Dark Matter Searches with the CUORE experiment

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on behalf of the CUORE collaboration

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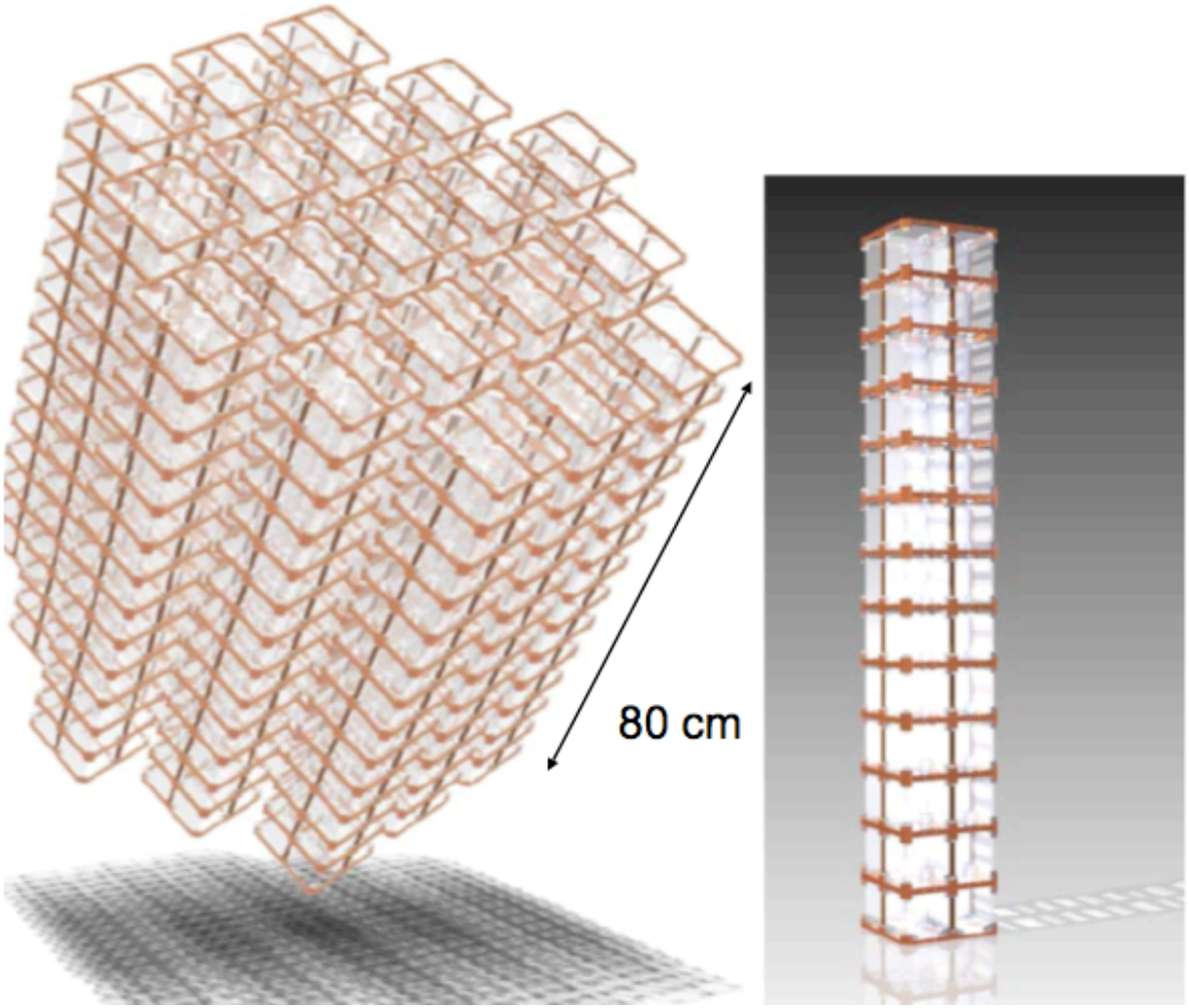
CUORE

Ton scale bolometric experiment for the search of neutrinoless double beta decay of ^{130}Te

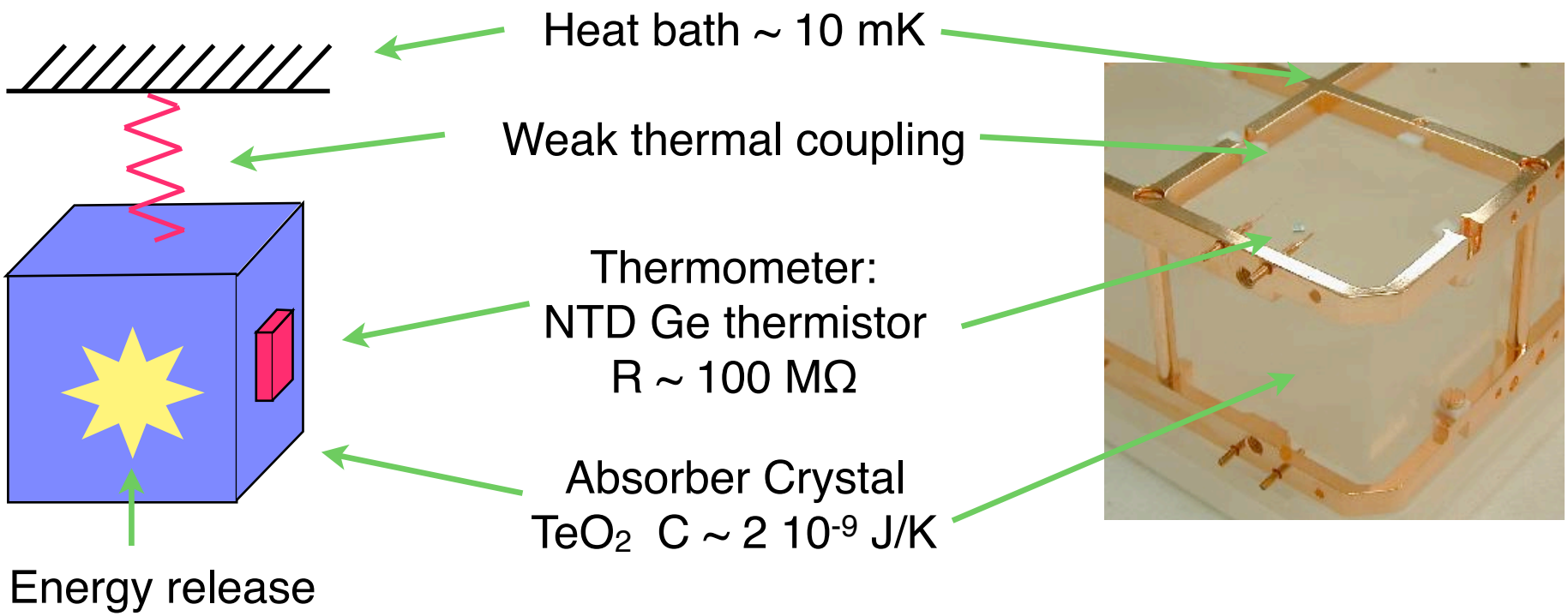
- 988 TeO_2 crystals
- 19 towers of 52 crystals each
- 750 g per crystal
- 741 kg TeO_2
  - 592 kg Te (206 kg ^{130}Te)
  - 149 kg O
- Start data taking in 2014



Hosted @ Laboratori Nazionali del Gran Sasso, Italy, a natural shield of 1400 m of rock (equivalent vertical depth: 3100 m.w.e.)

Bolometric technique

- Particle energy converted into phonons → temperature variation.
- TeO_2 crystals (dielectric, diamagnetic) → detector = source
- Low crystal heat capacitance and low base temperature to see small temperature variations → $\Delta T \sim E/C$



- Detector response in this configuration: ~ 0.1 mK / MeV
- Resolution @0νDBD (2527 keV) ~ 5 keV FWHM, @baseline ~ 0.7keV

The demonstrator: Cuoricino

Active mass:

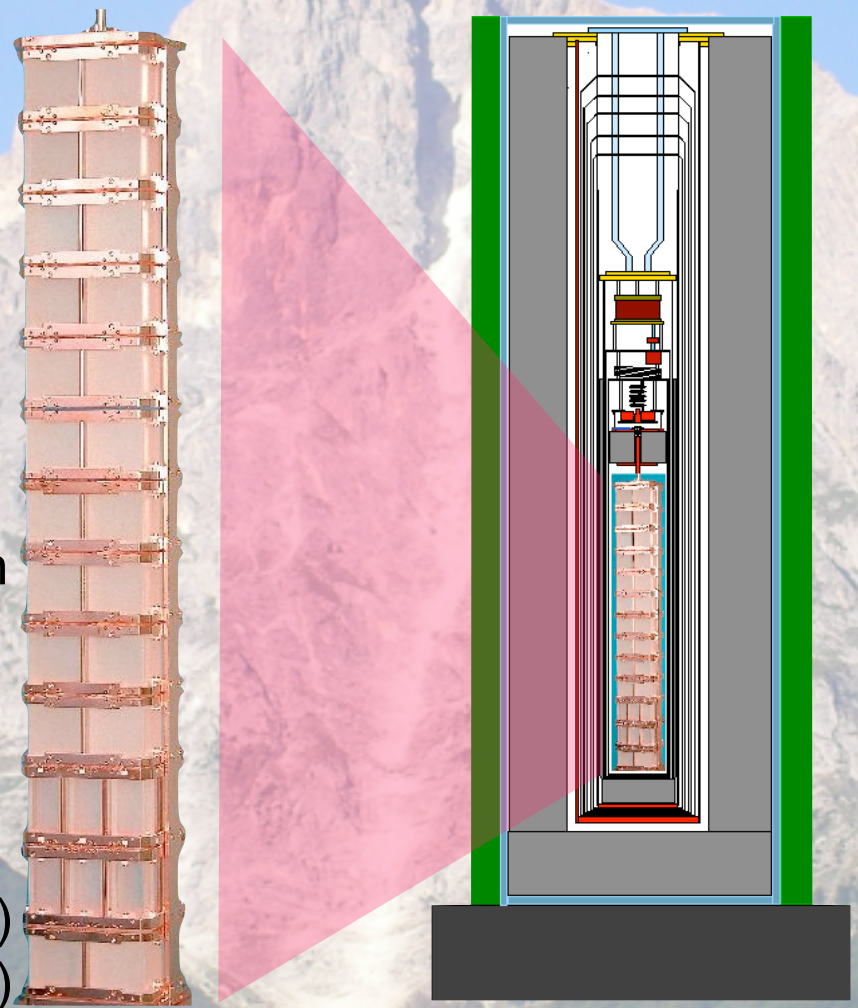
- TeO_2: 40.7 Kg
- ^{130}Te: 11.3 Kg
- ^{128}Te: 10.5 Kg

11 modules:

- 4 detectors of
  5x5x5 cm^3 = 790 g each

2 modules:

- 9 detectors of
  3x3x6 cm^3 = 330 g each
  2 enriched in ^{128}Te (82%)
  2 enriched in ^{130}Te (75%)



Data taking 2003-2008

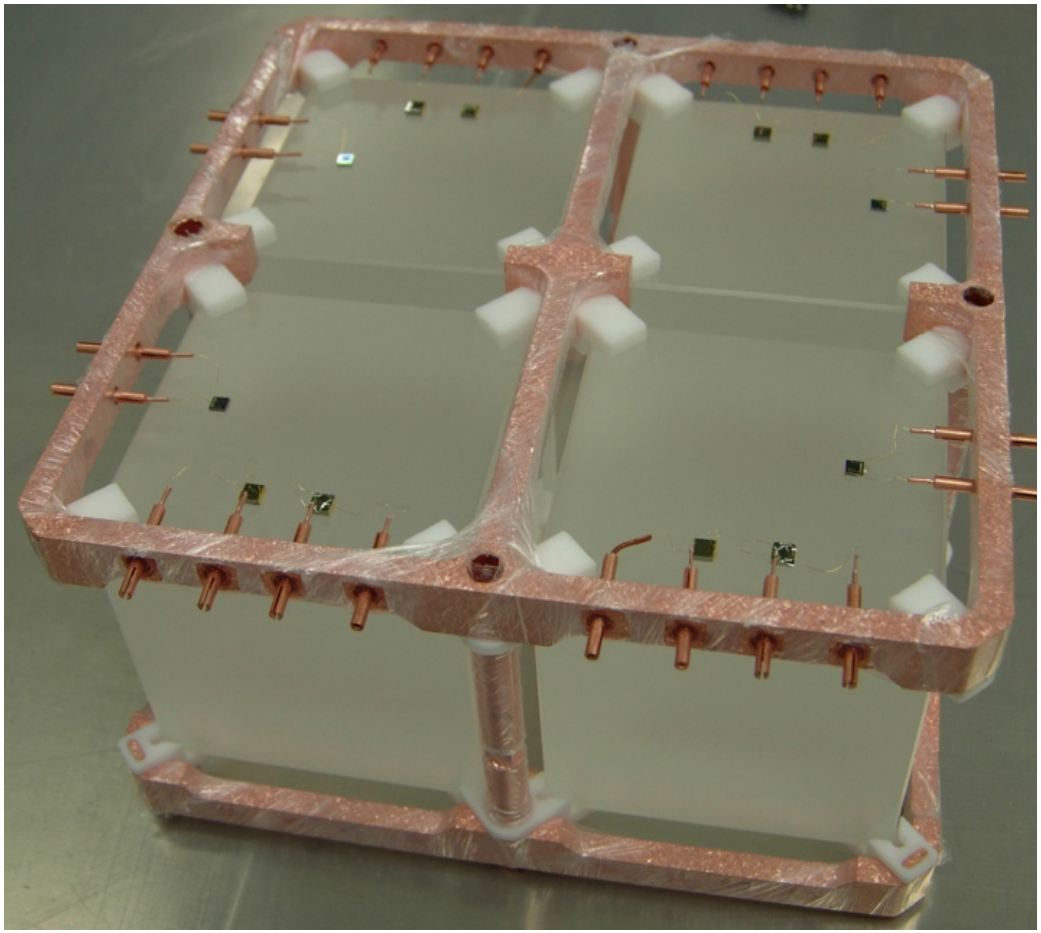
Installed in a dilution refrigerator:

- Inner shield:
  - 1cm Roman Pb
    A (^{210}Pb) < 4 mBq/Kg
- External Shield:
  - 20 cm Pb
  - 10 cm Borated polyethylene
- Nitrogen flushing to avoid Rn contamination.

On the way to CUORE

- R&D to reduce the background in the 0νDBD region.
- Periodic CUORE crystals radioactivity/bolometric checks as they arrive from China (CCVR: CUORE Crystals Validation Runs).
- Construction of a CUORE-like tower: CUORE-0 (52 crystals, 39 kg TeO_2)
  - test of new assembly and cleaning
  - cooling down in August
  - detector optimization phase

Results on a 4-crystal array



- 4 CUORE crystals arranged in a CUORE-like floor
- Operated in the Hall-C test cryostat at LNGS
- ~3 weeks live time

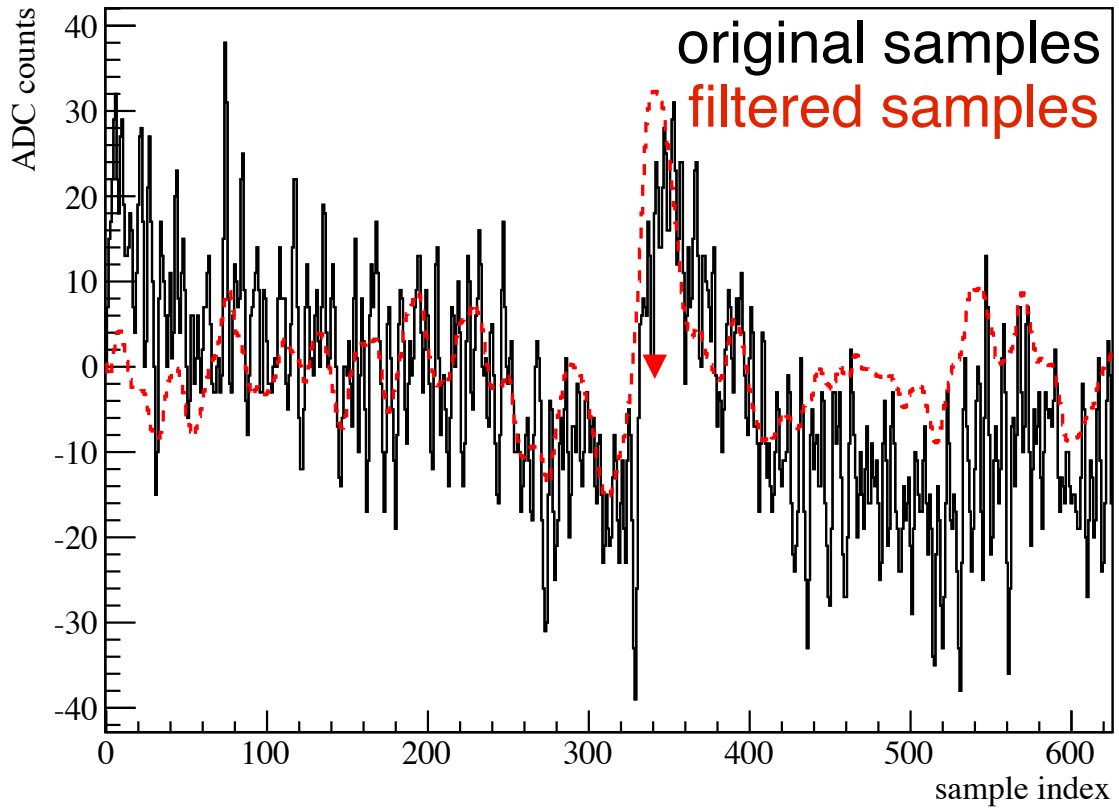
http://arxiv.org/abs/1209.2519

Dark matter with CUORE

- Dark matter searches require
  - high mass
  - good energy resolution
  - low background
  - low energy threshold
- The region of interest for WIMP and Axion interactions in TeO_2 is below 25 keV
  - The Cuoricino trigger worked on the raw samples acquired by the ADC.
  - Energy threshold in Cuoricino ~ 30 keV ⟶ too high

Triggering the data

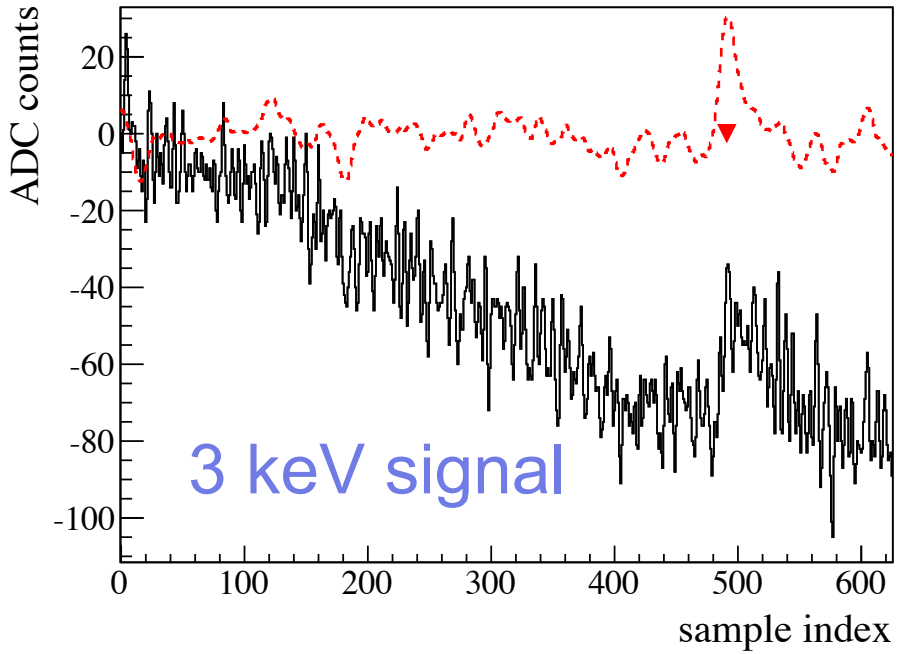
- The slices of data are filtered in the frequency domain with the optimum filter algorithm, maximizing the signal to noise ratio



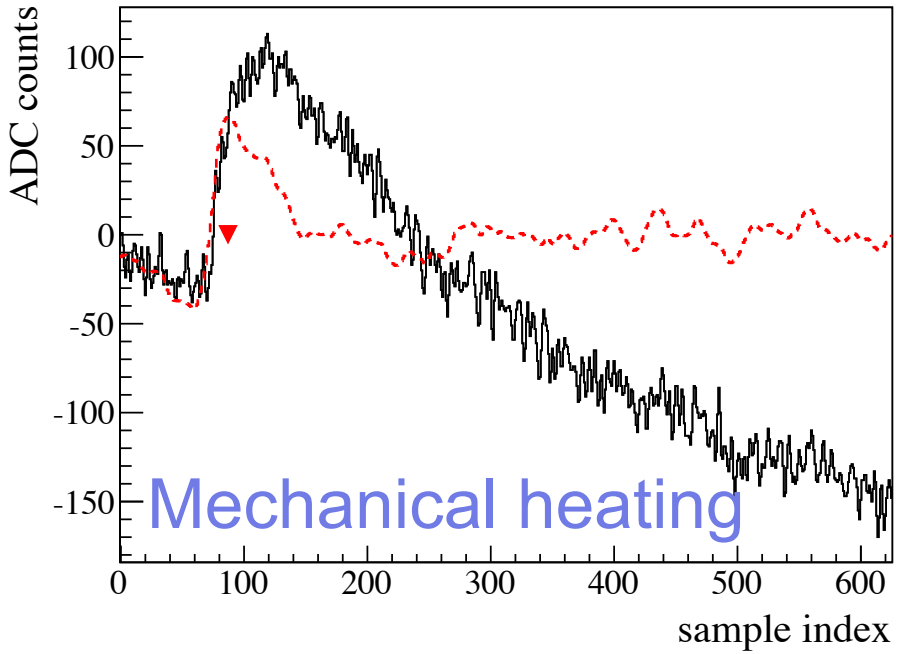
JINST 6 (2011) P02007

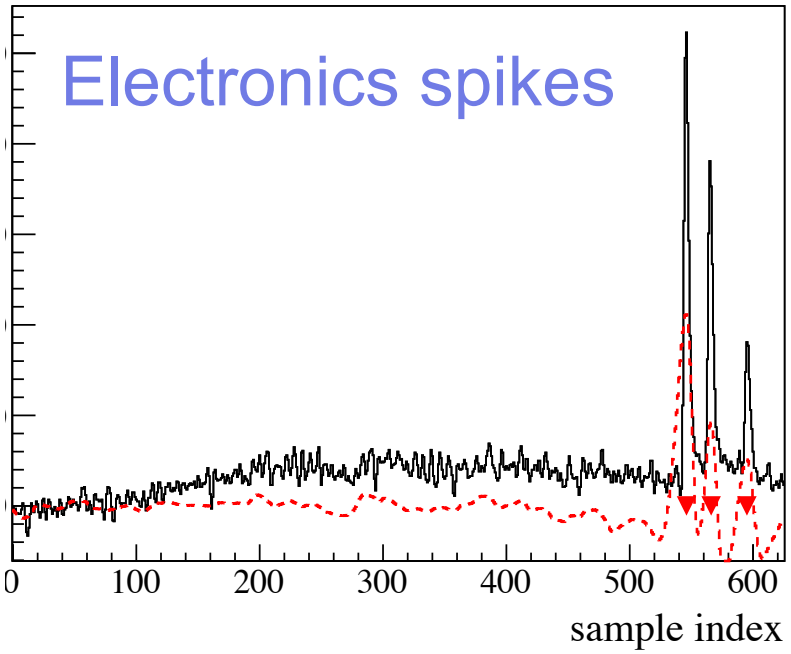
- The filtered samples are less noisy than the original ones.
- The trigger is implemented on the filtered samples setting a threshold and a debounce time.

Pulses in the 3-6 keV range



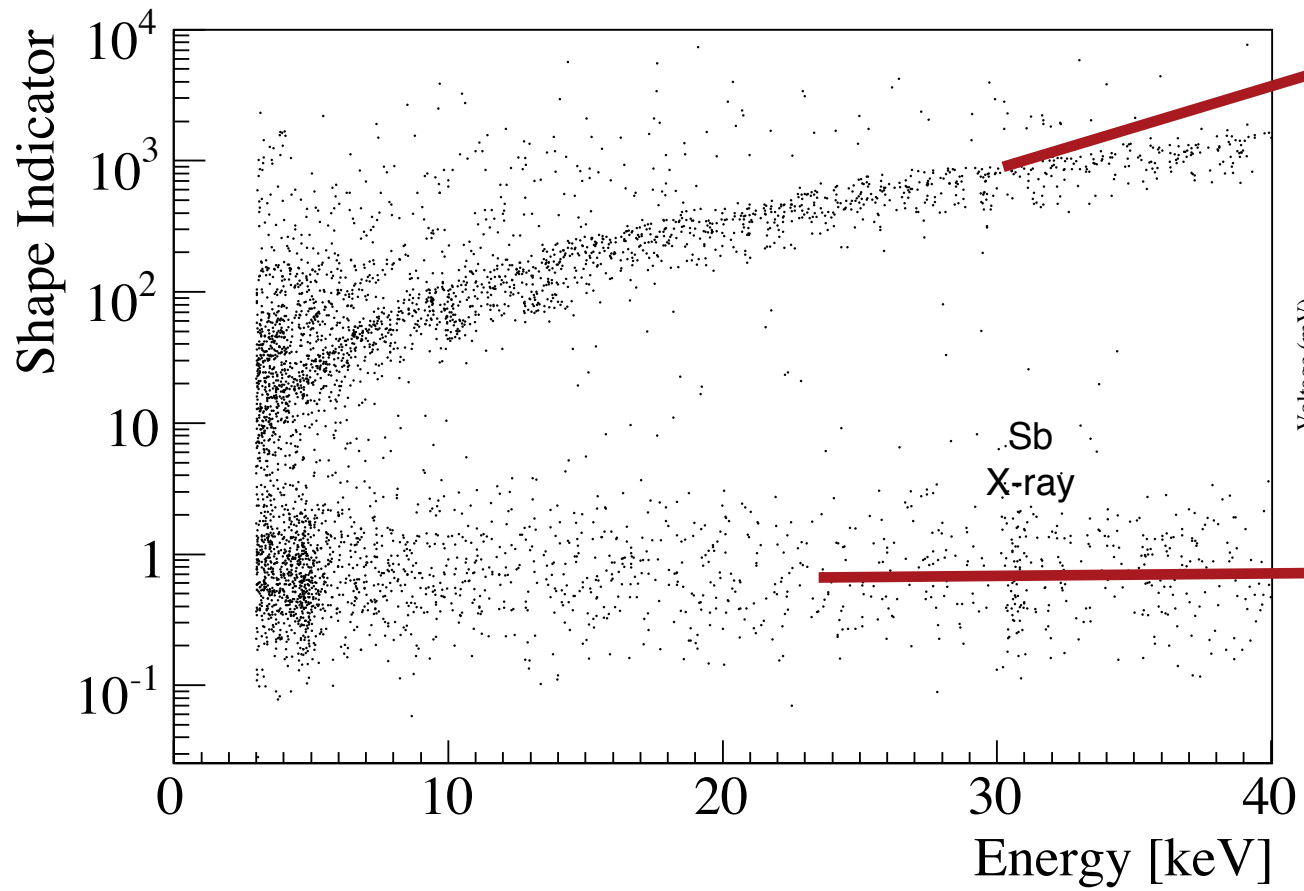
original samples
filtered samples

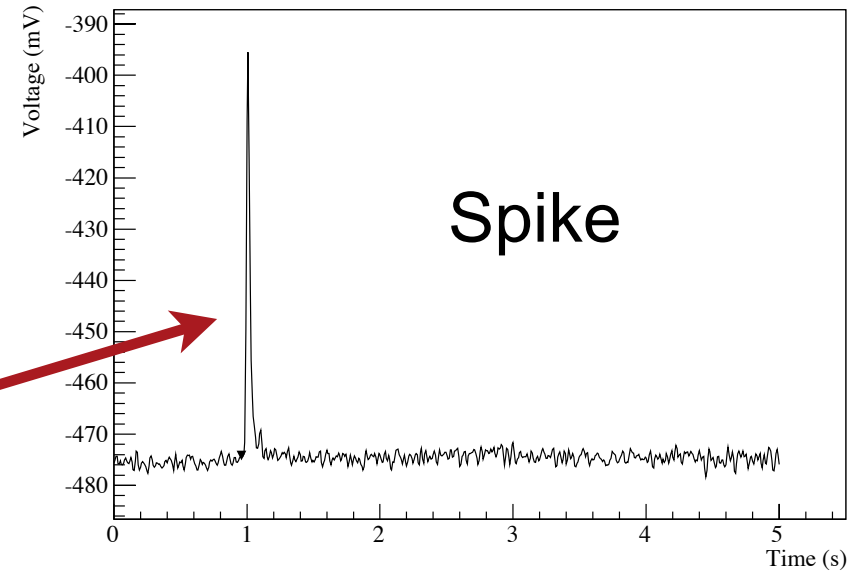


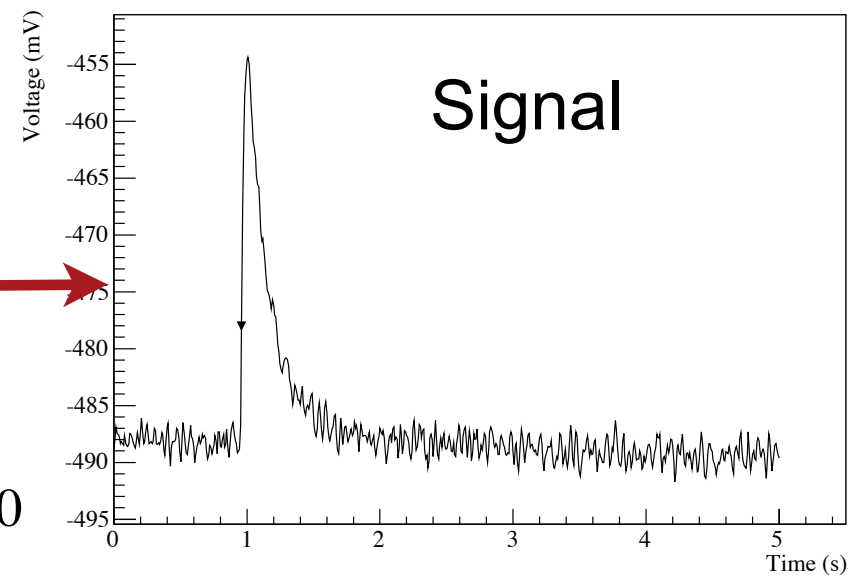


Pulse shape discrimination

- To remove non-physical pulses we fit the filtered pulses with the physical pulses known shape
- The χ^2/ndf is used as shape parameter.

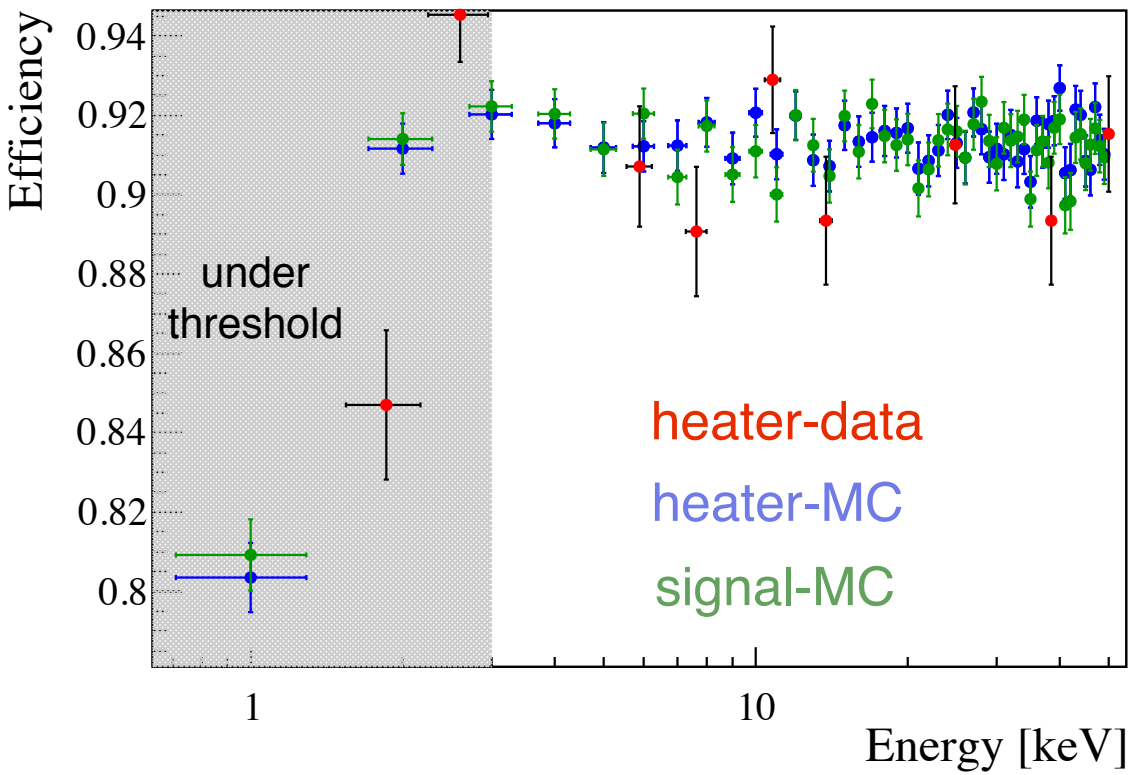






Detection efficiencies

- Each crystal has a joule heater attached, to emulate physical pulses.
- Heater pulses are controlled by the DAQ, and flagged in the data.
- We estimated the detection efficiencies on an energy scan performed on heater pulses.

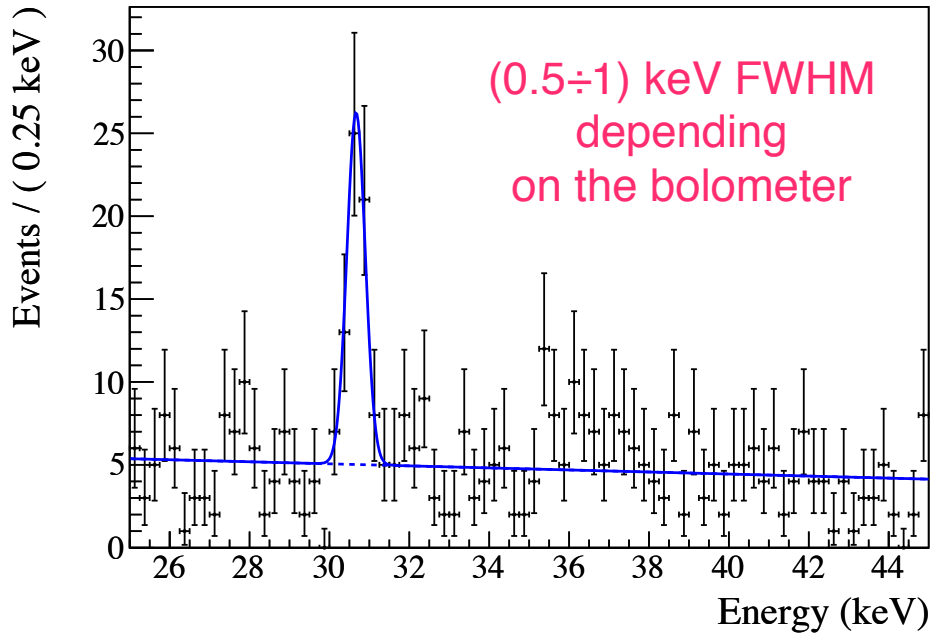


Efficiency above threshold: > 90 %

Energy threshold: ~3 keV

Energy Resolution

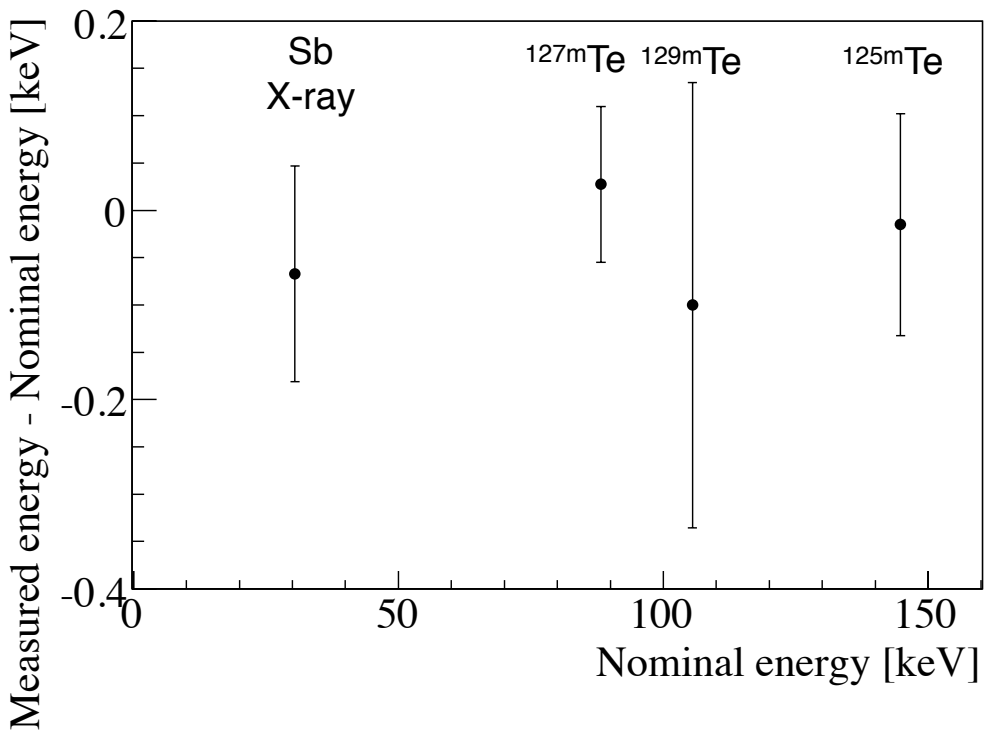
- Evaluated from a gaussian fit on the 30.5 keV Sb line



- Consistent baseline fluctuation at filter output
  - dominated by the noise at these energies
- Energy resolution is much better than at higher energies (5 keV @ 2.5 MeV)

Calibration

- The calibration function is evaluated on:
  - peaks of a ^{232}Th source exposed to the bolometers. These peaks lie in a [511,2615] keV energy interval.
  - low energy peaks from Te metastable isotopes visible in background runs. These peaks lie in a [30-150] keV energy interval.



Calibration check: E< 30 keV

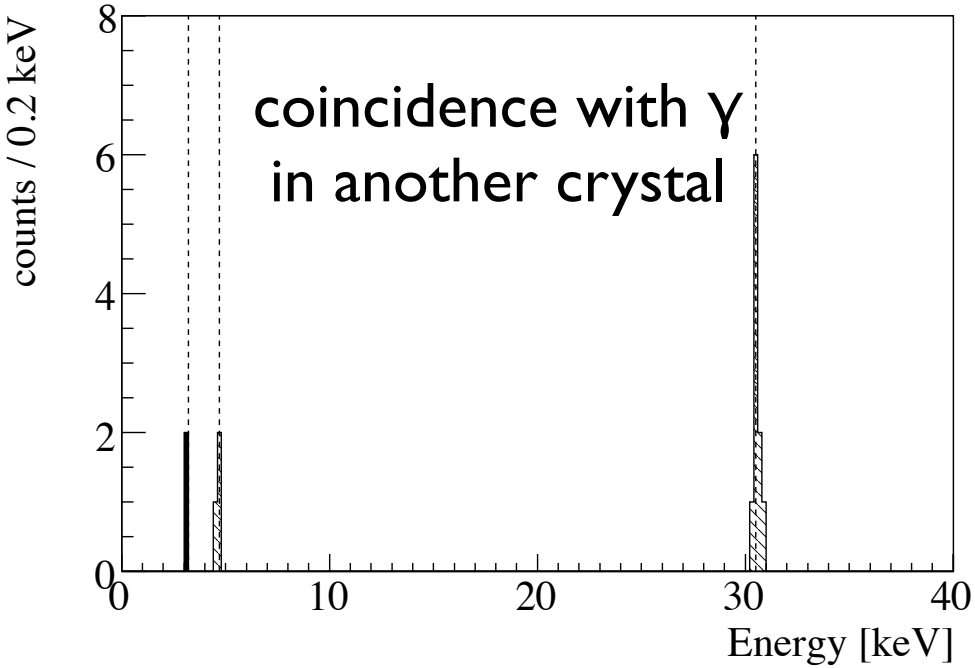
- From ^{121}Te and ^{40}K contaminations in crystals

1) ^{121}Te EC decay in ^{121}Sb

- γ-ray: 507.6 or 573.1 keV
- x-ray: L_1 shell (4.70 keV) or K shell (30.49 keV)

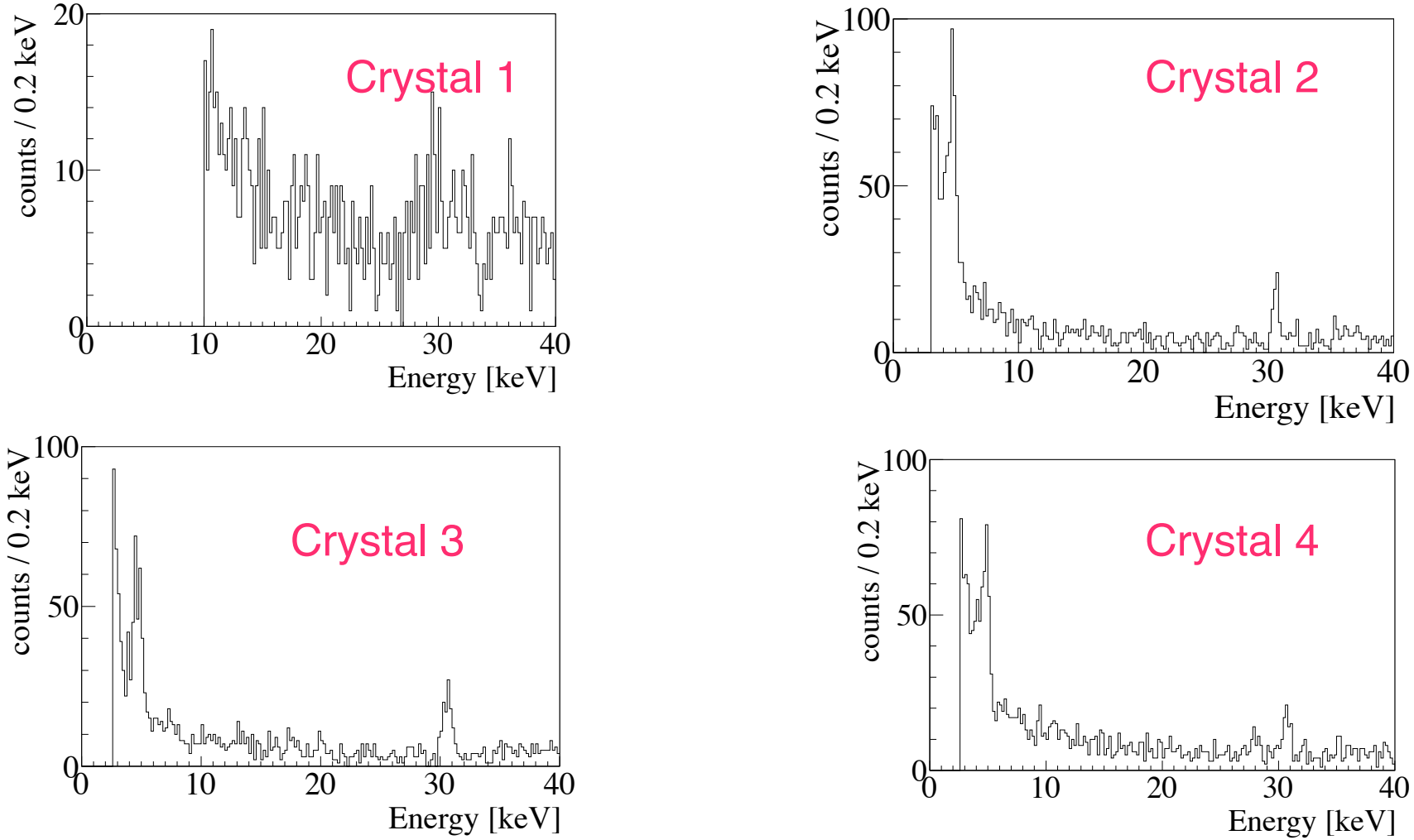
2) ^{40}K EC decay in ^{40}Ar

- γ-ray: 1461 keV
- x-ray: K shell (3.21 keV)



- Check with ^{55}Fe source
  - x-rays in [5.888-6.490] keV energy interval shifted by 48±16 eV

Energy spectra of the 4 crystals



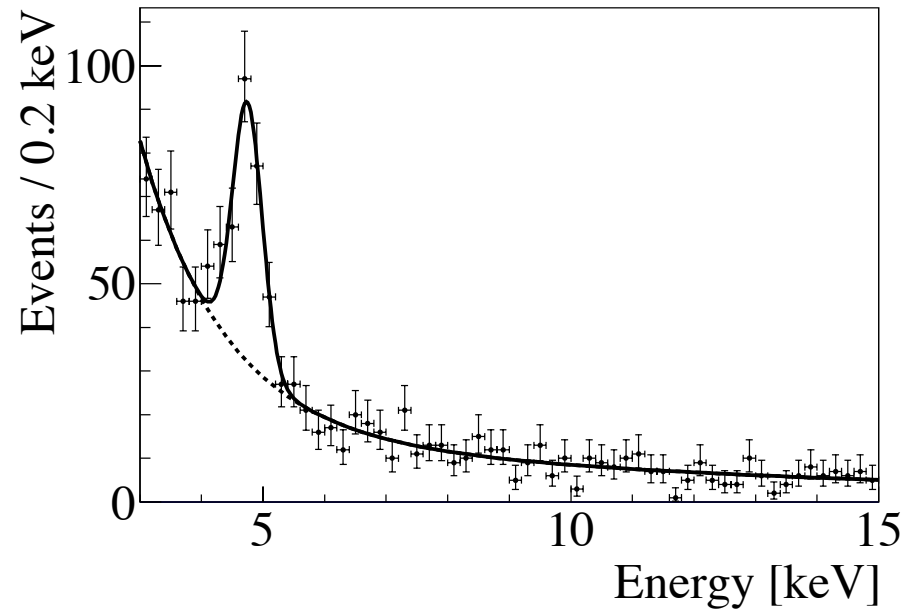
- Crystal 1 has the threshold at ~10 keV (high vibration noise)
- On the other crystals we set a software threshold at ~3 keV

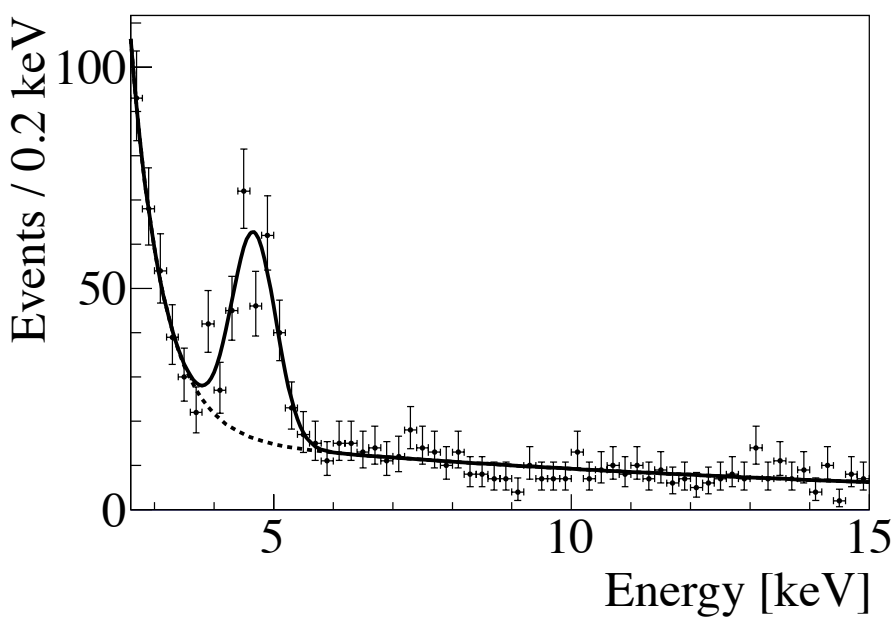
Analysis of the 4.7 keV peak

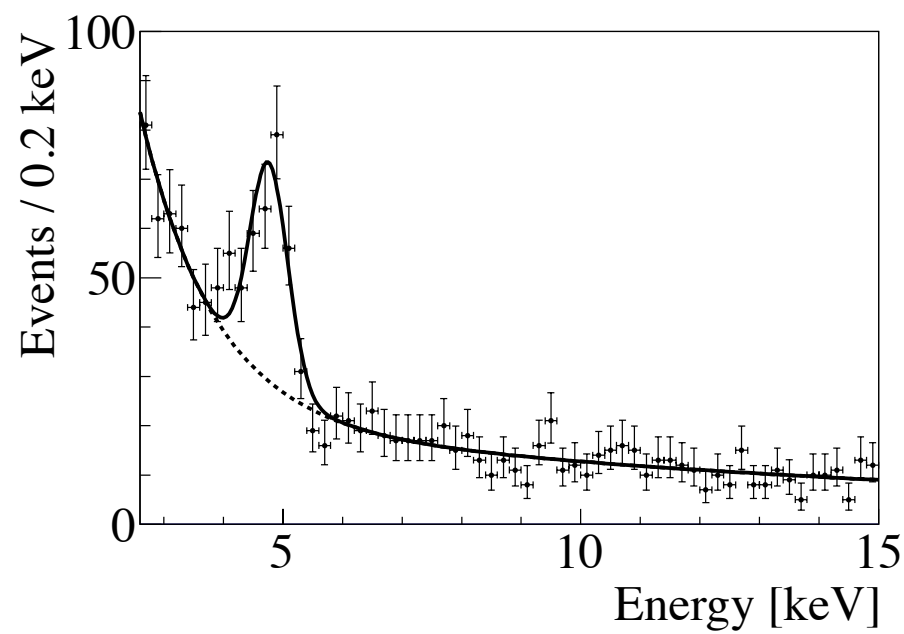
UML combined fit:
Gaussian + 2 exponential function

E = 4.72±0.18 keV

I = 15.3±1.5 cpd/kg

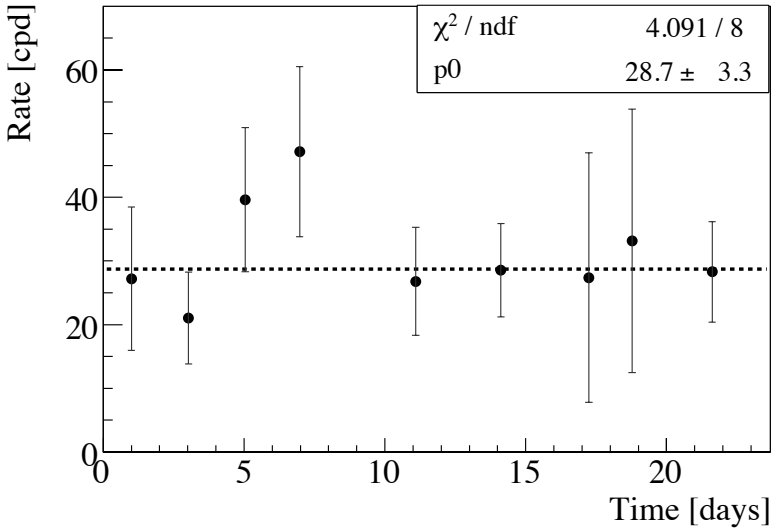






Interpretation of the 4.7 keV peak

- The peak is at 4.7 keV, the energy of the L_1 Sb atomic shell
- ^{121m}Te(daughters) decay via EC in $\tau_{1/2}$~154(17) days respectively but:
  - K/L intensity inconsistent with measured capture ratio
- Other EC metastable isotopes (and daughters) have $\tau_{1/2}$<4.7 days
  - peak intensity constant in time



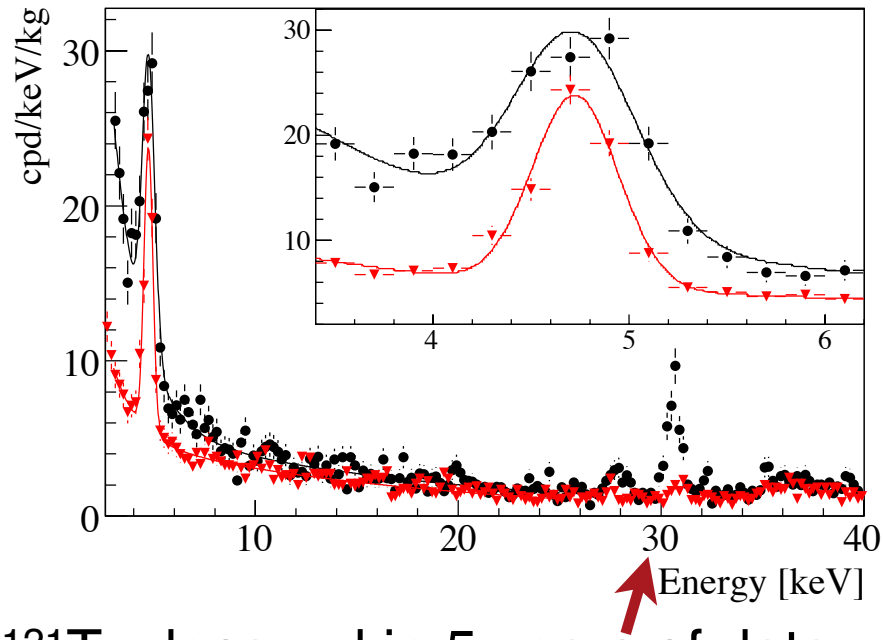
- ^{123}Te(i.a. ~0.91%) decays via EC to ^{123}Sb: Q=52.2±1.5 keV
  - 2nd forbidden unique transition proceeds mainly from the L_3 shell.
  - energy compatible with L_1 not L_3

Stability over long time

- Last two months of Cuoricino data equipped with CUORE DAQ
  - continuous data stream saved on disk
- Run the new trigger algorithm
  - 3 keV threshold on only 4 crystals (high vibrational noise)

CCVR
I = 15.3±1.5 cpd/kg

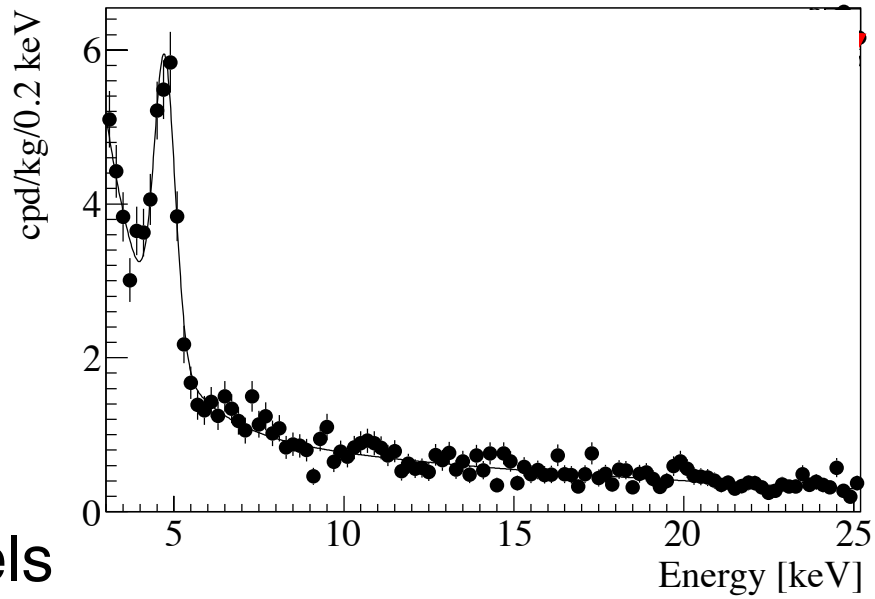
Cuoricino
(not efficiency corrected)
I = (10.0±0.6)/ε cpd/kg



Cuoricino: no 30.5 keV peak: $^{121m-121}$Te decayed in 5 years of data taking

Dark matter sensitivity study

- The background averaged over the 3 CCVR crystals can be projected to CUORE-0 and CUORE



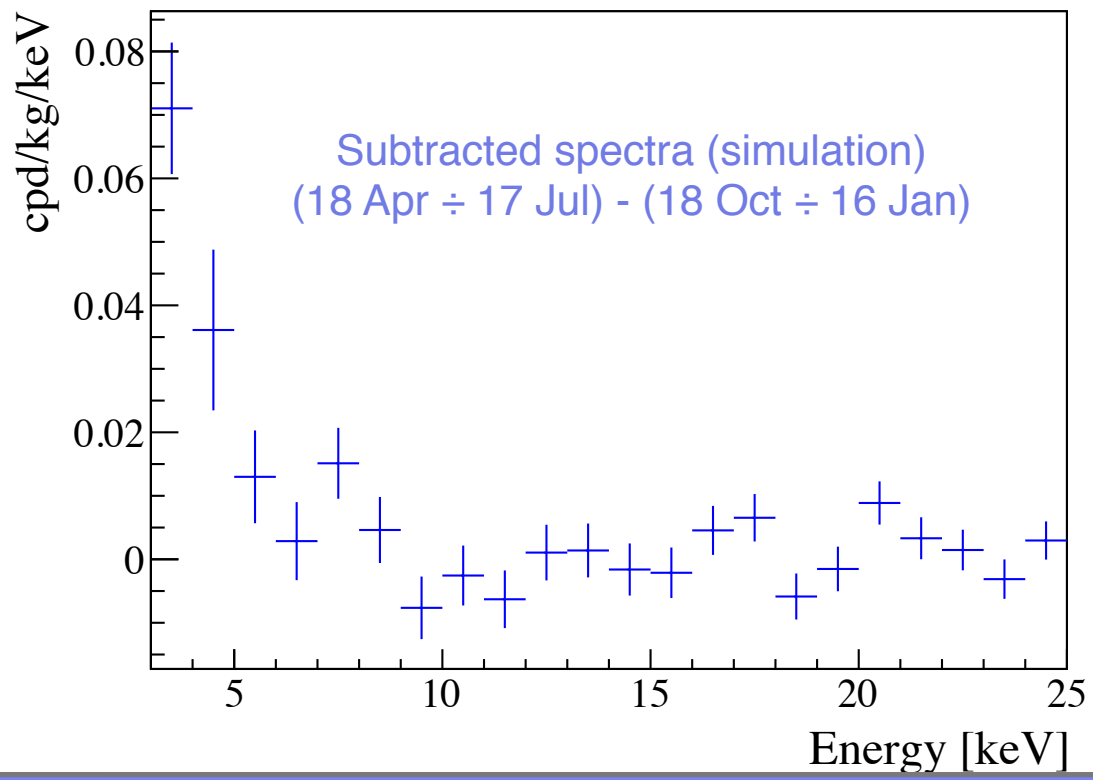
- Assume:
  - Energy threshold 3 keV on all channels
  - Unitary quenching factor for nuclear recoils in TeO_2 (*NIM A* ***409*** *451 1998)*

- We generate
  - background events according to CCVR spectrum
  - WIMP events according to Astropart. Phys. 6, 87,1996 with ρ_w =0.3 GeV/cm^3, v_0=220 km/s,v_{esc}=600 km/s

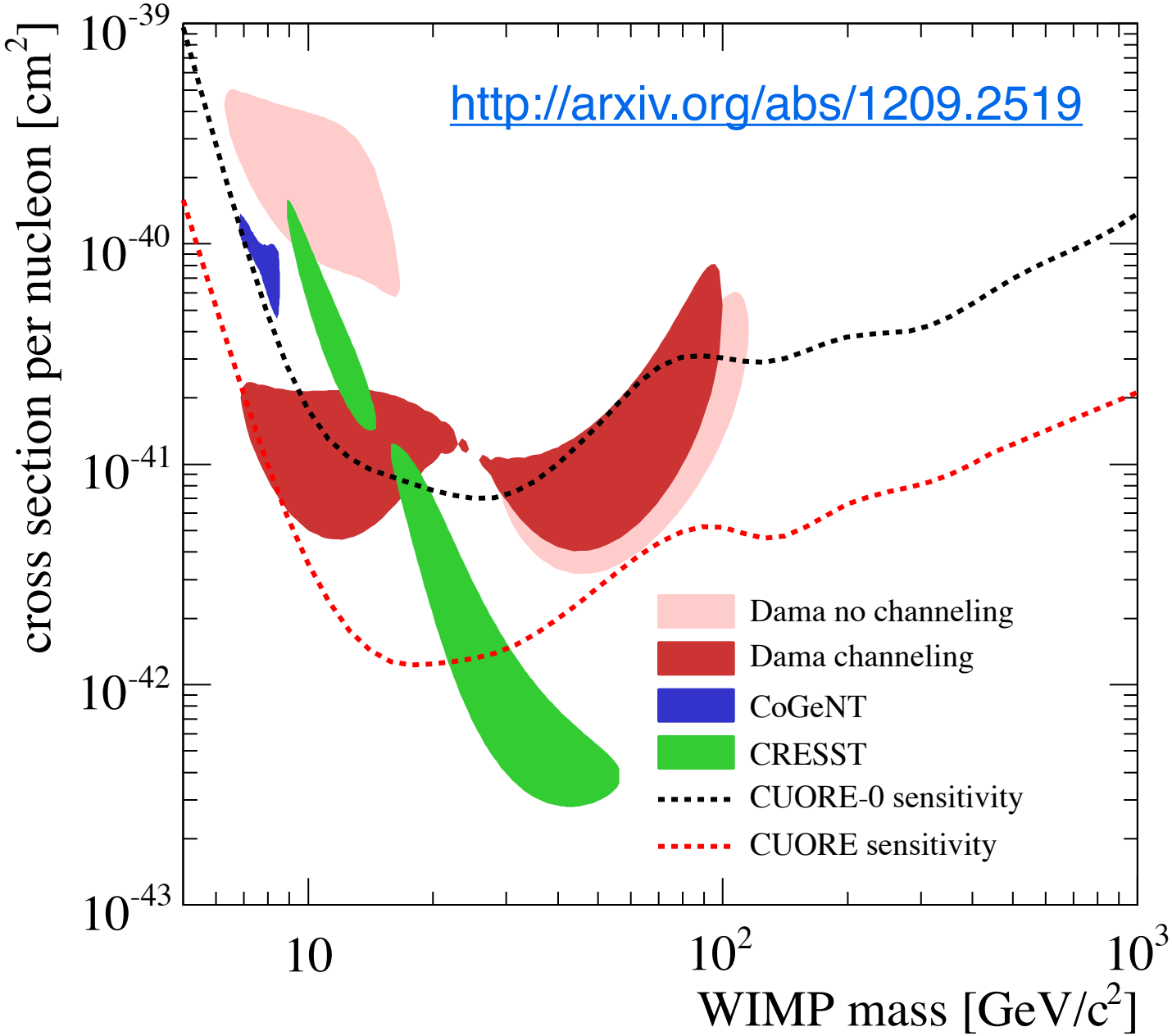
Sensitivity to WIMP modulation

- The sensitivity to a WIMP modulation signal in CUORE-0 (39 kg of TeO_2, 3 years) and in CUORE (741 kg of TeO_2, 5 years) is evaluated with toy MonteCarlo's.
- We compute the subtracted spectra: (18 Apr÷17 Jul)-(18 Oct÷16 Jan)
- Subtracted spectra fit with expected asymmetry function $H_1(M_w,\sigma)$ or a zero constant line H_0
- σ lowered till $H_1>H_0$ at least 90% of times

CUORE
simulated modulation (WIMP)
M_W = 10 GeV, $\sigma_0 = 10^{-41}$ cm^2

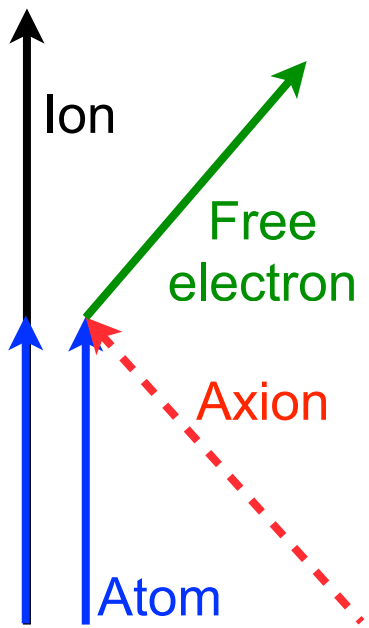


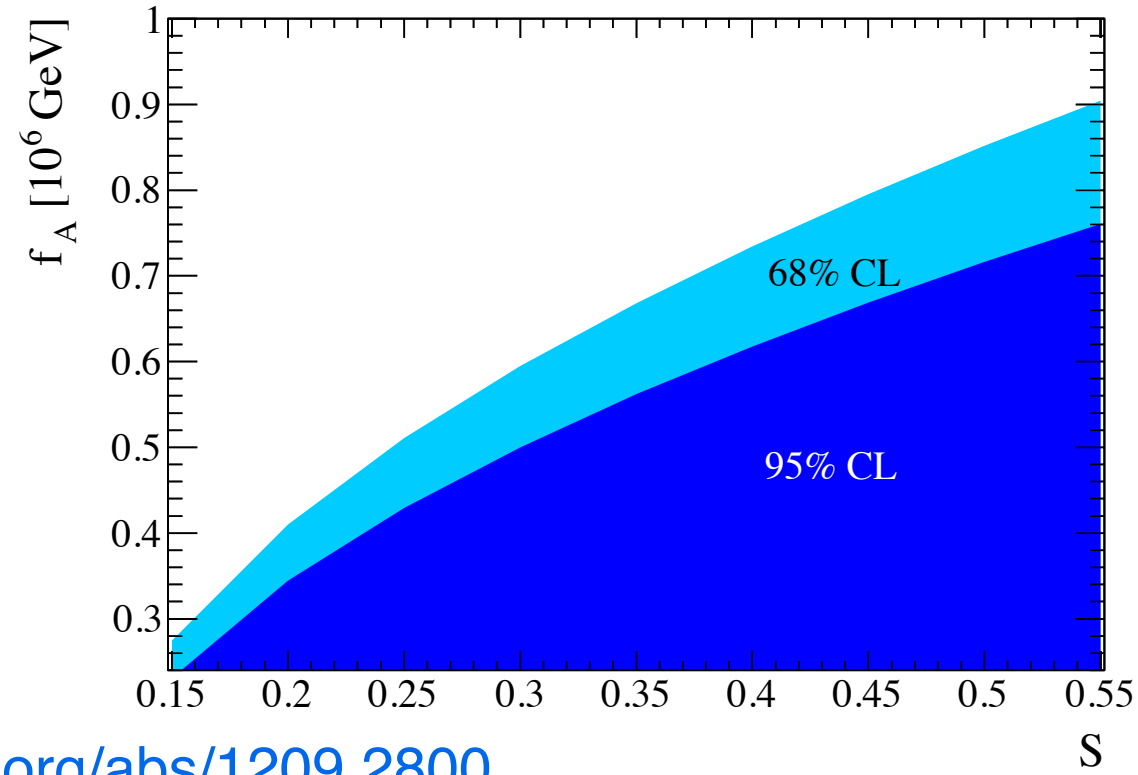
Sensitivity to WIMPs @90% CL



Axions

- Axio-electric effect of solar axions from ^{57}Fe M1: line at 14.4 keV.
- No events excess over background limit on the Peccei-Quinn energy scale $f_a > 0.76 \cdot 10^6$ GeV 90% C.L. for the flavor-singlet axial vector matrix element S=0.55
  - $m_a < 6$ eV





http://arxiv.org/abs/1209.2800

Conclusions

- CUORE, and its precursor, CUORE-0 could be sensitive to Dark matter interactions
  - Annual modulation of the counting rates in the DAMA/CoGeNT parameters space.
- CUORE-0:
  - Bolometric noise should be at the same level of the CCVR array showed in this talk.
  - Energy threshold and detector stability will be monitored continuously.
- Search for ^{57}Fe M1 solar axions through the axio-electric effect
  - $f_a > 0.76 \cdot 10^6$ GeV 90% C.L> for S=0.55, $m_a < 6$ eV

Backup

The optimum filter algorithm

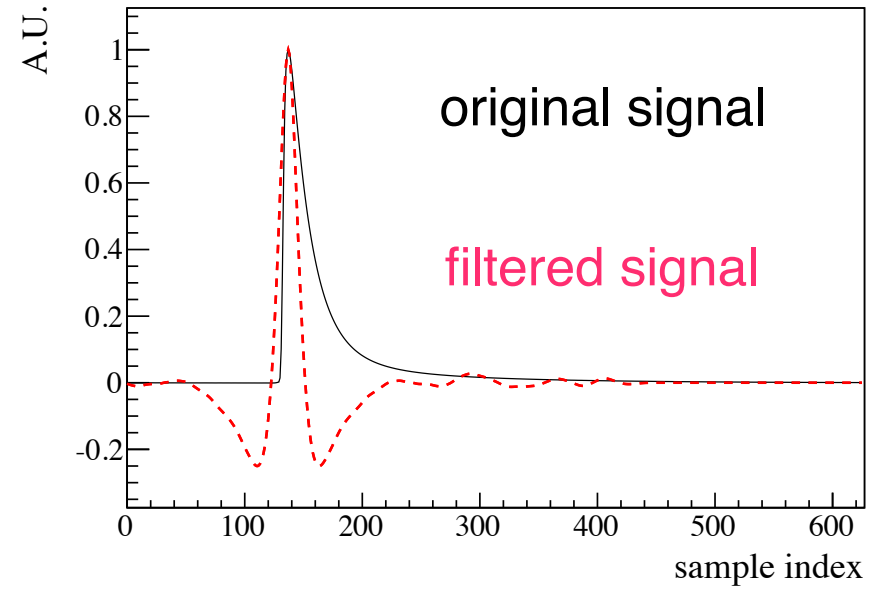
- The slices of data are filtered in the frequency domain with the optimum filter algorithm, maximizing the signal to noise ratio:

average signal shape (estimated from data)

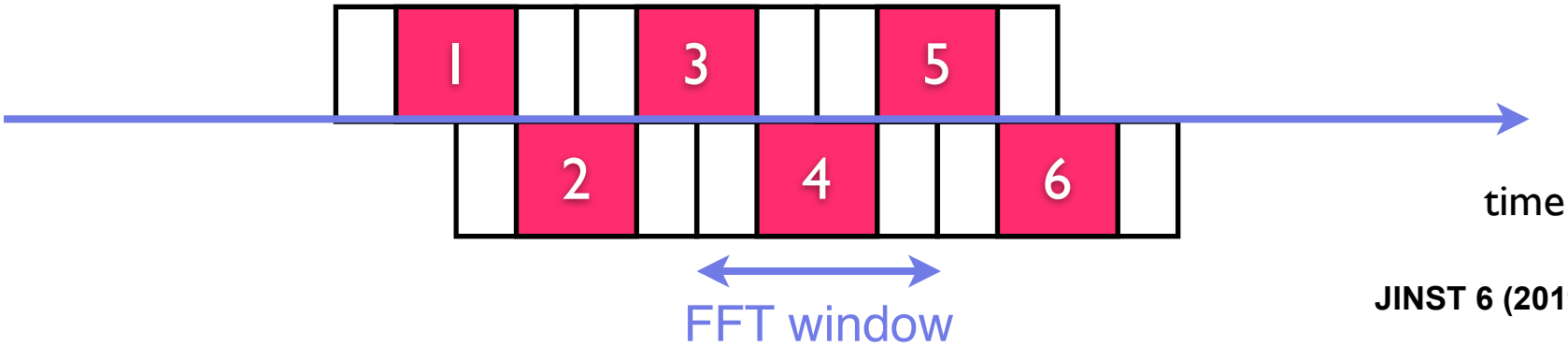
$$H(\omega) = \frac{S^*(\omega)}{N(\omega)} e^{-i\omega t_m}$$

maximum position

noise power spectrum (estimated from data)



- The continuous data flow is filtered at interlaced intervals, to ensure that the FFT convolution is always valid:



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