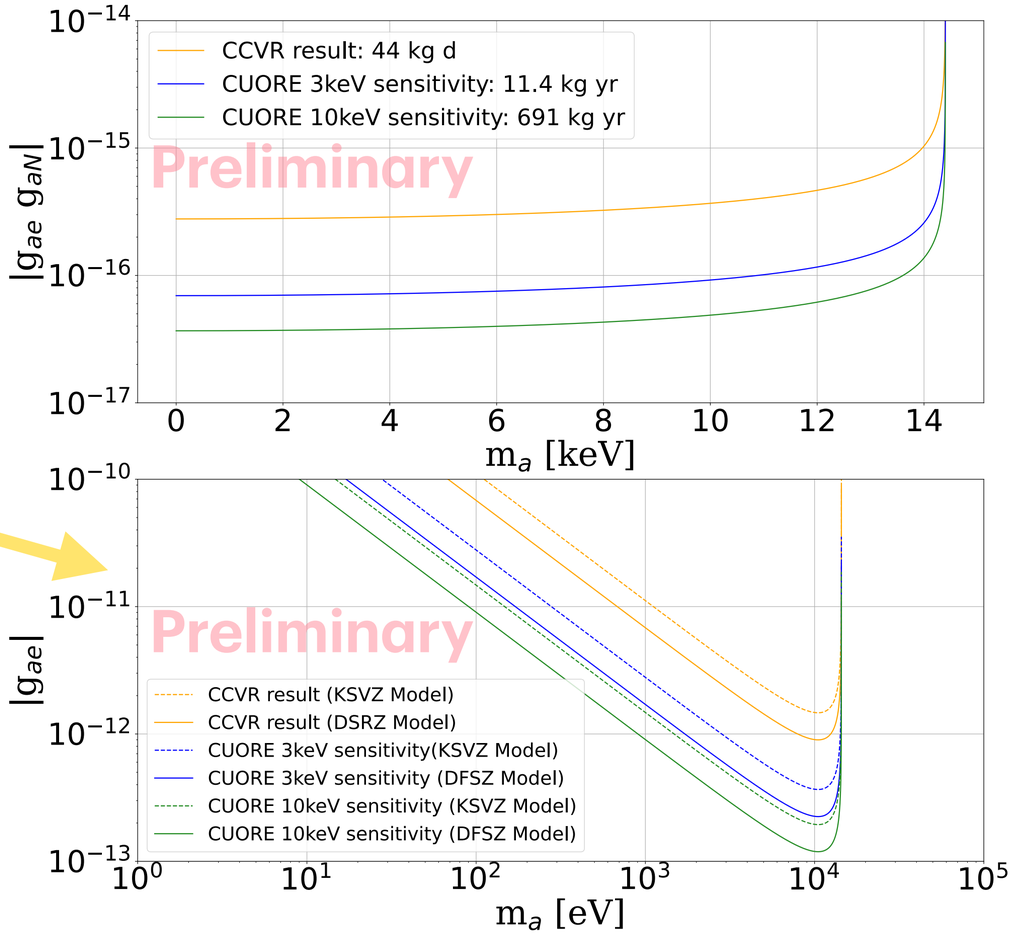
EDELWEISS-III: Phys. Rev. D 98, 082004

PandaX-II: Phys. Rev. Lett. 119, 181806

XENONnT: Phys. Rev. Lett. 129, 161805

M1 solar axion search sensitivity

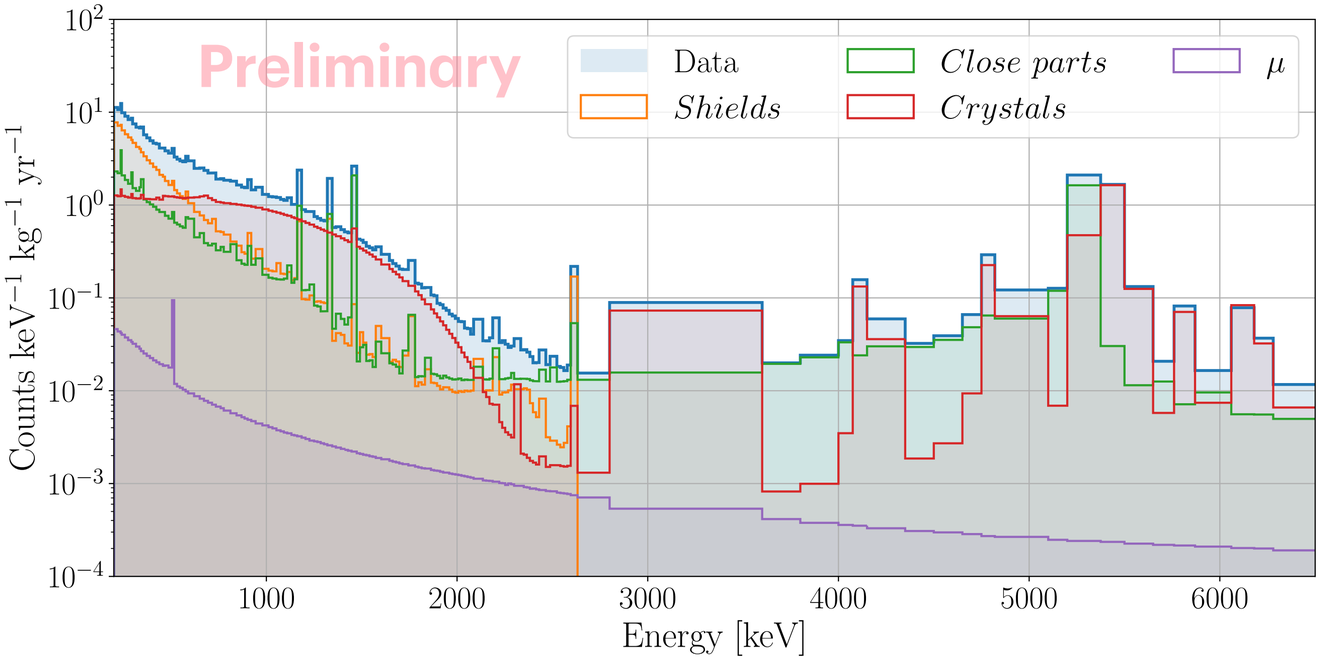




Ciaran O'Hare, https://cajohare.github.io/AxionLimits/

CCVR: JCAP05(2013)007

CUORE keV-scale background model



Data-driven background model for the CUORE Experiment
arXiv:2405.17937

Geant4 simulation combined with CUORE detector response

Over 60 simulated sources: Including 2νββ decay in the crystals and contaminants

Produces multiplicity, time resolution, energy dependent trigger efficiencies

Work is in progress to expand to the keV-scale

What comes after CUORE?

CUORE

CUORE

CUORE Low Energy Runs

CUPID

Continue successful data taking campaign to reach 3 tonne·yr of TeO_2 exposure

Proposed low-energy focused improvements
Added noise mitigation and detector upgrades

Upgraded Technology/Systems
$Li_2{}^{100}MoO_4$ scintillating cryogenic calorimeters
Particle identification
Muon veto
Noise mitigation

Conclusions

- CUORE has been stably taking data since 2019, and has collected over 2 tonne·yr of TeO_2 exposure.
- CUORE has produced several results and world-leading limits in the search for neutrinoless double beta decay. We are now pursuing work to extend analyses to lower energies.
- The 2 tonne·yr reprocessing included new variables and methods developed for keV-scale searches.
- We've completed this processing and are studying our energy spectrum below 100 keV down to thresholds as low as 3 keV.
- Dark matter searches are in progress for solar axions and WIMPS using this dataset!
- Dedicated low-energy focused runs are planned for after the completion of CUORE's data taking with enhanced vibration mitigation and other possible improvements.