Exploring CEvNS with NUCLEUS experiment & latest updates on the Cryogenic Outer Veto (COV)

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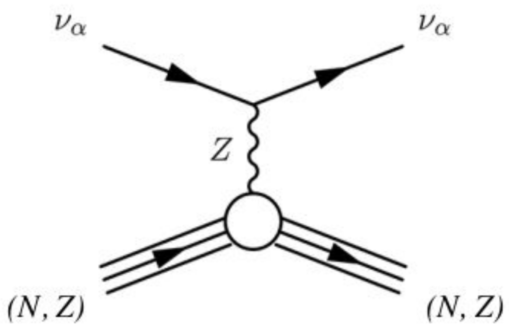
EXPERIMENT
nucleus

CEvNS

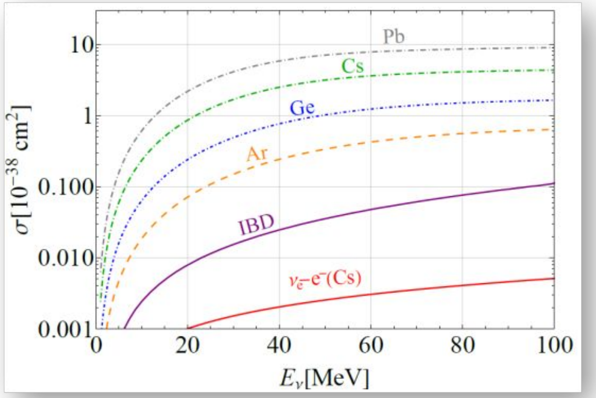
- The **Coherent Elastic Neutrino-Nucleus Scattering** (CEvNS) was **predicted within the Standard Model in 1973**
- It was **firstly observed in 2017** by the COHERENT collaboration
- Although the cross section is several odm larger than other ν process studied at low energies, **the recoil energy** (the observable) **is very difficult to detect** (~ few keV)



$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$$

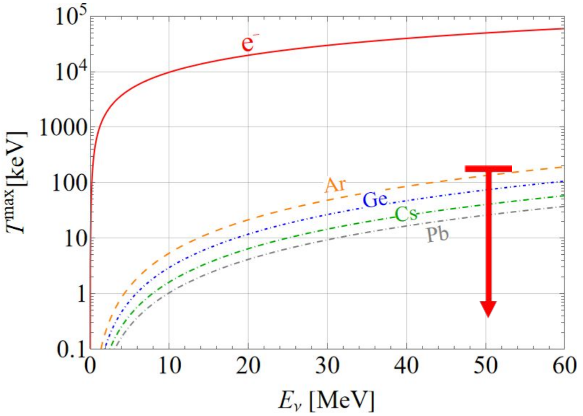
$$Q_W = N - Z(1 - 4\sin^2\theta_W) \sim N$$

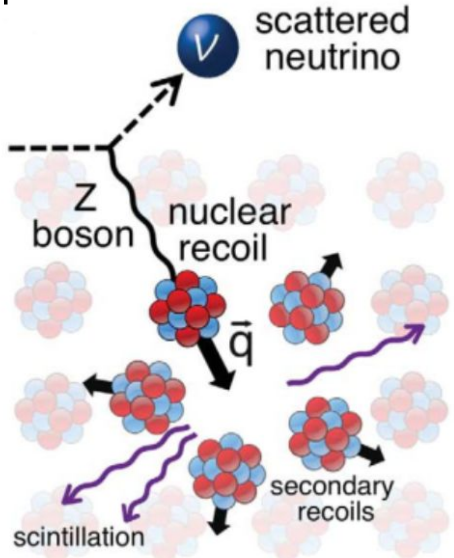
CEνNS Cross Section ∝ N^2



Observable: kinetic energy of nuclear recoil

$$T^{\max} = \frac{2E_\nu^2}{m_{\mathrm{target}}}$$





The NUCLEUS Experiment

NUCLEUS Aim:

- Precision measurement of **reactor CEvNS with cryogenic detectors** at lowest energies

NUCLEUS Location:

- **Measurements**: Chooz nuclear power plant in the French Ardennes (operated by EDF)
- **Detectors development and tests**: Underground Laboratory (UGL) at TUM (Technical University of Munich)

NUCLEUS Collaboration:

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SAPIENZA
UNIVERSITÀ DI ROMA

HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

EDF

MAX-PLANCK-INSTITUT FÜR PHYSIK

TUM

TU WIEN

cea

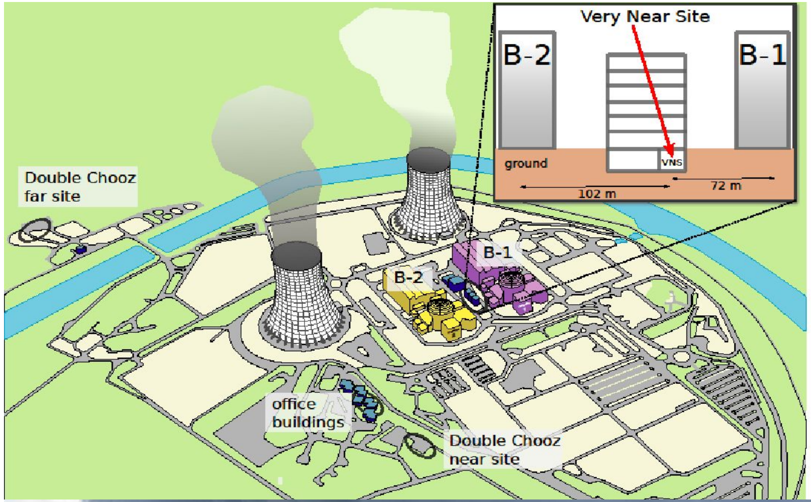
NUCLEUS Location: The VNS

- The **experimental site** (VNS) is located at 102 m and 72 m from the 2 reactors of the Chooz plant, **at ≈ 3 m.w.e. depth**

- **Cosmic-ray induced neutrons will be challenging to mitigate** with such a low overburden
  NUCLEUS Collaboration: Particle background characterization and prediction for the NUCLEUS reactor CEvNS experiment (arXiv:2509.03559)

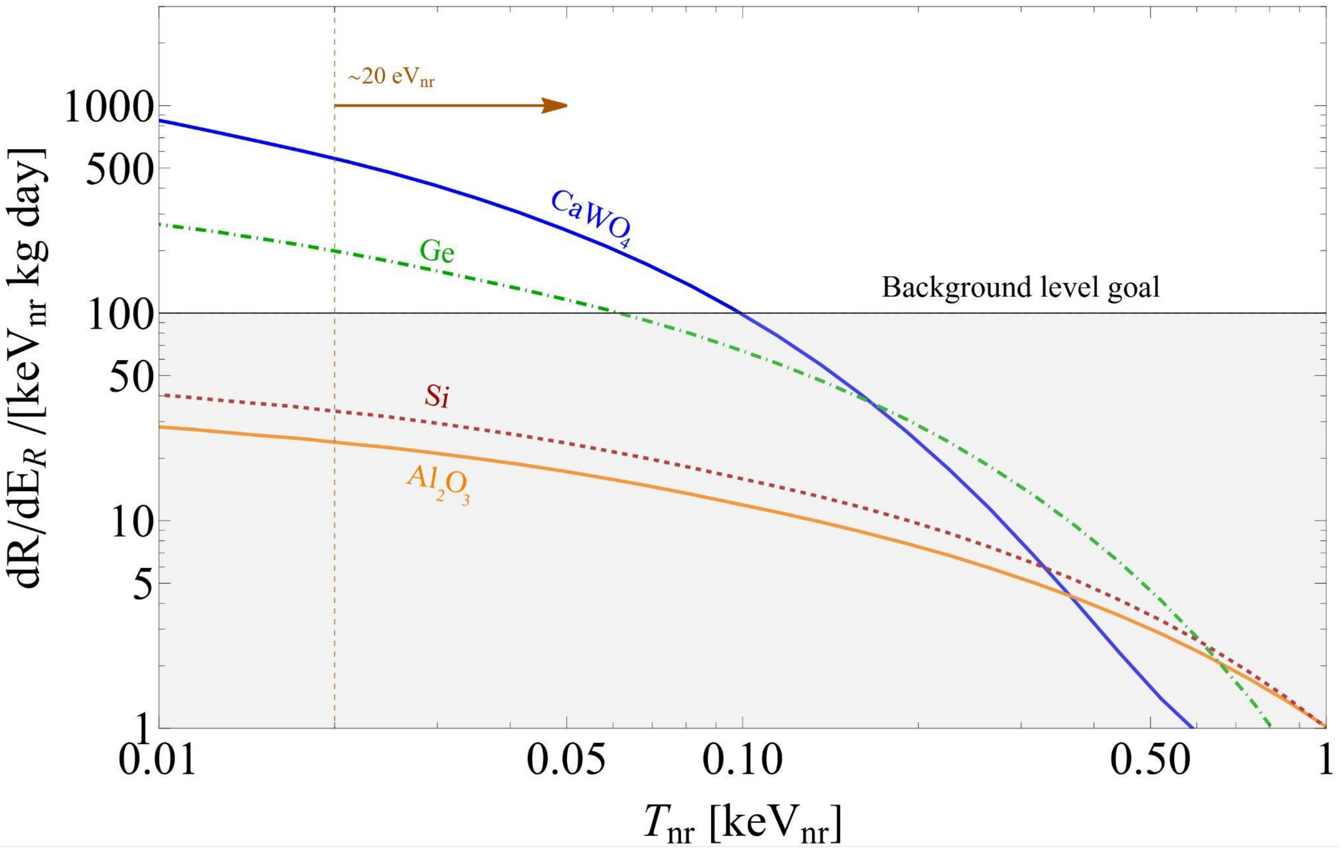
- **Reactor nominal thermal power**:
  2 x 4.25 GWTh

- **Expected ν flux at the detectors**:
  $1.7 \cdot 10^{12}$ ν/s/cm^2



CEvNS Signal at Nuclear Reactors

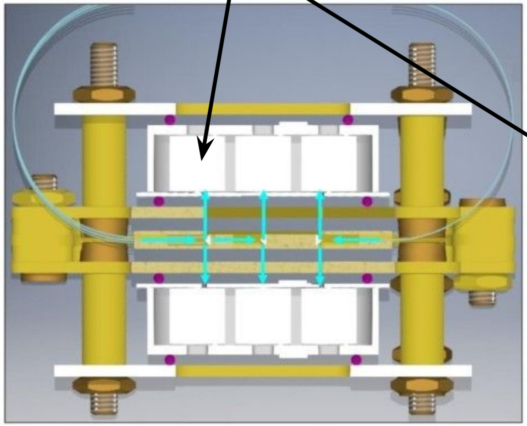
- ✓ **Nuclear Reactors are intense source of anti-neutrinos**, around 10^{20} neutrinos per GW per second
- ✓ The majority of this anti-neutrinos have **energy E_ν < 10 MeV** (fully **coherent domain**)
- ✗ Induced **nuclear recoils** for CEvNS interaction are in **sub-KeV range**
- ✗ **Low threshold** detectors and **low background** counting rate are **required**

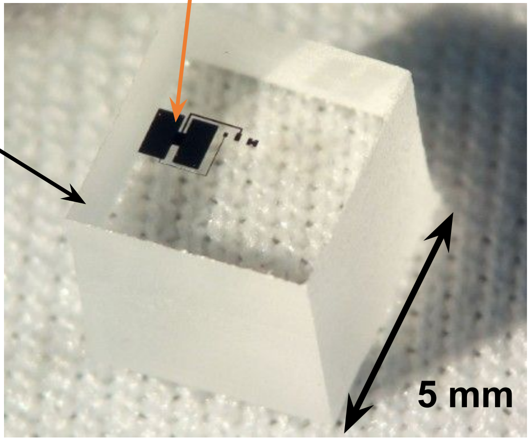


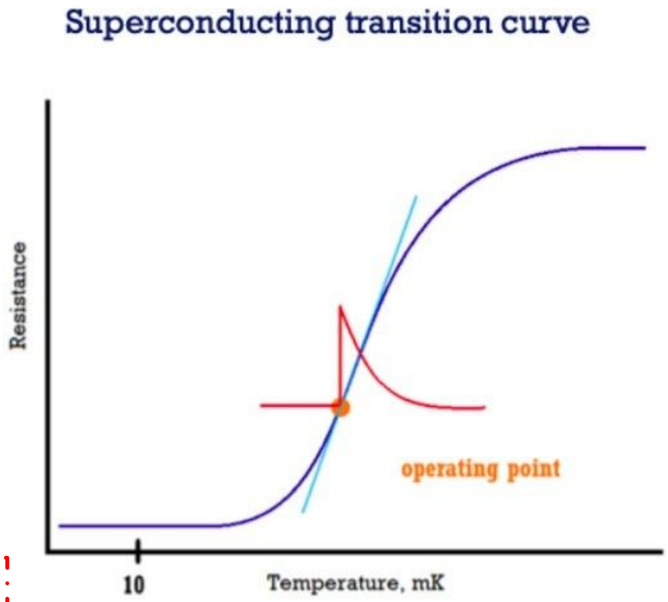
NUCLEUS expected signal:
~100 events per year in a gram-scale detector

NUCLEUS Cryogenic Target Detector

Absorber crystals + Transition Edge Sensors (TES)







NUCLEUS-10g Cryogenic Detector: two 3x3 matrices of target detectors

- **Baseline resolution** well under 10 eV
- **Threshold**: 10-50 eV

Particle Interaction → Phonon Production → TES heating → Resistance Change

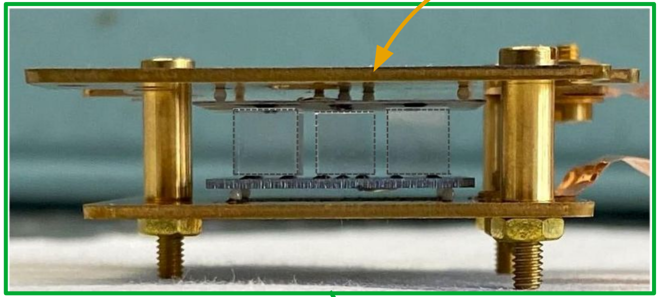
Multitarget approach:

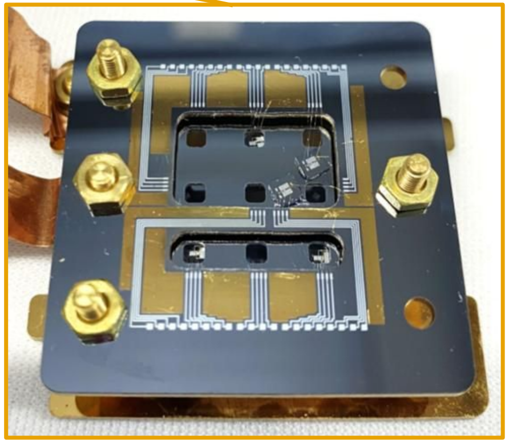
- **Al_2O_3:** used to probe background
- **$CaWO_4$:** similar background to Al_2O_3 but higher CEvNS rate

Inner and Outer Cryogenic Vetoes

Inner Veto:

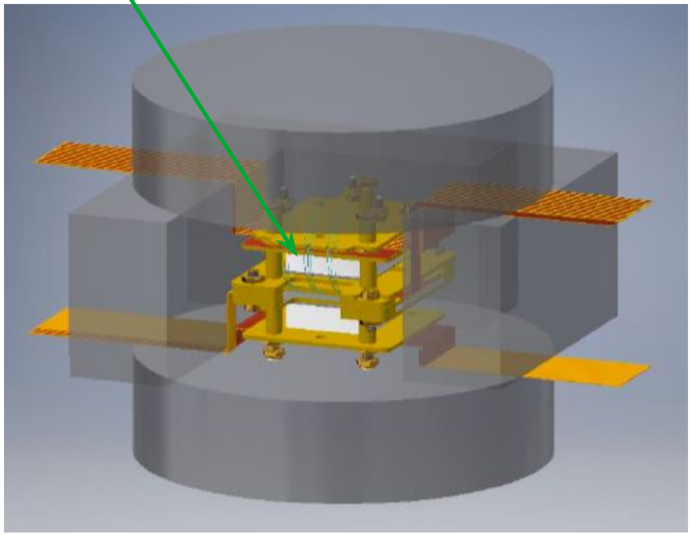
- **Si wafer** instrumented **with TESs** to hold and encapsulate the crystals (mechanical and thermal test concluded - in production)
- Veto **against mechanical stress events, surface contamination**
- **Sub-keV cryogenic detector with TES readout**





Cryogenic Outer Veto (COV):

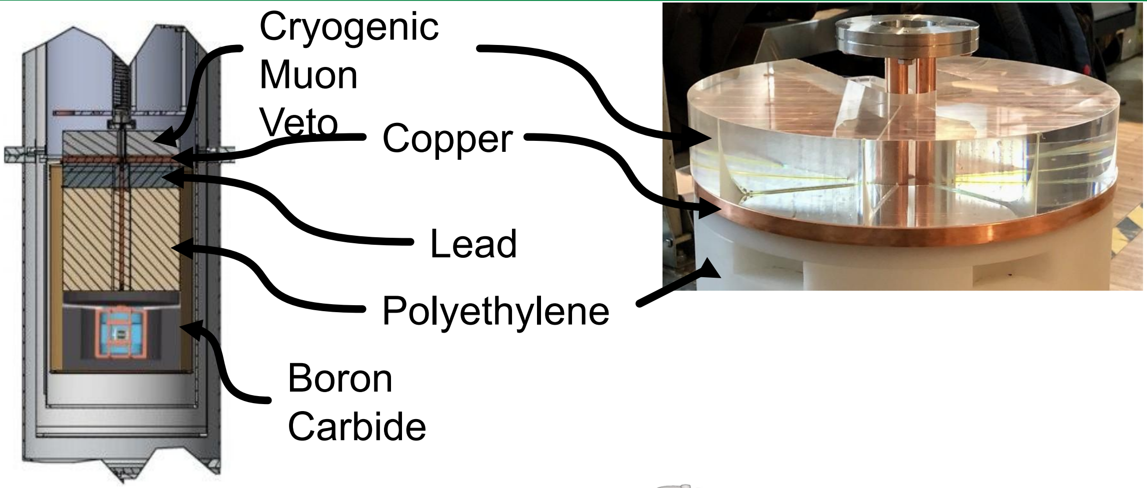
- **6 HPGe crystals** (2 cylindrical and 4 rectangular) of 2.5 cm thickness (under commissioning)
- Surround the inner detectors for **active γ and neutron background rejection** (almost 4π coverage)



Active and Passive Shieldings

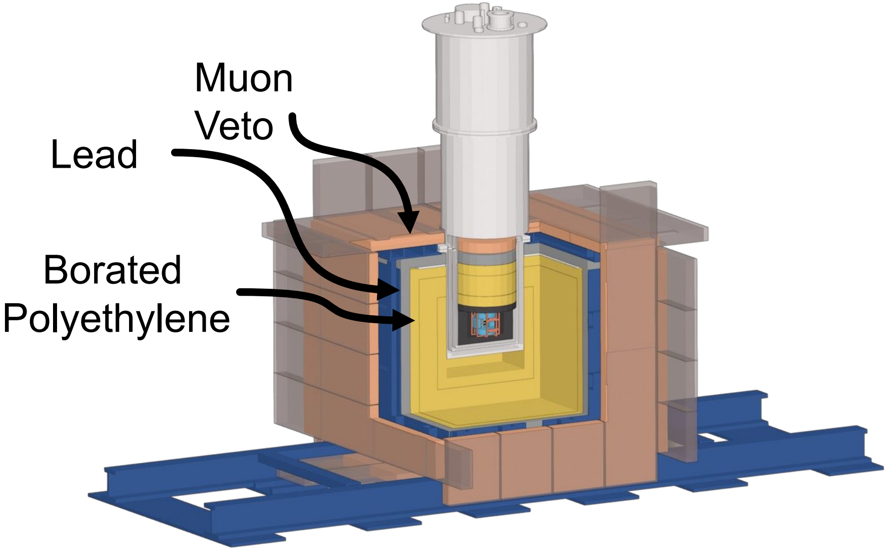
Inner Shielding:

- **Lead, Copper support** (acting also as a thermal contact), **PE, B_4C** for neutron reduction
- **Thermalized at 800 mK**



Outer Shielding:

- **Multilayer Passive Shield**: Lead and Borated Polyethylene
- **Muon Veto**: plastic scintillators with SiPM & WLS-fiber readout
- **Movable mechanical structure** to allow easy opening/closing of the external shield
- **Minimize μ induced neutrons**



My Main Contributions inside the Experiment

Data Analysis

Hardware

Trapezoidal filter implementation

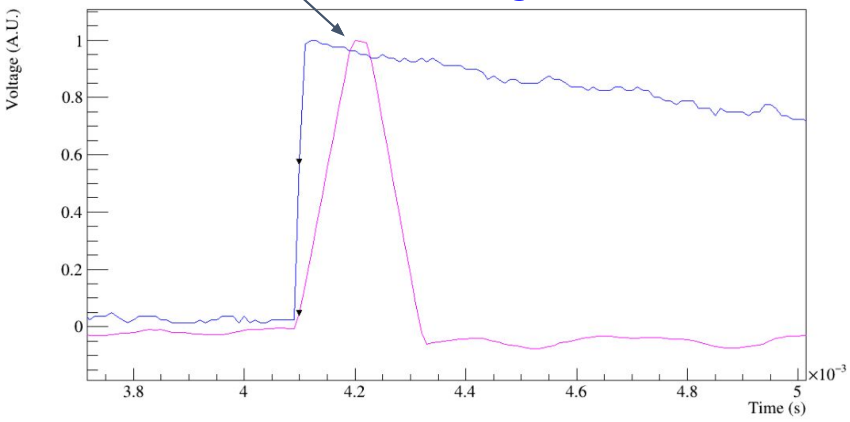
- The **optimal tool** used for TES data (Matched Filter) is **not suitable** to analyze COV data
- I decided to **implement** a **Trapezoidal filter** algorithm

INPUT $v(n)$	RECURSIVE ALGORITHM	DELAY l	PULSE SHAPE
	$s(n) = s(n-1) + v(n) - 2v(n-k) + v(n-2k)$		$2k$
	$s(n) = s(n-1) + v(n) - v(n-k) - v(n-l) + v(n-l-k)$	$l = k + m$	m, $2k+m$
	$p(n) = p(n-1) + v(n) - v(n-k) + v(n-l) - v(n-l-k)$ $s(n) = s(n-1) + p(n) - [v(n-k) + v(n-l)]k - v(n-l) + v(n-l-k)$	$l = k + m$	m, $2k+m$

[Jordanov, Knoll, Digital synthesis of pulse shapes in real time for high resolution radiation spectroscopy, 1994]

- **The algorithm used is the one highlighted**
- **Amplitude is the maximum point on the top basis of the trapezium**

signal vs filtered

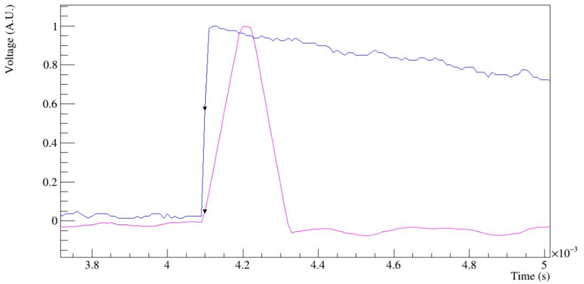


N.B.: this is normalized to 1 for both pulses, the real gain of the filter is not 1

Trapezoidal filter upgrade

- **I improved the standard trapezoidal filter to obtain better results from our data**

Trapezoidal Algorithm



Derivative + Integral

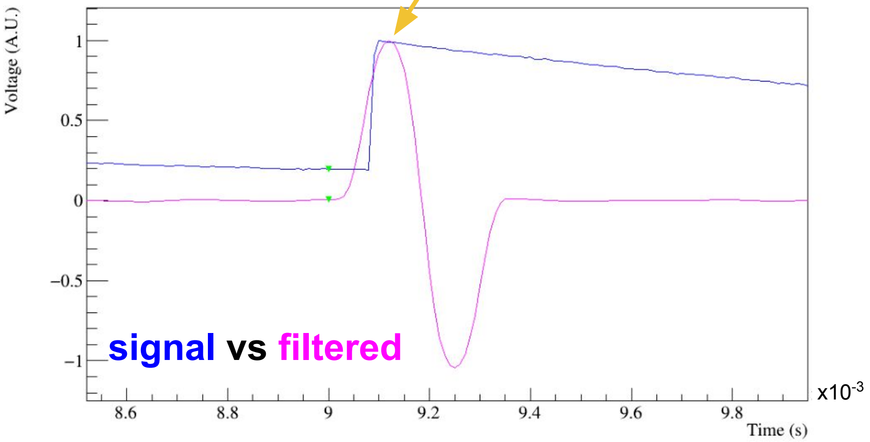
Zero baseline granted

Moving average (low pass filter with settable cutoff freq)

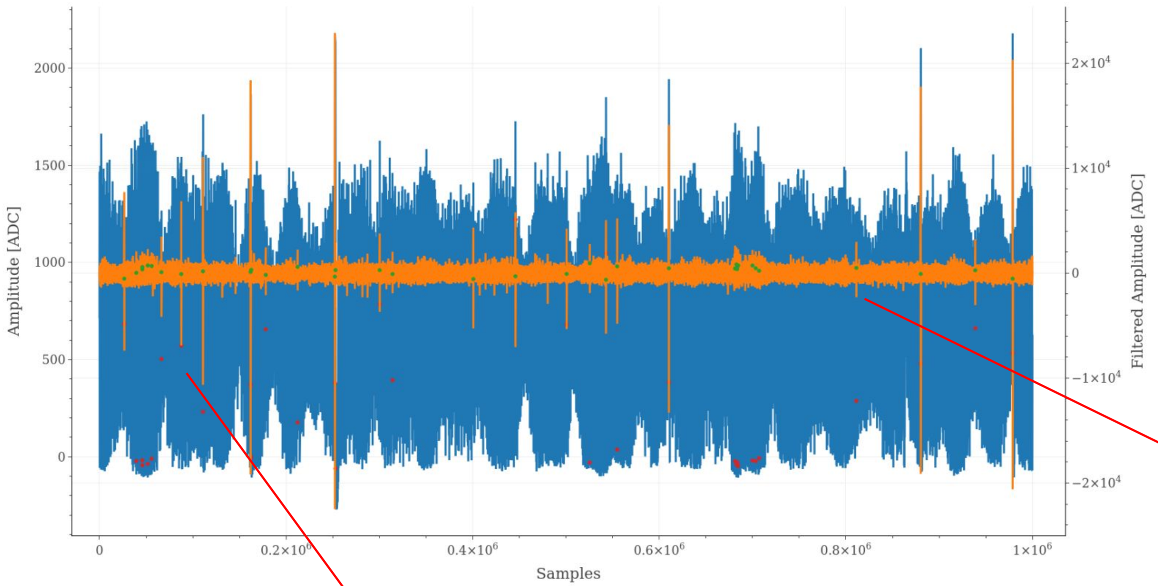
(Average of the upper basis - better amplitude reconstruction)

Parabolic interpolation

From 6% to 1.5% resolution on ^{137}Cs peak (662 keV) on average on COV crystals

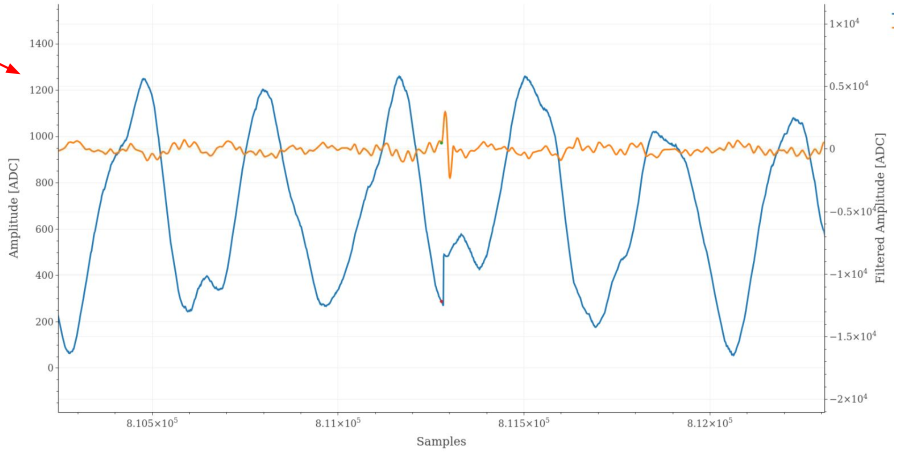


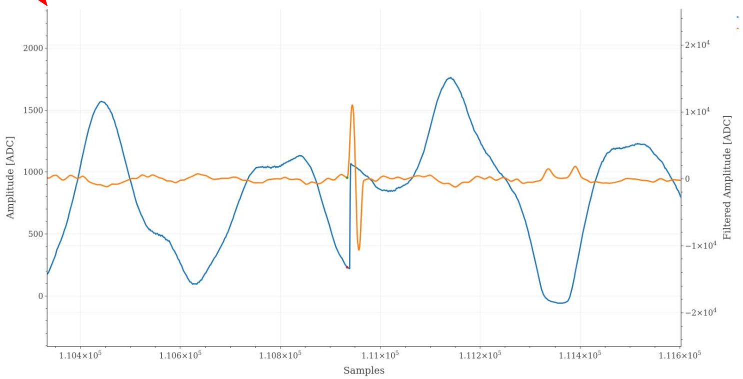
Trapezoidal Filter example - bad noise



Even in bad noise conditions, **this algorithm can spot pulses efficiently**

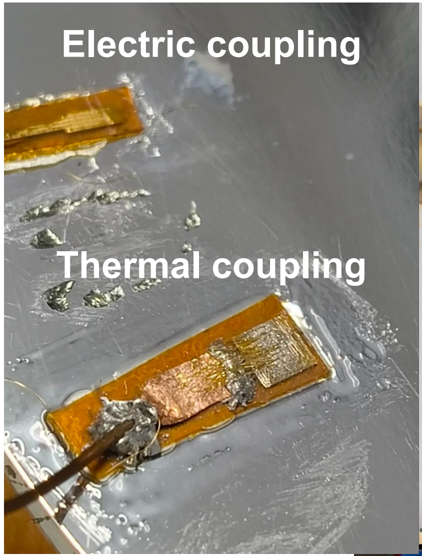
signal vs filtered

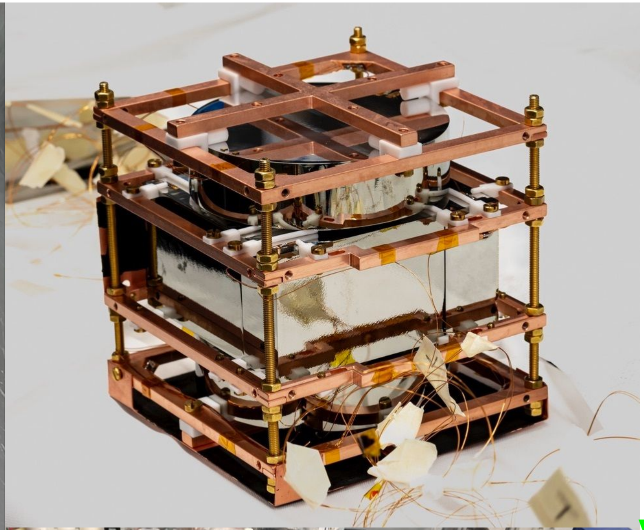


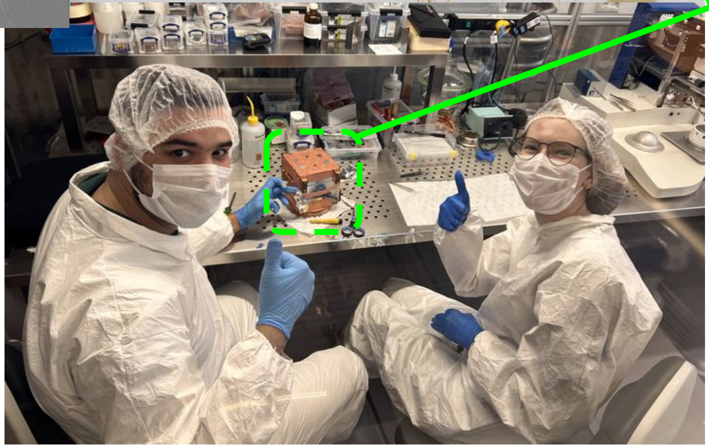


COV: from 1 to 6 HPGe Crystals

COV Cage V1 while being mounted from scratch

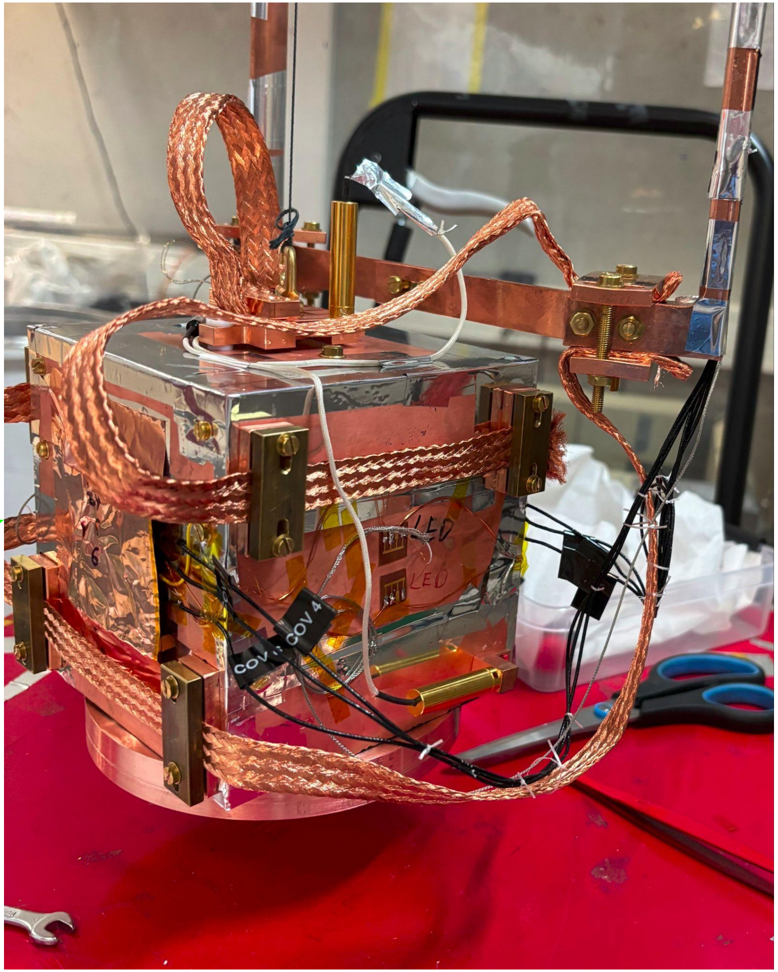




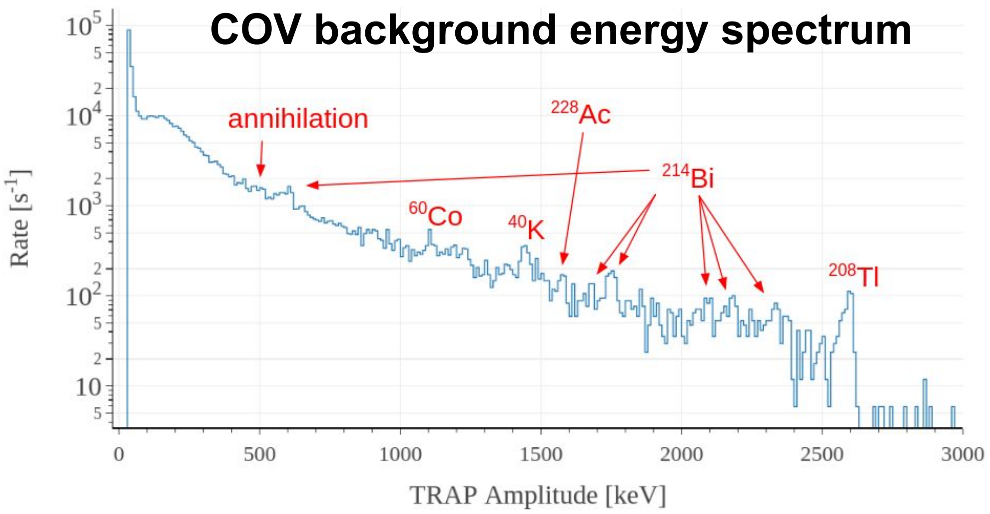


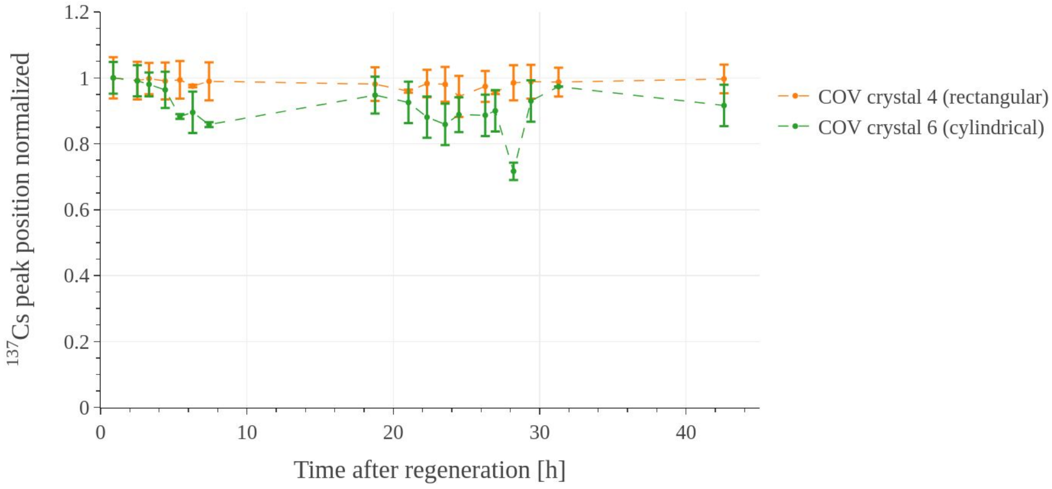
All 6 COV crystals working together and on specs.
Tests concluded with no detector module inside

COV Cage V1 inside the cryostat



Results of Cage V1 tests

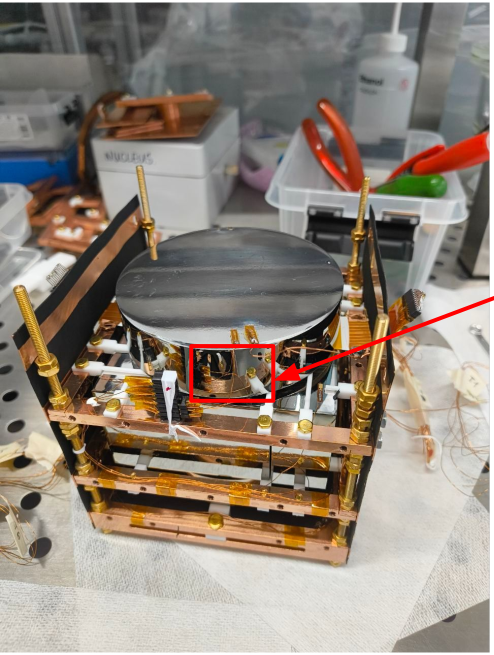


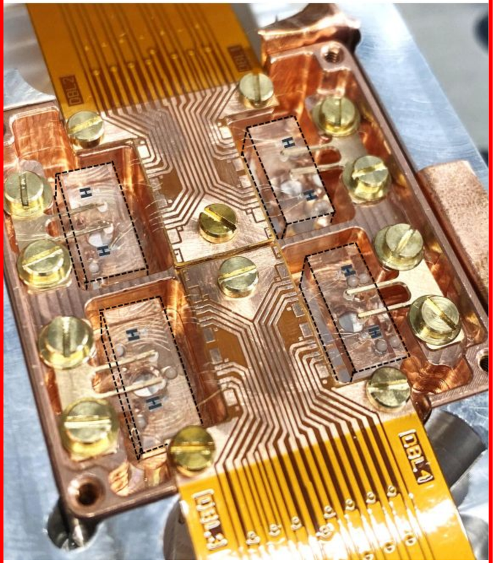


- **All 6 COV crystals reached nominal performances** i.e. less than 2 keV of baseline resolution
- **From ~2h to >36h crystals operational time** needed between regeneration
- **Changed crystal regeneration procedure**
  - **From ~3h** with LEDs **to 20 min** using bias voltage flips
- To mitigate the effect of mechanical vibrations, **a new version of the Cage was designed**

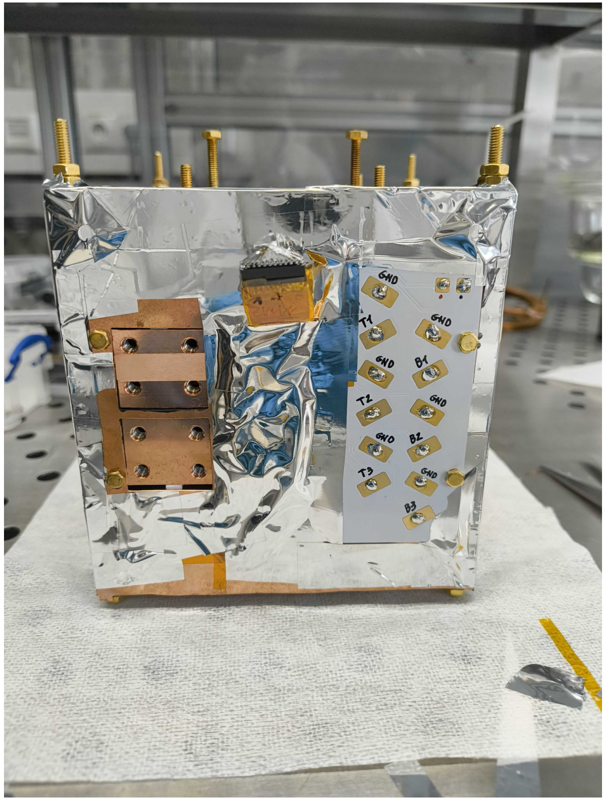
Ongoing: COV Cage V2

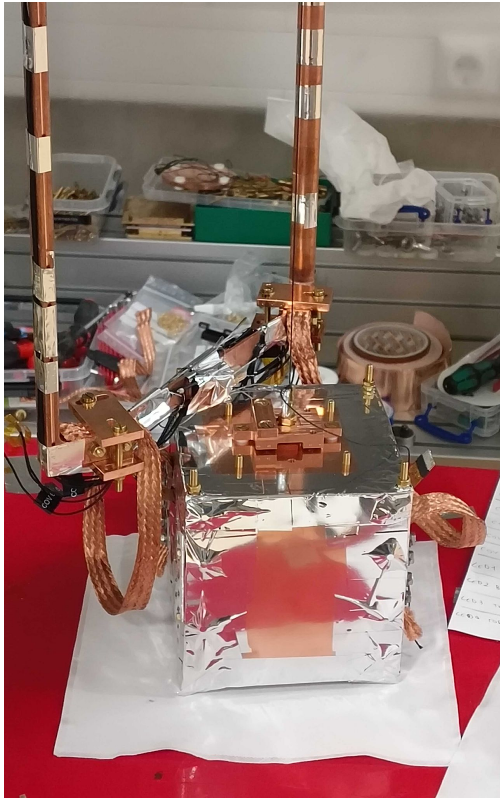
COV Cage V2: ready to be tested





Detector module assembled **inside** the new COV cage:
4 $CaWO_4$ cubes with double-TES

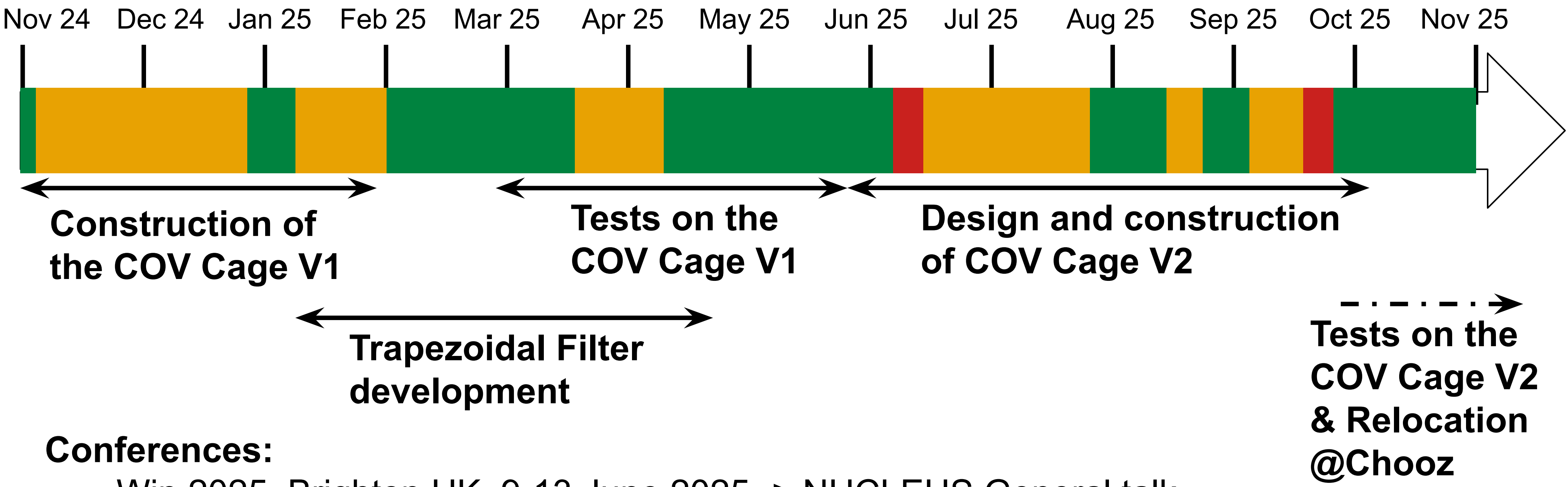




COV V2 cage fully assembled and ready to be tested (ongoing)

Recap of my 2nd year of PhD

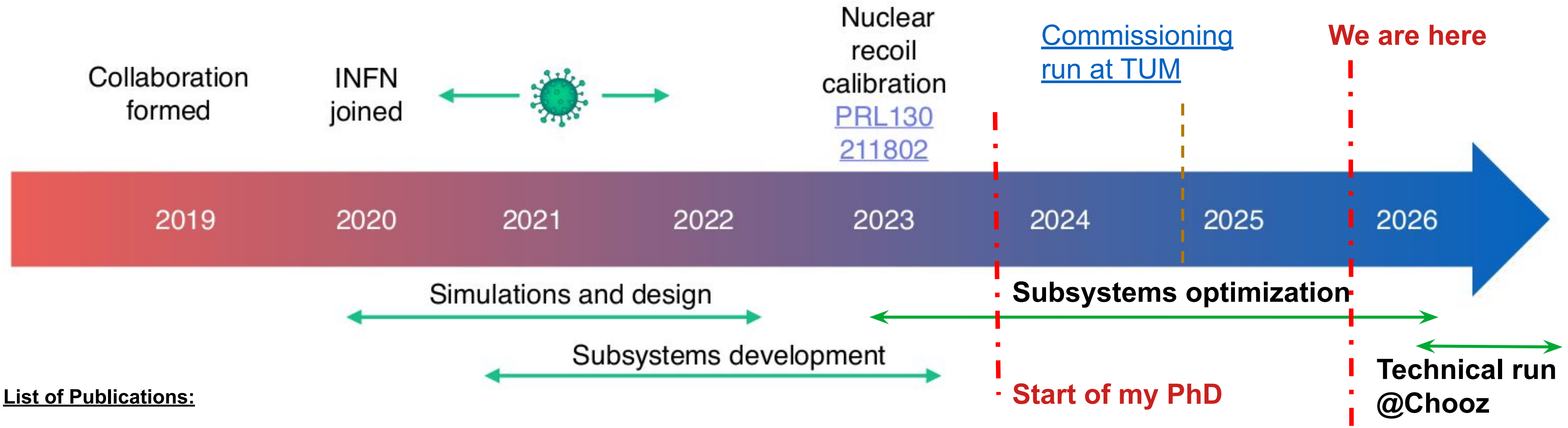
Legend: Tor Vergata (~6.5 months), Munich (~5 months), Conferences (2 weeks)



Conferences:

- Win 2025, Brighton UK, 9-13 June 2025 -> NUCLEUS General talk
- SIF 111 Congress, Palermo IT, 22-26 Sept 2025 -> NUCLEUS General talk

NUCLEUS Timeline



List of Publications:

NUCLEUS: recent results and perspectives, M. Giammei for NUCLEUS Collaboration, PoS ICHEP2024 (2025) 228, DOI:10.22323/1.476.0228

Decoupling pulse tube vibrations from a dry dilution refrigerator at milli-Kelvin temperatures, A. Wex, J. Rothe, L. Peters et al, JINST 20 (2025) 05, P05022, DOI:10.1088/1748-0221/20/05/P05022

Sub-keV Electron Recoil Calibration for Macroscopic Cryogenic Calorimeters using a Novel X-ray Fluorescence Source, NUCLEUS Collaboration, J.Low Temp.Phys. (2025), DOI:10.1007/s10909-025-03330-2

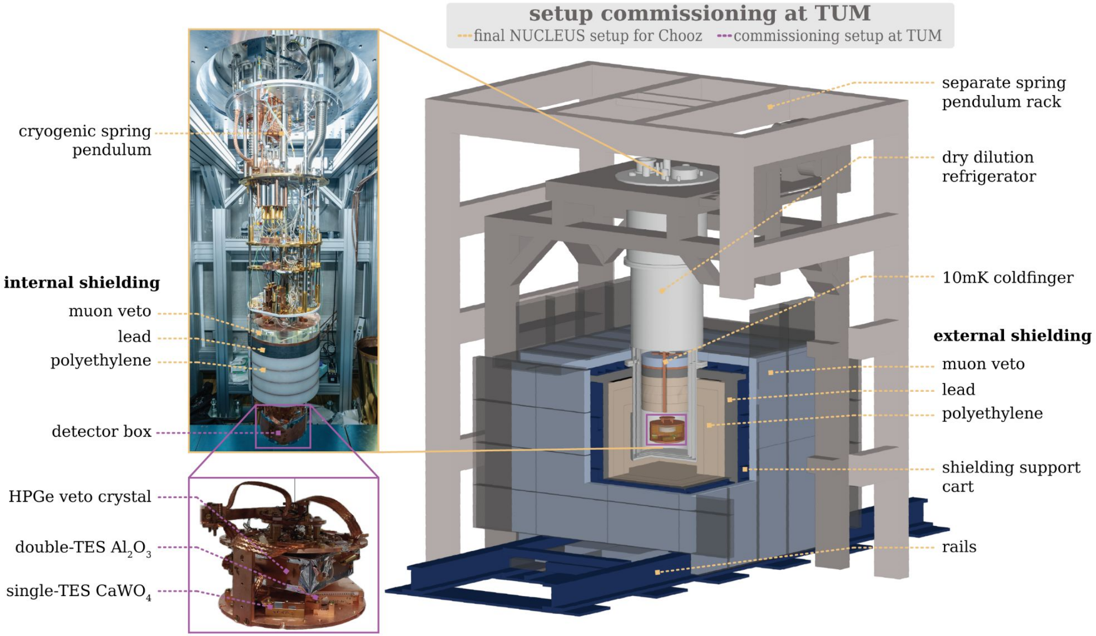
Commissioning of the NUCLEUS Experiment at the Technical University of Munich, NUCLEUS Collaboration, American Physical Society (PRD), DOI:10.1103/c95p-8kh2

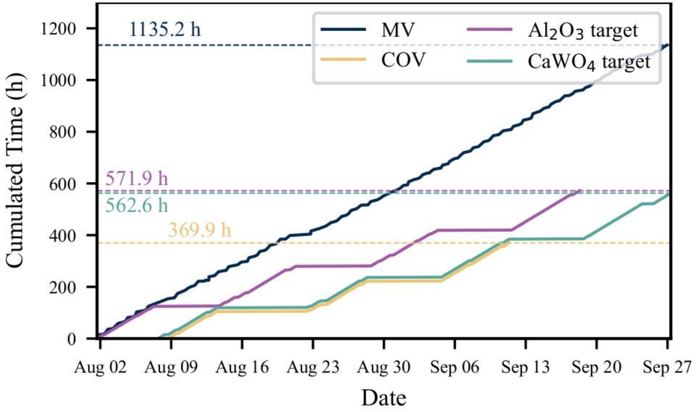
Particle background characterization and prediction for the NUCLEUS reactor CEvvNS experiment, NUCLEUS Collaboration, DOI:10.48550/arXiv.2509.03559

Thank you for your attention!

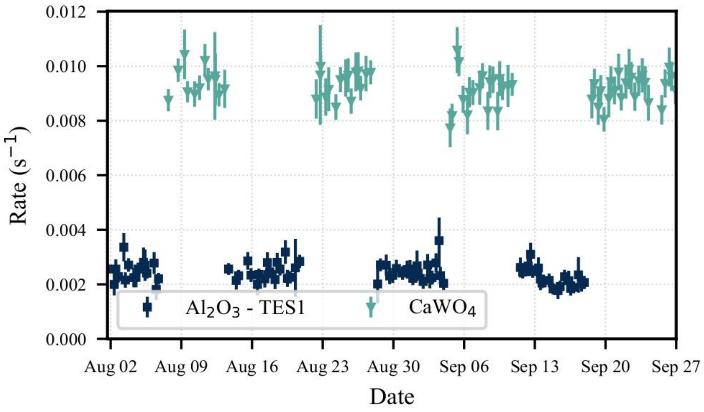
Backup: Commissioning Run at TUM

- Concluded in summer 2024 in the UGL (TUM); **it's a milestone for the experiment**
- **Essential version of the experiment tested**
  - Limited by the old DAQ of the experiment at the time
  - B_4C to be tested soon (crucial for neutron reduction)



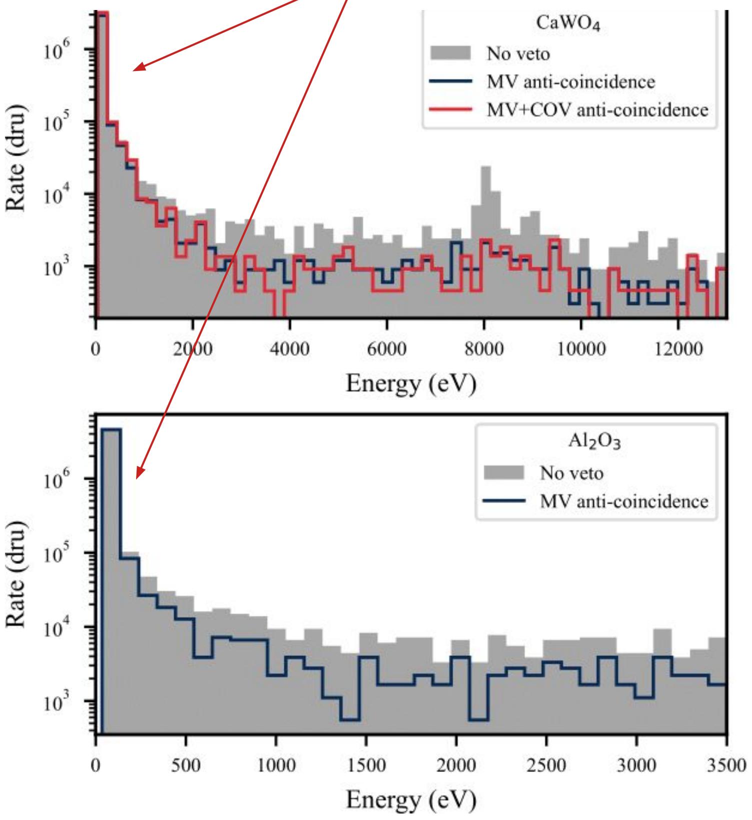


Cumulated time and TESs stability over time measured during the run



BU: Commissioning Run at TUM : results

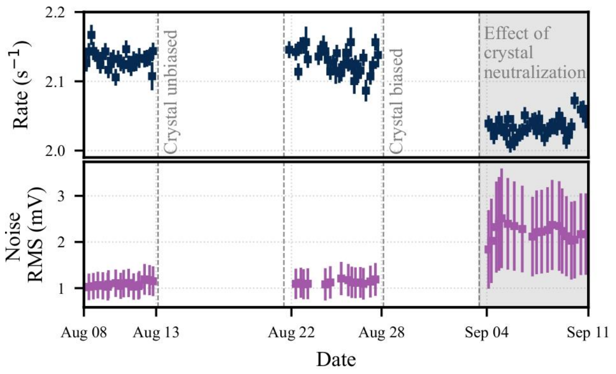
Low Energy Excess



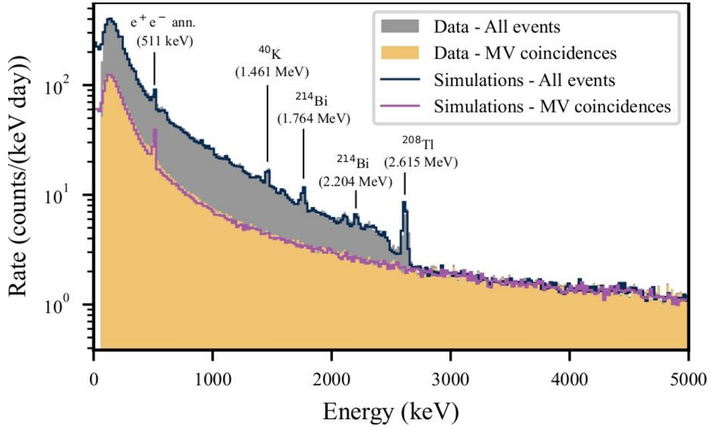
TESs energy spectra with vetoes coincidences

Main results:

- ✓ **All** installed **parts of the detector worked together**
- ✓ Quite **stable operation of all parts for the entire duration** of the run (~2 months)
- ✓ **Validation of shielding strategy**
- ✓ **Good agreement with simulations** (above 1 keV)



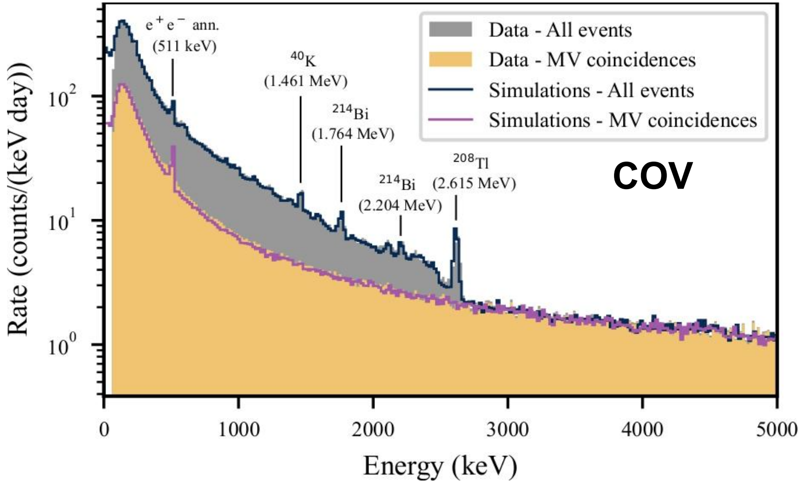
COV stability over time

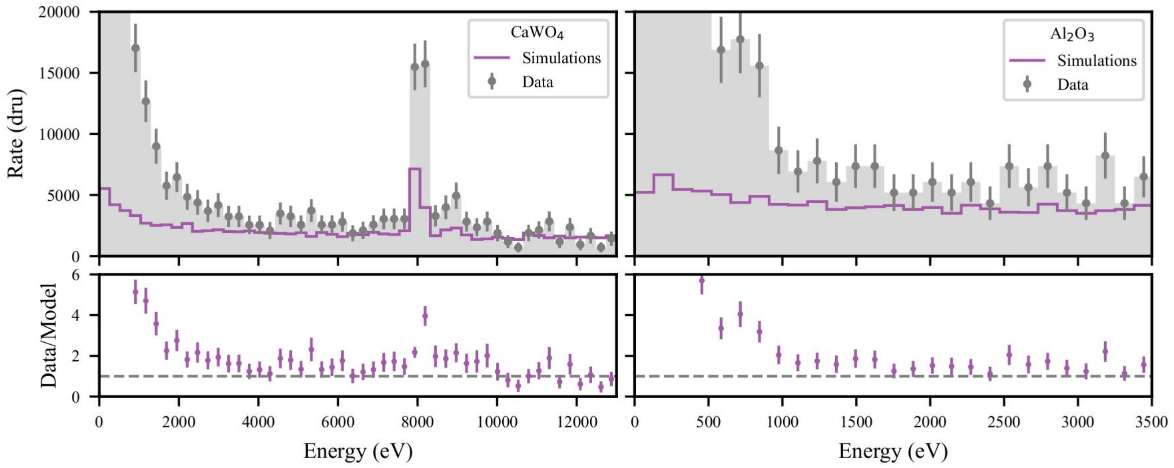


COV Energy Spectrum

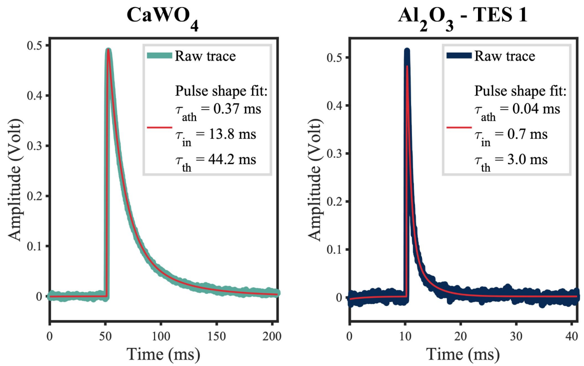
[NUCLEUS collaboration: Commissioning of the NUCLEUS Experiment at the Technical University of Munich (arXiv:2508.02488)]

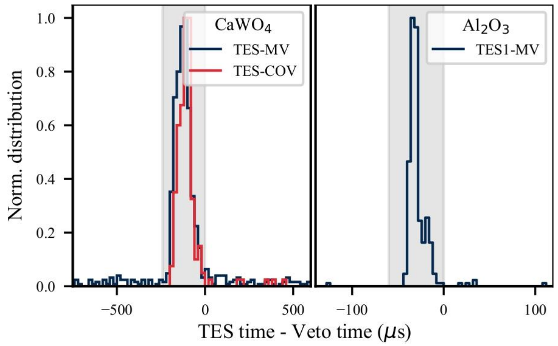
Backup: Commissioning Run at TUM

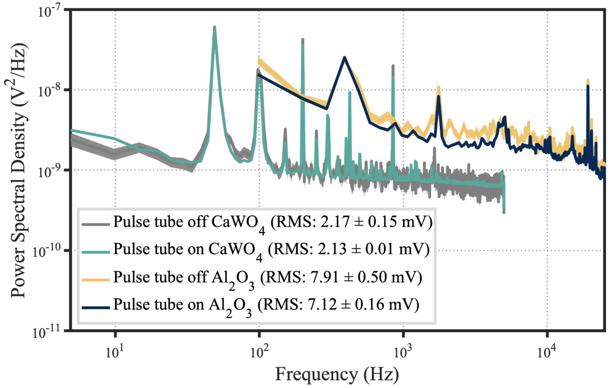




NB: UGL is at ≈ 15 m.w.e. depth



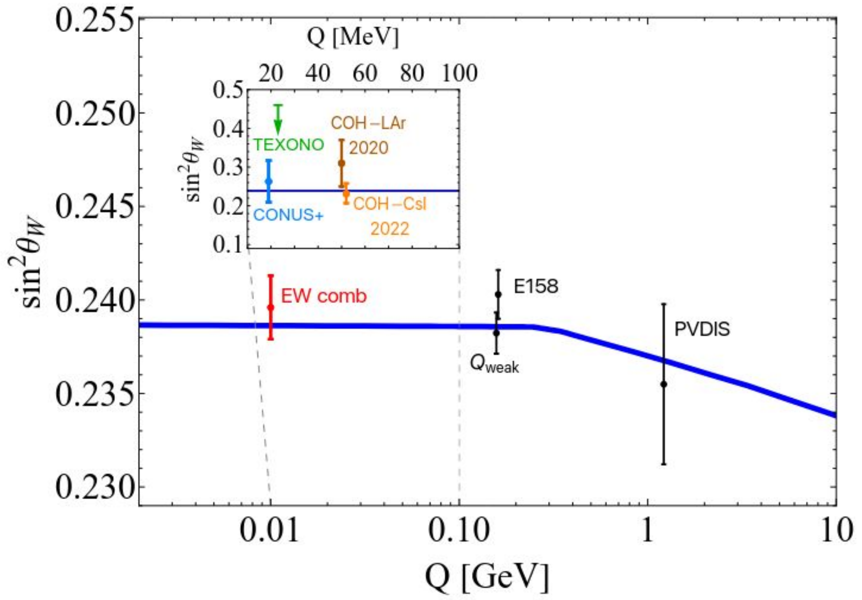




Backup: CEvNS Physics reach

$\sin^2\theta_W$ at low momentum transferred

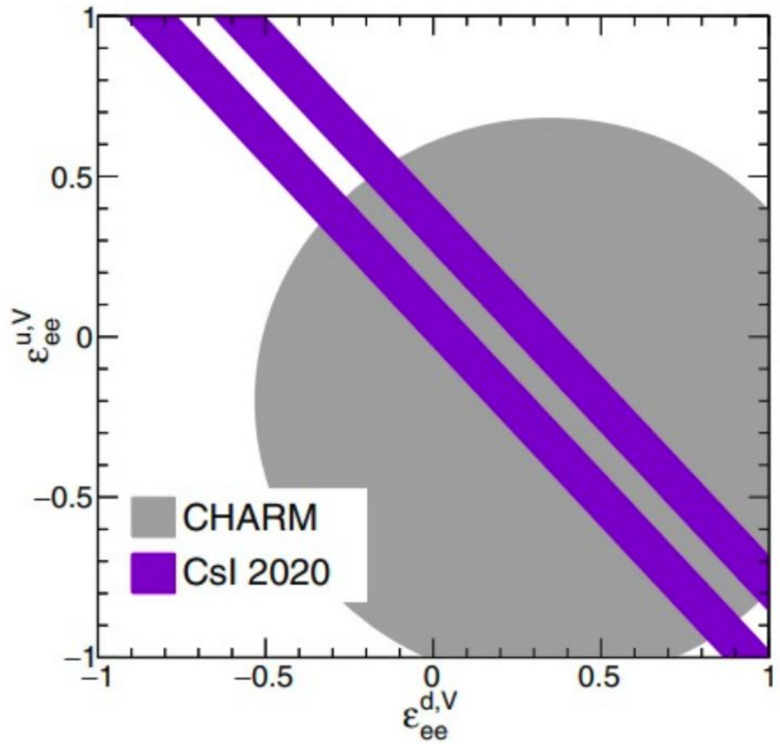
$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2 \qquad Q_W = N - Z(1 - 4\sin^2\theta_W) \sim N$$



Phys.Rev.D 112 (2025) 1, 015007

Non standard interactions (NSI)

$$\mathcal{L}^{\mathrm{NSI}} = -\epsilon_{\alpha\beta}^{qV} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\mu \nu_\beta)(\bar{q}\gamma^\mu q)$$

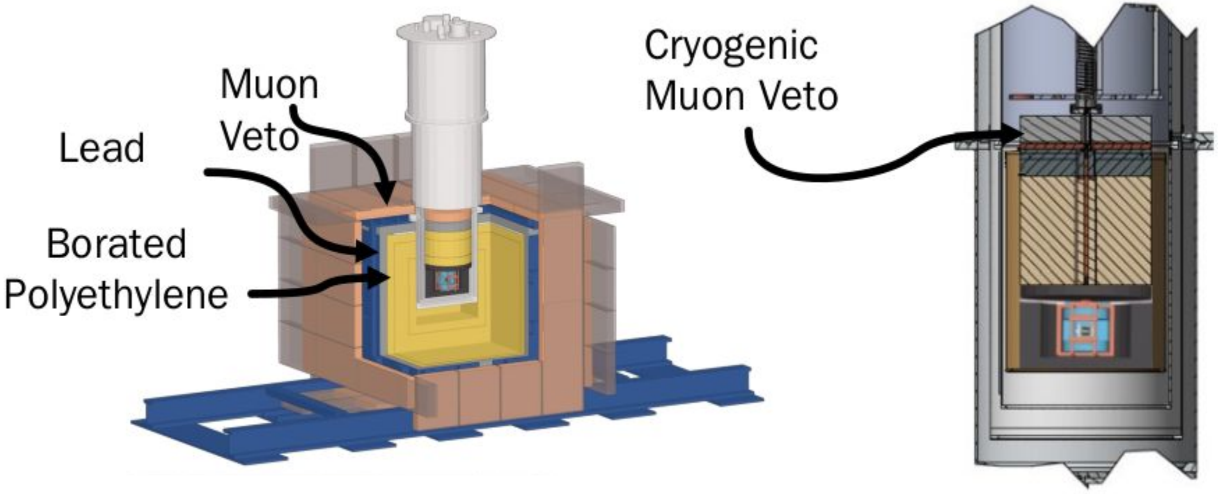


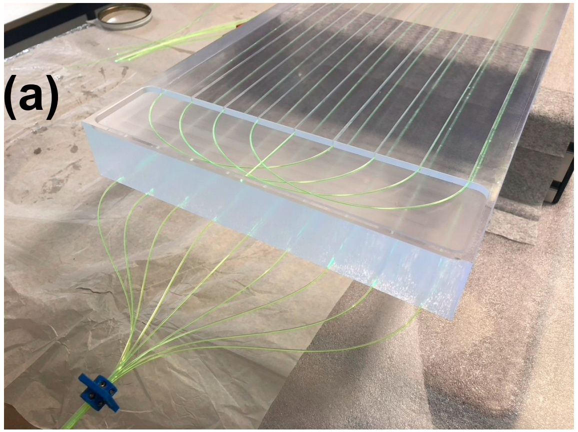
Phys.Rev.Lett. 129 (2022) 8, 081801

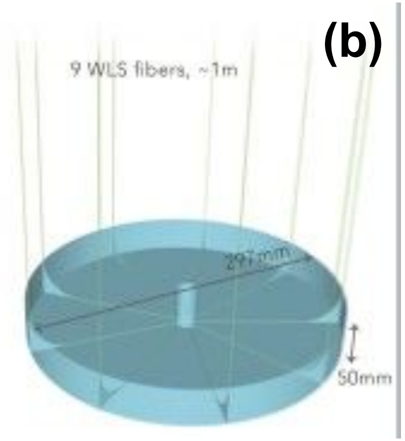
Backup: Muon Veto

Muon Veto:

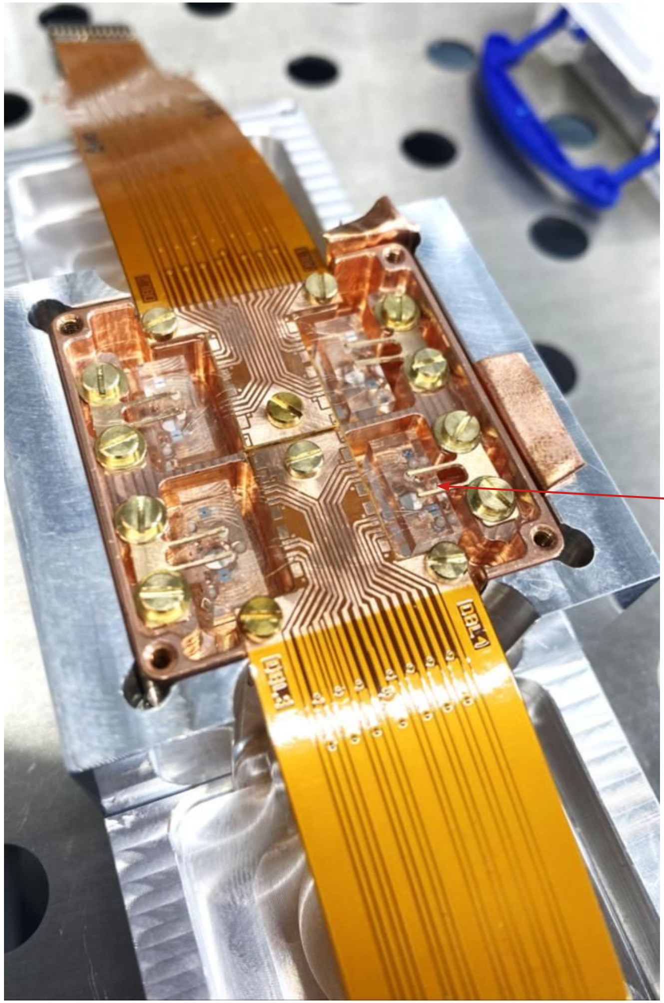
- Made of 5 cm thick **plastic scintillators** with **SiPM & WLS-fiber readout**
- **High efficiency** for muon detection (>99%)
- Expected **μ counting rate of ~325 Hz** (induced dead time on target detectors <10%)
- **4π coverage of the set-up**
- Consists in **2 different parts**:
  - **Warm part**: 28 rectangular plates (a)
  - **Cold part**: 1 cylindrical plate (b)



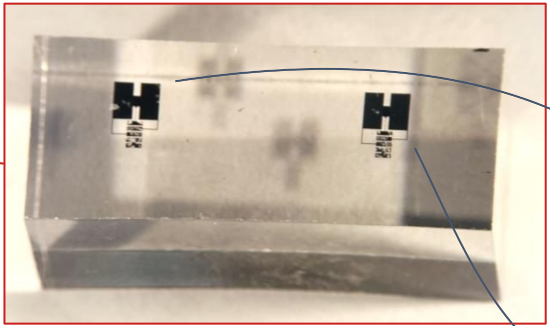


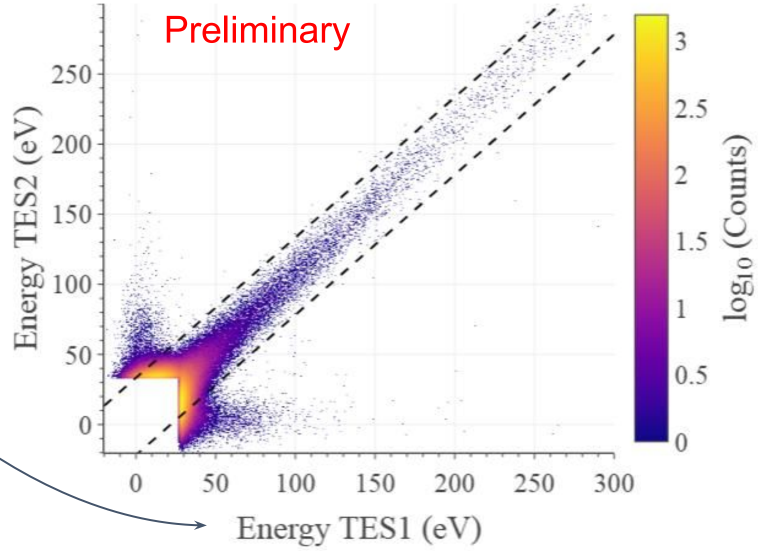


Backup: Minimal Detector Module



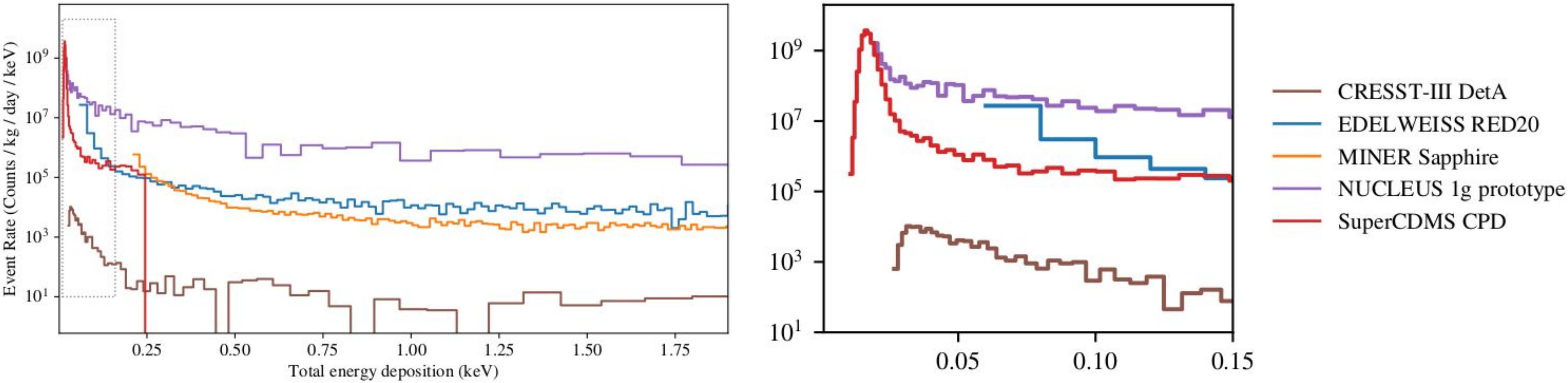
- **4 x $CaWO_4$ detectors with double-TES**, inside minimized copper encapsulation (**compatible with technical run @Chooz**)





Baseline resolution is 3-6 eV (for the first detectors and the first test)

Backup: Excess Background



P. Adari, et al.: EXCESS workshop: Descriptions of rising low-energy spectra SciPost Phys. Proc. 9 (2022) 001

Not understood *excess* background rising at low energies:

➔ **Phonon bursts** (crystal-support friction) **?**

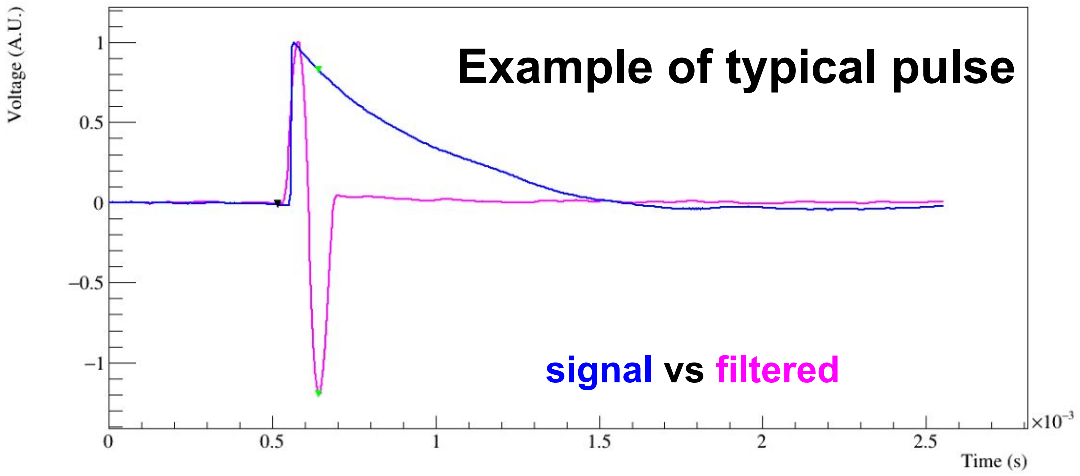
➔ **Phonon leakage** from interactions in the supports **?**

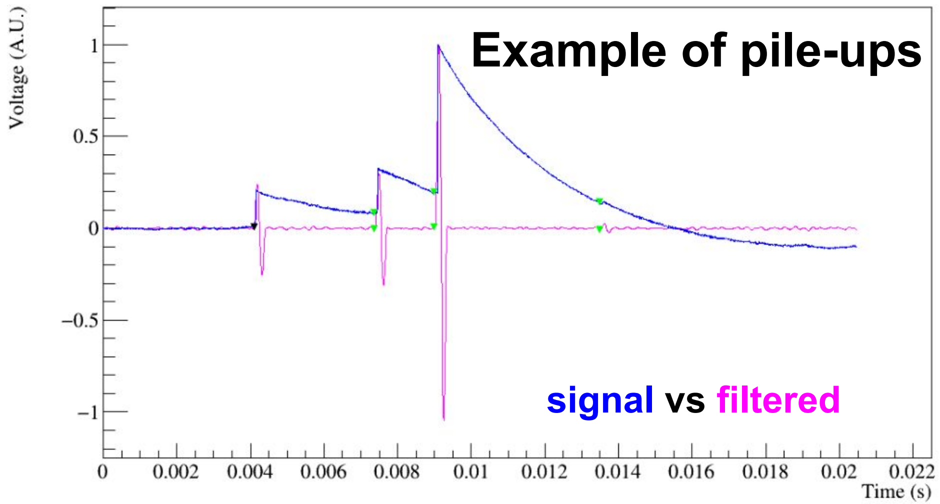
➔ **Lattice relaxations** after cool down **?**

➔ ~~Neutrons (cosmic ray induced, radioactivity) ?~~ **(excluded)**

- **This background limits NUCLEUS sensitivity**
- **Paper in preparation** with the latest results

Backup: Examples Trapezoidal Filter



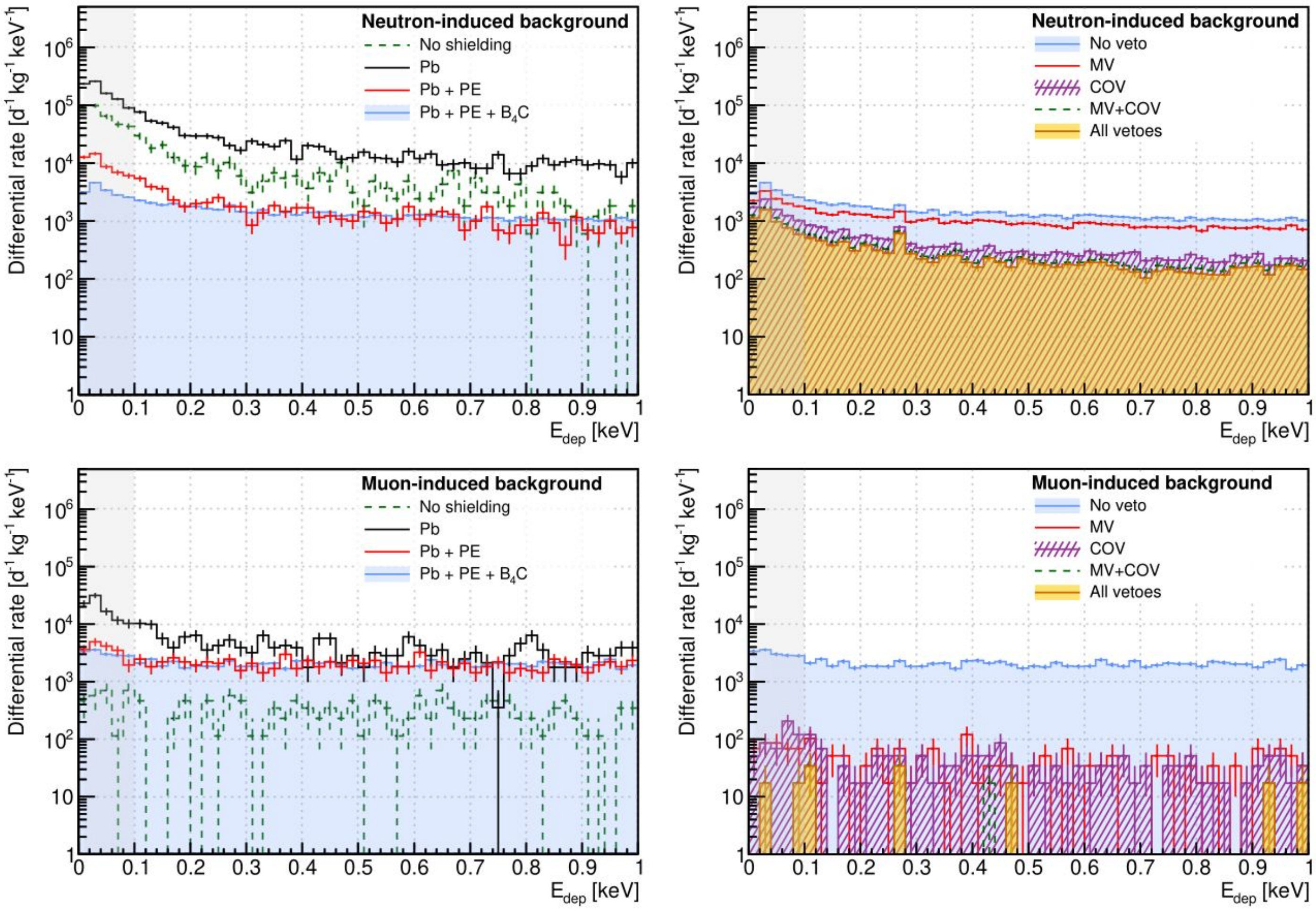


Improvements wrt standard Trapezoidal filter algorithm:

- **Zero baseline granted**
- **From 6% to 1.5% resolution on ^{137}Cs peak** (662 keV) on average on COV crystals

Backup: Neutron and muon background

[NUCLEUS Collaboration: Particle background characterization and prediction for the NUCLEUS reactor CEvNS experiment (arXiv:2509.03559)]



Backup: Gamma induced background

NUCLEUS Collaboration: Particle background characterization and prediction for the NUCLEUS reactor CEvNS experiment (arXiv:2509.03559)

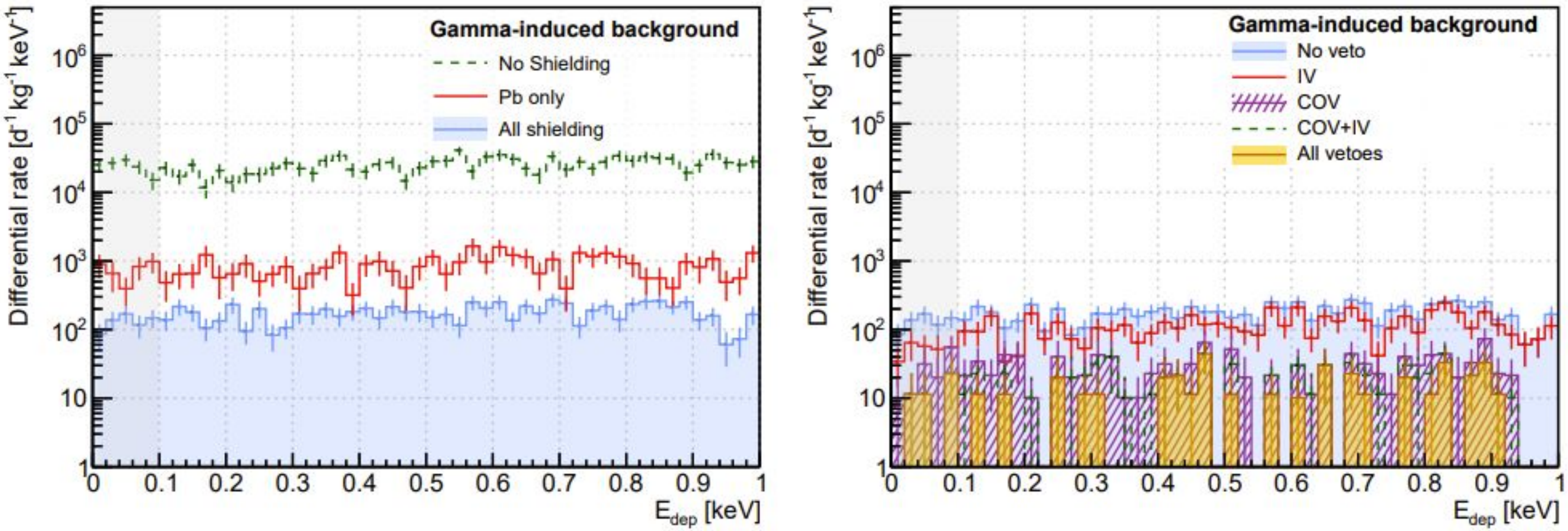


Figure 9: Reduction of the ambient gamma ray-induced backgrounds with the NUCLEUS shielding. Each histogram shows the rate of events with deposited energy between 0 and 1 keV in the $CaWO_4$ array of target detectors. Uncertainties are statistical only. The impact of the NUCLEUS setup passive materials is shown on the right panel. The left panel illustrates the complementary rejection brought by the use of the IV and COV. The CEνNS RoI is indicated by the light gray filled area.

Backup: NUCLEUS Sensitivity

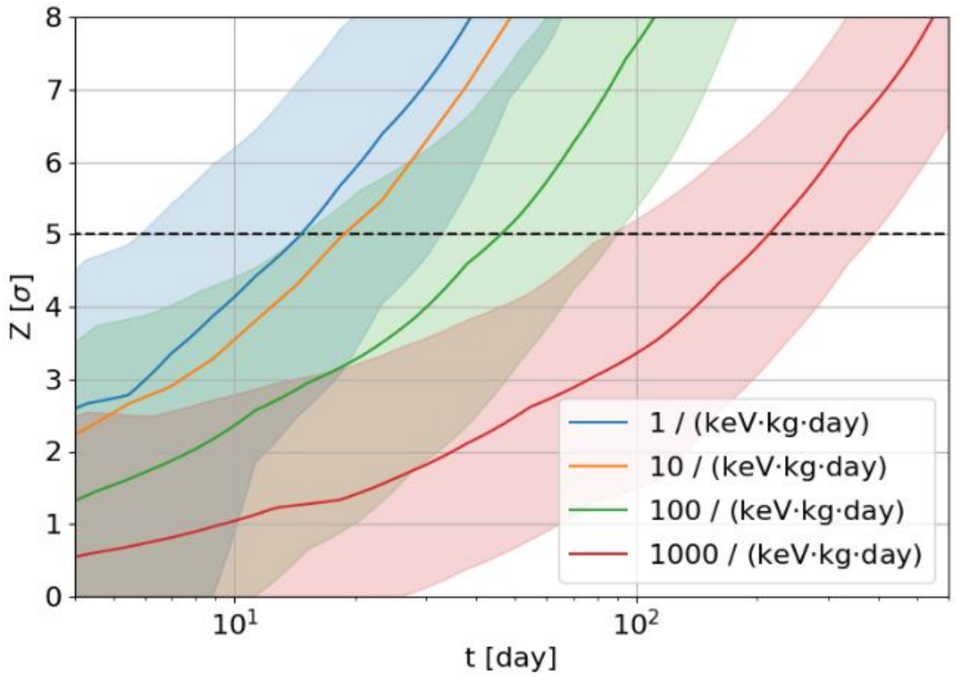


Figure 11: Statistical significance of CEνNS observation as a function of live time for NUCLEUS-10g, for different background indices, using the expected neutrino flux at the VNS and an energy threshold of 10 eV. For each background index, the median line and 90% probability bands (computed from 600 simulated random spectra at each point) are shown. For the background index of 10 counts/(keV·kg·day), only the median line is shown for clarity.