DEVELOPMENT OF A SILICON BOLOMETER FOR RARE EVENT DETECTION WITH LED SELF-CALIBRATION

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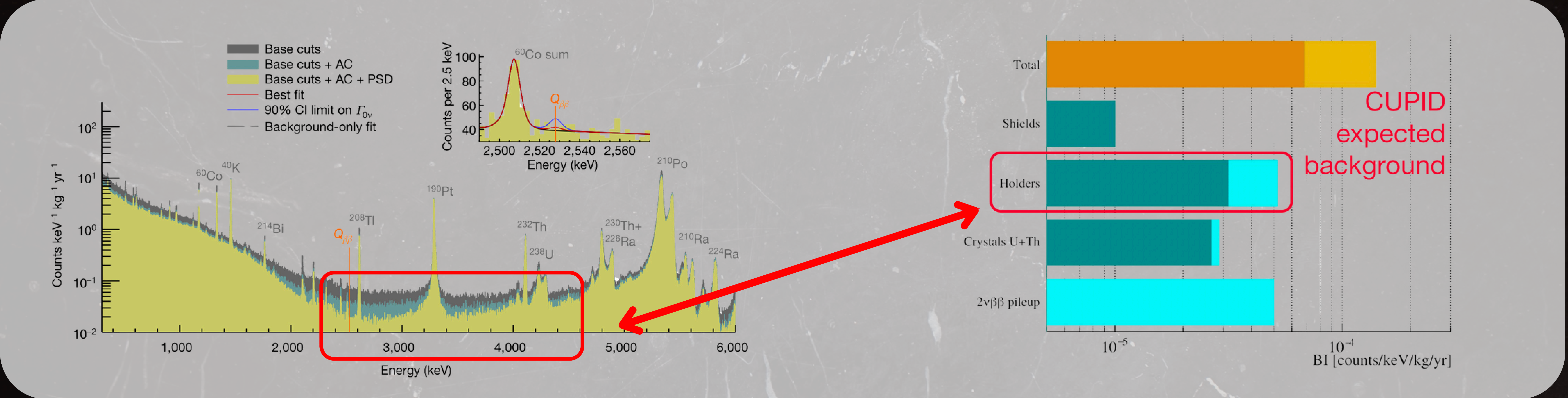
LRT 2024

SURFACE α's AS A BACKGROUND



0νββ BOLOMETRIC SERCHES

- Bolometric experiments (e.g., CUORE) face high background from degraded α particles in support materials (mainly copper).
- Next-gen experiments (CUPID, AMoRE) will use scintillating crystals for better particle ID.
- Surface β's (e.g., ^{214}Bi) remain a significant background source.

WIMP SEARCHES

- Searches with scintillating crystals are sensitive to surface contamination of the reflector.
- Searches with bolometers face β and nuclear recoil background from surface contamination.
- Searches with TPCs are affected by ^{222}Rn diffusion; Rn outgassing can be measured for some materials only.

REQUIREMENTS FOR NEXT-GENERATION α DETECTOR

- Sensitivity to surface ^{232}Th or ^{238}U contamination down to a few nBq/cm^2
  - Area ⩾ 1 m^2
  - Background ⩽ 10^{-8} counts/s/cm^2 in the full α range
- Capability to distinguish different parts of the ^{232}Th and ^{238}U chain that are out of equilibrium
  - Energy resolution ⩽ 20 keV FWHM to distinguish different α peaks
- Sensitivity to depth profile of surface contamination
  - No deformation induced by e.g. dead layers
  - Energy resolution of few keV FWHM

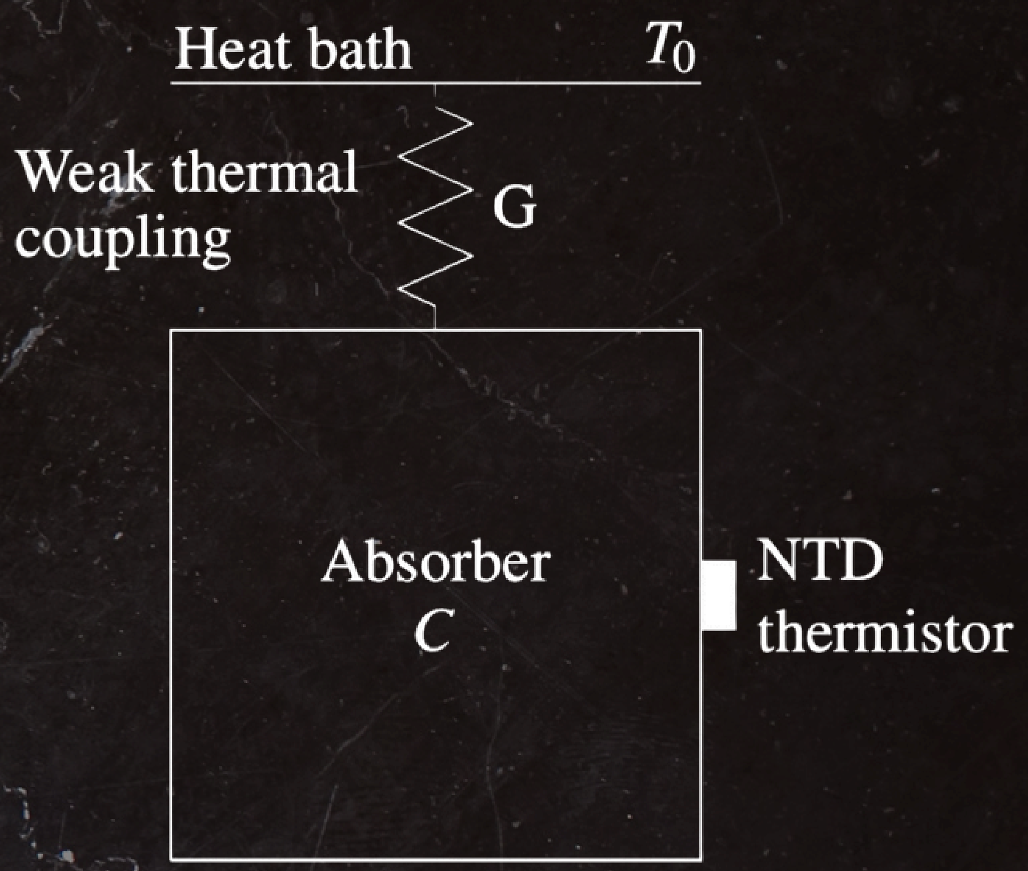
NONE OF THE EXISTING TECHNOLOGIES SATISFY ALL THESE REQUIREMENTS!

Name	Producer or location	Background level [10^{-9} cts/s/cm^2]	Background region [MeV]	FWHM @5 MeV [keV]	Active area [m^2]	Sensitivity [nBq/cm^2]
UltraLo-1800	XIA	~250	2.5-10	~400	0.18	~30
PIPS	various	~10^4	1-10	≥20	0.0012	~10^4
Bi-Po	LSC	0.1			3.6	~0.1
TPCs	various	1-30	2.5-10	150-300	≤0.24	1-30

CRYOGENIC CALORIMETERS

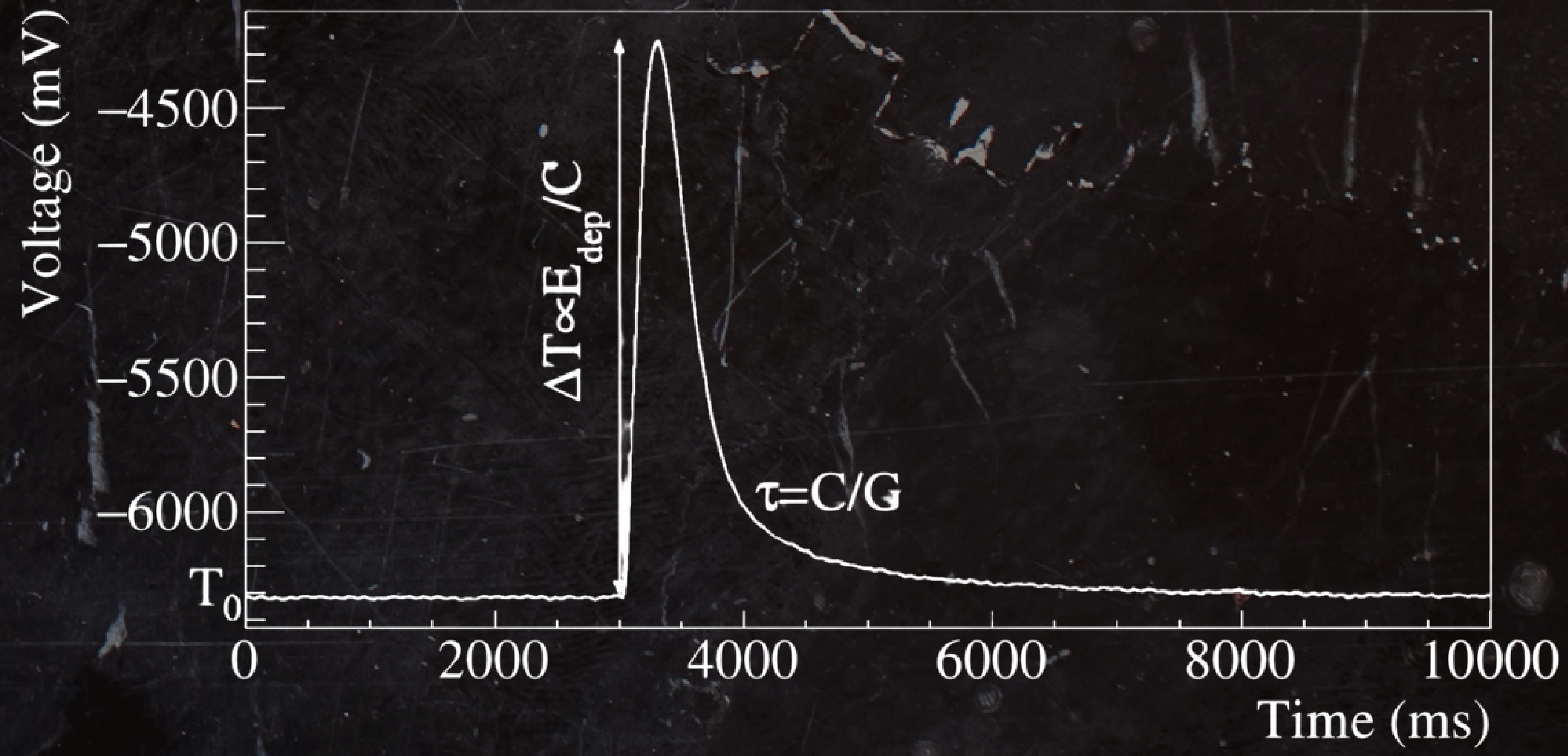
Highly sensitive calorimeter operated at cryogenic temperature (~10 mK).
Energy measured as temperature variation of the absorber:

$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau}\right) \qquad \tau = C/G$$

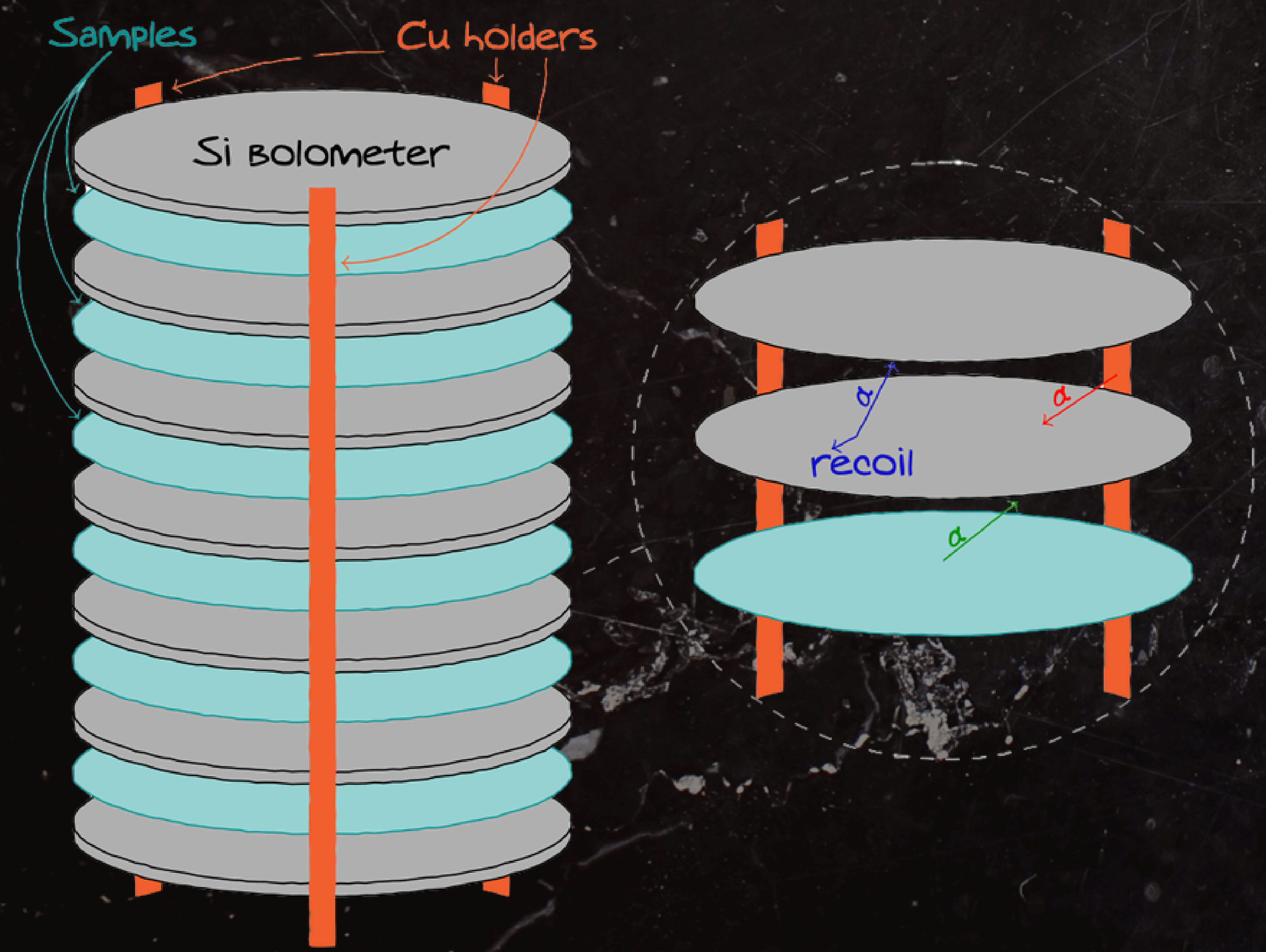


MAIN ADVANTAGES

- Detector modularity
- Stable long-term operation possible
- Great dynamic range, few keV to 10 MeV
- Excellent energy resolution (≲10 keV FWHM)
- Possibility to use different absorber crystals and select the one with the lowest radioactive contamination



THE DETECTOR CONCEPT



DETECTOR STRUCTURE

- Large-area crystal wafer as an energy absorber.
- Mounted on a minimally-sized frame.
- Readout by a Neutron Transmutation Doped (NTD) thermistor glued on it.

MATERIAL CHOICE

- Silicon is selected for its purity and accessibility.
- High-resistivity intrinsic float-zone silicon is preferred.
- Resistivity ⩾ 10 kΩ·cm for low heat capacity.
- Wafer size: 15 cm (29 modules for 1 m^2)

DETECTOR HOLDER DESIGN

- Area facing wafer: ~20 cm^2 (1/10 of wafer's side).
- Frame is suitable for mounting one tower in a 40-50 cm diameter cryostat.
- Features for easy mounting, dismounting, and sample exchange.

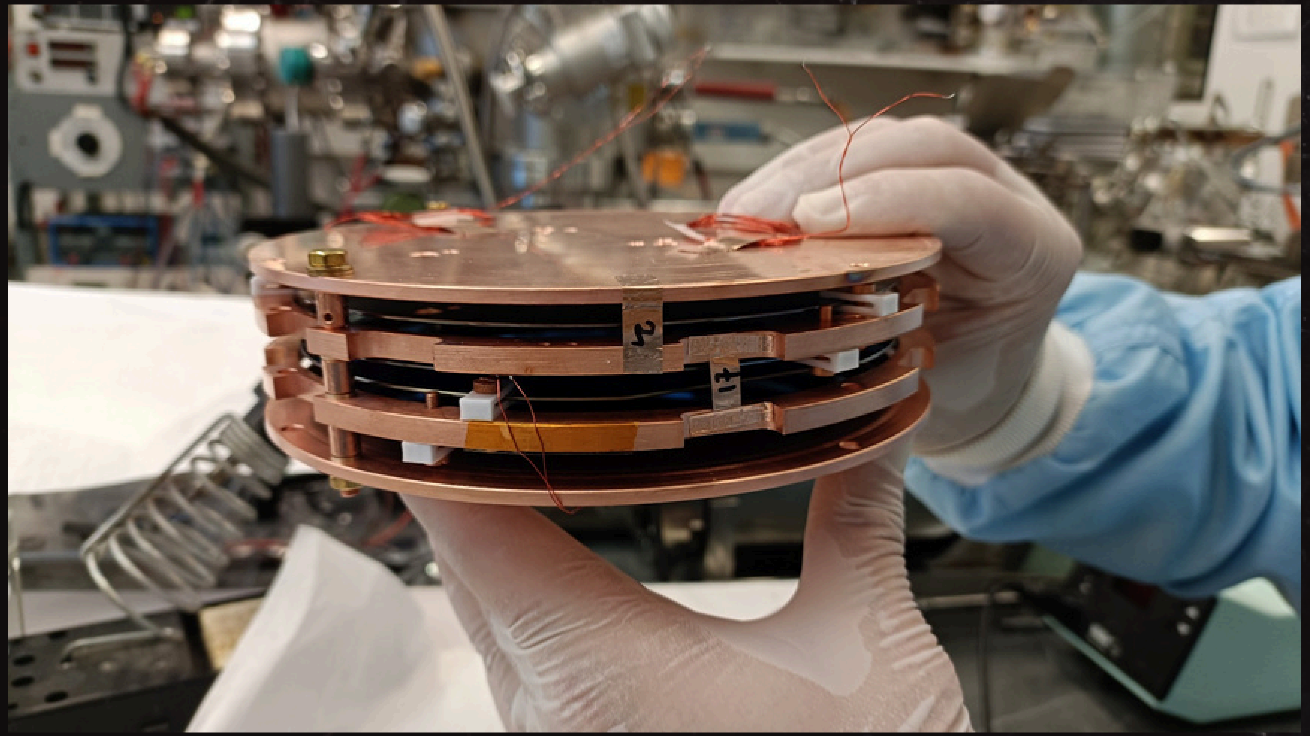
THE DETECTOR PROTOTYPE

PROTOTYPE CONSTRUCTION

- 4 silicon wafers
- **Diameter**: 15 cm
- **Thickness**: 1 mm
- Mounted on 2 copper frames (2 wafers/frame)

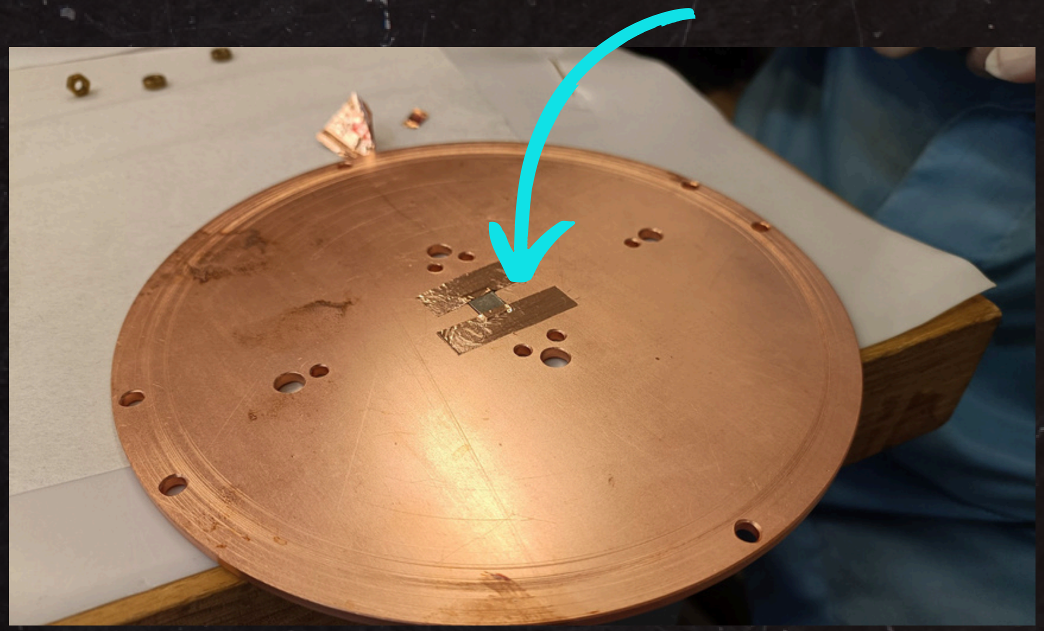
TESTING

- Several runs between February 2023 and April 2024
- Location: installed in the **CROSS** cryostat at Canfranc



DATA

- **Runs:**
  - 1-day run with LED pulses, January
  - 7-days run for alpha measurements, January
  - 3-days background run with 3 detectors, March
- **Detectors:**
  - A wafer w/o alpha sources (ch 80, 81)
  - A wafer with an alpha source ^{210}Po (ch 82)



Run	Channels	Acquired data
January	80 82	^{55}Fe, LED ^{210}Po, LED
March	80, 81, 82	Background

LED CALIBRATION SYSTEM

SYSTEM DESIGN

- Utilizes a light source (LED or laser) at room temperature
- Light is distributed to detectors via optical fibers

CALIBRATION METHOD

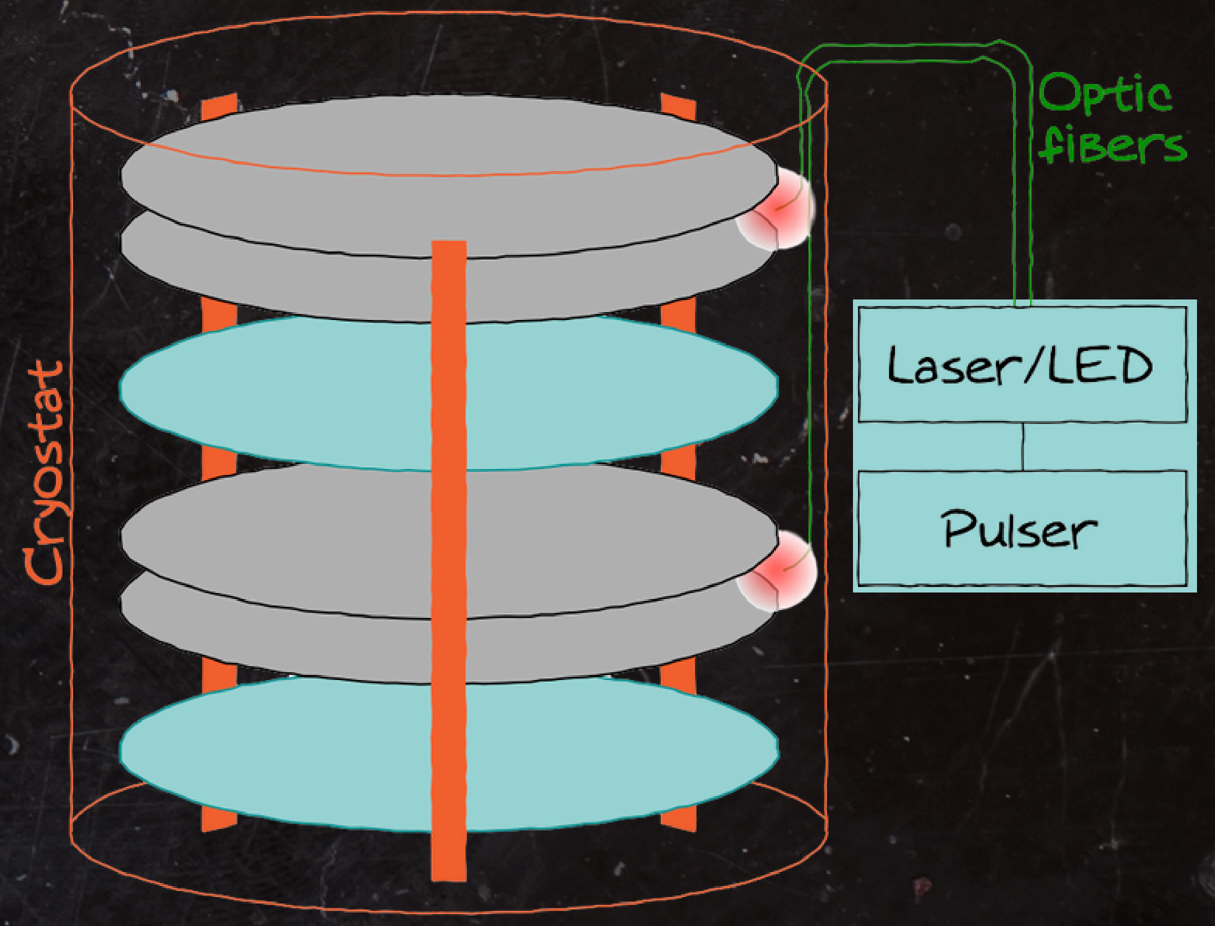
- Injects light pulses with varying amplitudes to linearize the detector response
- Energy calibration: the Poisson statistics of the light

CURRENT ACHIEVEMENT AND GOALS

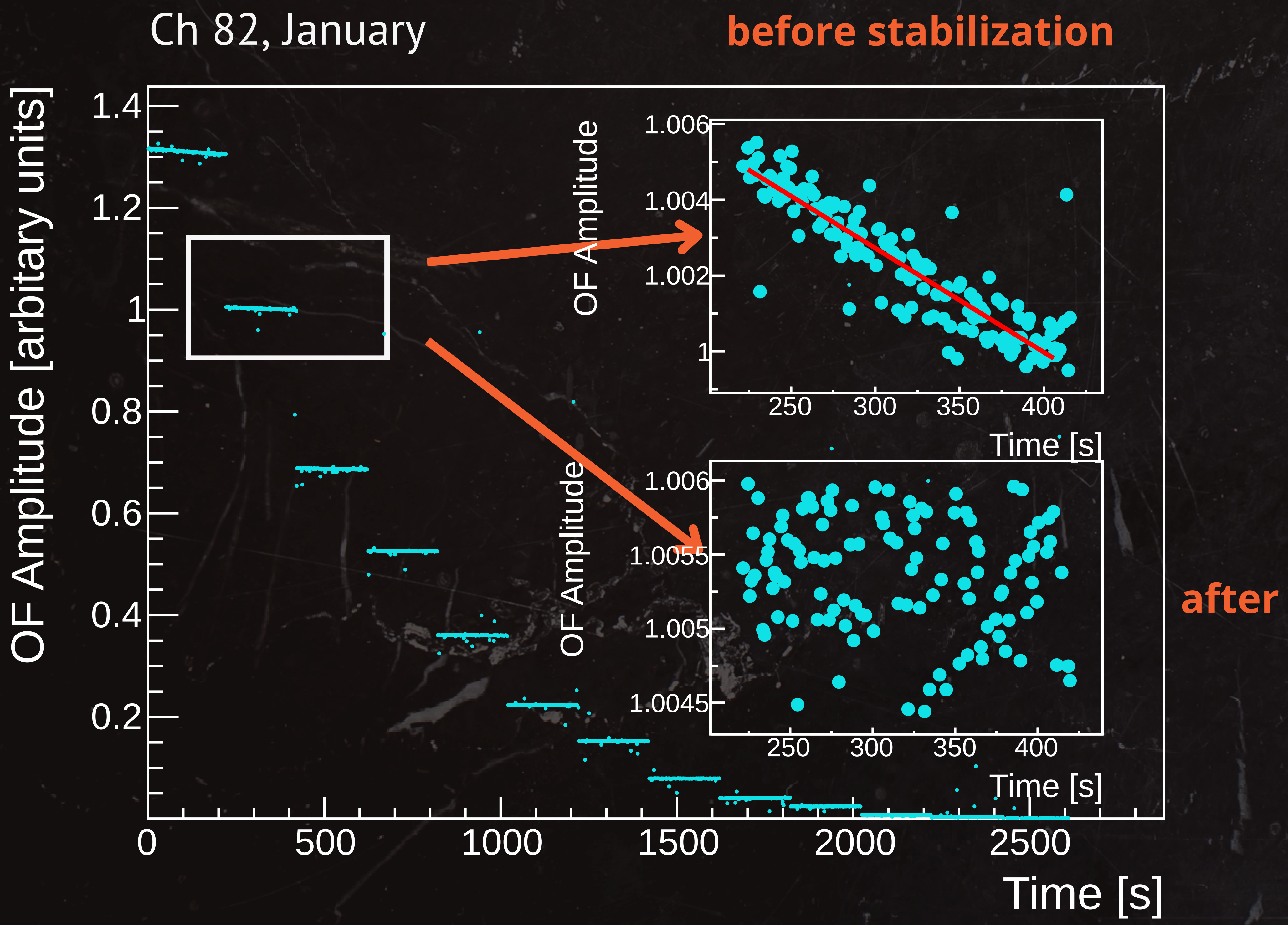
- Technique proven effective from ~100 eV to 10 keV
- Aim to extend this method up to 10 MeV

ADVANTAGES

- Simplifies the operation of the detectors
- Could potentially replace heater-based stabilization



LED RUN DATA PROCESSING



A RUN WITH LED PULSES

- **13** amplitudes
- **200** pulses per amplitude
- **Amplitude Variation**: Pulse widths change according to a set pattern
- **Pulse Width Pattern**: 200, 150, 100, 75, 50, 30, 20, 10, 5, 3, 1, 0.5, 0.2 μs

A CUSTOM SOFTWARE

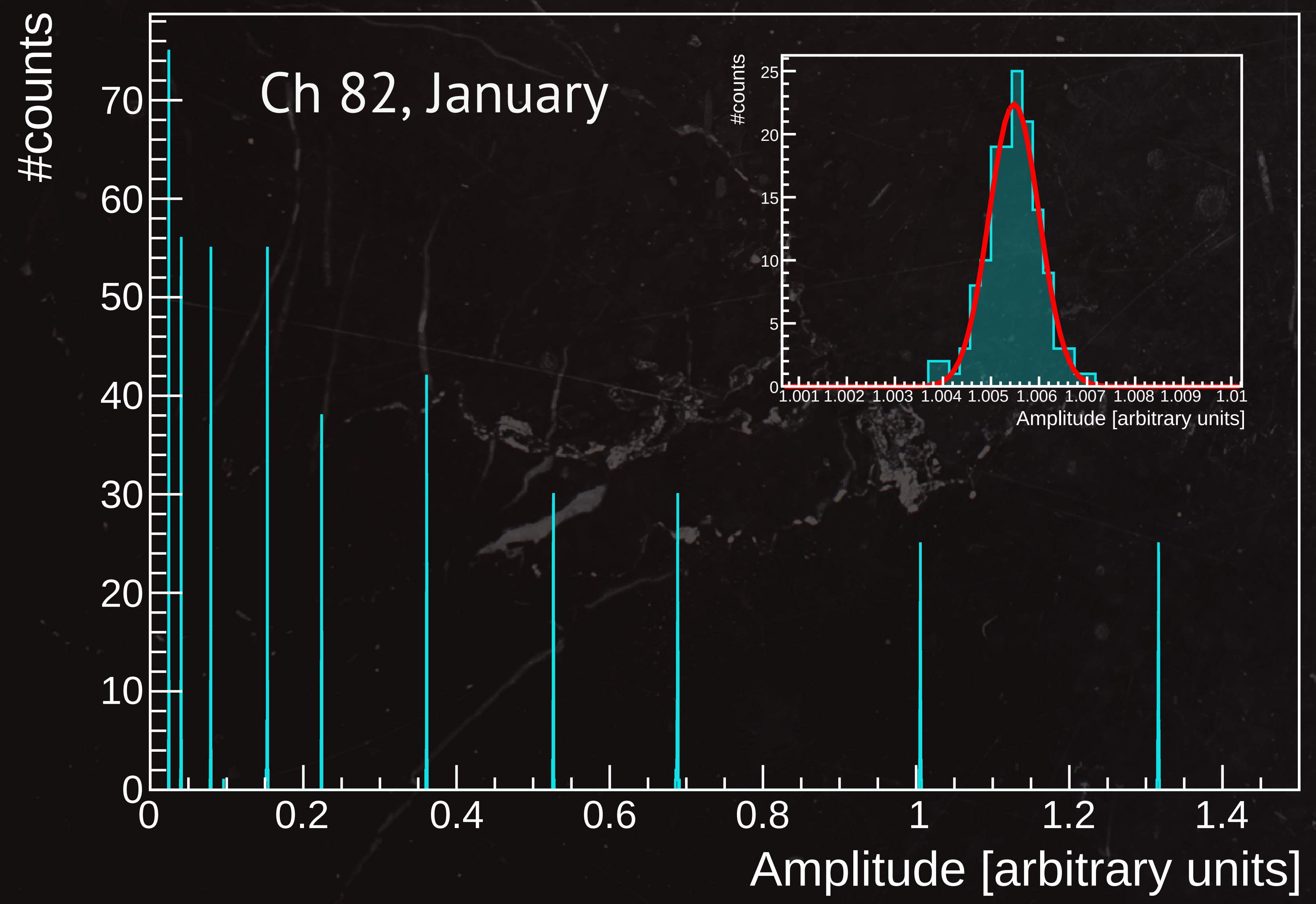
- Allows a fast data processing
- Operates on continuous data
- Employs software triggers
- Uses a modular structure

LED RUN DATA PROCESSING

Standard **Optimum Filter** → **Pulser Finder** → **Stabilization** in time

↓

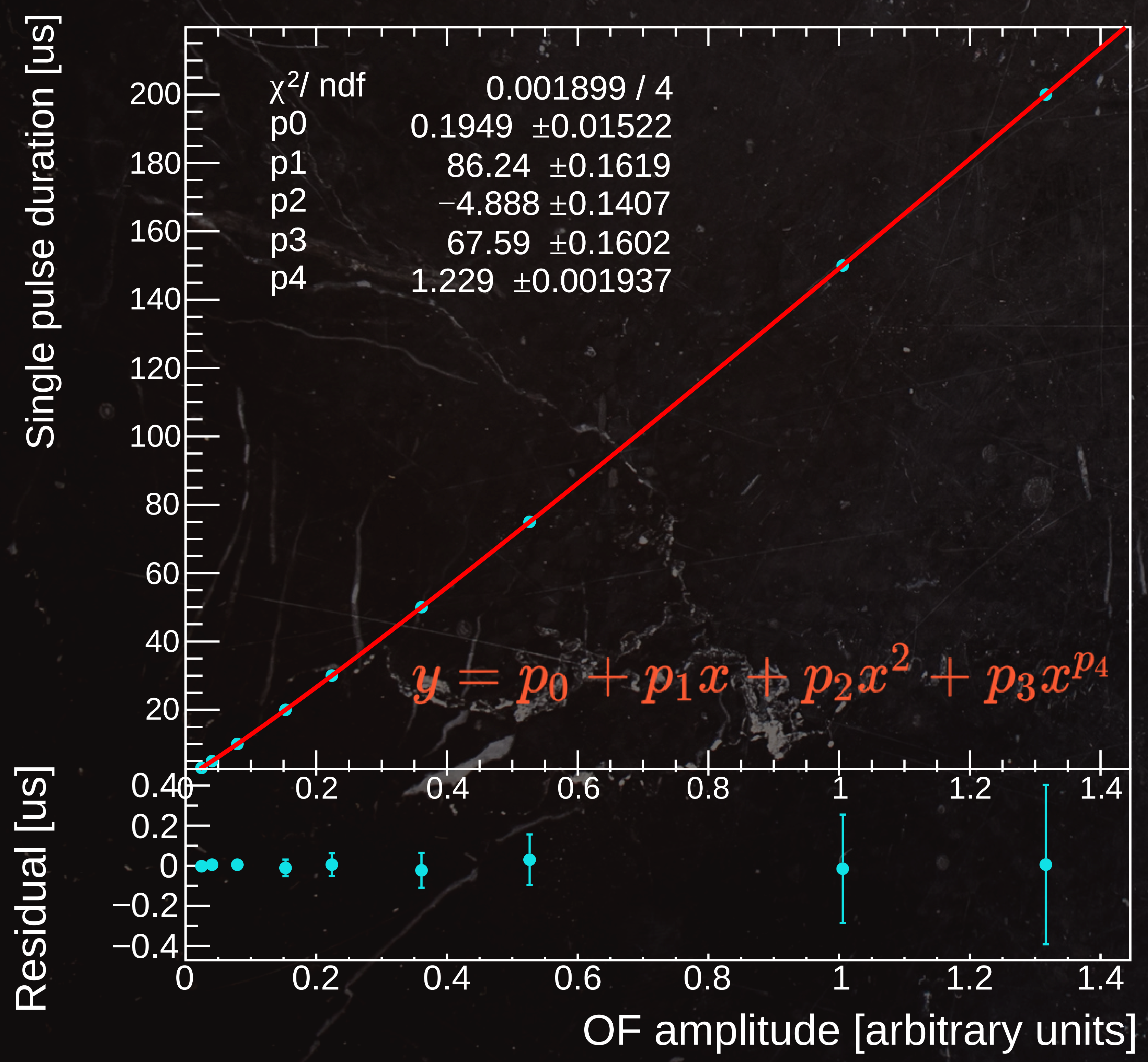
Self-calibration based on the Poisson statistics of the light



RESIDUALS

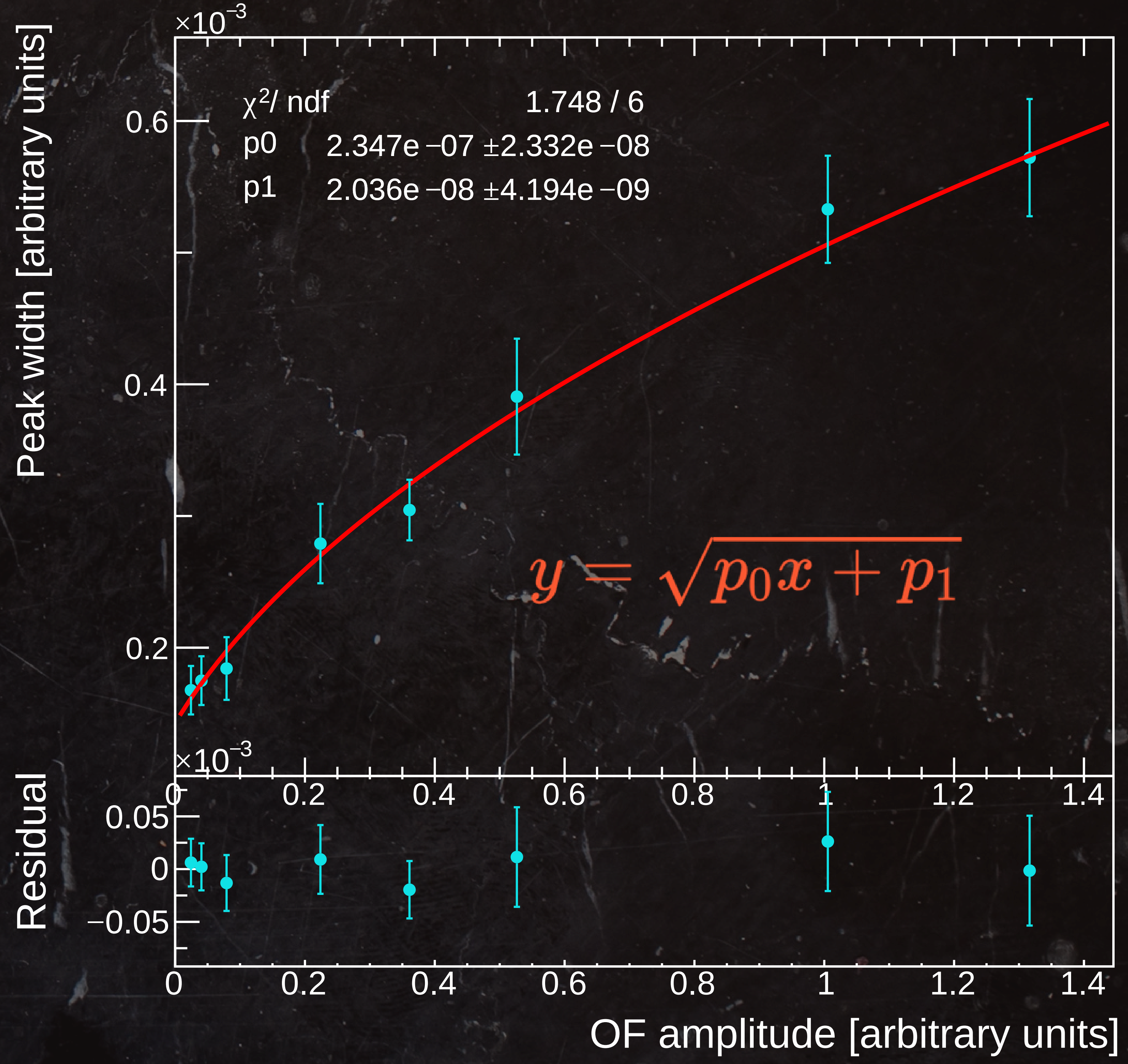
Ch 82, January

PEAK POSITION



Ch 82, January

PEAK WIDTH



SELF-CALIBRATION PRIPCIPLE

$$A_{OF} = R \cdot A_{keV} = R \cdot N_\gamma E_\gamma$$

Number of photons

Single photon energy

$$\sigma_{\mathrm{kev}} = E_\gamma \sqrt{N_\gamma + b}$$

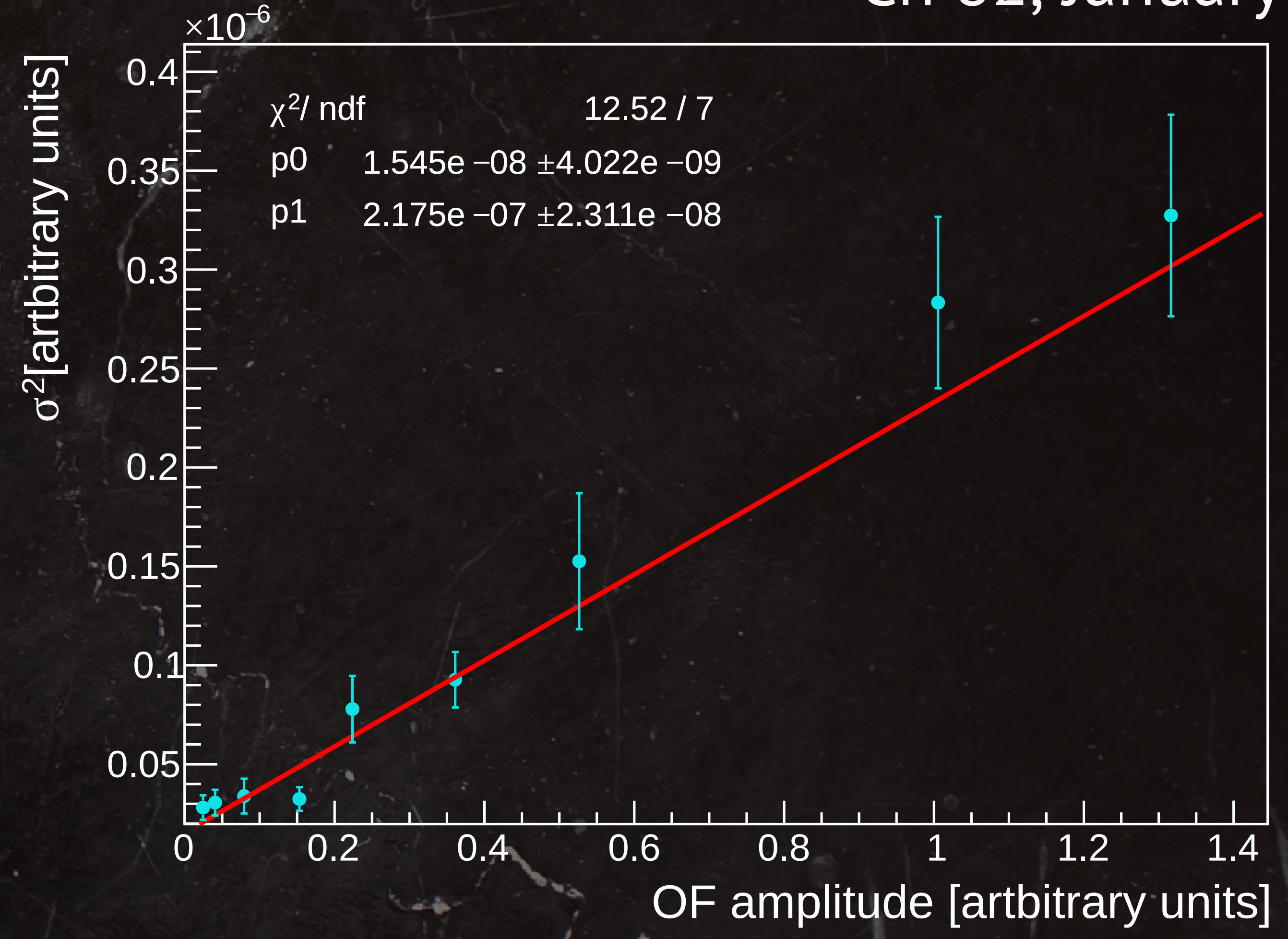
Poissonian term

Baseline resolution

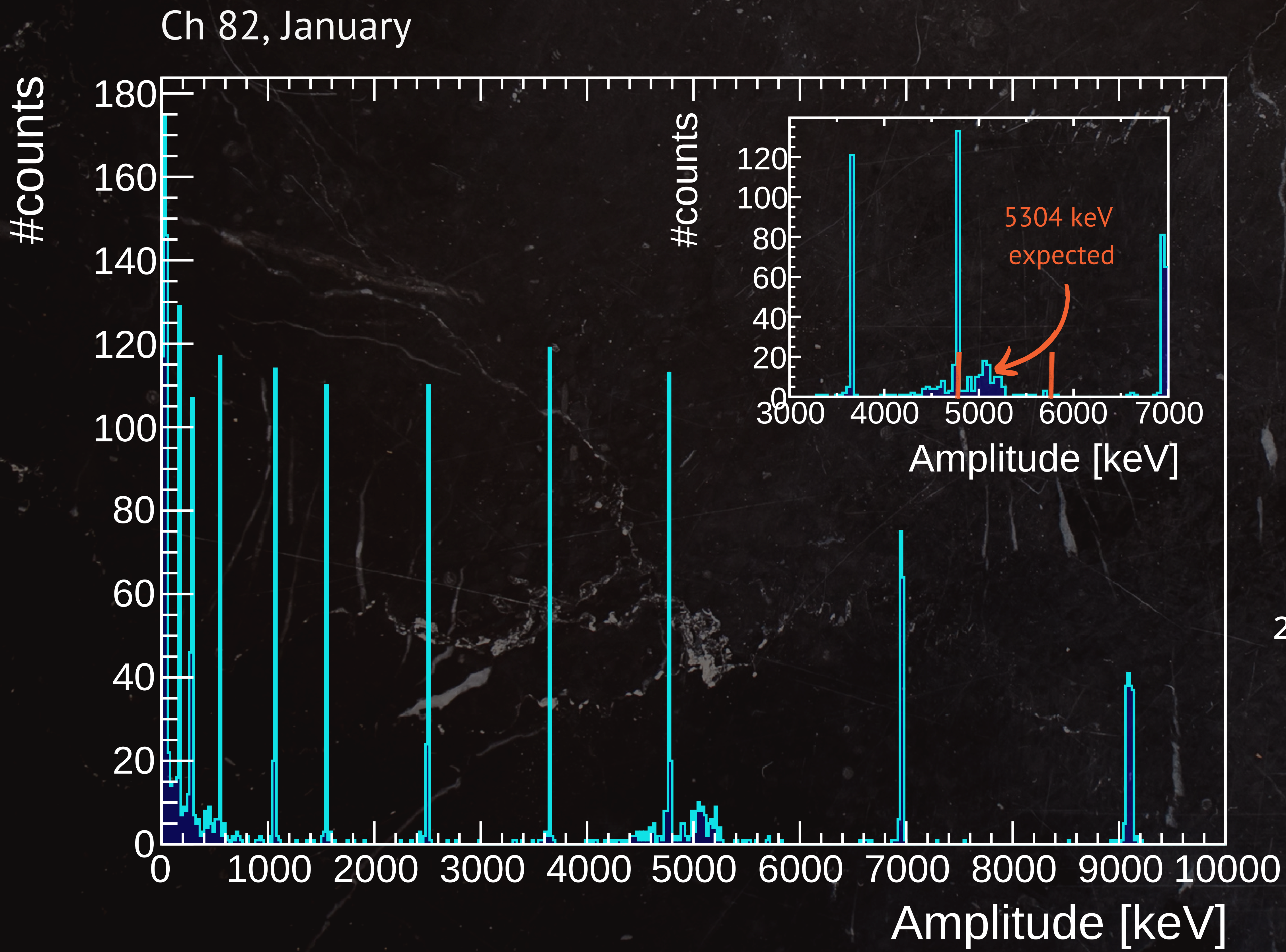
$$\sigma^2_{OF} = R^2 \sigma^2_{kev} = B^2 + R^2 N_\gamma E^2_\gamma = B^2 + A_{OF} E_\gamma R$$

$$A_{\mathrm{kev}} = \frac{A_{\mathrm{OF}}}{R}$$

Ch 82, January



SELF-CALIBRATION RESULT



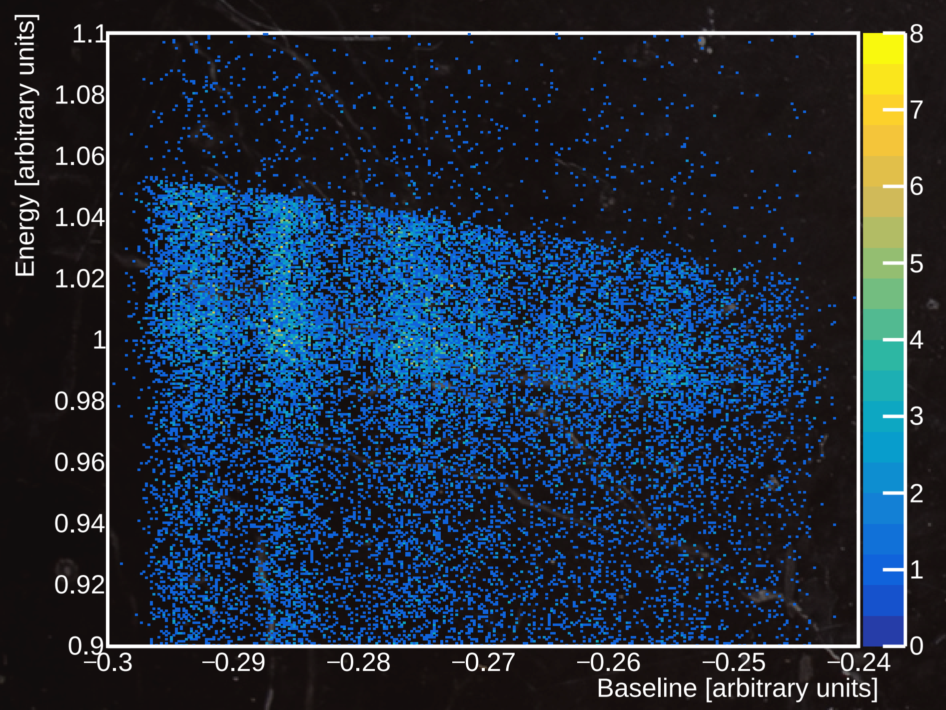
$$E_\gamma = 1.51 \text{ ev } (\lambda = 820 \text{ nm})$$

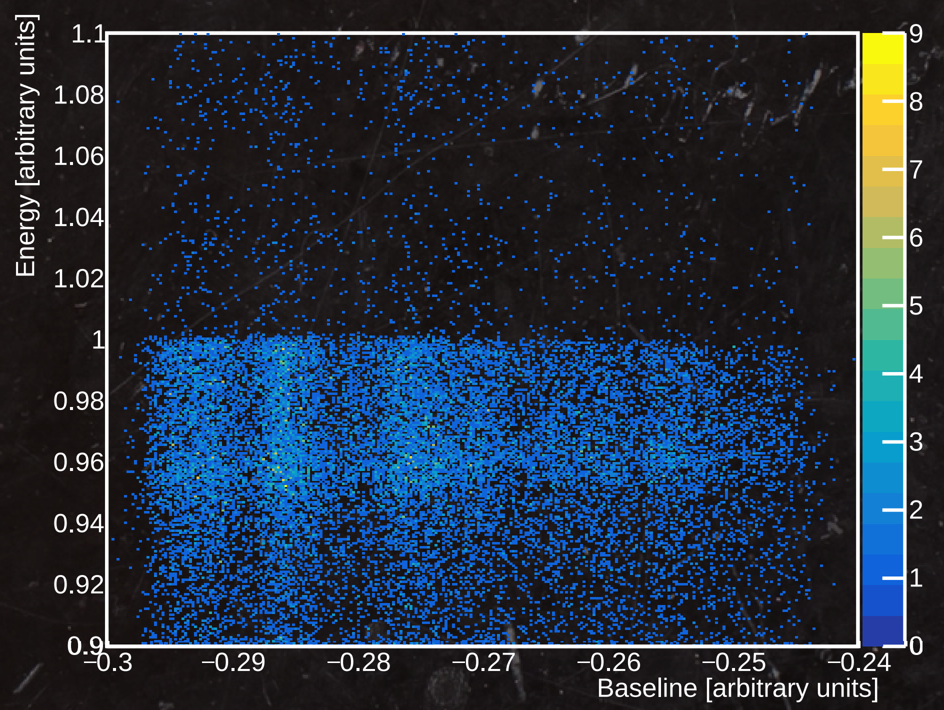
$$R = 1.44 \times 10^{-4} \pm 1.5 \times 10^{-5}$$

^{210}Po peak is inside expected region

self-calibration works!

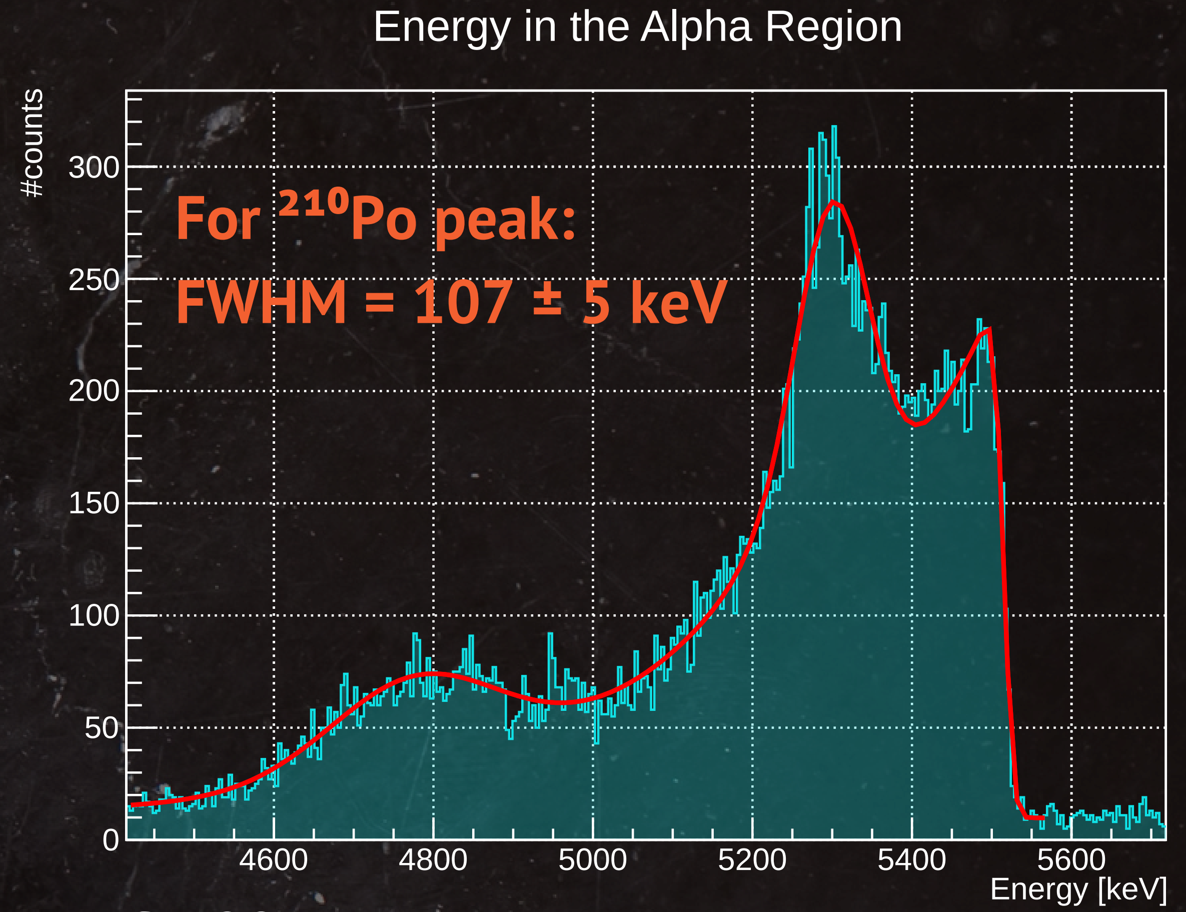
MEASUREMENT WITH α SOURCE





Ch 82, January

TEMPERATURE DRIFT CORRECTION



Ch 82, January

FIT FUNCTION

Gaussian

Flat backgroung

$$f(E) = A\exp\left(-\frac{(E-\mu)^2}{2\sigma^2}\right) + B$$

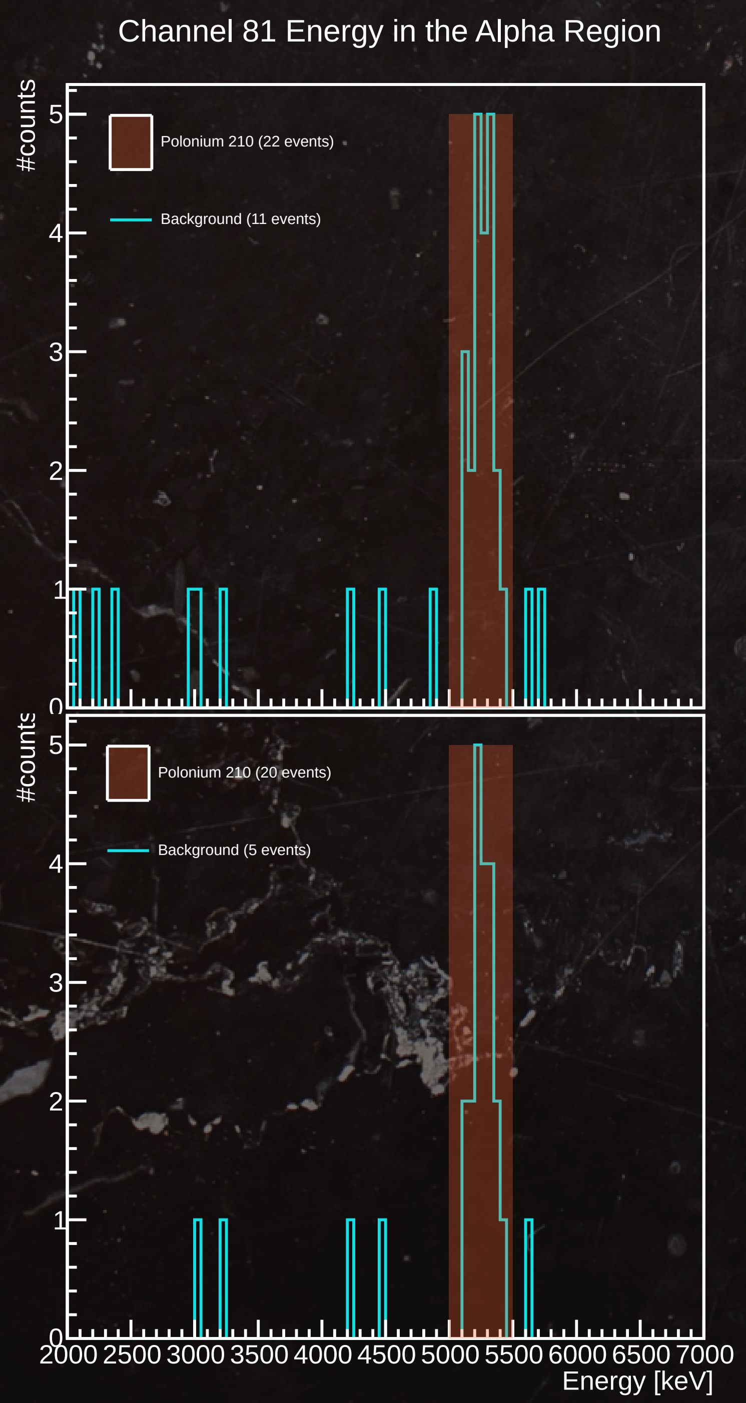
Low-energy tail

$$+ C\exp\left(\frac{E-\mu}{\delta}\right)\operatorname{erfc}\left(\frac{E-\mu}{\sqrt{2}\sigma} + \frac{\sigma}{\sqrt{2}\delta}\right)$$

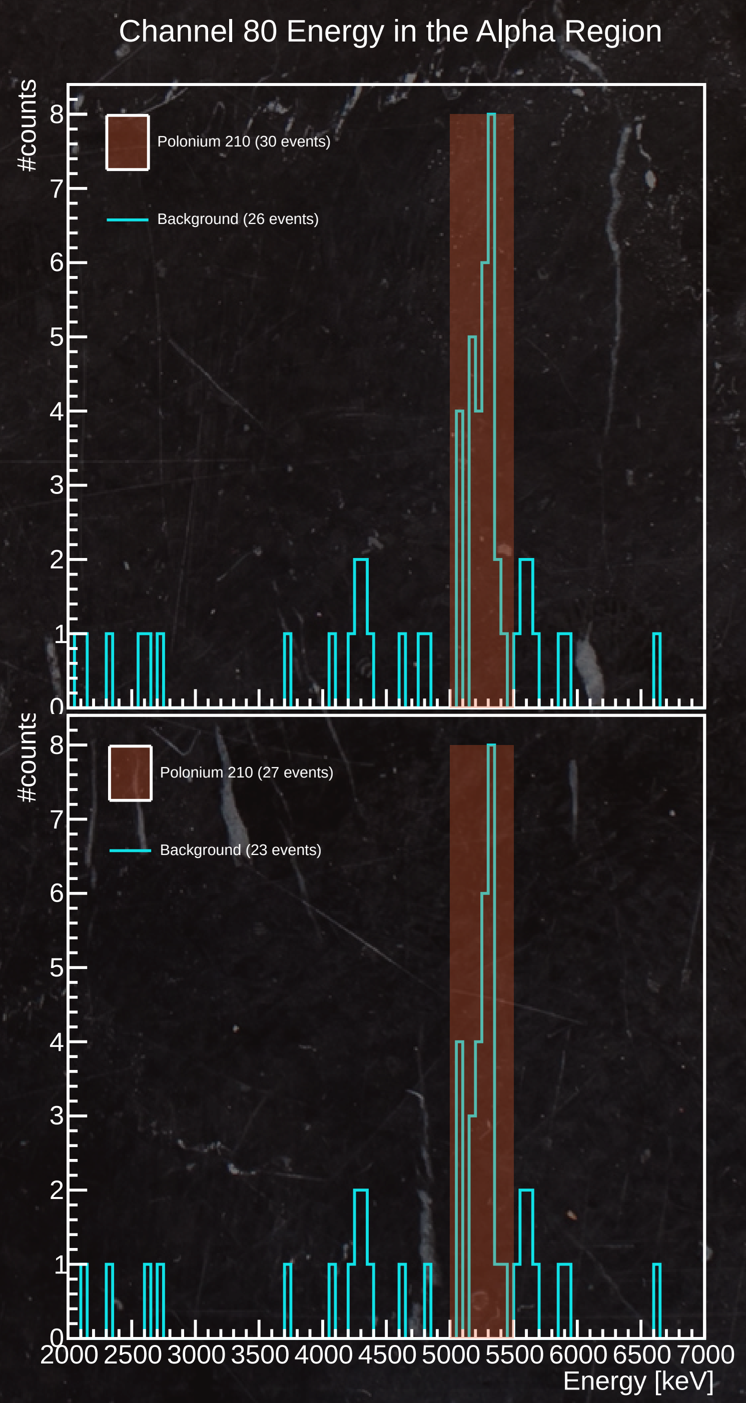
HIGH-ENERGY BACKGROUND

BEFORE COINCIDENCE ANALYSIS

AFTER COINCIDENCE ANALYSIS (M1 ONLY)



Ch 81, March



Ch 80, March

Number of events in ROI

$$B = \frac{N_e}{2 \cdot \pi R^2 \cdot \Delta t}$$

Radius of the wafer (7.5 cm^2)

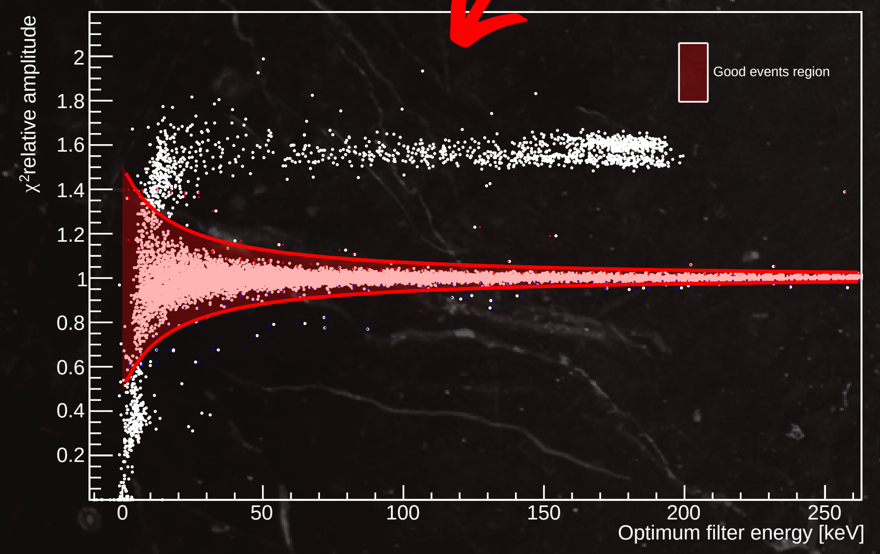
Run time

Channel	M1 background rate	M2 background rate
80	2.67×10^{-7}	3.50×10^{-8}
81	5.84×10^{-8}	7.01×10^{-8}

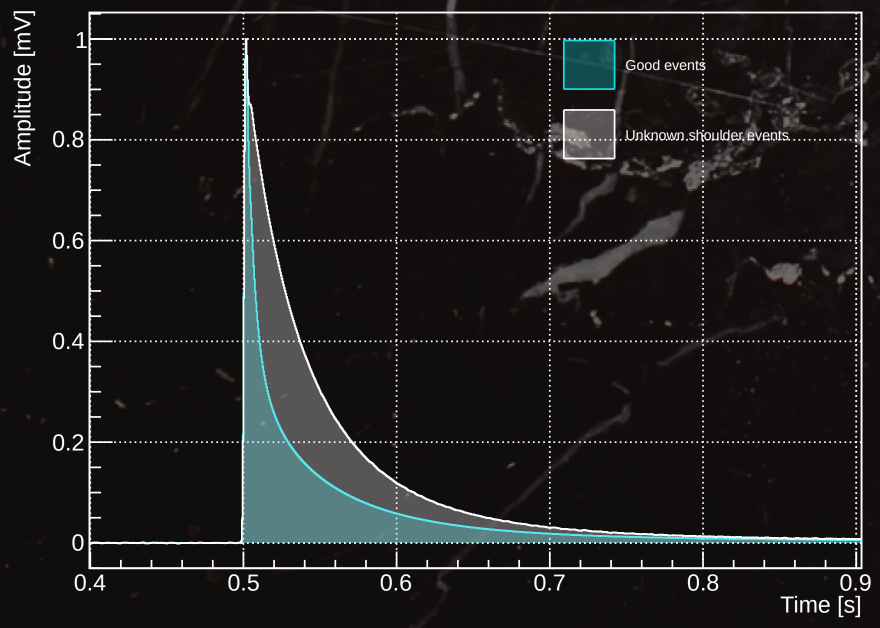
LOW-ENERGY BACKGROUND

Ch 81, March

Unknown shoulder

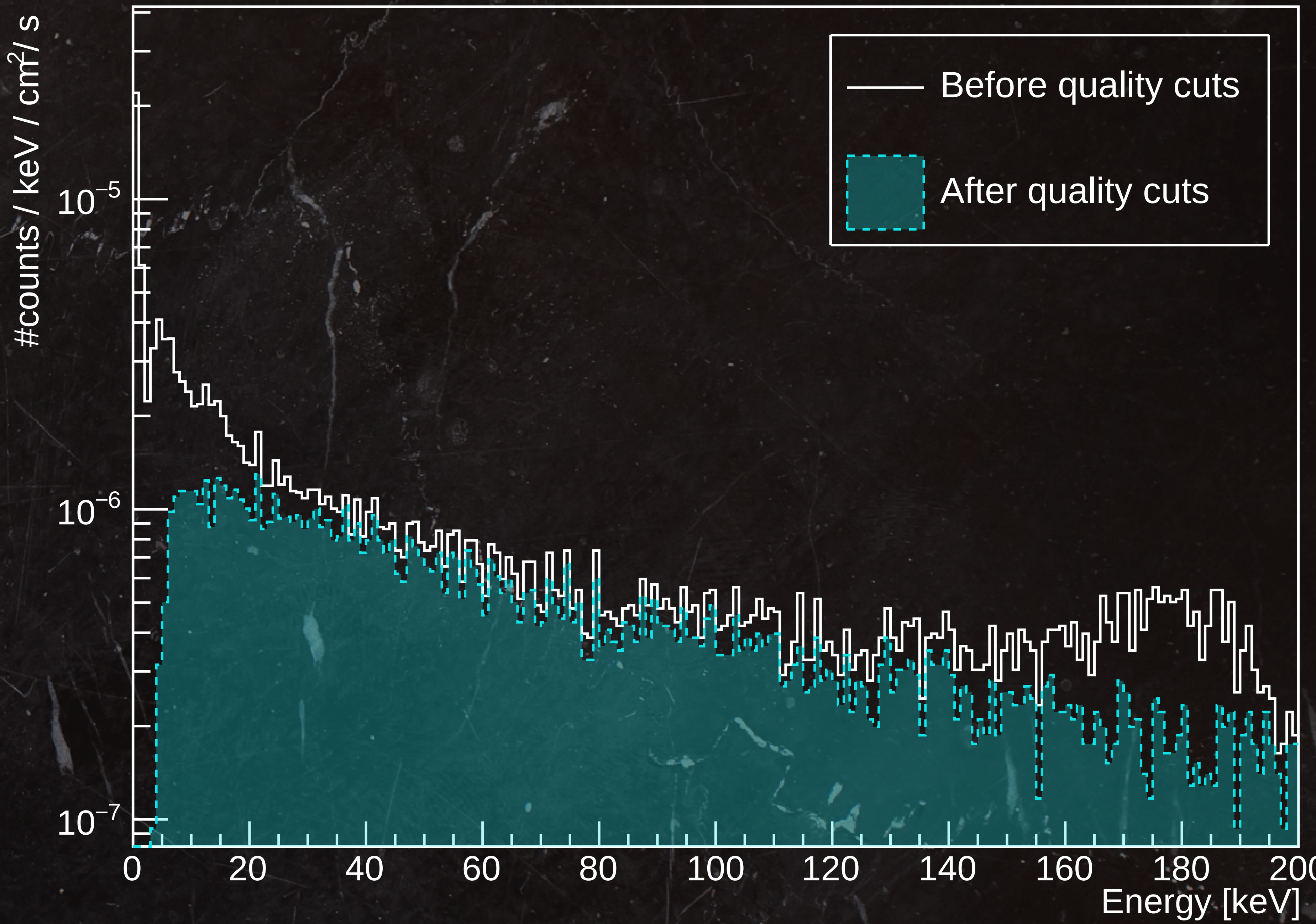


Average pulse comparison



Ch 81, March

Ch 81, March



For E < 20 keV

$$B = (1.10 \pm 0.11) \times 10^{-6}\ \mathrm{counts/keV/cm^2/s}$$

CONCLUSIONS

- Successfully developed a silicon bolometric detector optimized for rare event detection.
- Demonstrated the effectiveness of the LED self-calibration system, covering a wide energy range from ~ keV to 10 MeV.
- First alpha measurement was conducted.
- The detector's sensitivity in both high-energy alpha and low-energy regions highlights its potential for next-generation neutrinoless double beta decay and dark matter experiments.

NEXT STEPS

- Replace the LED calibration system with a laser-based system for better precision.
- Assemble the detector in a cleanroom environment to minimize contamination and improve background levels.
- Consider switching to sapphire wafers to improve energy resolution.

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