Exploring the keV scale energy spectrum of CUORE

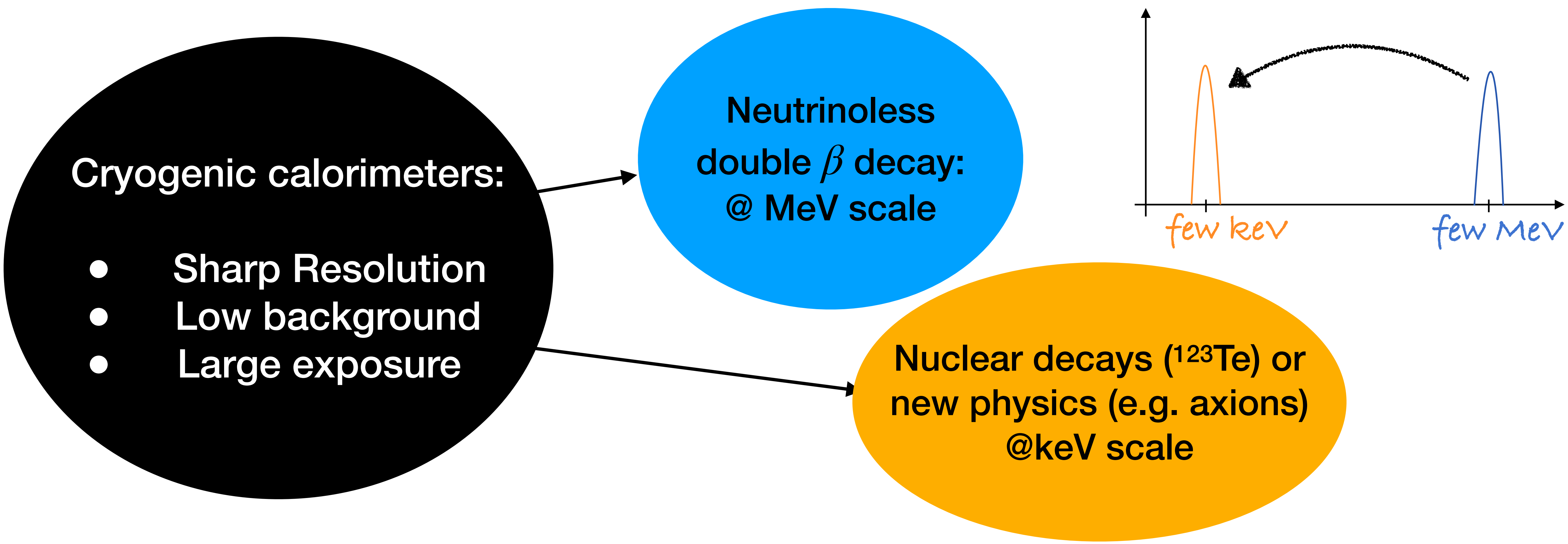
Alberto Ressa on behalf of the CUORE Collaboration

LRT 2024, Kraków

Istituto Nazionale di Fisica Nucleare

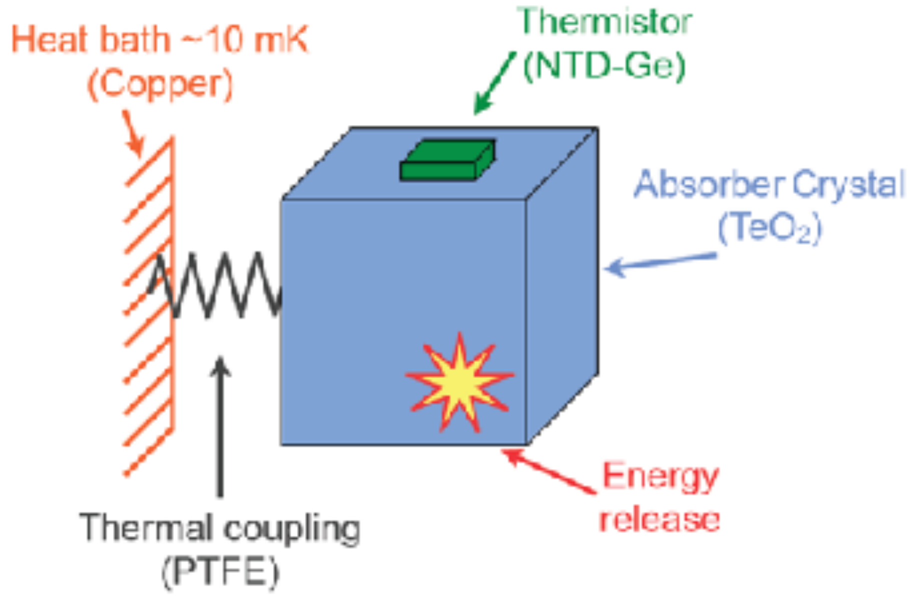
Introduction

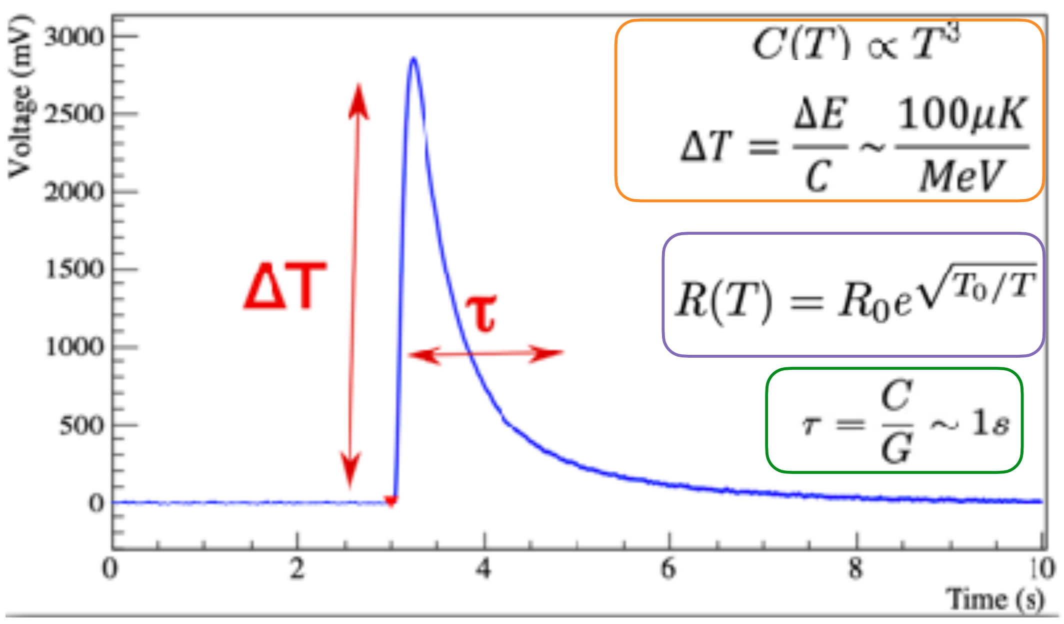
- Thermal phonon detection with cryogenic calorimeters allows the study of a wide energy range
- Fully exploit CUORE >2 ton yr of TeO_2 exposure down to keV scale for a broad variety of searches
- CUORE demonstrated this technology at the ton-scale in a low background environment to search for the neutrinoless double beta decay



Cryogenic Calorimeters

1. Interacting particles deposit energy into the crystal
2. The energy release heats up the crystal via thermal phonons
3. The temperature increase is converted into an electric signal by a cryogenic sensor (e.g. thermistor)



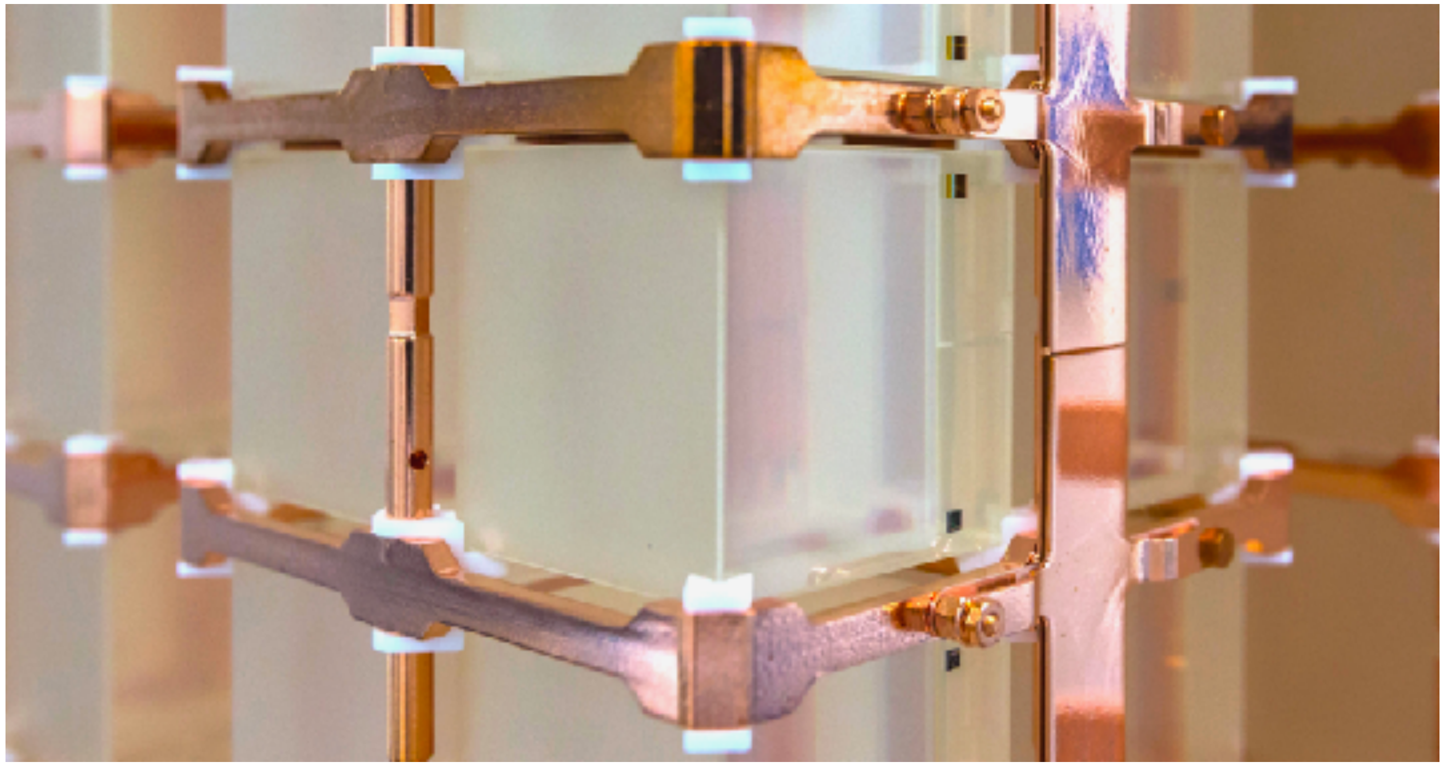


➡ Cryogenic temperatures (about 10 mK) make it possible to turn the energy deposit into a readable temperature increase

➡ Thermalization of crystals requires ~ seconds

- handle only low rate processes
- allow pulse shape reconstruction

Cryogenic Calorimeters



Cryogenic Calorimeters

Energy Resolution
(<1% @MeV)

Thermal phonon detection:

Negligible intrinsic resolution (~ 10 eV)

Limited by vibrational and electronic noise (~keV)

Low Energy Threshold (~ keV)

Cryogenic Calorimeters

Low Background:

Radiopure materials and strict cleaning procedures

Operated underground to shield against cosmic rays

External layers against natural radioactivity

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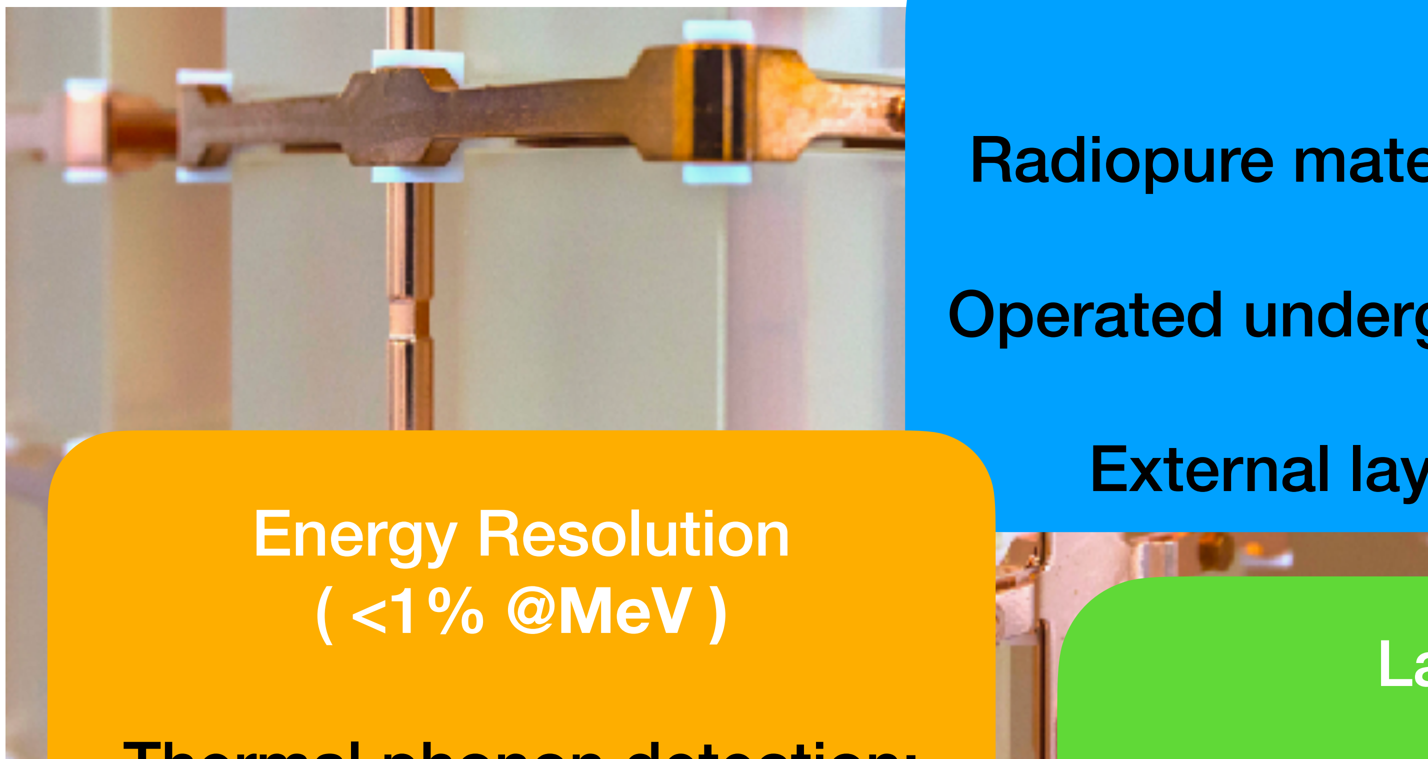
CUORE

Cryogenic Calorimeters



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Energy Resolution (<1% @MeV)

Thermal phonon detection:

Negligible intrinsic resolution (~ 10 eV)

Limited by vibrational and electronic noise (~keV)

Large Exposure (up to ton yr):

The technology can be scaled with a modular structure

Limited only by cryogenic power

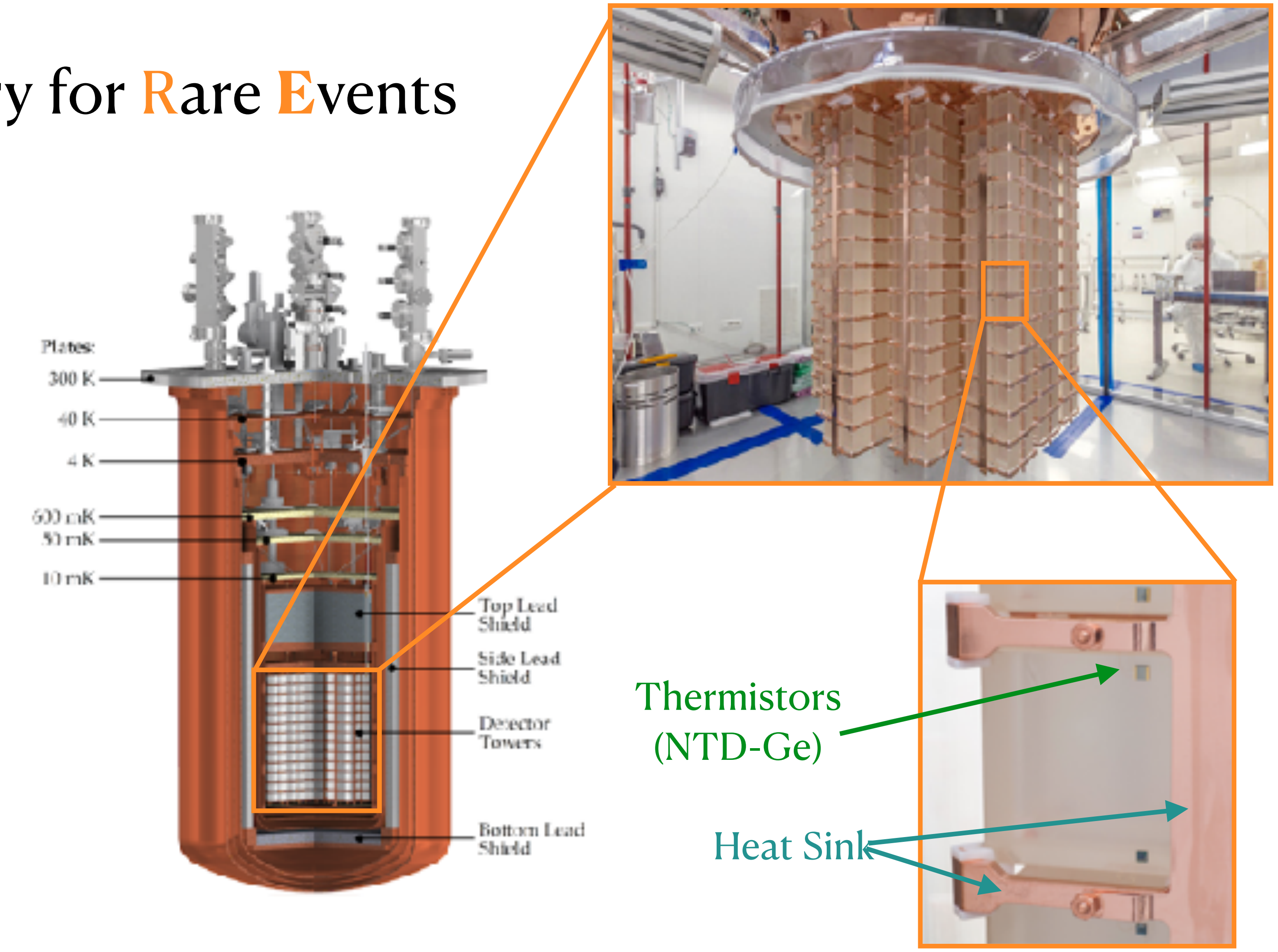
Low Energy Threshold (~ keV)

old (~ keV)

CUORE Experiment

Cryogenic Underground Observatory for Rare Events

- 988 natural TeO_2 5x5x5 cm^3 crystals equipped with NTD-Ge thermistors
- 19 towers of 13 floors
- 742 kg of TeO_2 (i.e. 206 kg of ^{130}Te)



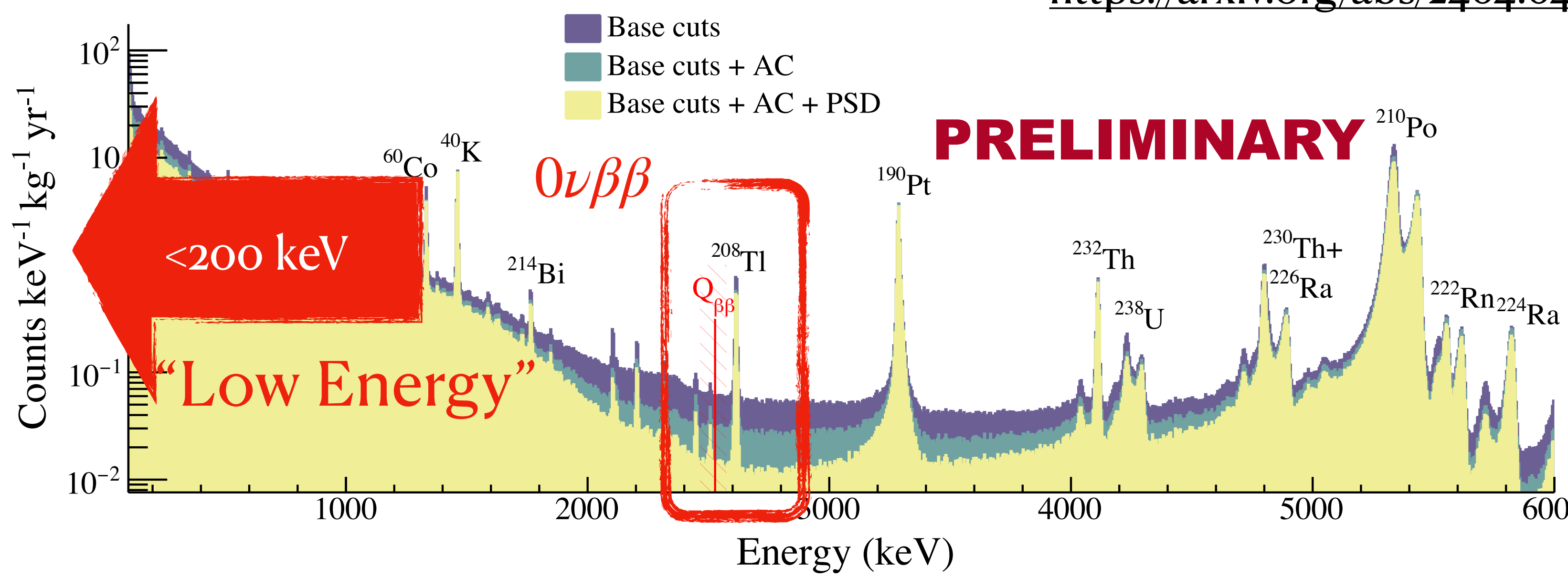
- Operated in one of the world-leading dilution refrigerators in terms of power and size
- 1 m^3 experimental volume: TeO_2 crystals kept at ~12-15 mK
- Located at Laboratori Nazional del Gran Sasso (LNGS)

CUORE Energy Spectrum

https://arxiv.org/abs/2404.04453

Can we go to lower energies?

?



You just heard S. Dell'Oro's talk!

Checkout Poster of S. Ghislandi about Background Model of CUORE

CUORE Energy Spectrum

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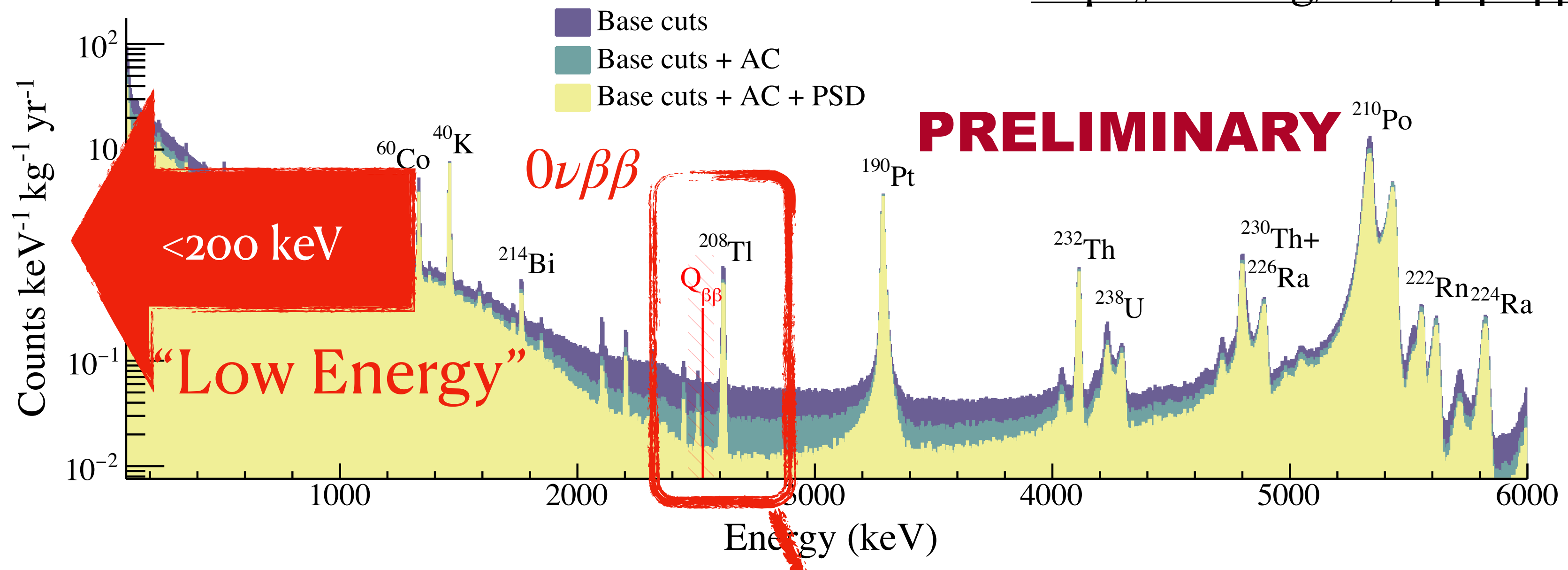

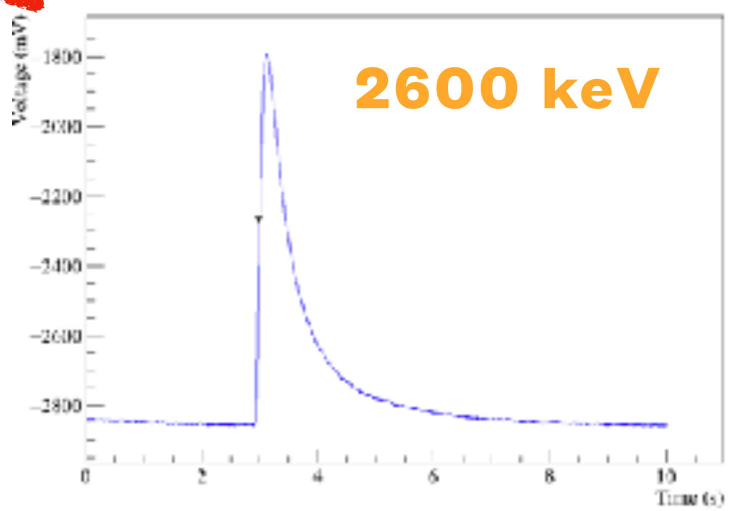

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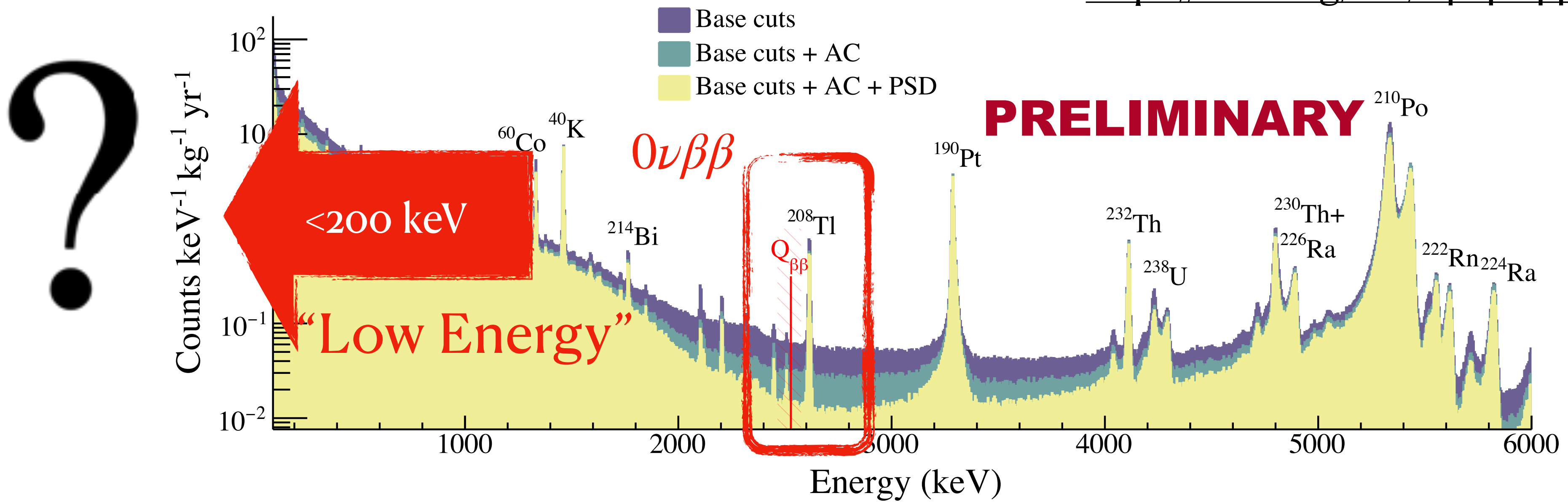
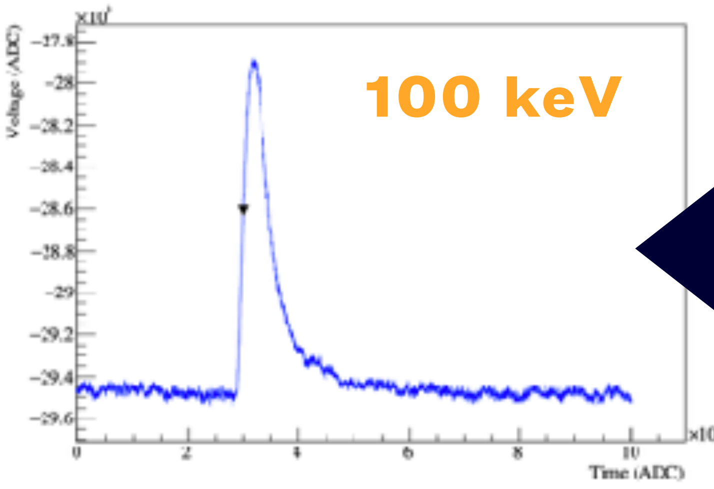
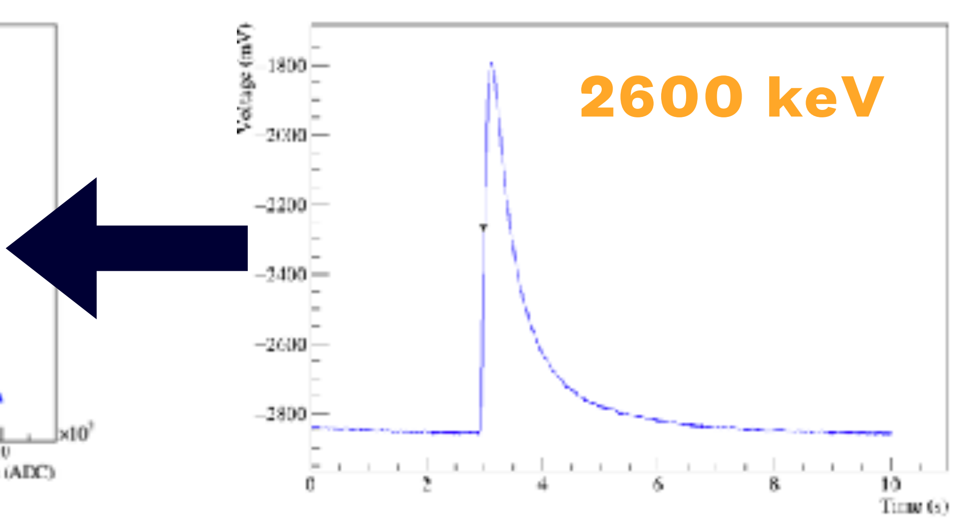




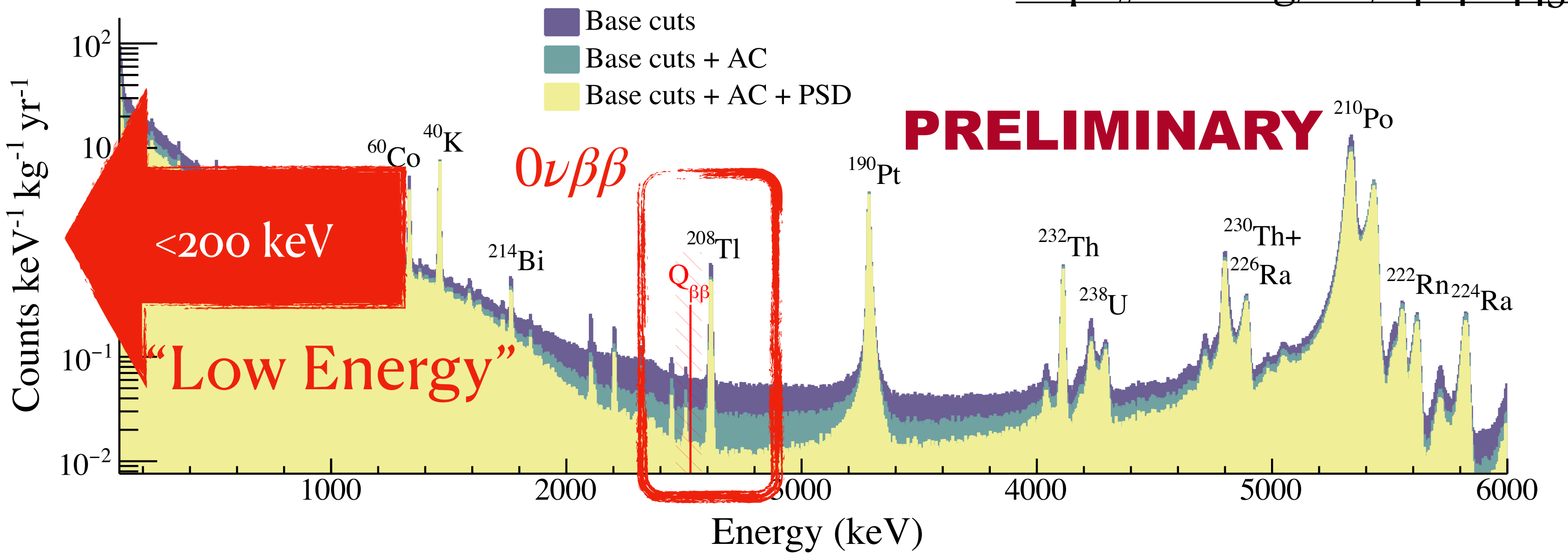


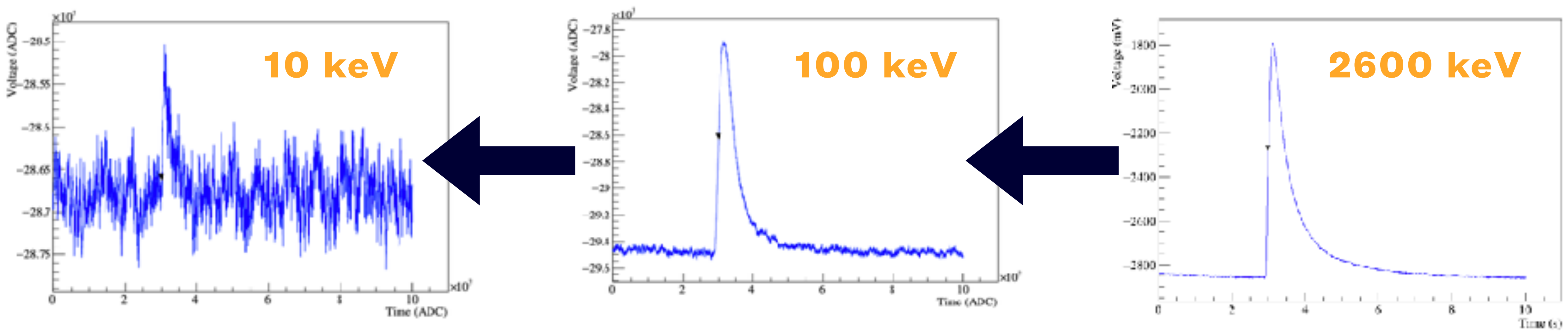
CUORE

CUORE Energy Spectrum

- Noise strongly affects the detected events
- Only a subset of CUORE array detectors achieve this energy threshold
- We need a dedicated analysis procedure

https://arxiv.org/abs/2404.04453

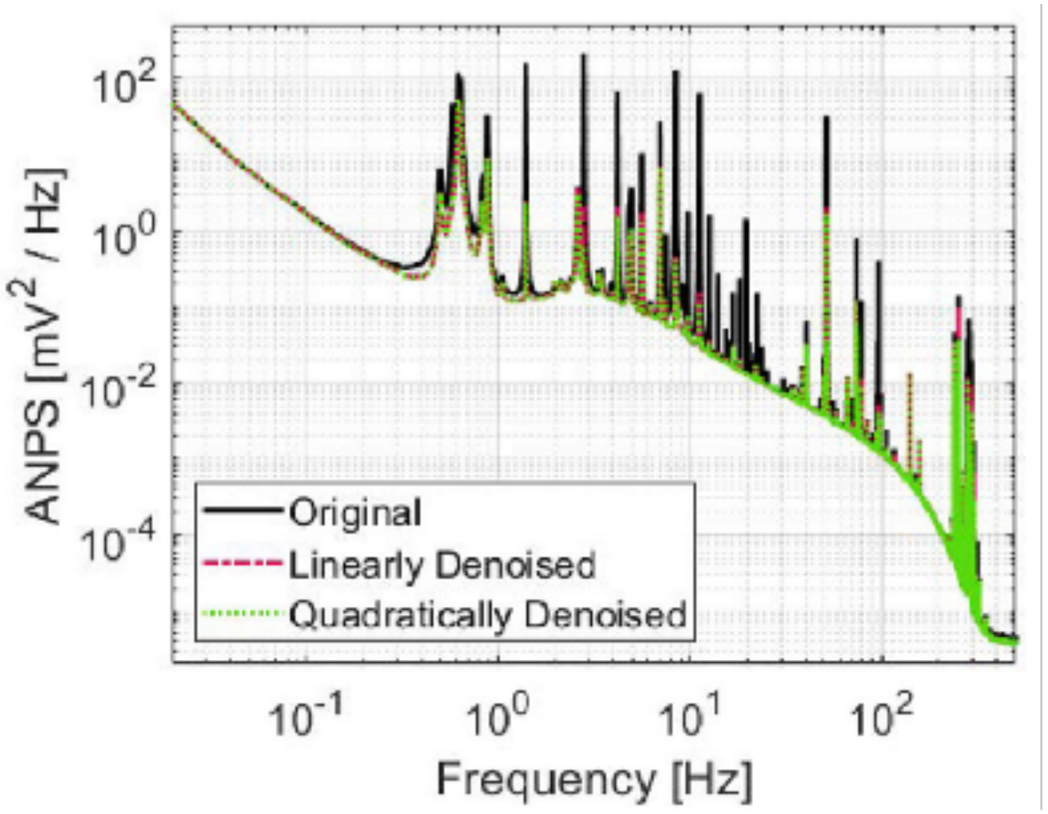




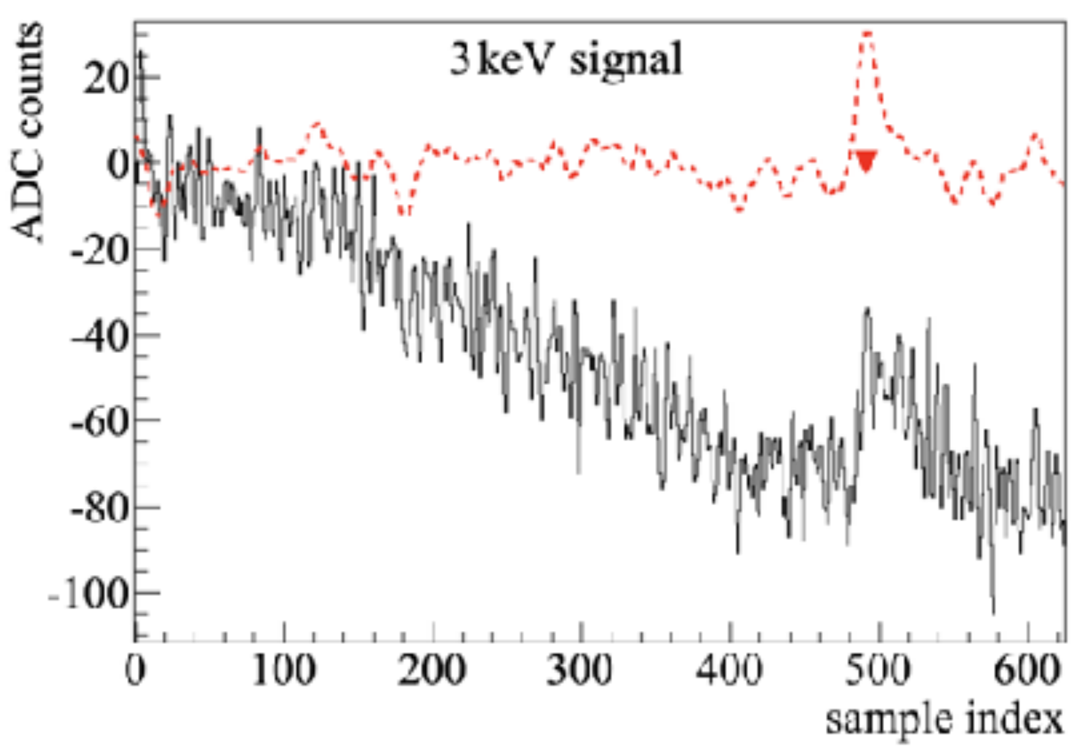
Analysis Methods

- **Denoising:** mitigate the noise by correlating it with auxiliary devices (microphones, accelerometers, seismometers)

- **Optimum Trigger**: apply an offline trigger on filtered waveforms to lower the energy threshold



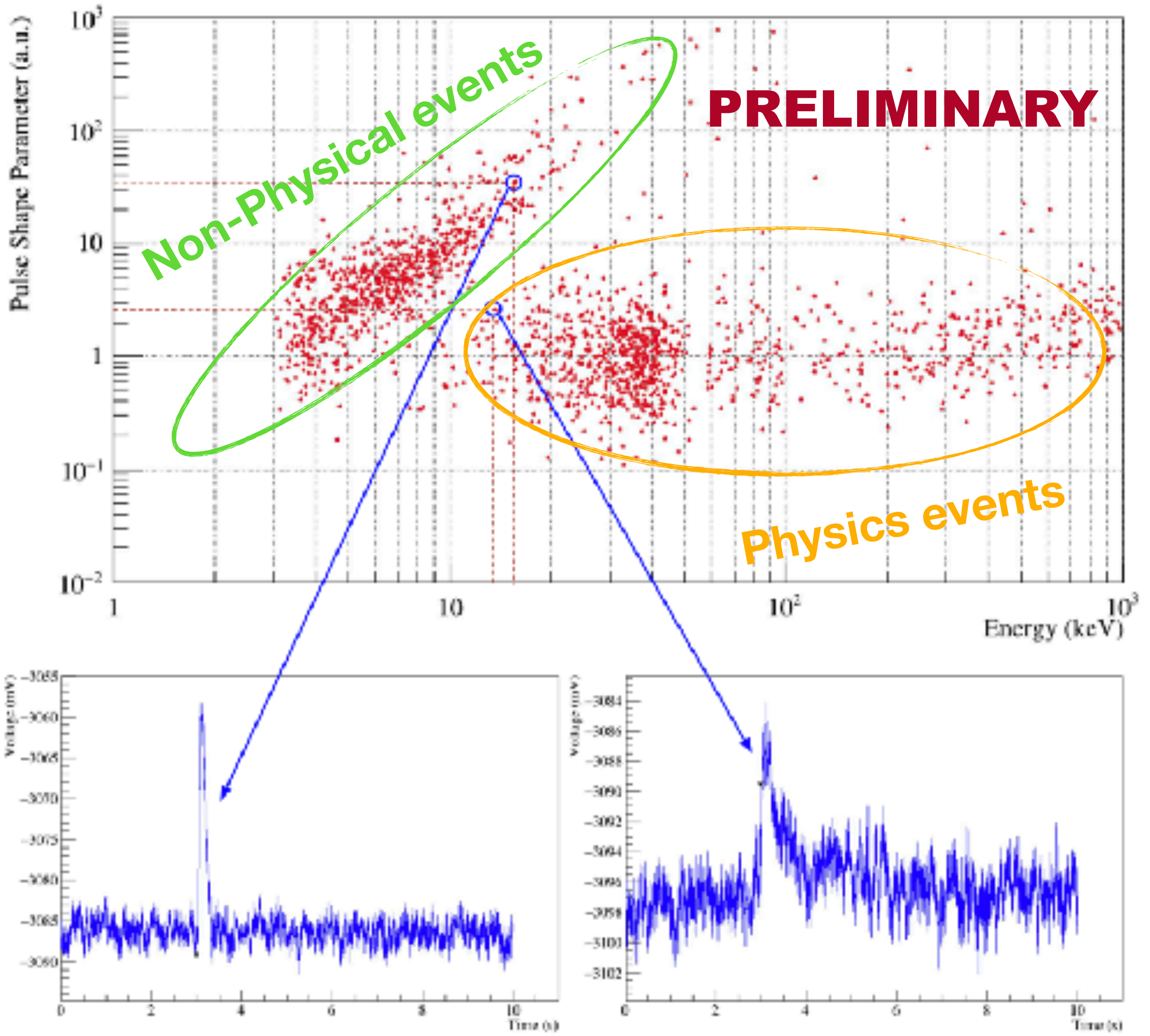
https://doi.org/10.1140/epjc/s10052-024-12595-y



https://doi.org/10.1088/1748-0221/6/02/P02007

Low Energy Events

- A variety of non-physical phenomena (e.g. induced vibrations, electronic spikes) produces temperature rise in cryogenic calorimeters
- To identify spurious events, we rely on pulse shape studies based on similarity of a pulse to the ideal one
  - This estimate is less reliable at lower energies due to higher levels of noise.
  - Down to what energy we can separate the two populations?
  - It depends detector-by-detector

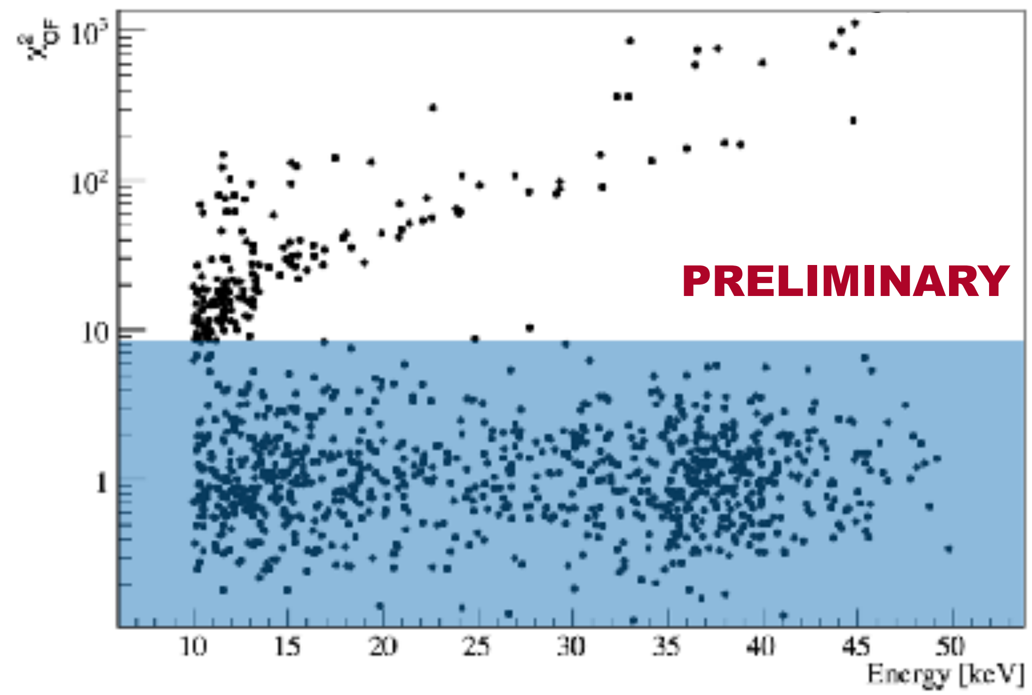


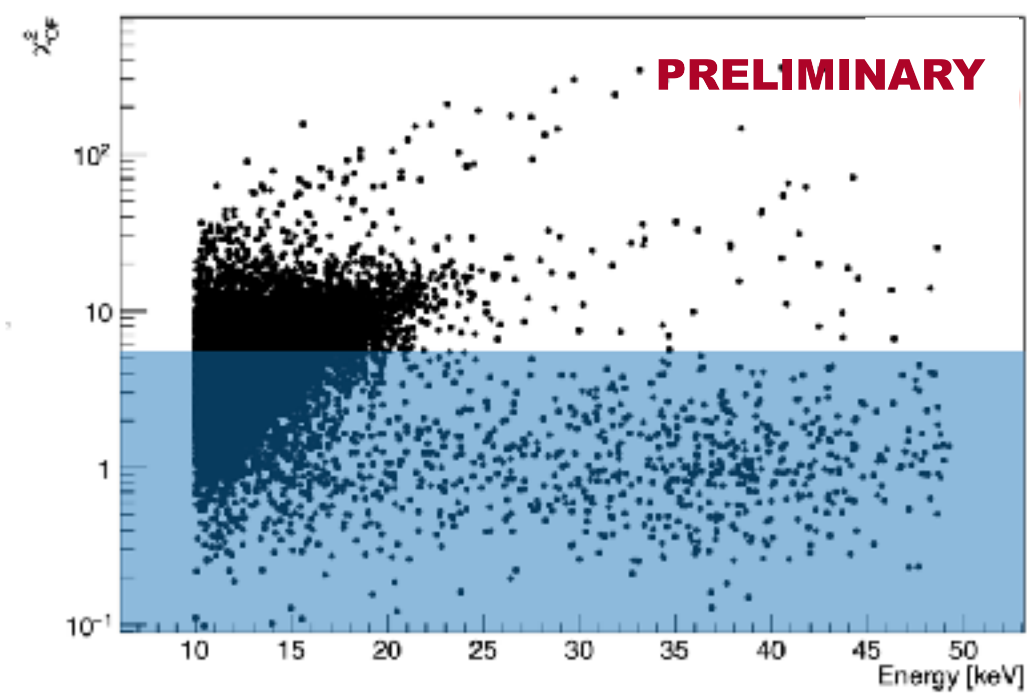
Low Energy Data Selection

Selection procedure:

1. **Events Selection**:
   apply a detector by detector pulse shape cut

Two example detectors from the CUORE array

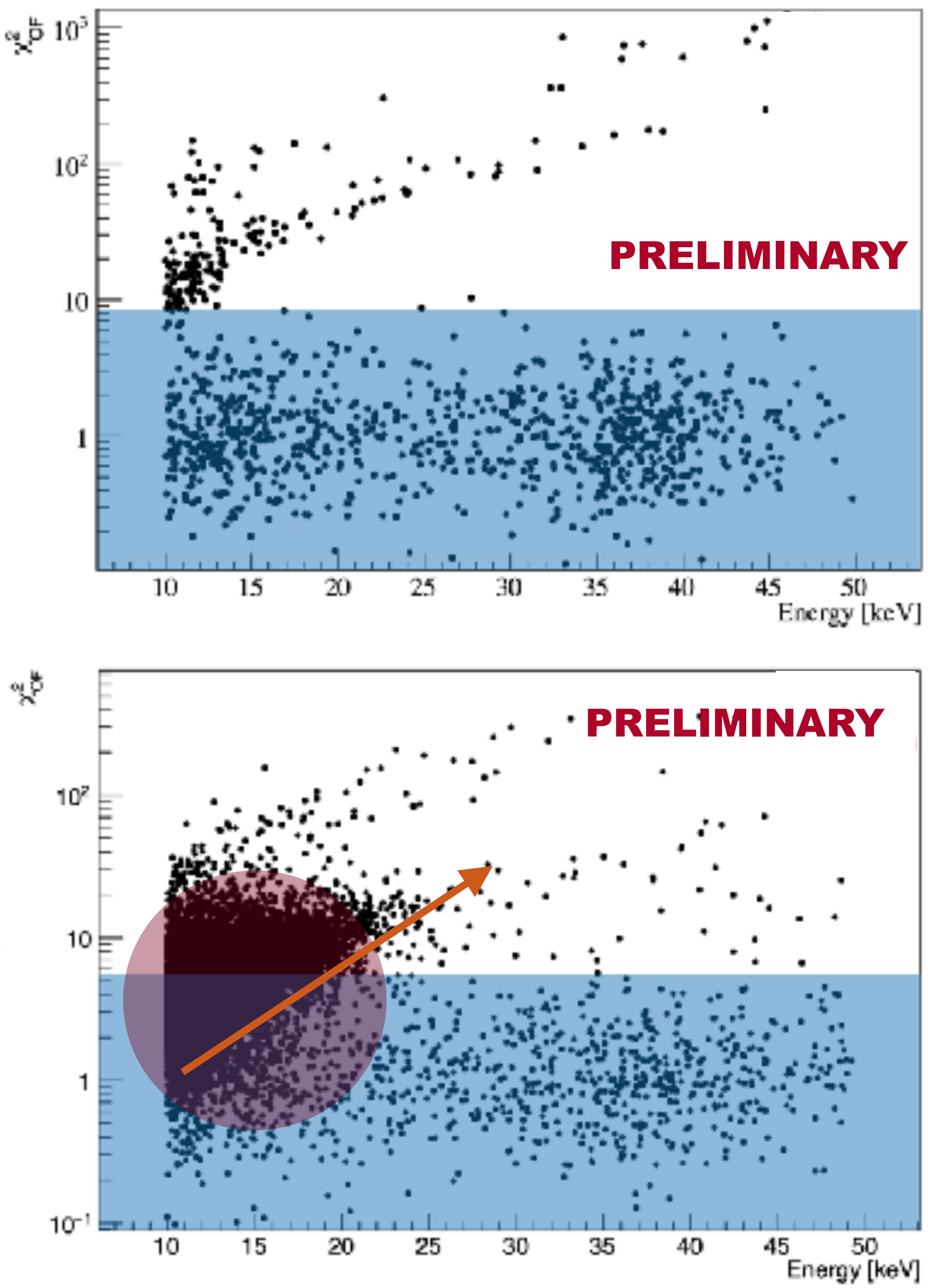




Low Energy Data Selection

Selection procedure:

1. **Events Selection**:
   apply a detector by detector pulse shape cut
2. **Detectors Selection**:
   The presence of non-physical events is identified by:
   - Rise in the pulse shape parameters
   - Increased events rate at lower energy



Low Energy Data Selection

Selection procedure:

1. **Events Selection**:
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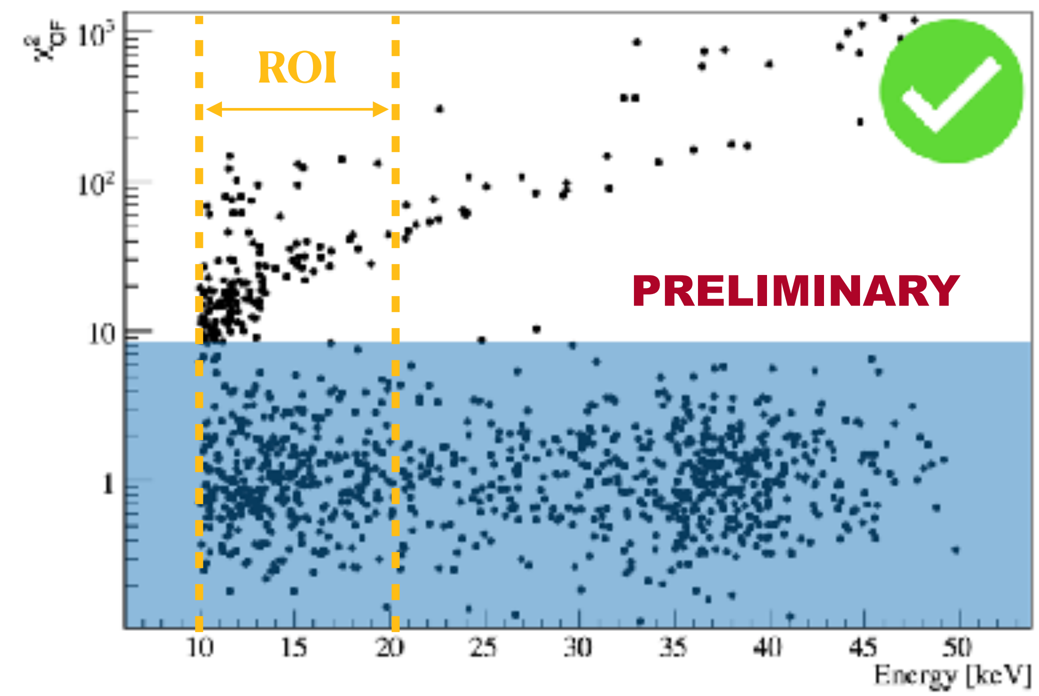
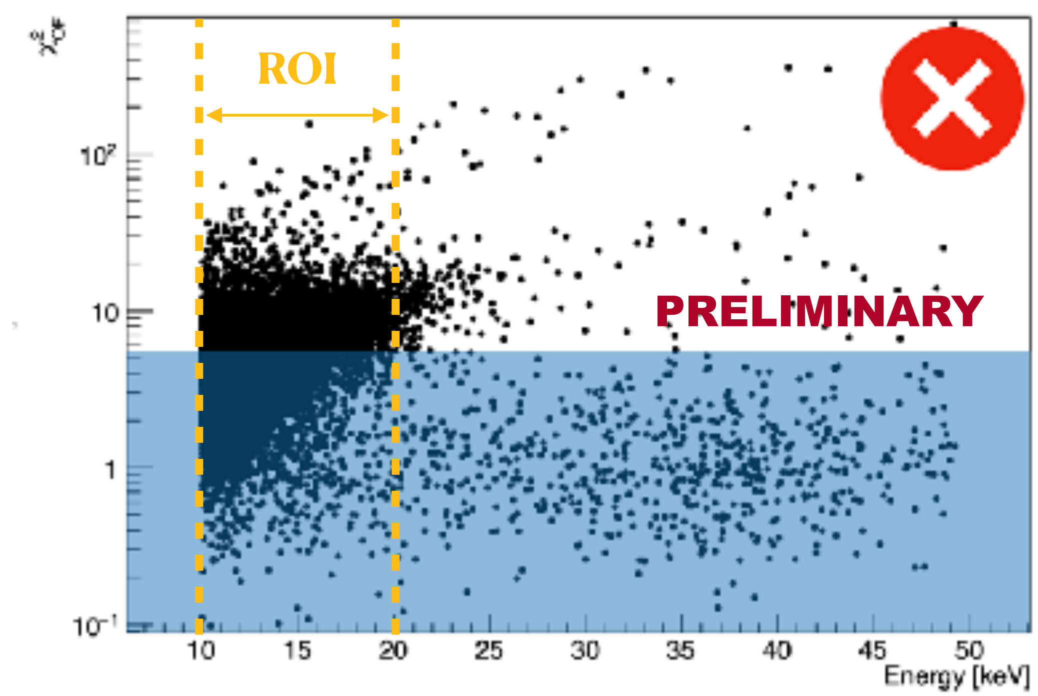
2. **Detectors Selection**:
   The presence of non-physical events is identified by:
   - Rise in the pulse shape parameters
   - Increased events rate at lower energy

➡ determine if the cut is sufficient to reject spurious events in a given **Region of Interest (ROI)**.

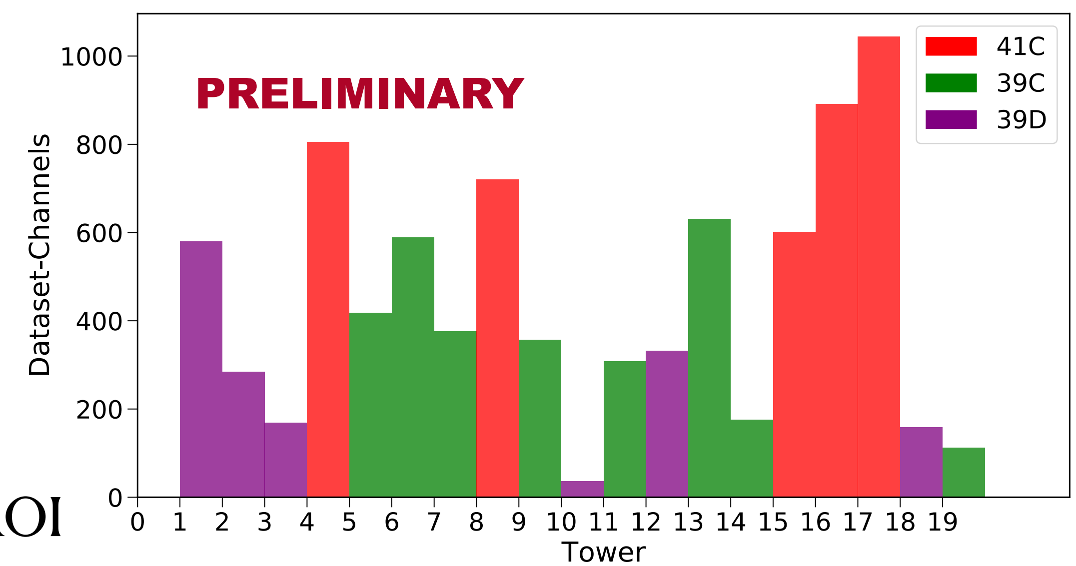
➡ Selection cuts defined to balance the loss of **efficiency** and **exposure** with the reduction in **background level** in the ROI



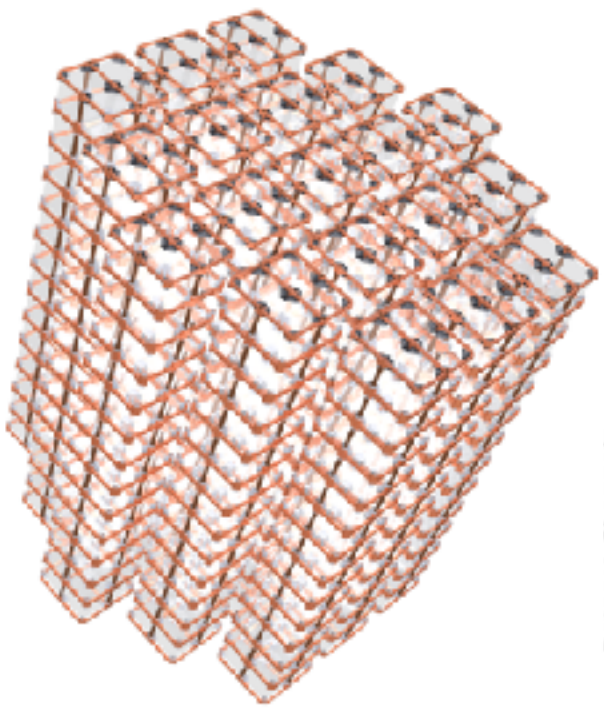


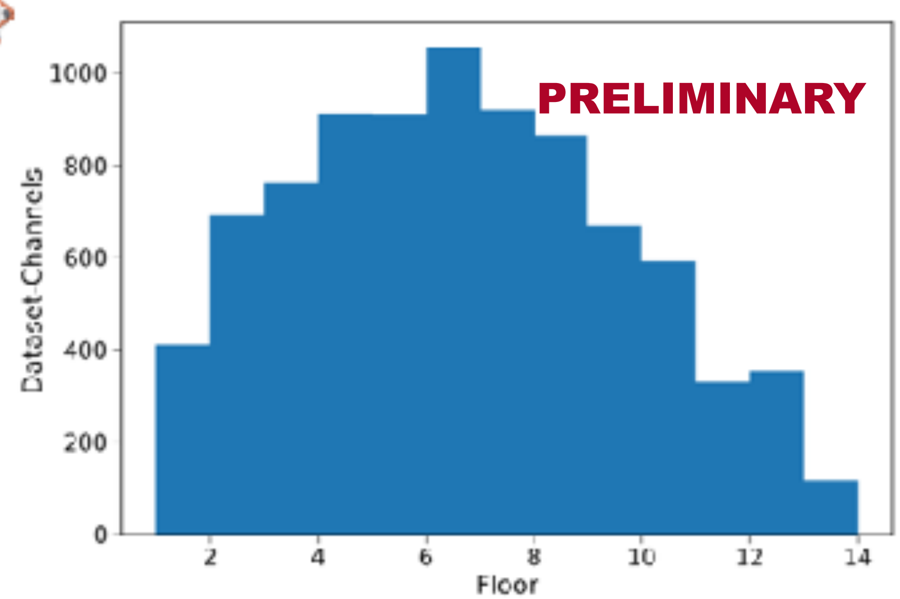
Data Selection Results

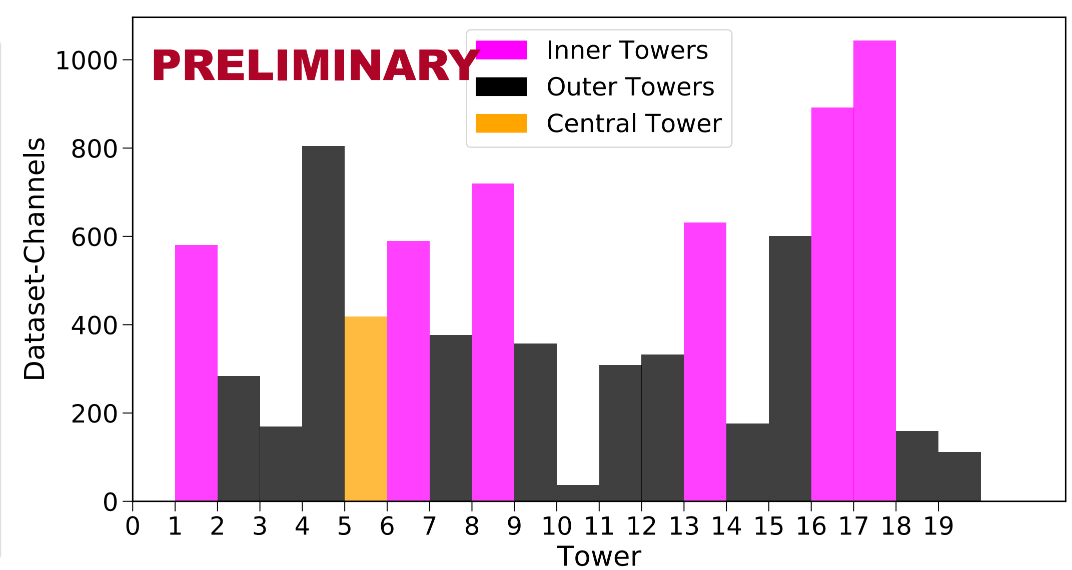
- Which CUORE detectors are selected for low energy?
  - a specific production batch of thermistors (lower thermal noise)
  - inner CUORE towers (higher screening)
  - central floors (lower effect to vibrations)



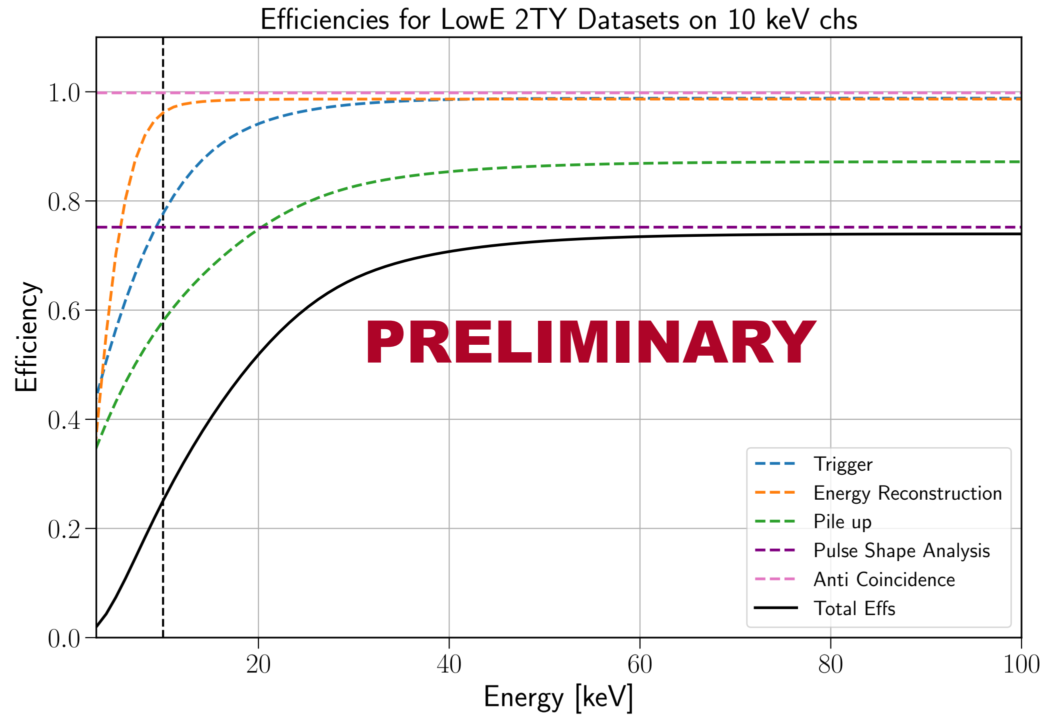
From [10,20] keV ROI





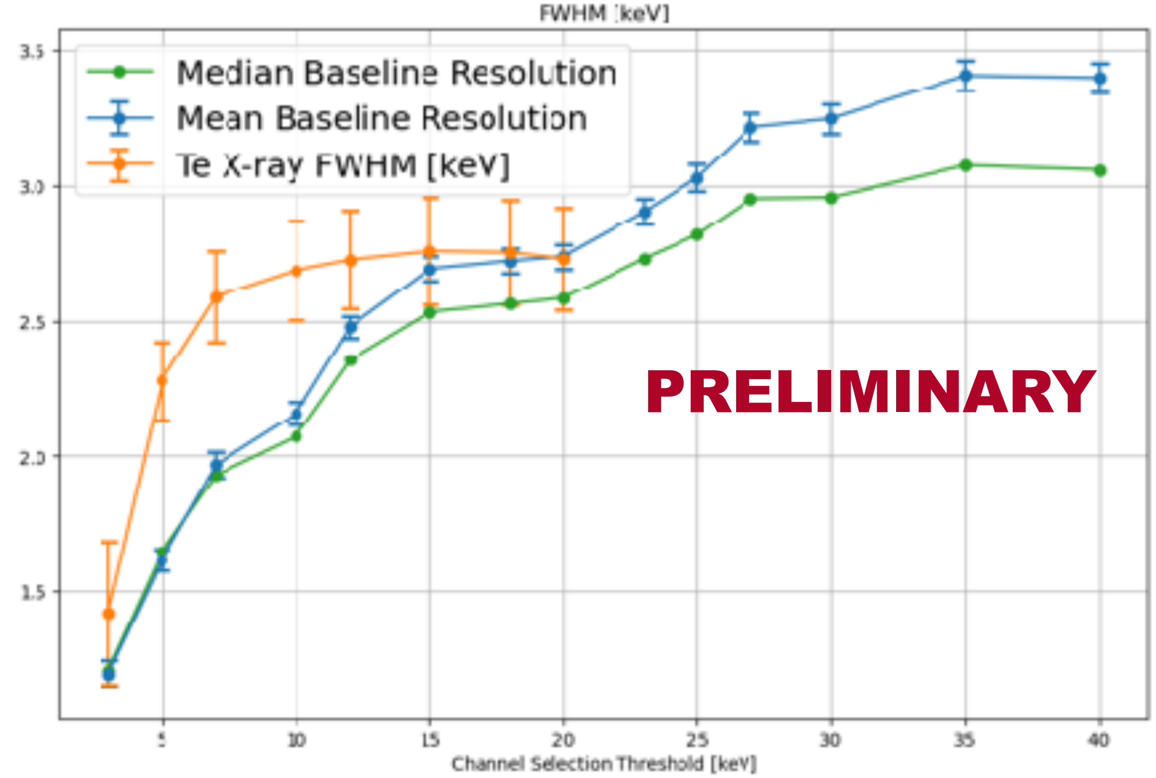


Performance at Low Energy

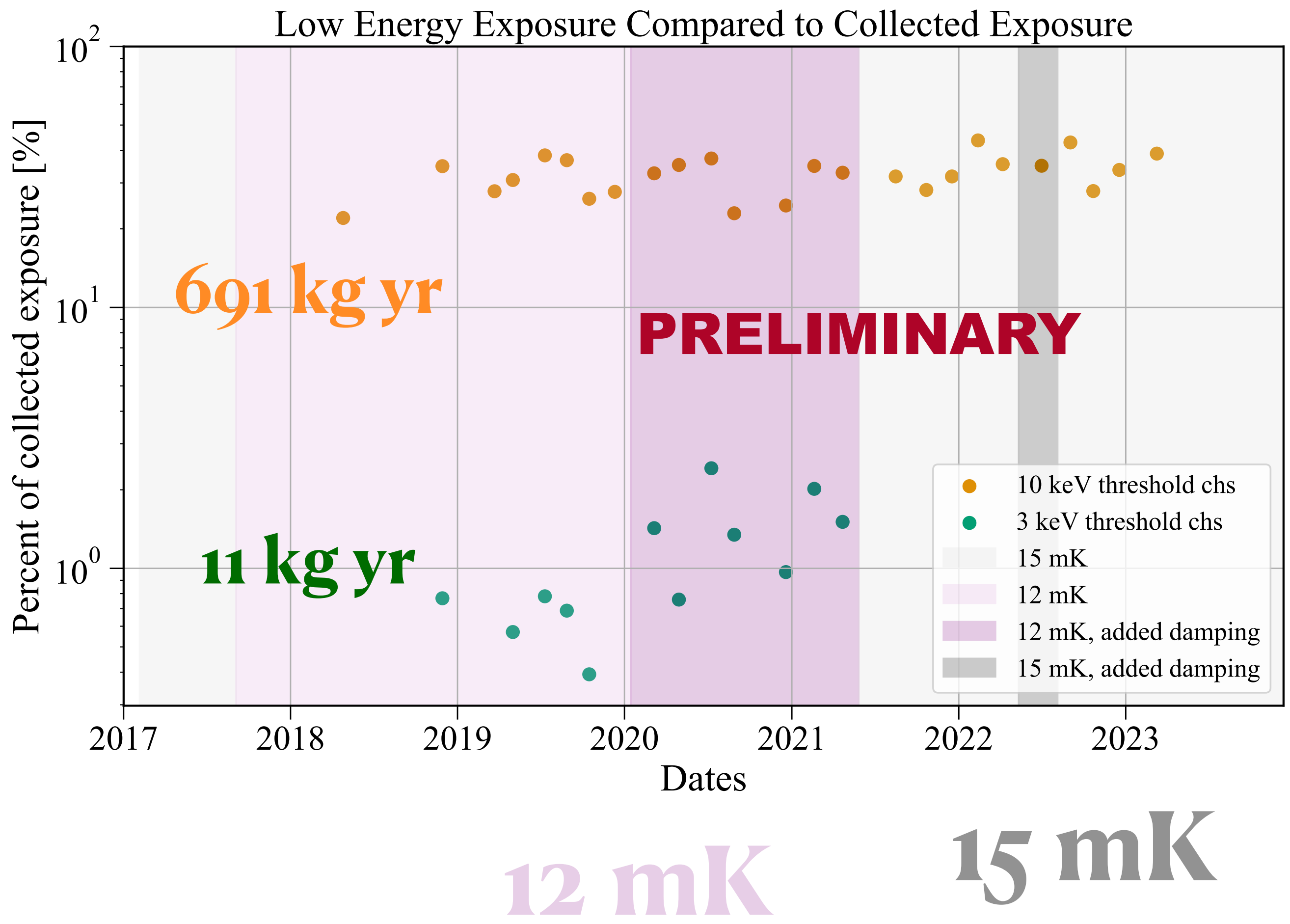


- We estimate efficiencies at low energy by:
  - Te X-ray peaks at 27-31 keV (Pulse Shape efficiency)
  - Injected thermal pulses at varying amplitude

- We estimate energy resolution at the baseline and with Te X-rays
- We varied ROIs energy intervals from 3 to 40 keV



Data Selection Results

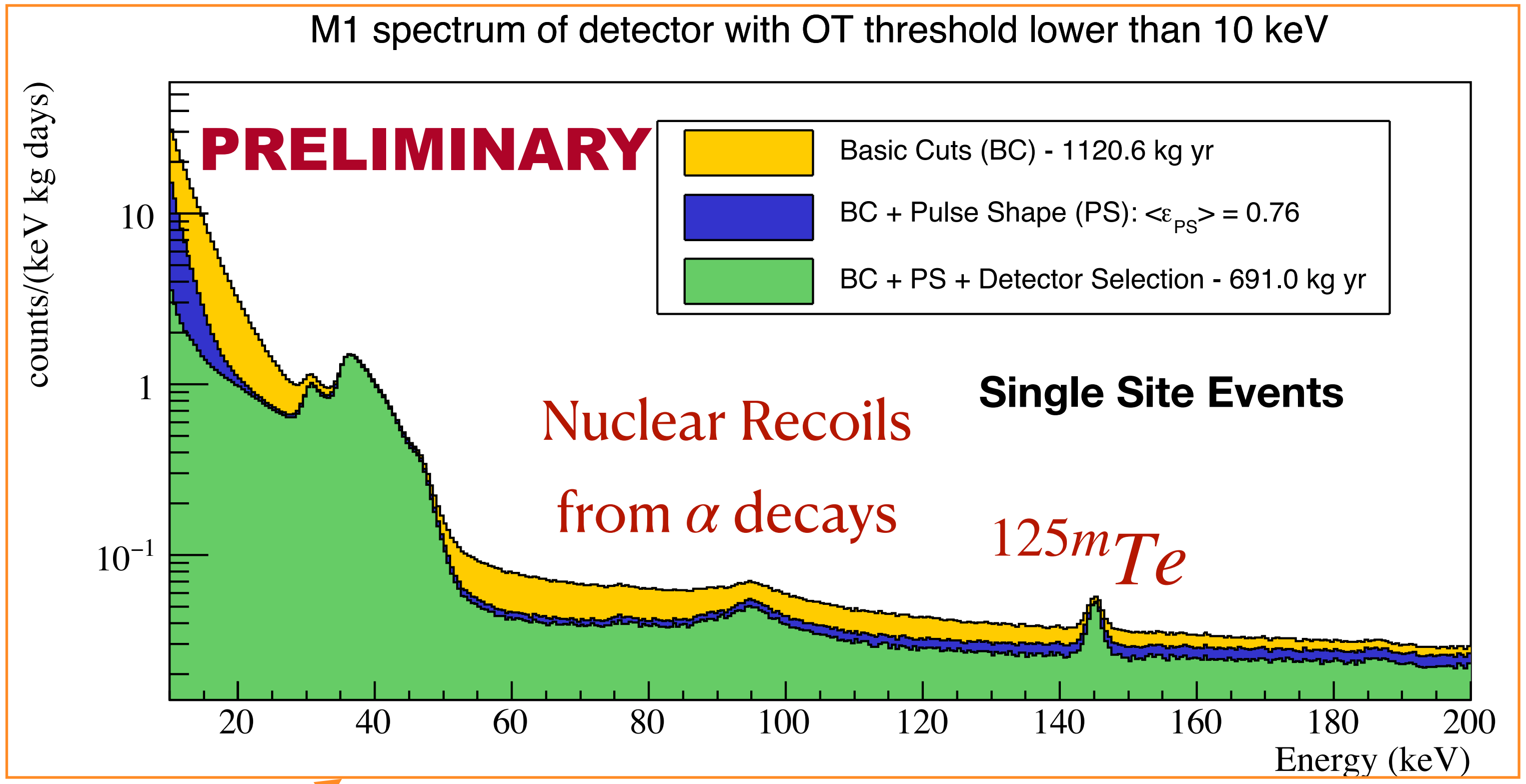


We focused on two ROIs:

- [10,20] keV: minimum required for Solar Axion search at 14.4 keV
  - About 30% of exposure is saved
- [3,10] keV: the lowest accessible in CUORE
  - Few % of the exposure is saved
  - Available only at ~12 mK
  - Improved with oscillation damping system

Low Energy Spectrum

- **Single Site events: fully contained in a single CUORE crystal**
- **Detectors with Optimum Trigger threshold < ROIs lower edge**
- **Pulse shape cut applied**
- **Selected Detectors**

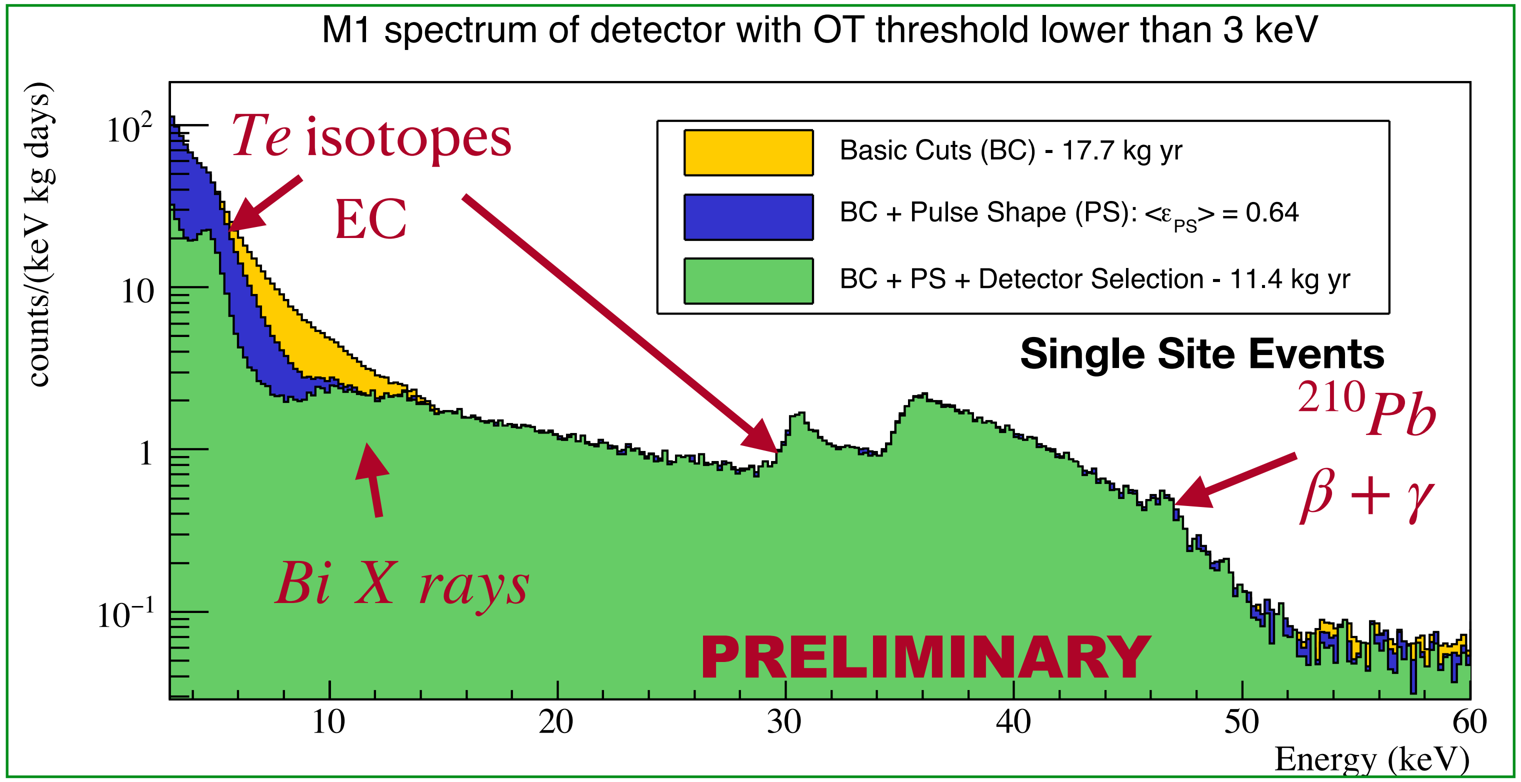


[10,20] keV ROI

691 kg yr out of 2 ton yr

Low Energy Spectrum

- The stricter selection improves resolution and highlights background structures
- Spectral features are under investigation
  - Tellurium Isotopes (^{125}Te, ^{123}Te, ^{121}Te)
  - Surface lead contaminations (^{210}Pb)



11.4 kg yr out of 2 ton yr

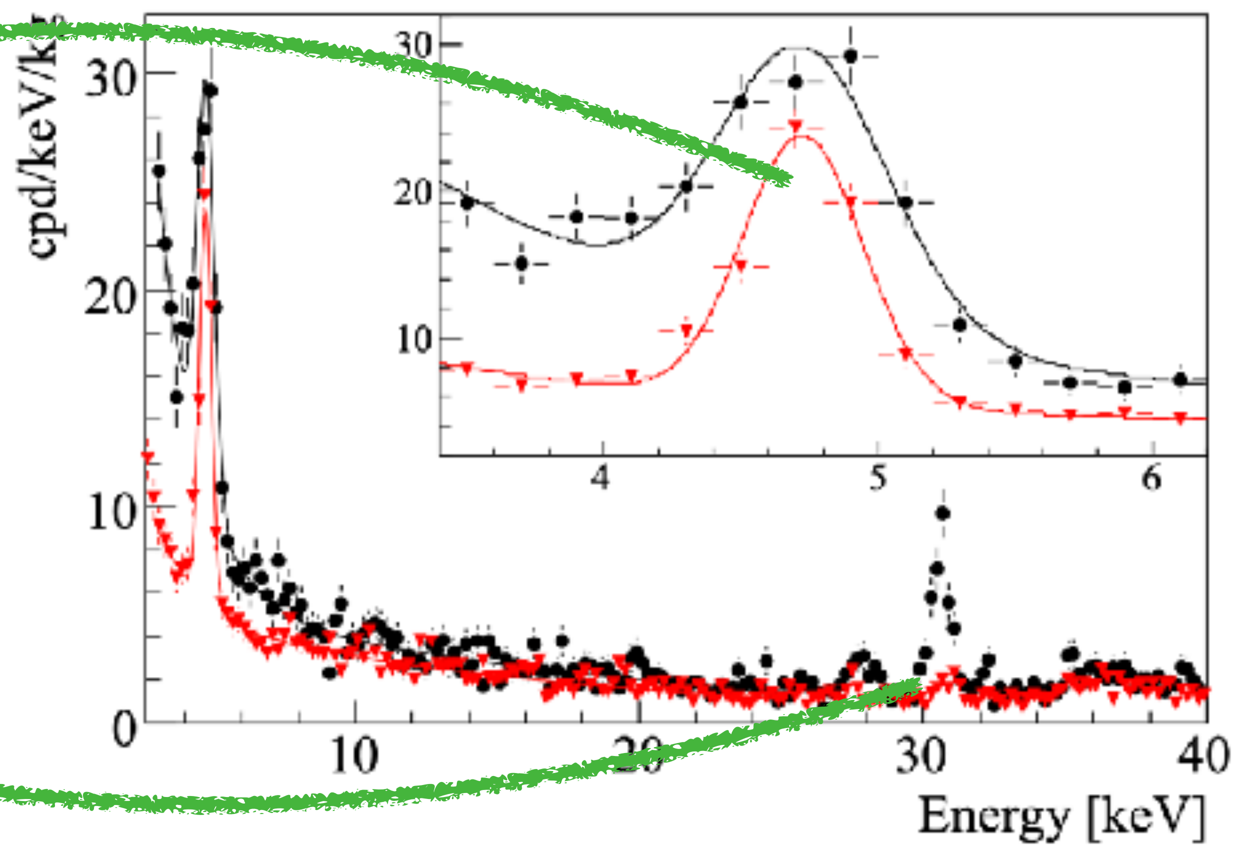
[3,10] keV ROI

^{123}Te investigations

- ^{123}Te has 0.9% of natural abundance (about 1.8 kg in CUORE)
- Predicted to decay by EC, its detection has a controversial history (first detected than refuted)

L1-Shell electron line at 4.7 keV

K-Shell electron line at 30.5 keV



CUORE Crystals Validation Runs

CUORICINO

https://journals.aps.org/prc/pdf/10.1103/PhysRevC.67.014323

https://iopscience.iop.org/article/10.1088/1475-7516/2013/01/038

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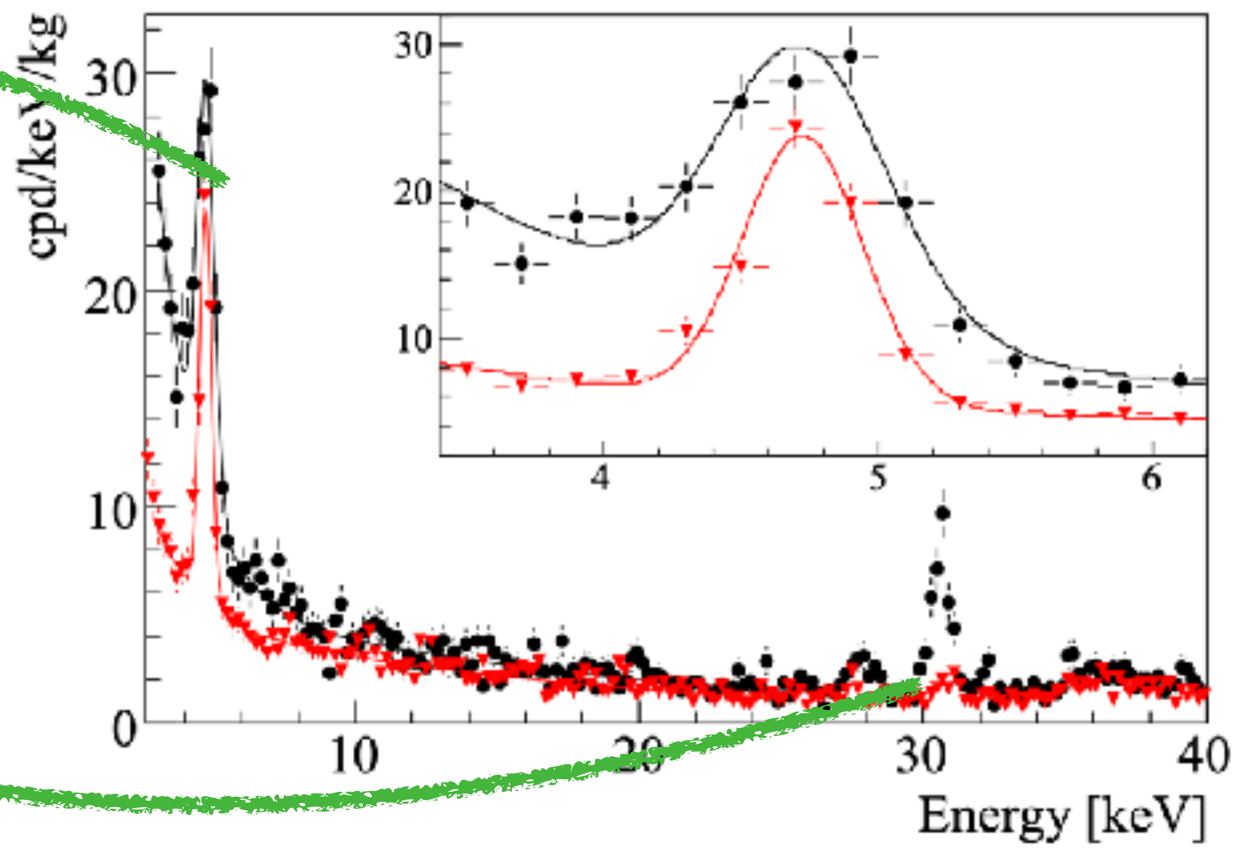
Peak at 4.7 keV still there after underground storage!

Decayed after underground storage: ascribed to ^{121}Te from neutron activation



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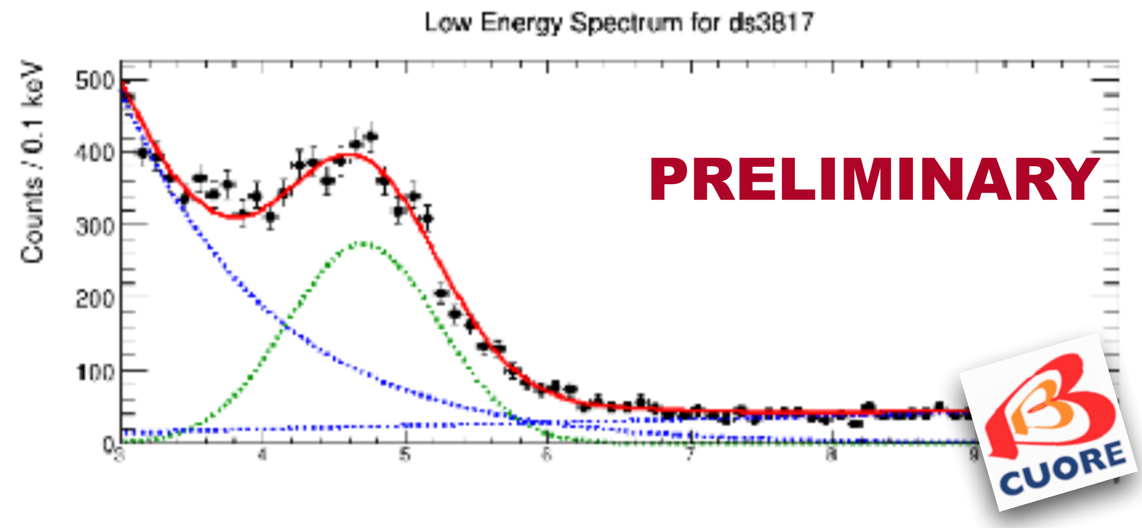
CUORE Crystals Validation Runs

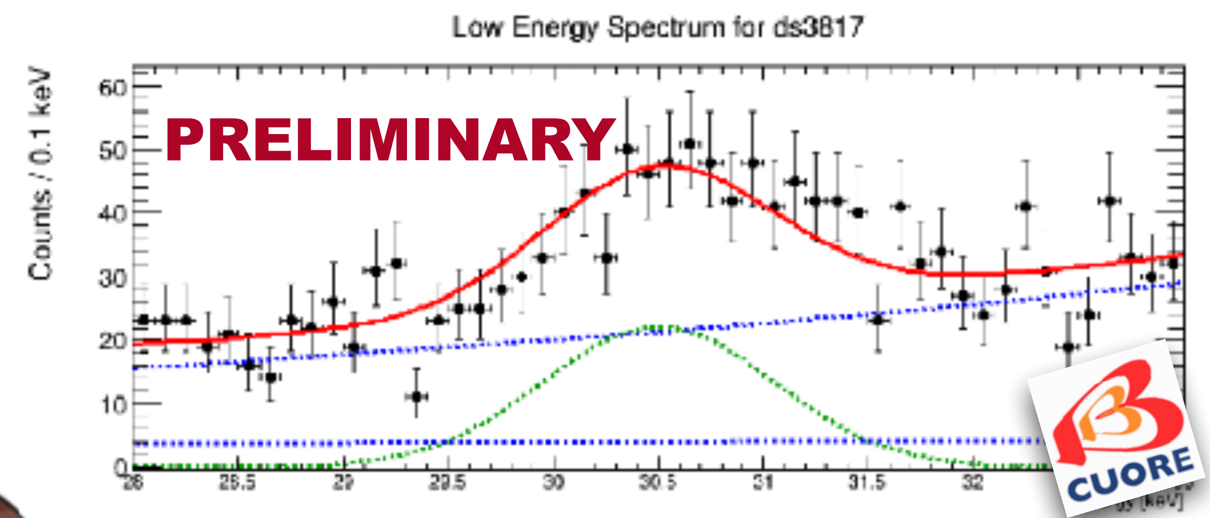
CUORICINO

^{123}Te investigations

https://journals.aps.org/prc/abstract/10.1103/PhysRevC.56.R1675

- In CUORE we observe again peaks corresponding to the K (30.5 keV) and L1 (4.7 keV) shells
    - Rate is constant in time, and the associated half-life longer than the best limit
- The L3 line at 4.1 keV is predicted to have the highest intensity, but is missing in our spectrum!
- Investigations are ongoing





Conclusions & Perspectives

- Operation of a a ton-scale cryogenic calorimeter experiment down to keV scale (~ 3 orders of magnitude of energy scale)
  - CUORE as a multipurpose experiment (neutrinos, nuclear decays, dark matter…)
  - Spectrum investigation foreseen in the next months with the optimized set of data

See next talk from P. Loaiza

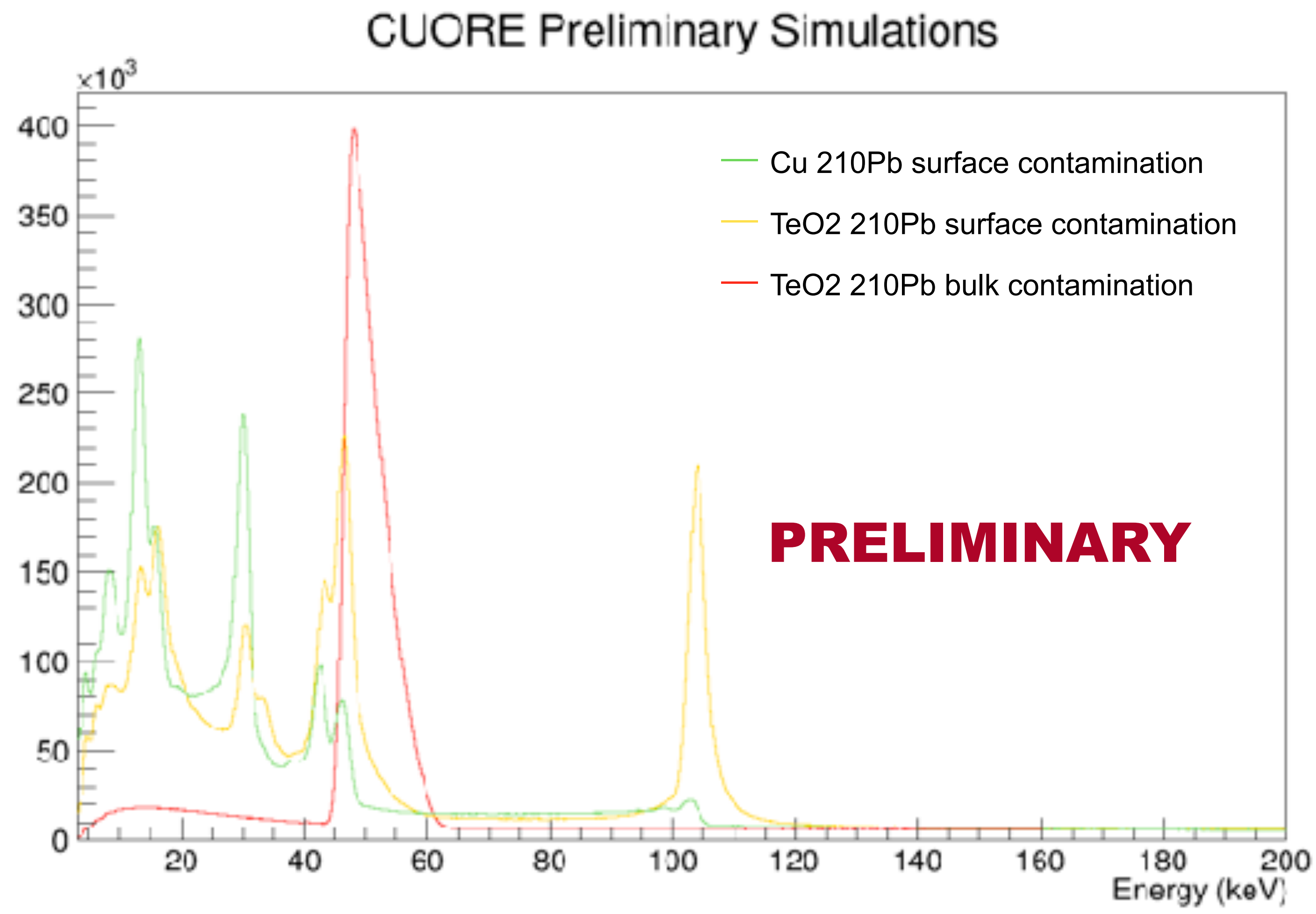
- CUORE cryostat upgrade in view of CUPID:
  - A 2nd CUORE run is foreseen, with improved vibration environment
  - It aims at accessing lower thresholds for dark matter studies
  - Low Energy studies provide key insight for the upgrade

Thank You!

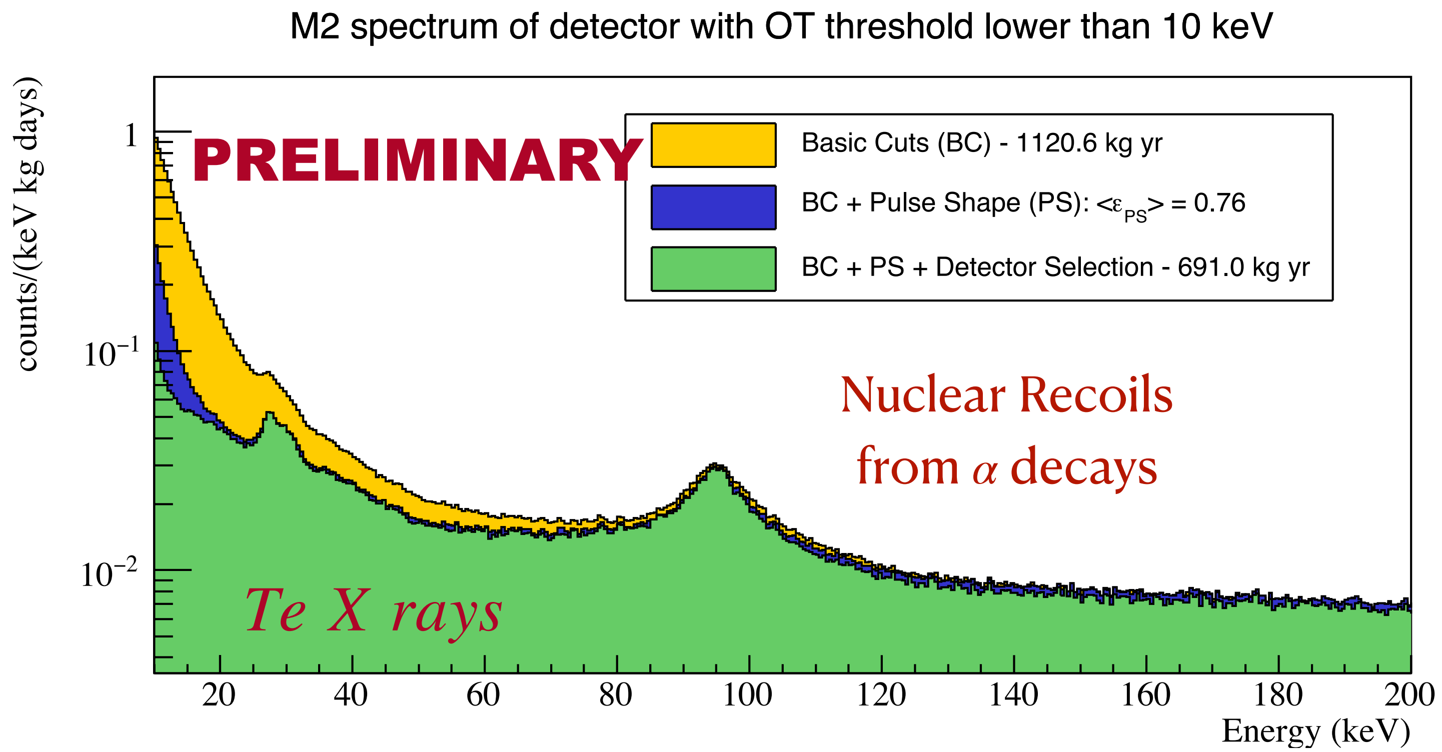
Backup Slides

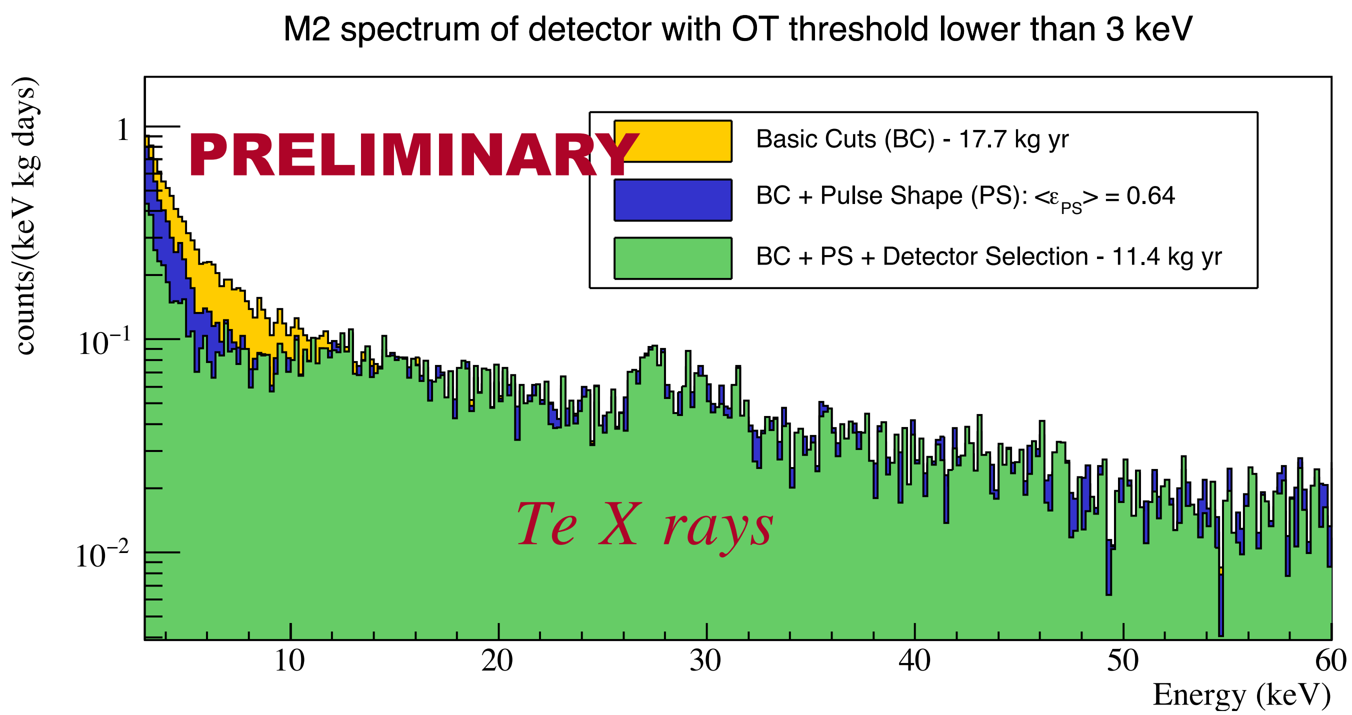
210Pb contaminations

- Surface contamination of TeO2 and copper
- It can explain the structures we observe at 10-13, 30 and 37 keV
- It evidences nuclear recoils at 100 keV



Double Site events

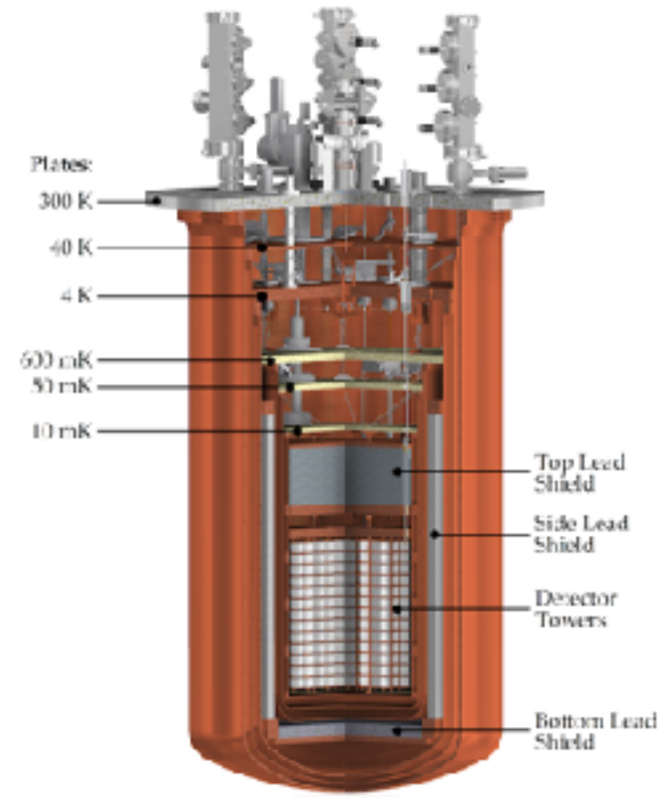


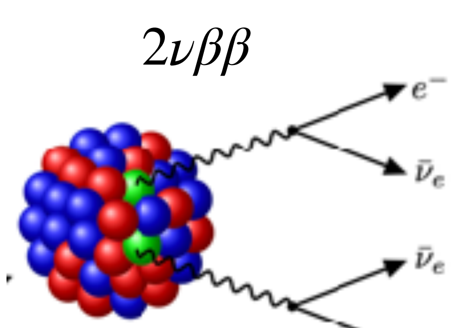


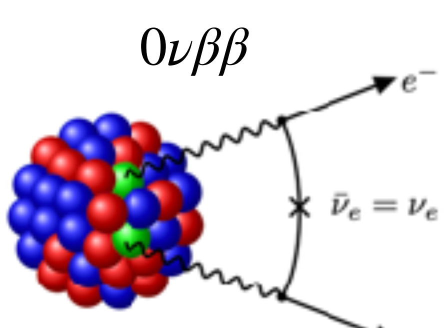
CUORE

Cryogenic Underground Observatory for Rare Events

- Operated in a world leading dilution refrigerator in terms of power and size
- Equipped with 4(+1) Pulse Tubes for cooling to 4K
- Nested co-axial copper vessels at decreasing temperatures
- 15 tons cooled below 4 K and 3 tons below 50 mK

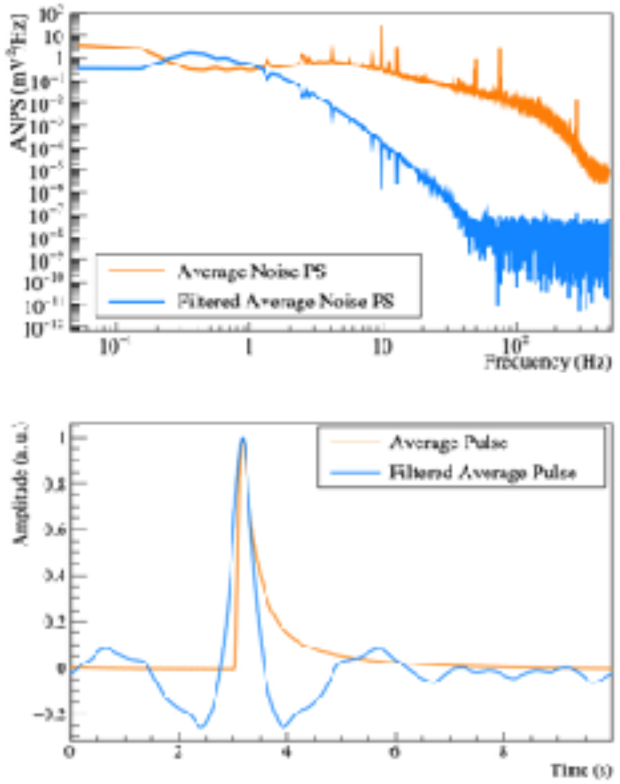


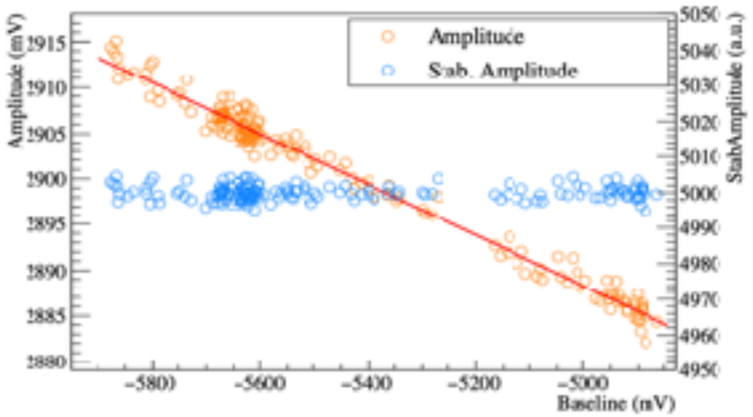


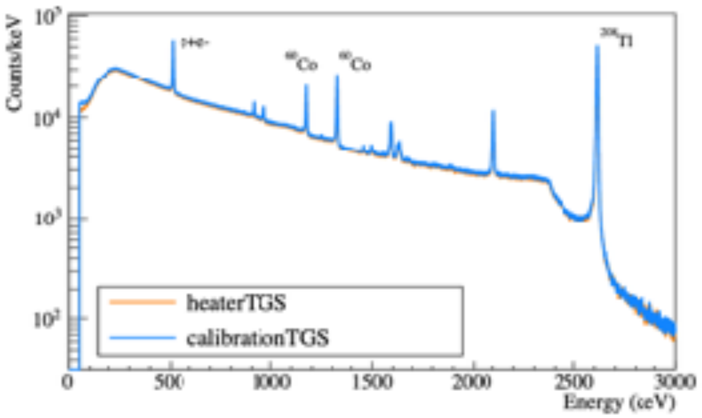


- Searching for $0\nu\beta\beta$ of ^{130}Te at $\sim 2.5 MeV$
  - Alternative mode of the Standard Model $2\nu\beta\beta$
  - Test Majorana nature of the neutrino and Total Lepton Number violation

Analysis Methods







Optimum Filter: suppress the frequencies most affected by the noise relying with ideal pulse and noise spectrum

Thermal Gain Correction: correct amplitude dependence on the operating temperature (~ baseline) drift by using the injected thermal pulses

Energy Calibration: based on measurements with external ^{232}Th-^{60}Co source deployment

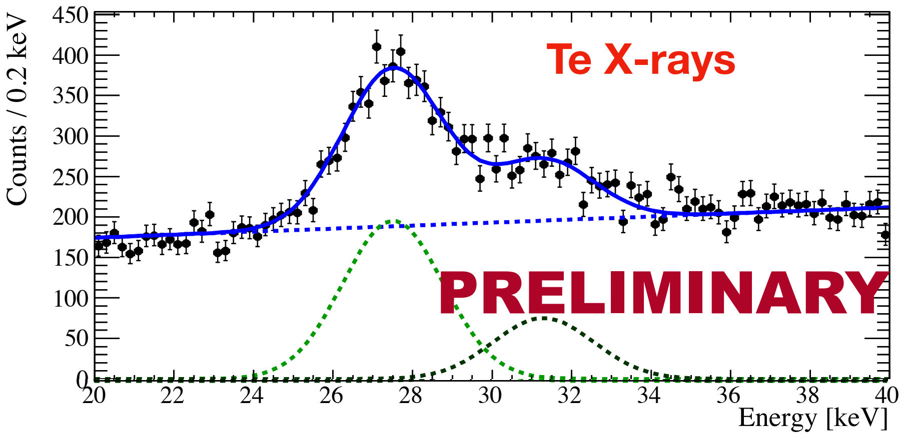
https://arxiv.org/abs/2404.04453

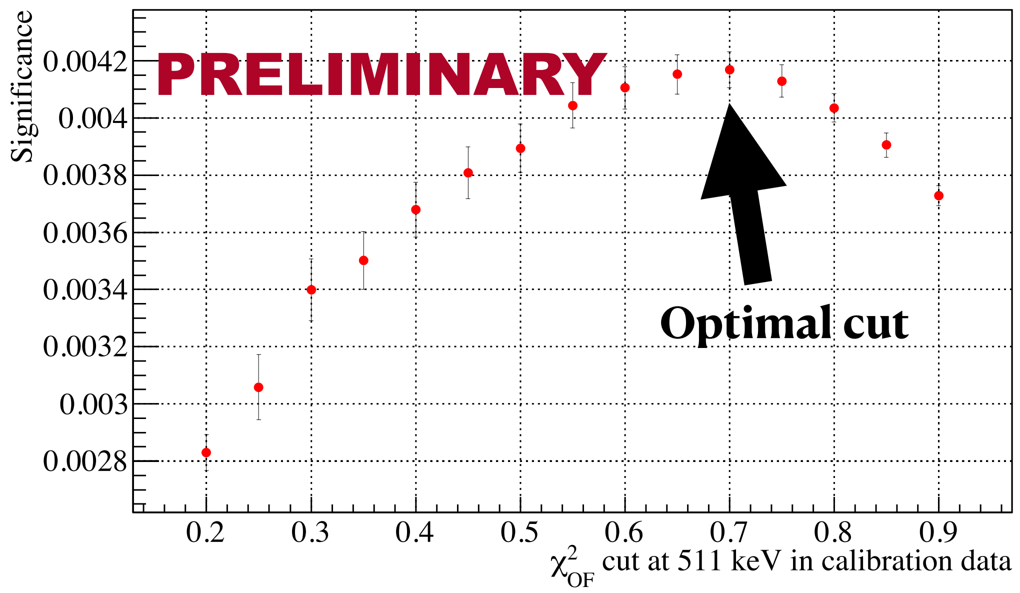
Low Energy Data Selection

The pulse shape cut levels and the subset of selected detectors are defined to maximize the Significance and optimise the sensitivity to the axions coupling constant

$$\mathcal{S} = \frac{\varepsilon_{PS} \cdot M\Delta T}{\sqrt{B}}$$

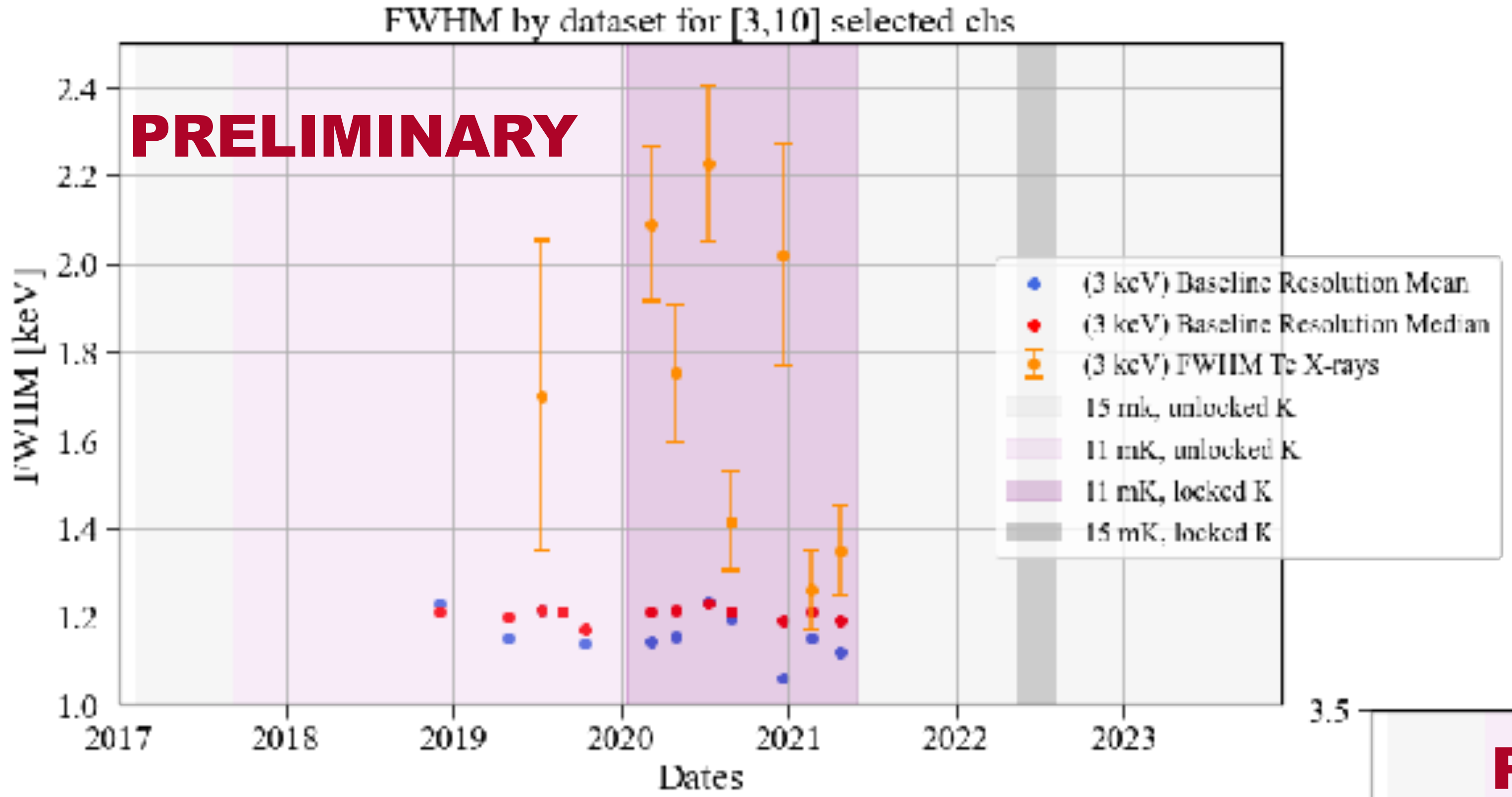
- Evaluated from a low energy signal template: Te X-rays at 27-31 keV
- Defined by the selected detectors
- Estimated in the ROI

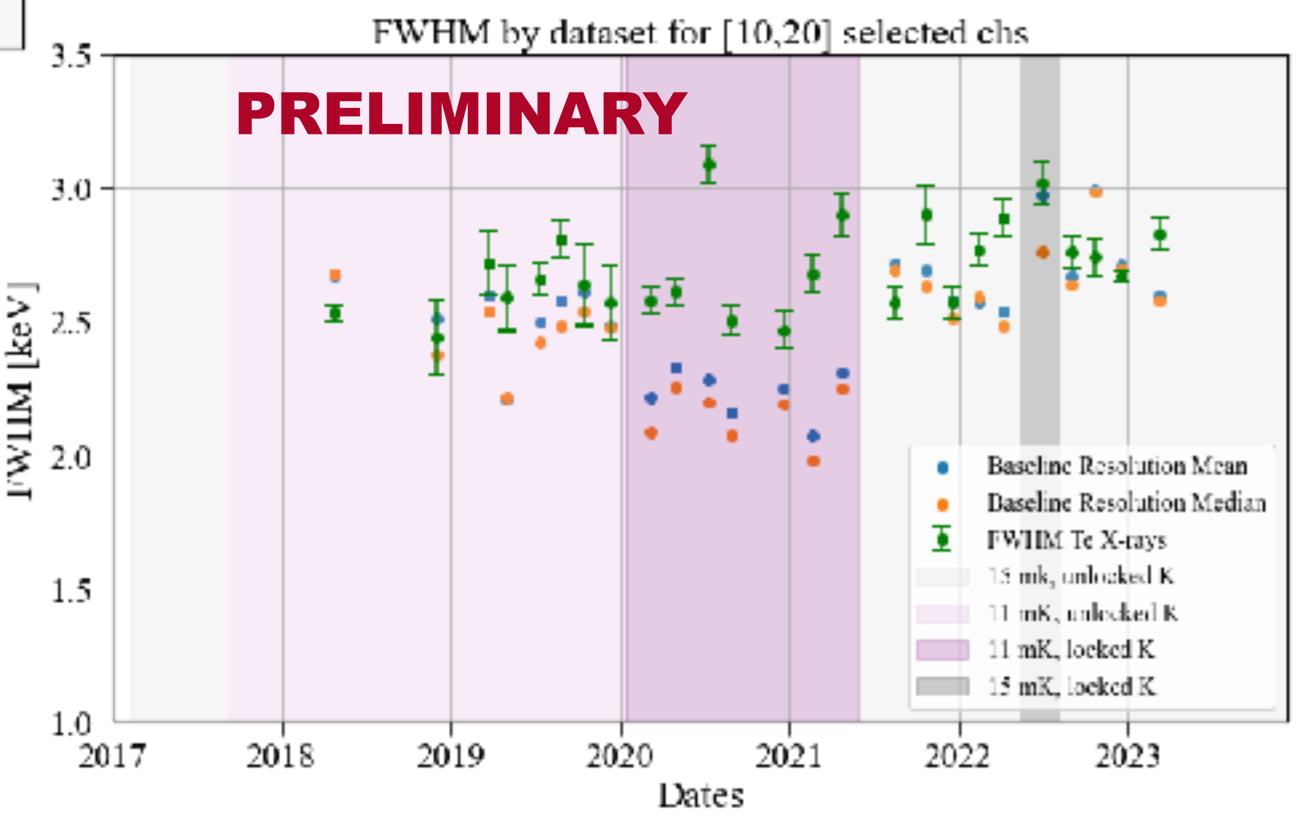




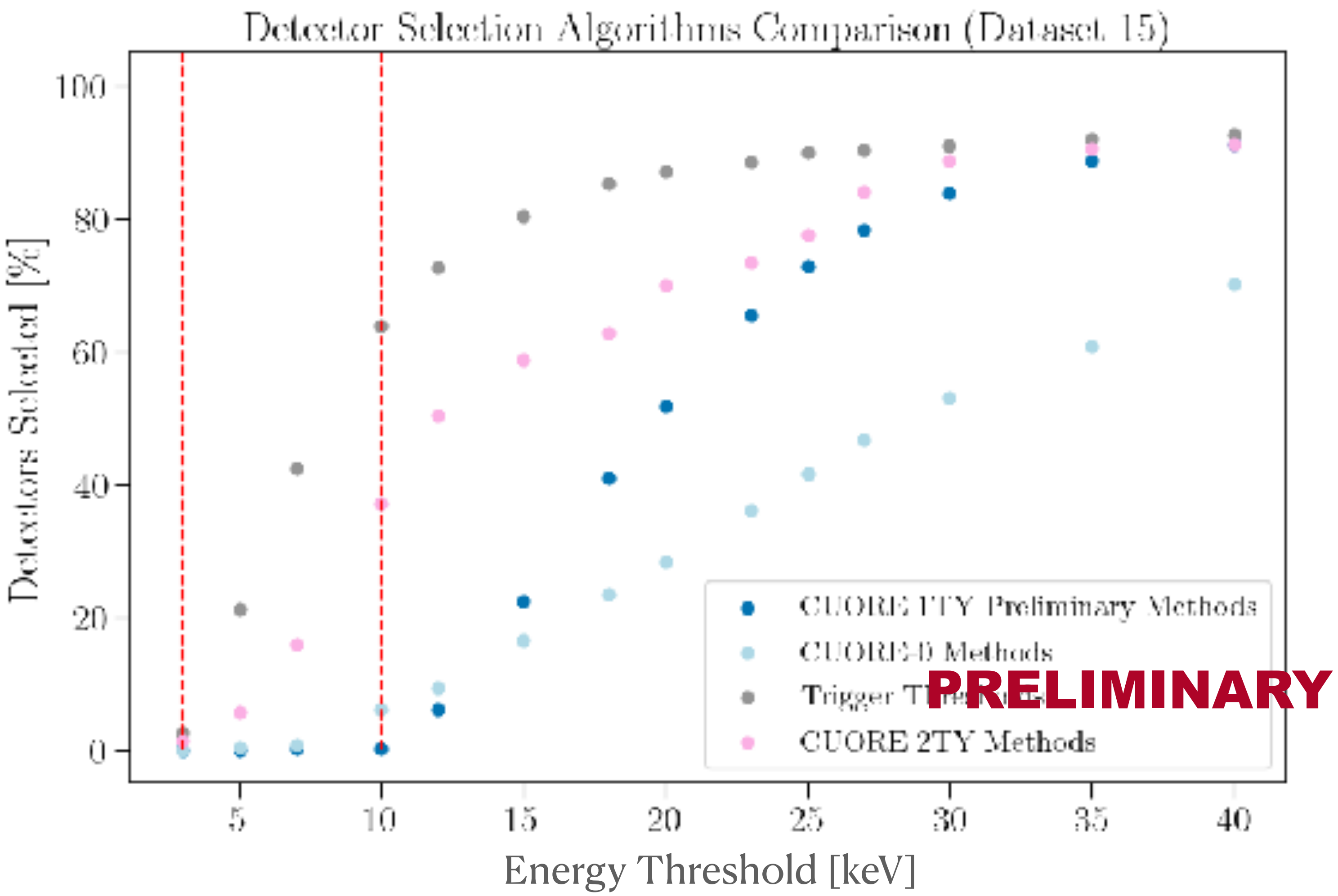
It balances the loss in **signal efficiency** and **exposure** with the gain in **background level**.

Energy Resolution



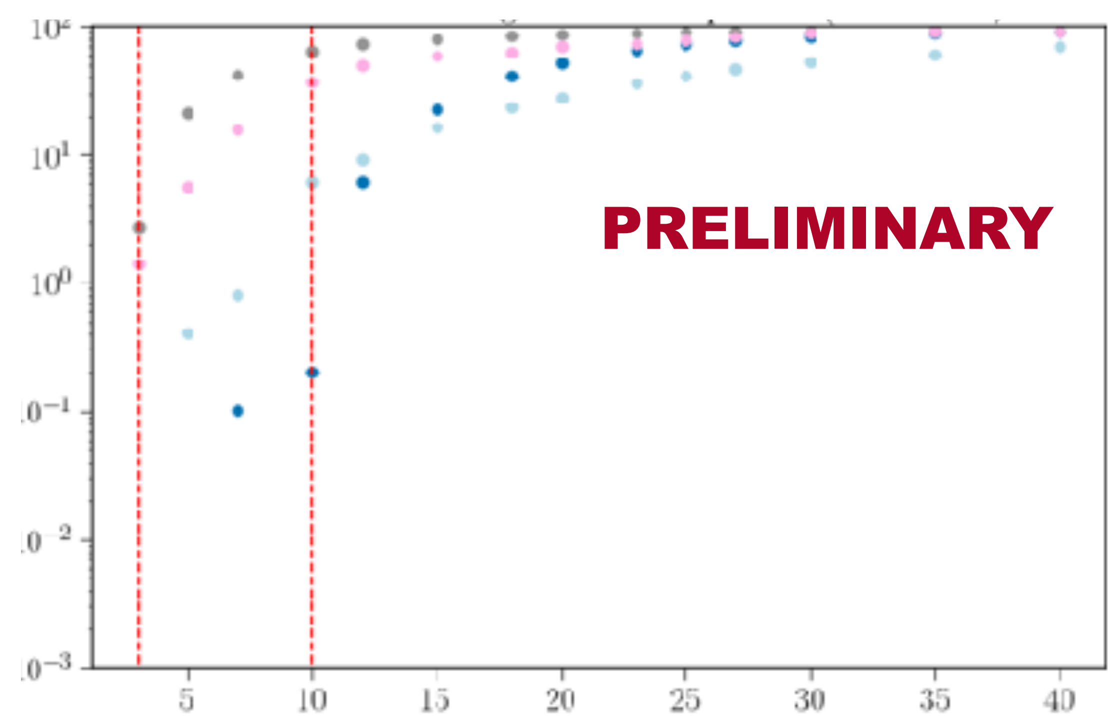


Other Threshold algorithms



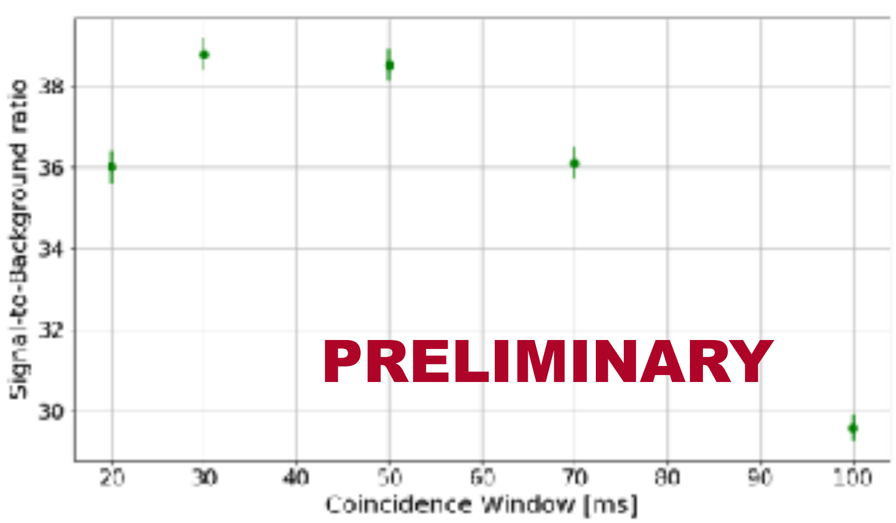
- The adopted detectors selection procedure is not an algorithm assigning a threshold as the other methods
- It is repeated step by step at different energies

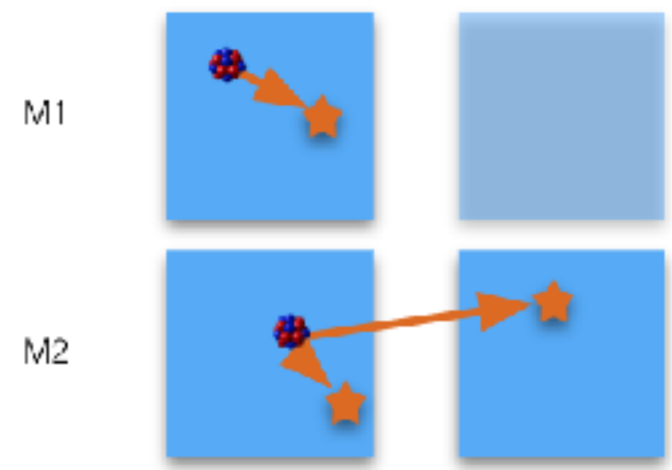
Log scale



Coincidence Tagging

- Time window optimized on Te X-rays signal-to-background ratio
- The algorithm takes into account detectors location in the array





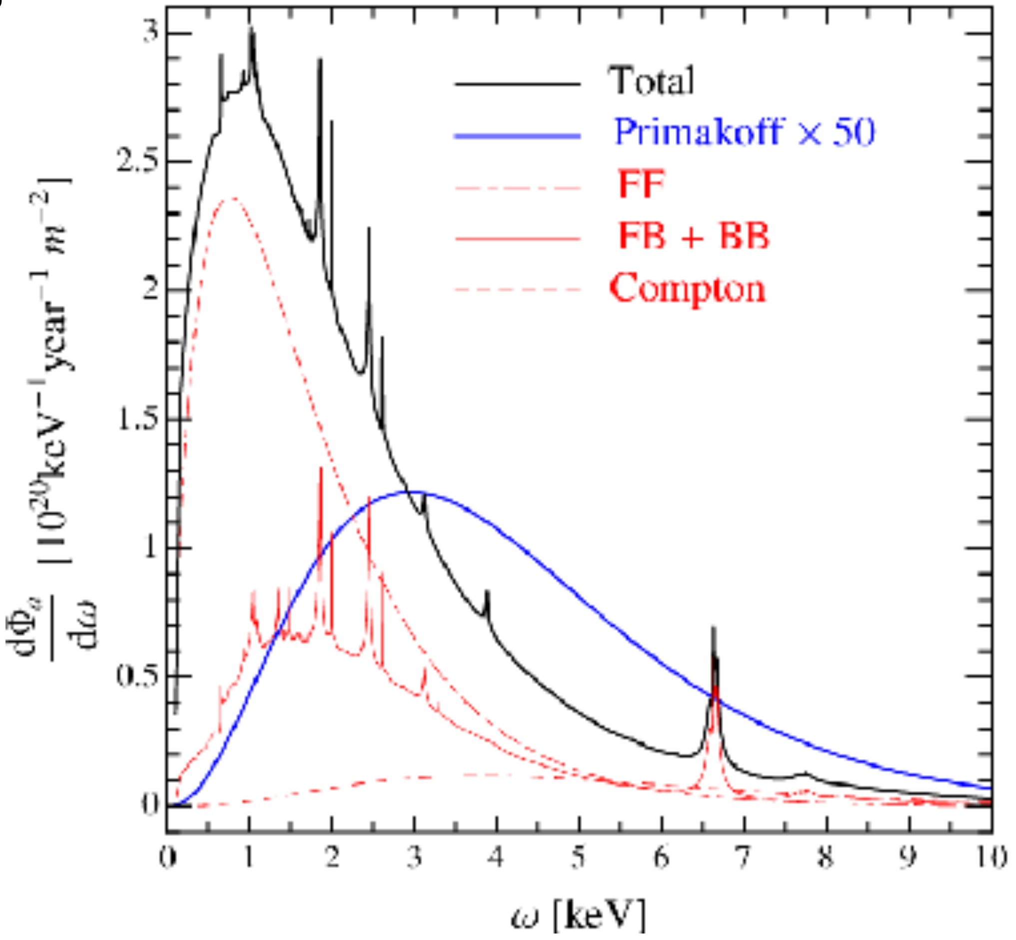
Solar Axions signatures

Production

- Primakoff conversion: nuclear plasma interacts with blackbody photons (kT = 3keV), and produce an axion
- Atomic Fe deexcitation, axio-Bremmstralhung, axil-compton scattering

Detection

- Convert axions back to photon
  - by interacting with crystalline electric field: modulated signal
  - Through a magnetic field (inverse Primakoff)
- Compton Scattering axions to photon

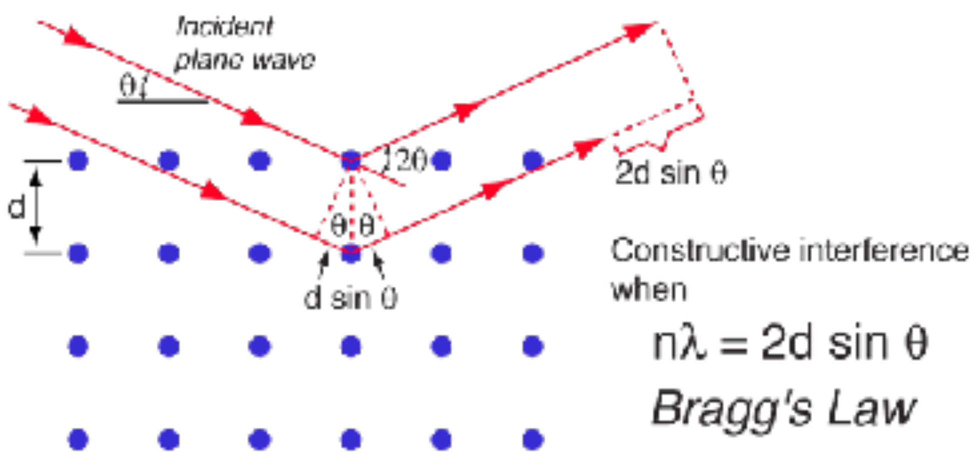


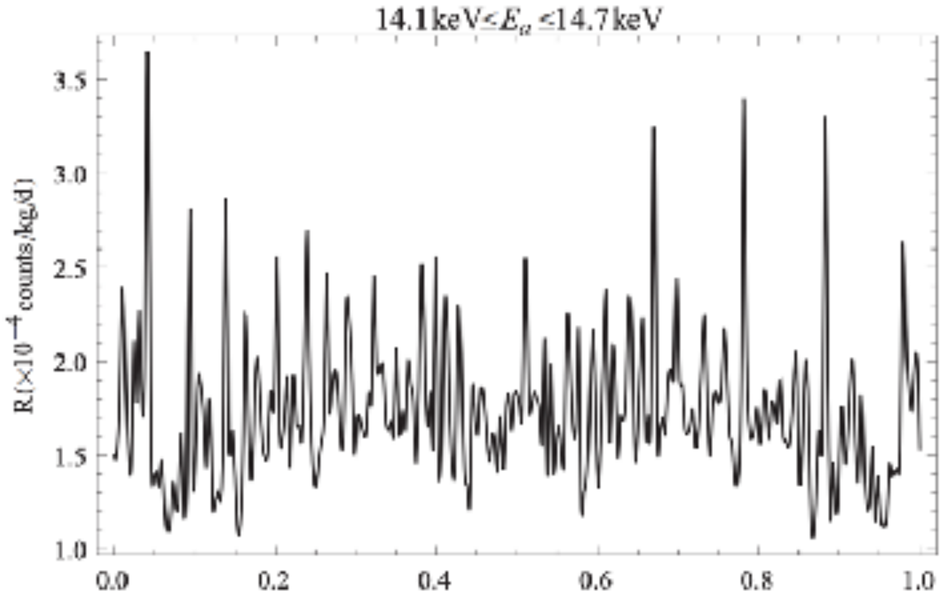
10.1088/1475-7516/2013/12/008

Solar axions interaction with crystalline structure

Different mechanism to detect the axions from ^{57}Fe line: **Inverse Coherent Bragg-Primakov Conversion**

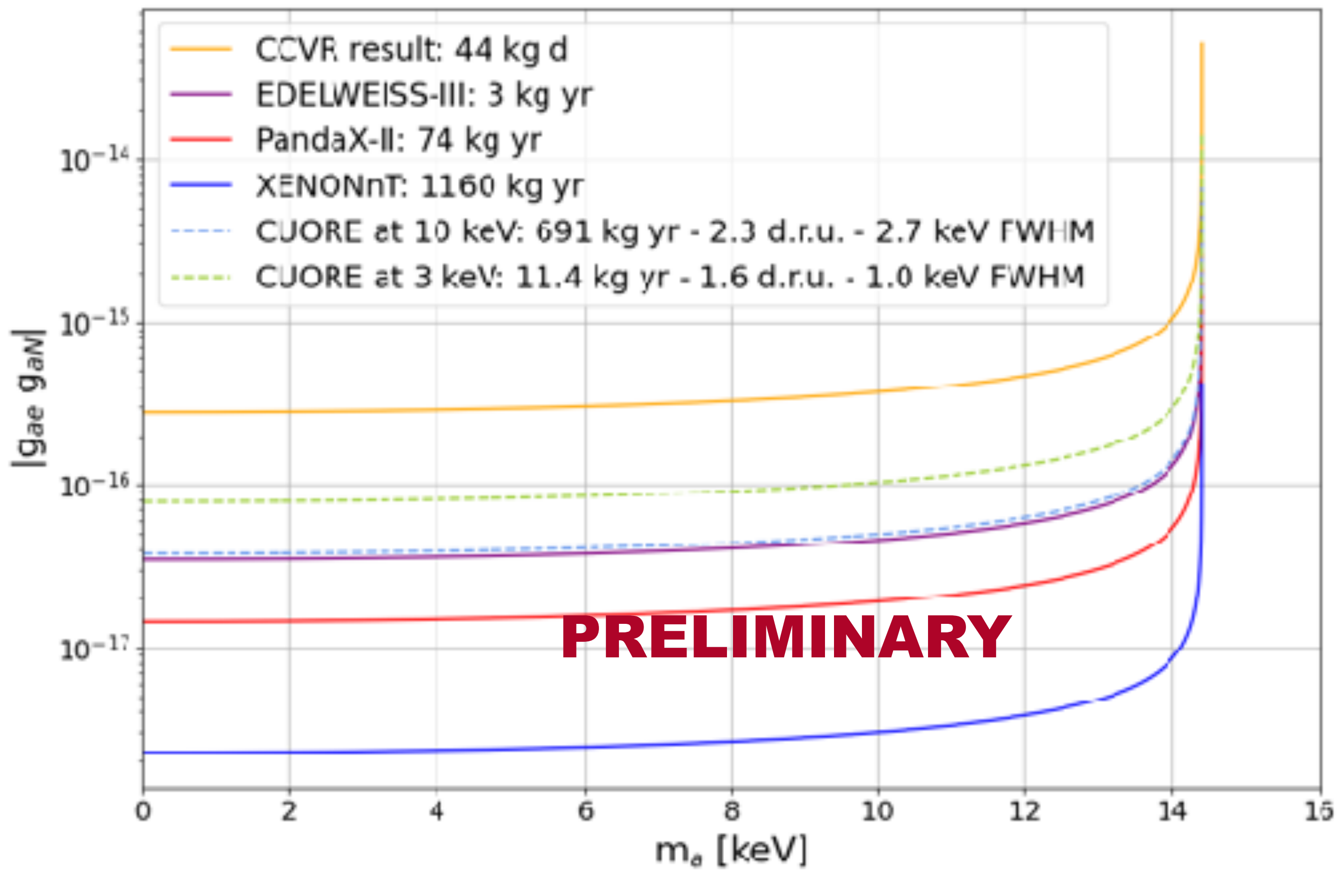
- Axion couples to a crystal lattice charge through a virtual photon
- The interaction produce a photon only if the Bragg's condition is satisfied
- dependent by the Sun-CUORE angle which varies over a day





https://iopscience.iop.org/article/10.1088/1475-7516/2016/02/031

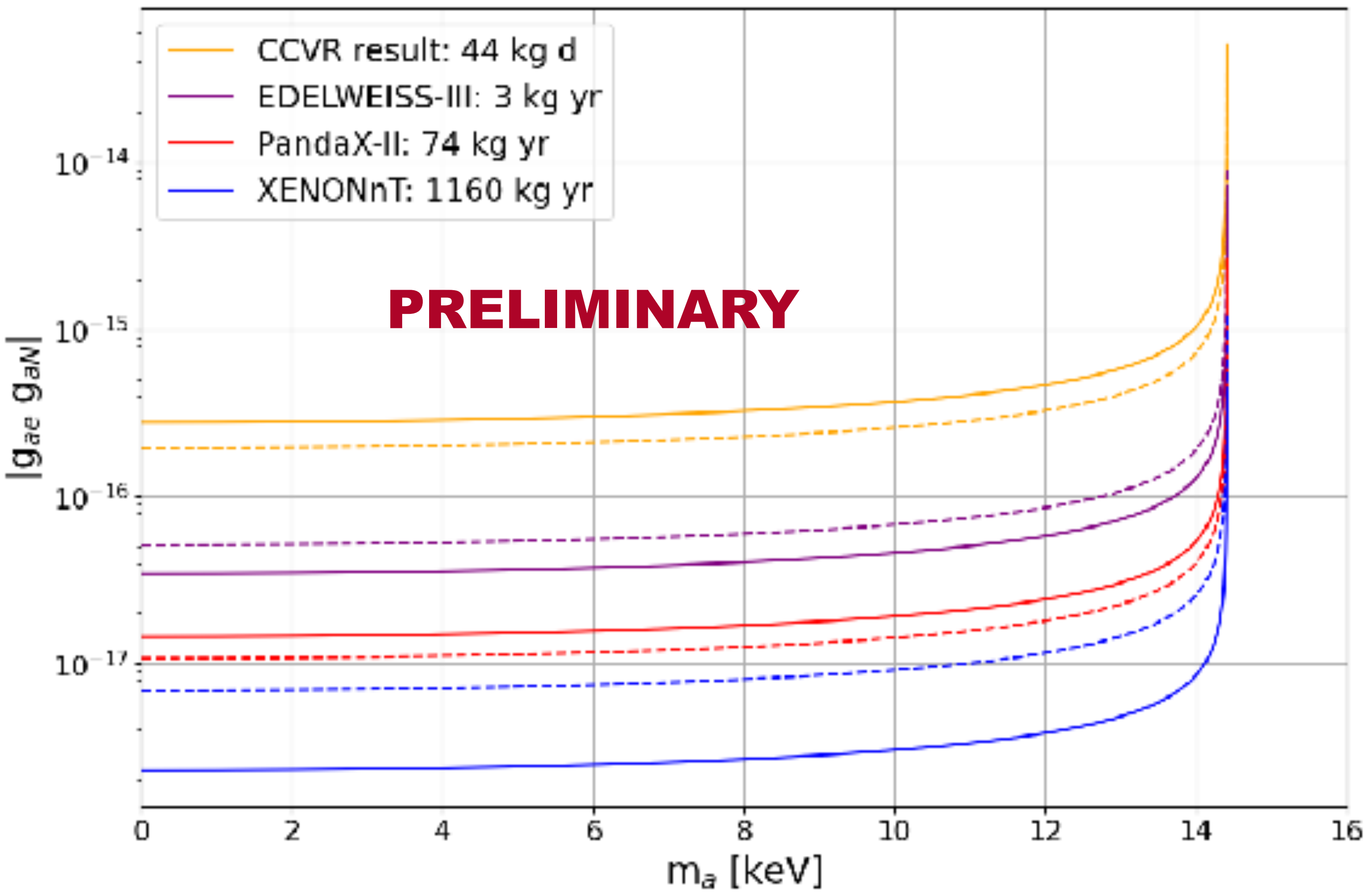
Other Experiments



	Exposure [kg yr]	Background level [counts/(keV kg yr)]	Energy Reosolution [keV]
CCVR	0.12	70	0.7
CUORE [10,20] keV	691	840	2.7
CUORE [3,10] keV	11.4	580	1.0
EDELWEISS-III	3	300	0.5
PandaX-II	74	1	4
XENONnT	1160	0.02	3

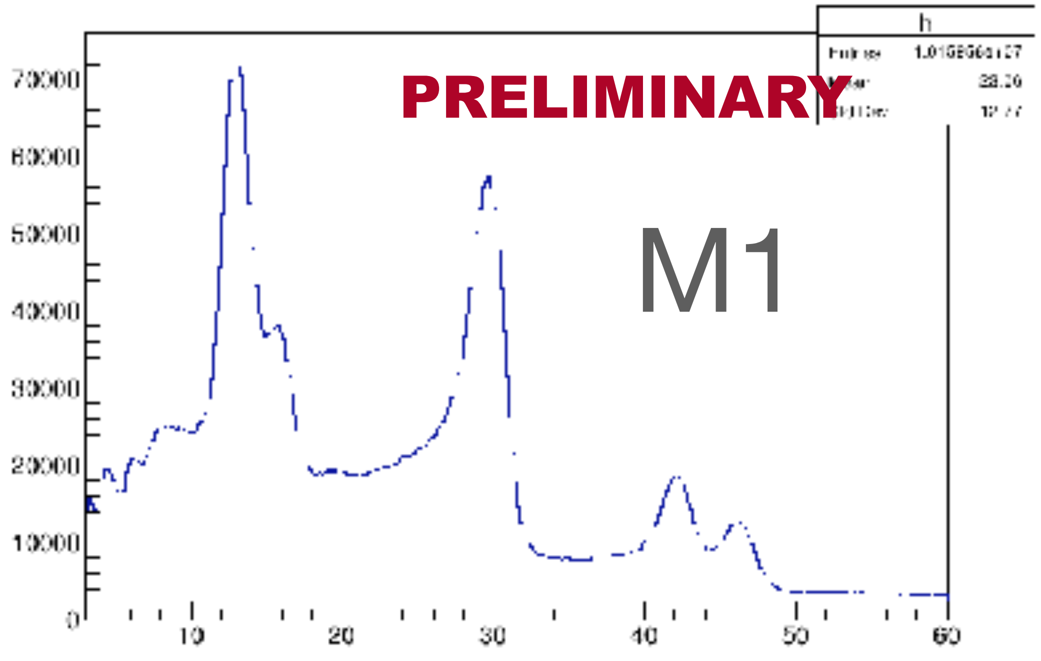
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.161805
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.98.082004
https://iopscience.iop.org/article/10.1088/0256-307X/38/1/011301

Sensitivity Validation



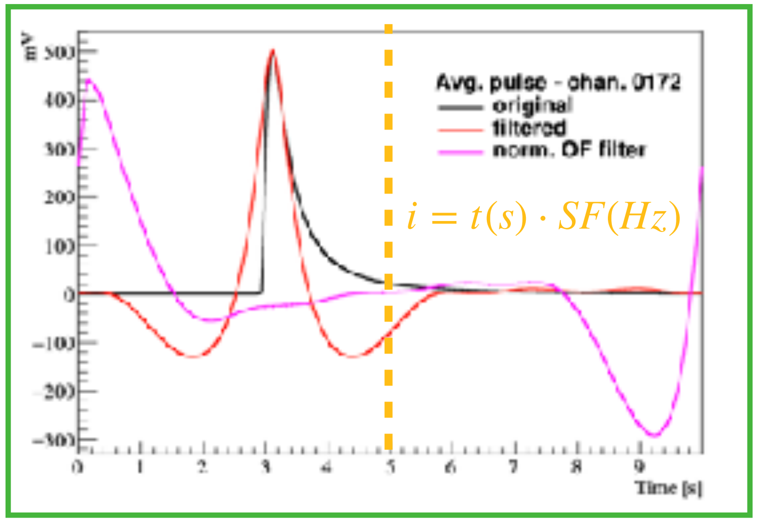
CUORE

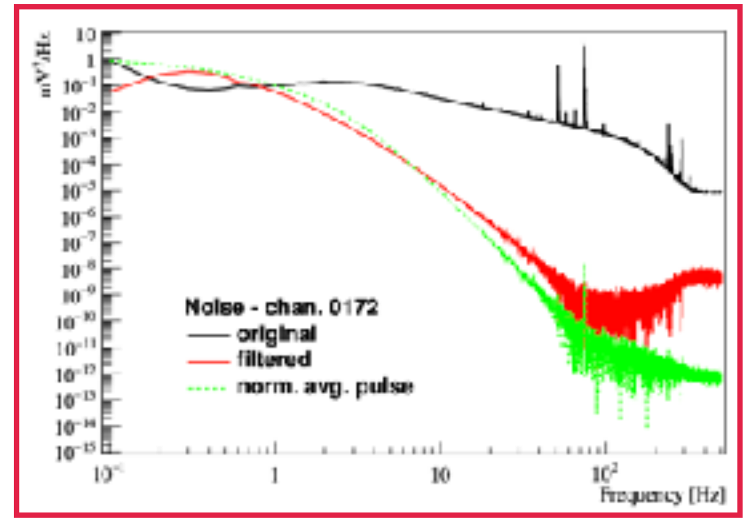
210Pb From Copper surfaces

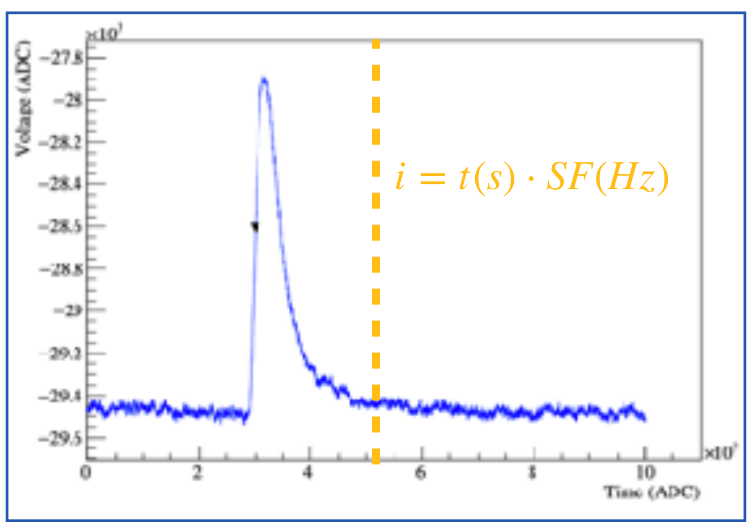


- Surface 210Pb can decay emitting x-rays that hit TeO2 producing this spectrum in single site events
- Peaks are present in all copper components of CUORE
- This can explain our excess at 13 keV
- It also provides a peak at about 30 keV

Pulse Shape Parameter: Optimum Filter χ^2



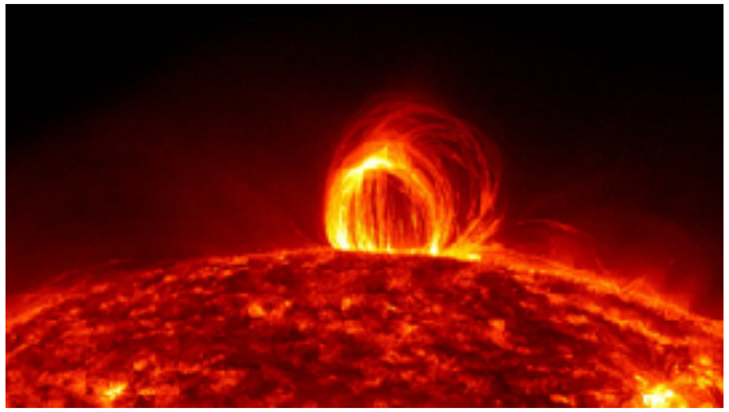


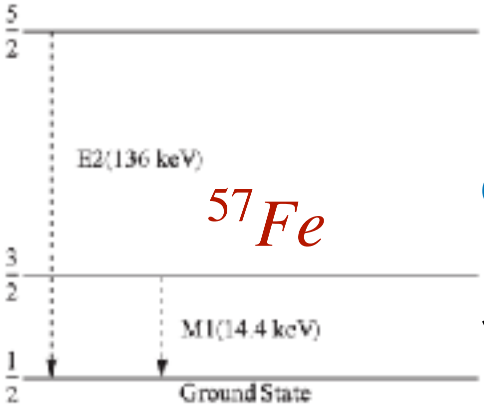


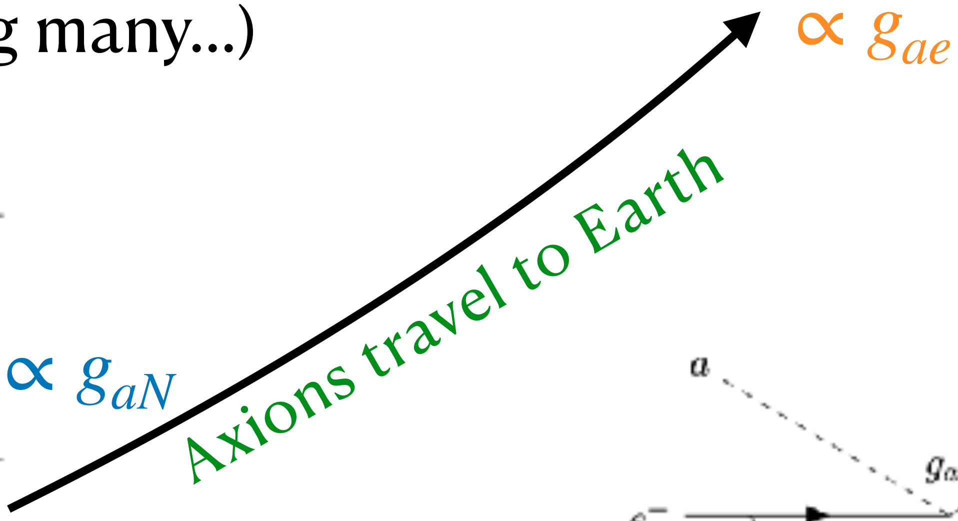
$$\chi^2_{OF} = \frac{1}{L-2} \sum_{i=0}^{L-1} \frac{(y_i - f_i)^2}{\sigma_L^2}$$

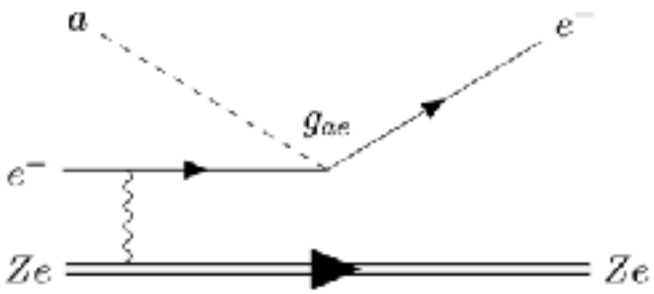
Solar Axions

- Axions are appealing dark matter candidates in addition to solving the strong CP problem
- The Sun is an optimal axion flux source thanks to the high temperature and density, and it provides a simple experimental signature (among many…)









Monochromatic **14.4 keV** flux from thermally populated ^{57}Fe excited level

Converted into monochromatic **14.4 keV** peak by interacting with absorbing material's electrons

https://iopscience.iop.org/article/10.1088/1475-7516/2013/05/007

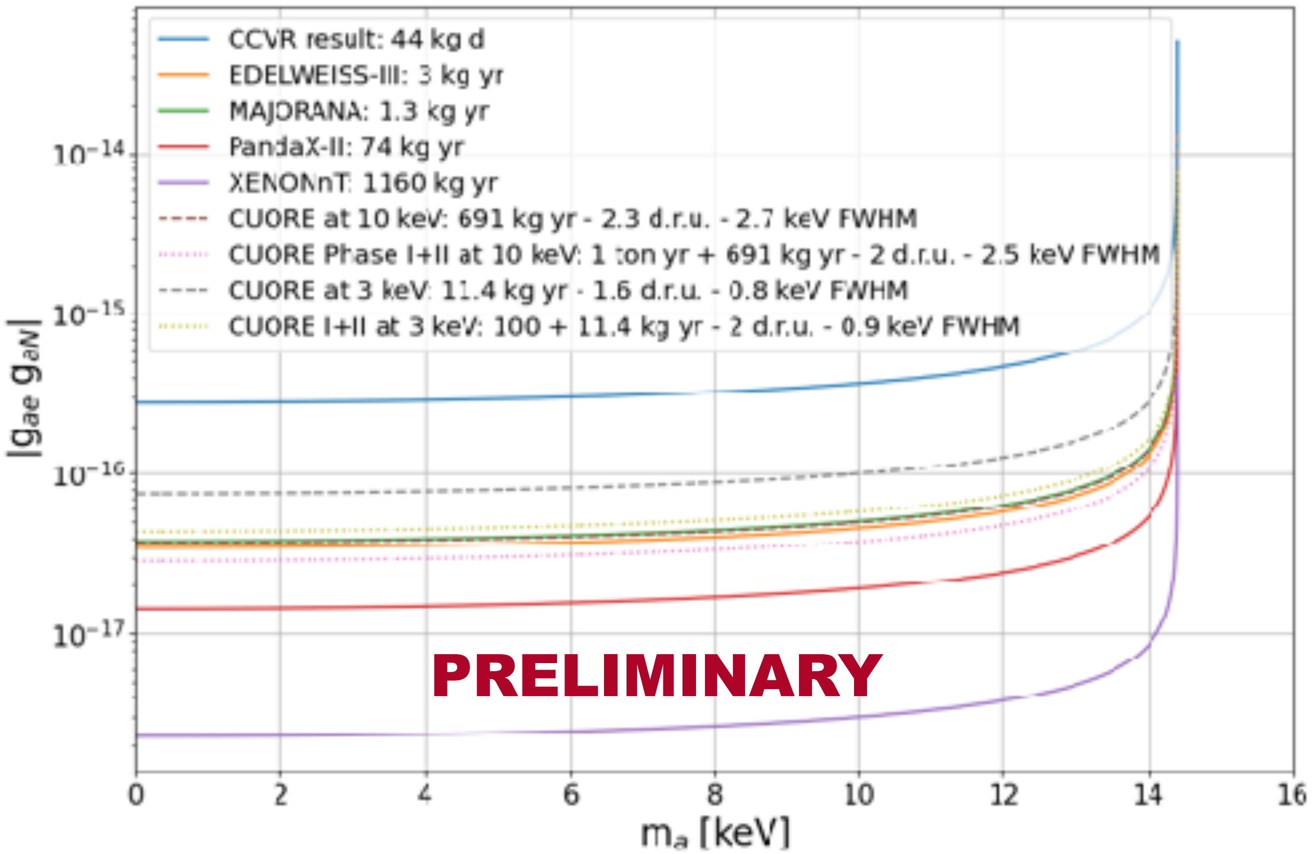
Sensitivity to Solar Axions

$$N_a = \Phi_a^{Fe} \cdot \sigma_{ae} \cdot N_{TeO_2} \cdot \Delta T$$

Axio-electric effect cross section $\propto g_{ae}^2$

Axion flux from ^{57}Fe in the Sun $\propto g_{aN}^2$

- Assume a continuous background and no signal
- Use Exposure, Background Level, and Energy Resolution as input
- Estimate count sensitivity at 90% C.I. from Poisson probability



We aim to improve the previous result with CUORE technology (4 crystal data collection in a different cryostat) by an order of magnitude