# Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) with NUCLEUS experiment

Giammei Marco on behalf of the NUCLEUS collaboration - WIN2025 - 10 June 2025

INFN

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

EXPERIMENT
nucleus

# The NUCLEUS Experiment

## NUCLEUS Aim:

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

## NUCLEUS Location:

- **Measurements**: Chooz-B 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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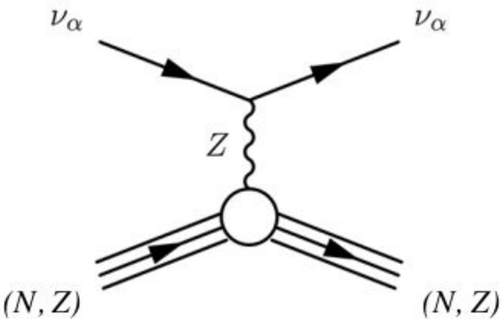
cea

# CEvNS

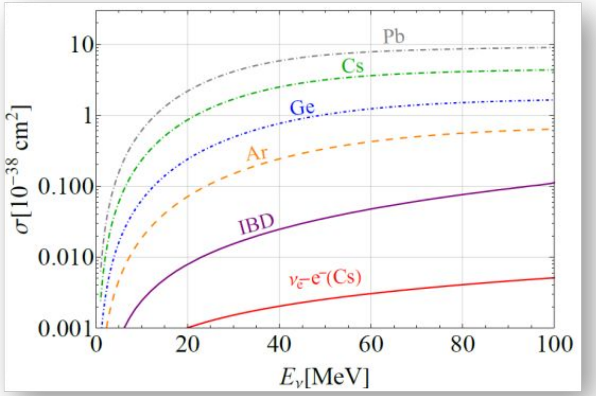
- The **Coherent Elastic Neutrino-Nucleus Scattering** (CEvNS) was **predicted within the Standard Model in 1973**
- It was **firstly observed in 2017** by the COHERENT collaboration
- Although the cross section is 2 odm greater than the inverse β decay (the other main process studied using reactor ν), the recoil energy (the observable) is 4 odm smaller (see below)



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

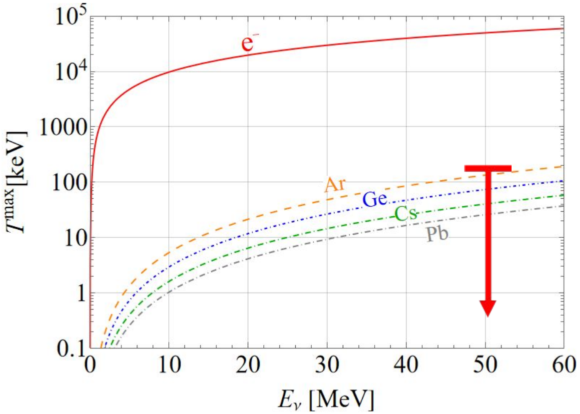
$$Q_W = N - Z(1 - 4\sin^2\theta_W) \sim N$$

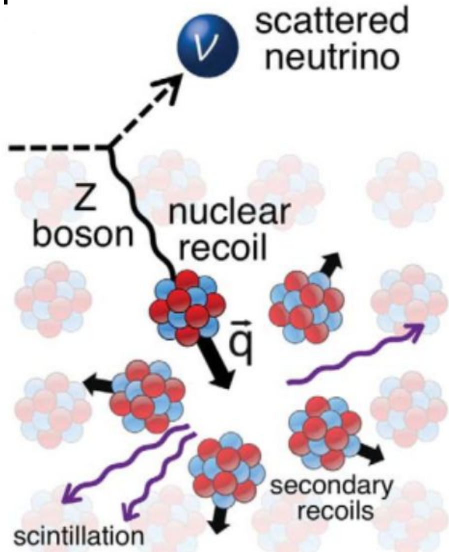
**CEνNS Cross Section ∝ $N^2$**



**Observable**: kinetic energy of nuclear recoil

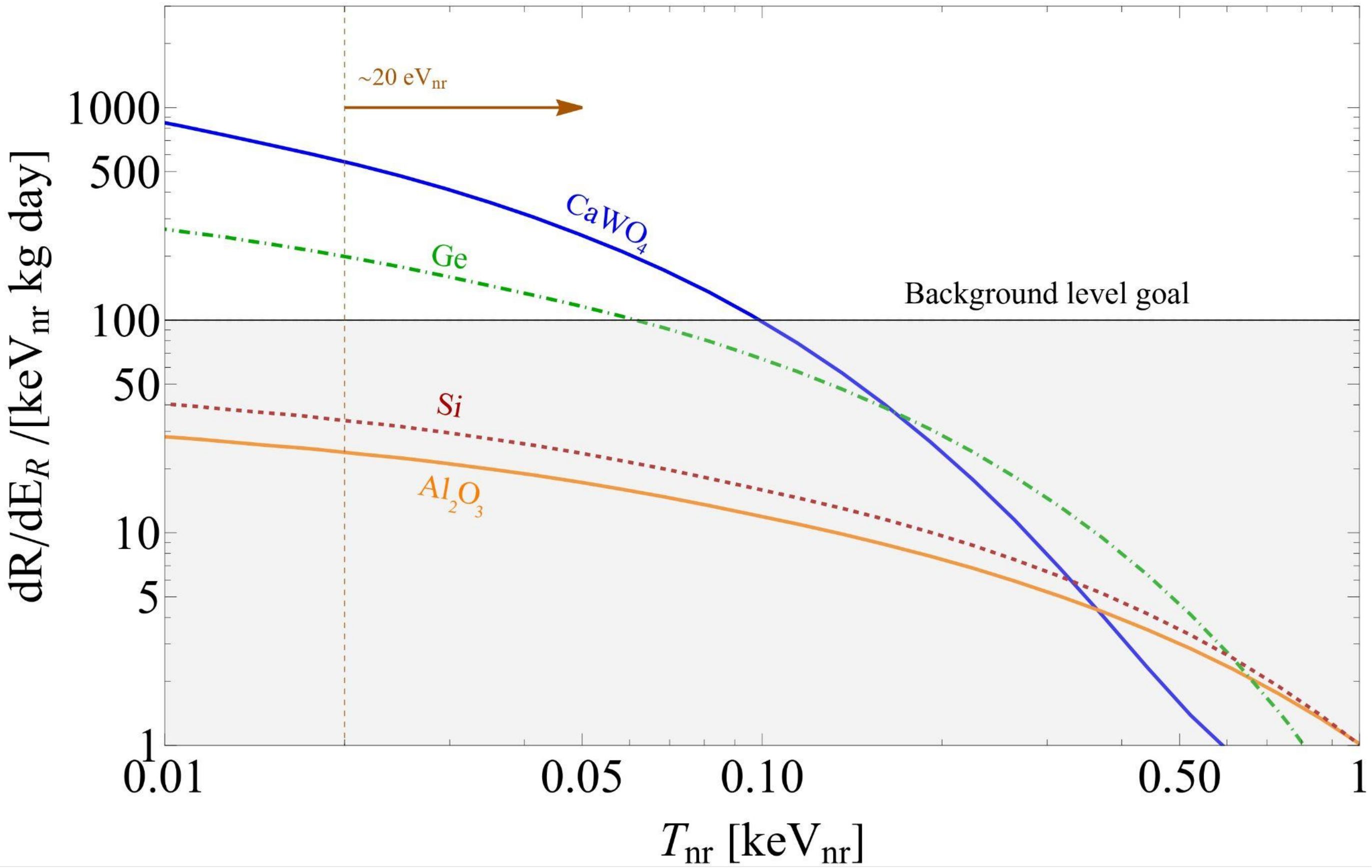
$$T^{\max} = \frac{2E_\nu^2}{m_{\mathrm{target}}}$$





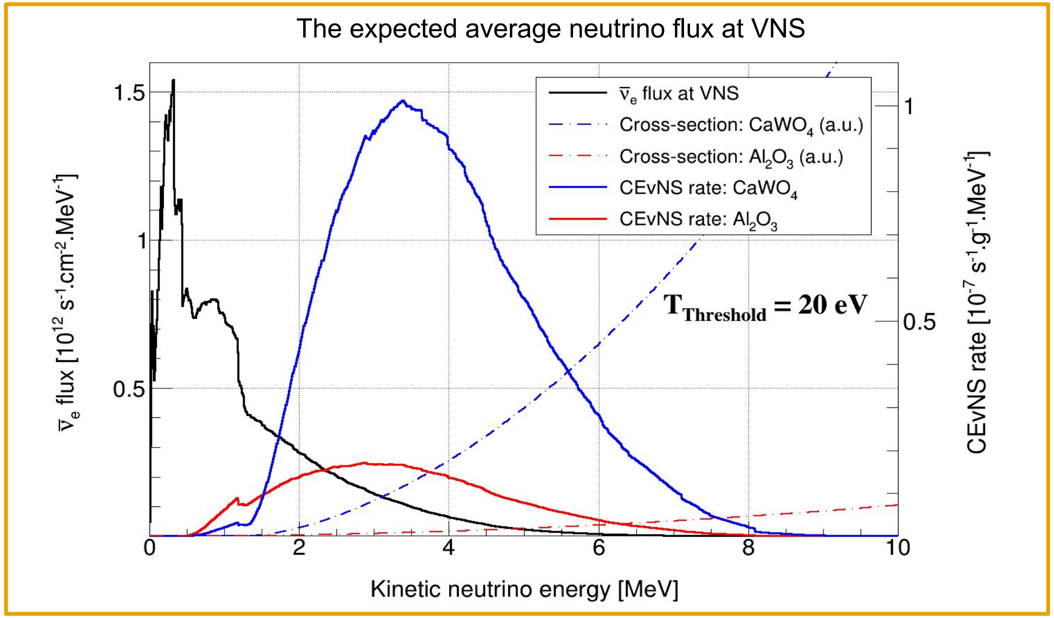
# CEvNS Signal at Nuclear Reactors

- **Nuclear Reactors are intense source of anti-neutrinos**, around $10^{20}$ neutrinos per GW per second
- The majority of this anti-neutrinos have **energy $E_\nu$ < 8 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**

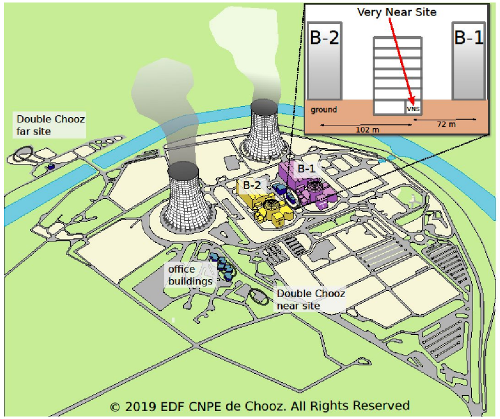


# NUCLEUS Location: The VNS

- The **experimental site** (VNS) is located at 102 m and 72 m from the 2 reactors of the Chooz B plant, **<u>at ≈ 3 m.w.e. depth</u>**
- Cosmic-ray induced **neutrons will be challenging to mitigate** with such a low overburden <u>(paper in preparation for a background prediction)</u>


The expected average neutrino flux at VNS

- **Reactor nominal thermal power**: 2 x 4.25 GWTh
- **Expected ν flux to reach the detectors**: $1.7 \cdot 10^{12}$ ν/s/cm$^2$



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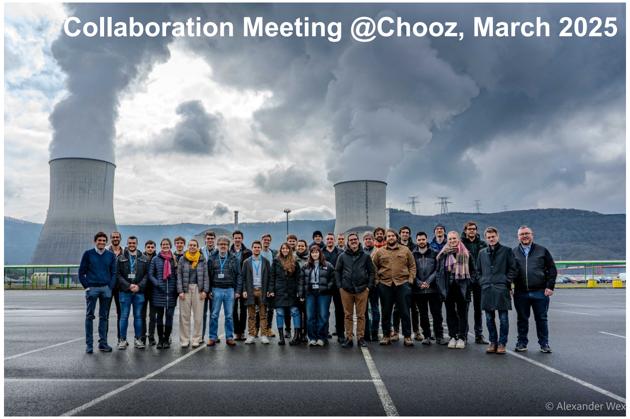
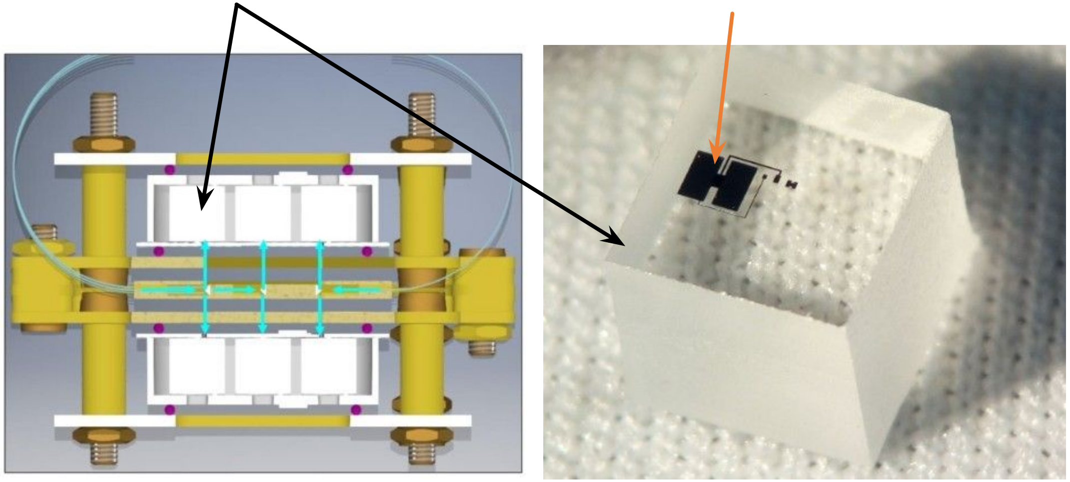

Collaboration Meeting @Chooz, March 2025
© Alexander Wex

# NUCLEUS Cryogenic Target Detector

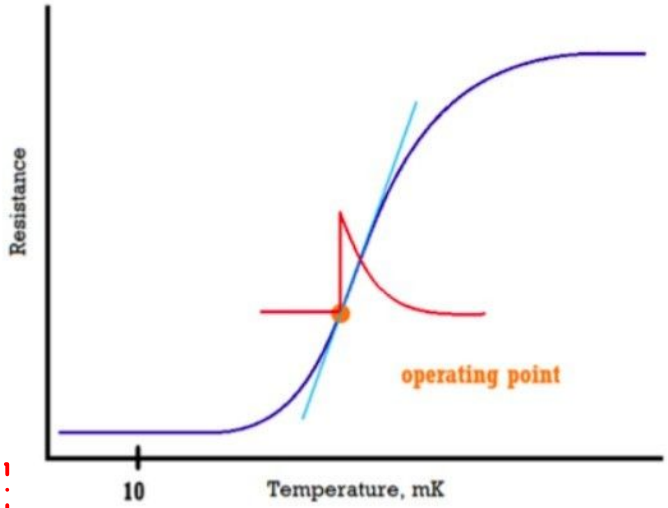
Absorber crystals + Transition Edge Sensors (TES)



**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



Superconducting transition curve

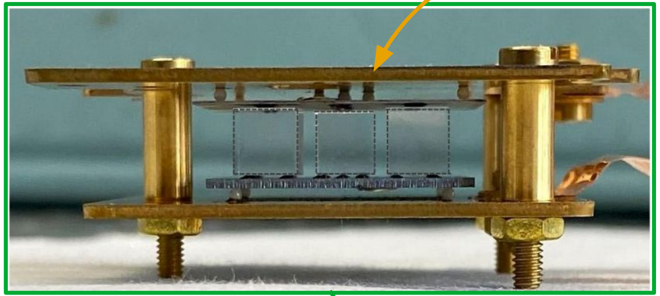
**Multitarget approach:**

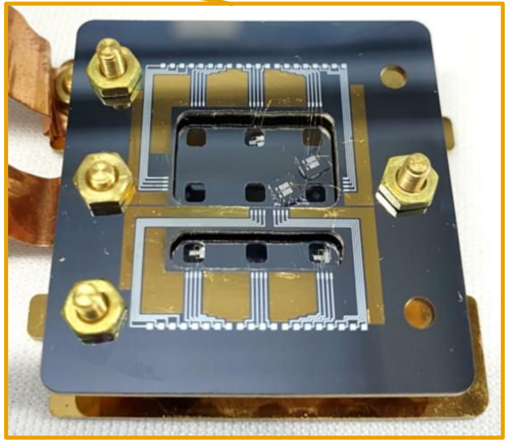
- **$Al_2O_3$:** used to probe background
- **$CaWO_4$:** similar background to $Al_2O_3$ but higher CEvNS rate

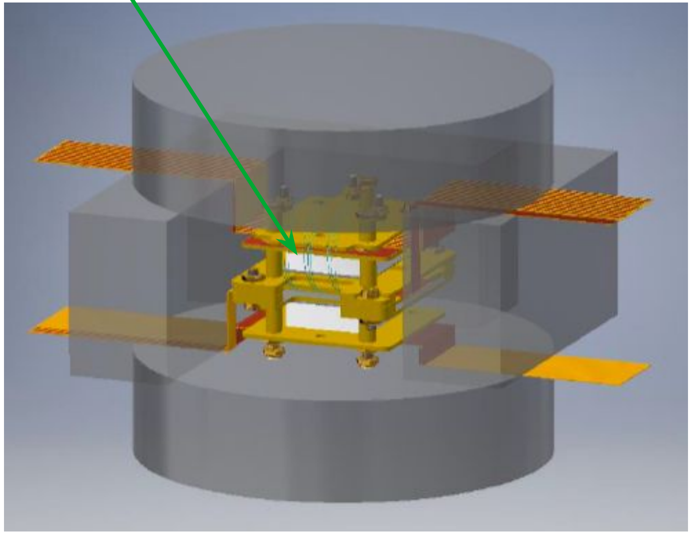
# Inner and Outer Cryogenic Vetoes

## Inner Veto:

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







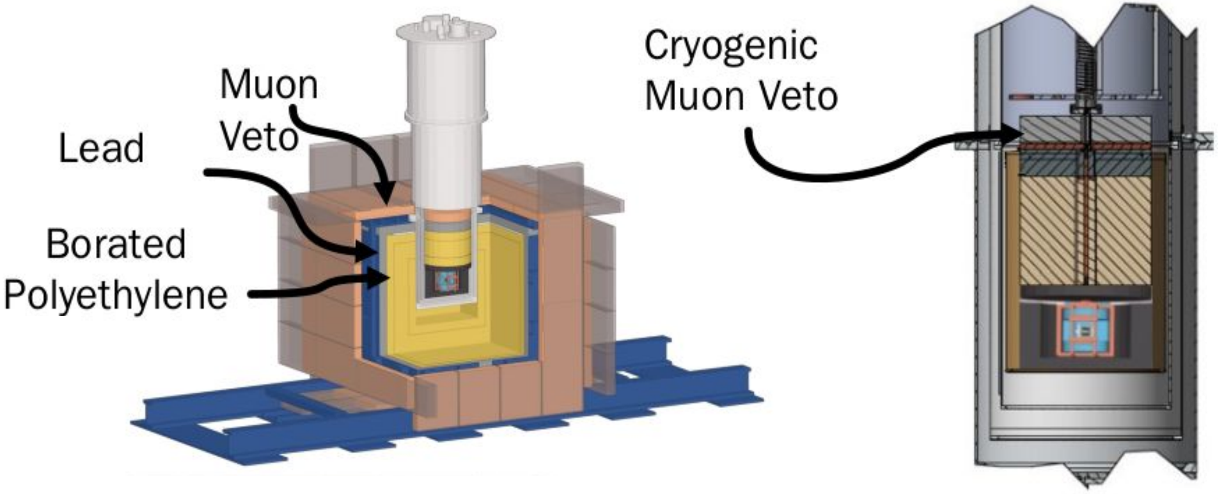
## Outer Veto:

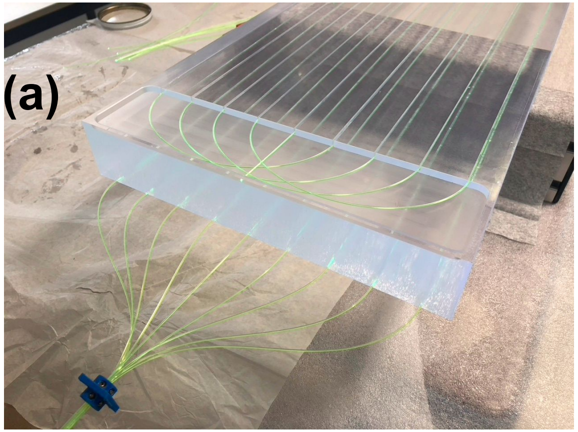
- **6 HPGe crystals** (2 cylindrical and 4 rectangular) of 2.5 cm thickness (under commissioning)
- Surround the inner detectors for **active γ and neutron background rejection** (almost 4π covering)

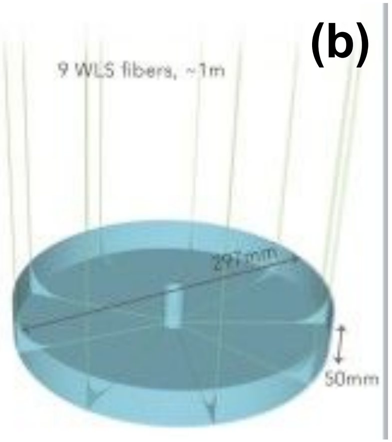
# Muon Veto

## 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)



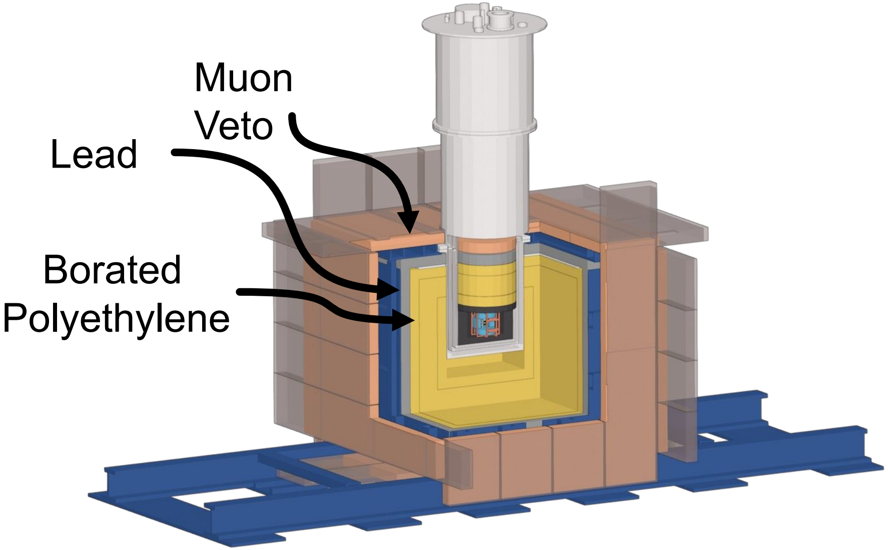


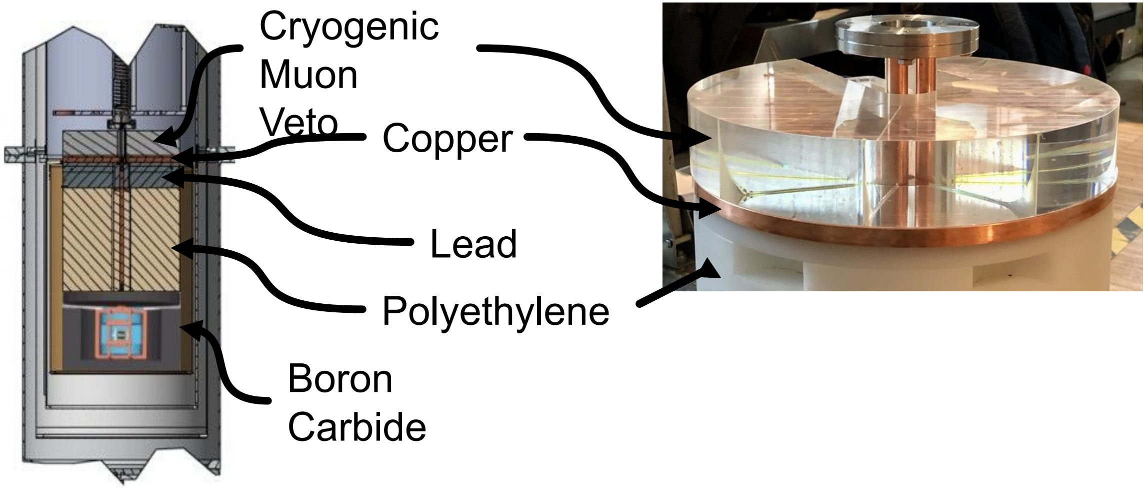


# Passive Shielding

## Inner Shielding:

- **Aligned with external Active and Passive shield**
- **Lead, Copper support** (acting also as a thermal contact), **PE, $B_4C$** for neutron reduction
- Thermalized at 800 mK



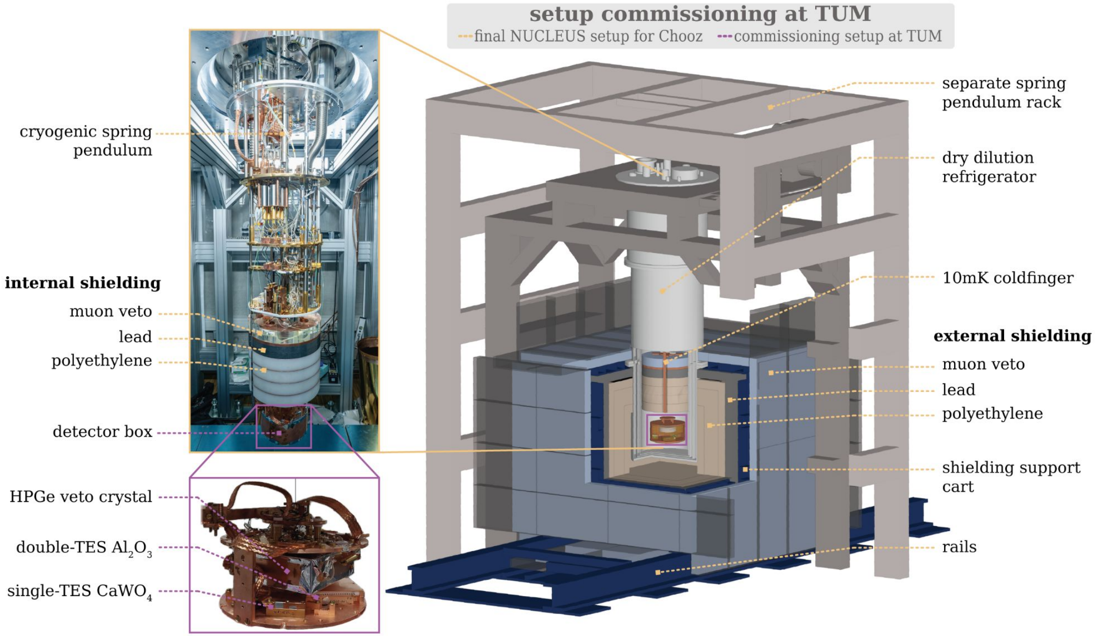


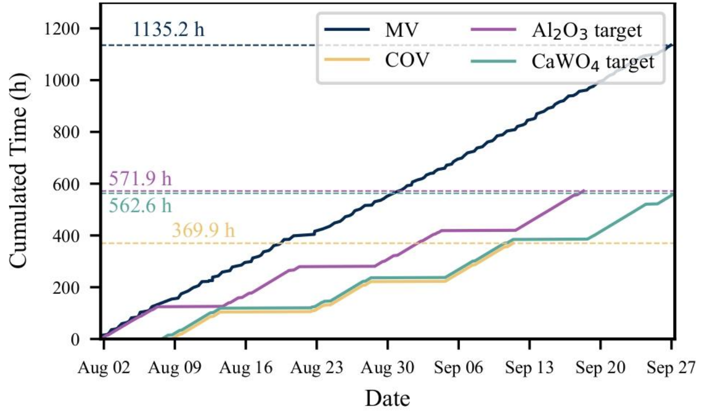
## Outer Shielding:

- **Multilayer Passive Shield**: Lead and Borated Polyethylene
- **Movable mechanical structure** to allow easy opening/closing of the external shield
- **Minimize μ induced neutrons**

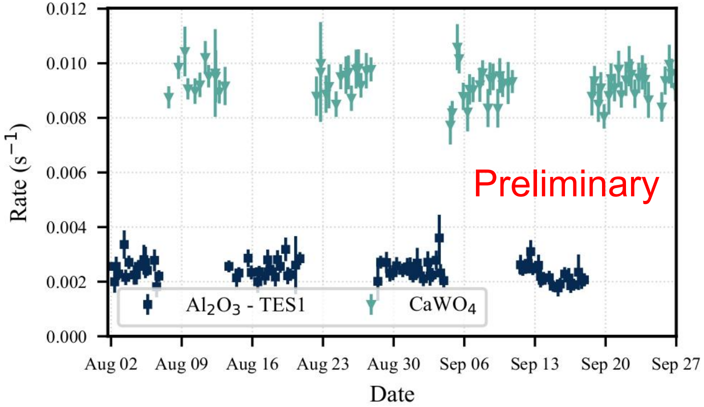
# Commissioning Run at TUM

- 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)

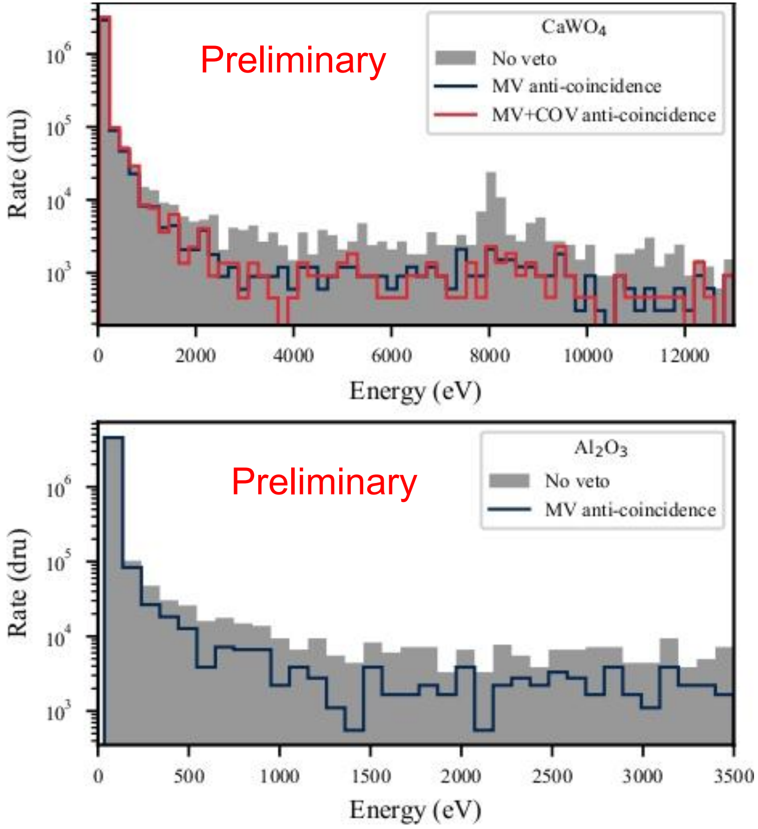




**Cumulated time and TESs stability over time measured during the run**



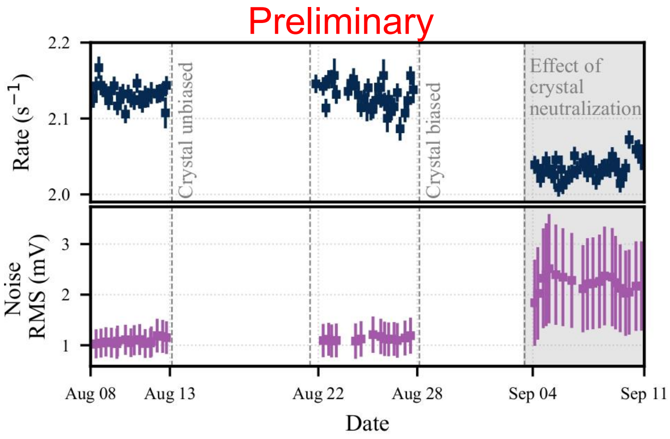
# Commissioning Run at TUM : results



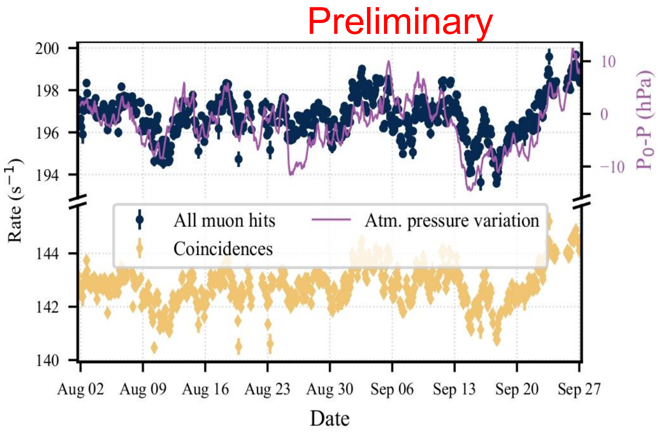
**TESs energy spectra with vetoes coincidences**

## Main results (paper in preparation):

- **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**
- **Comparison with simulations** (in progress)



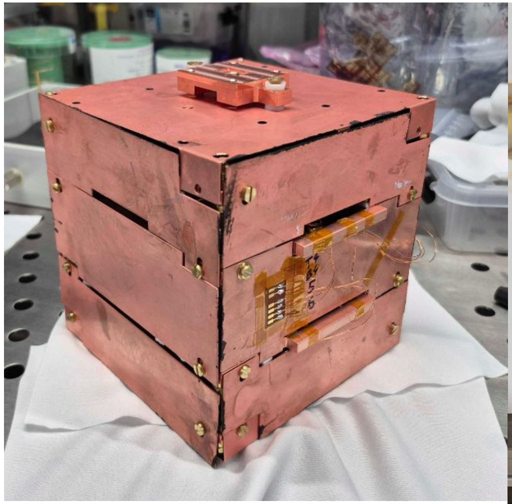
**COV stability over time**

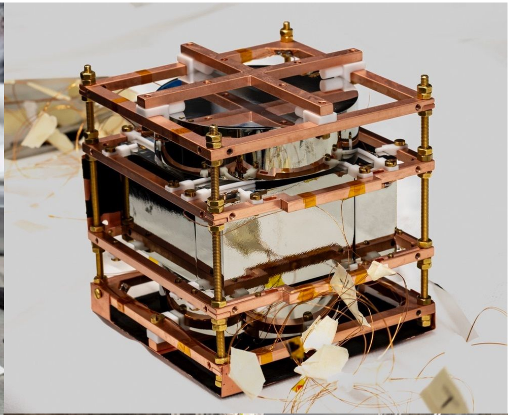


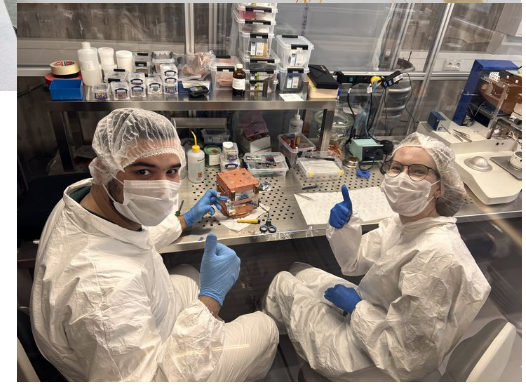
**MV stability over time**

# Ongoing: COV cage design

## V1: tests concluded

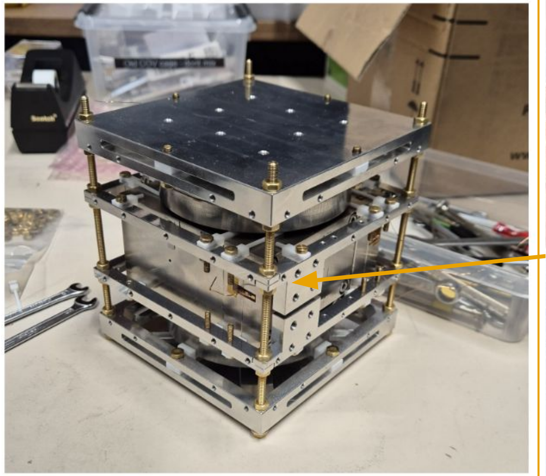


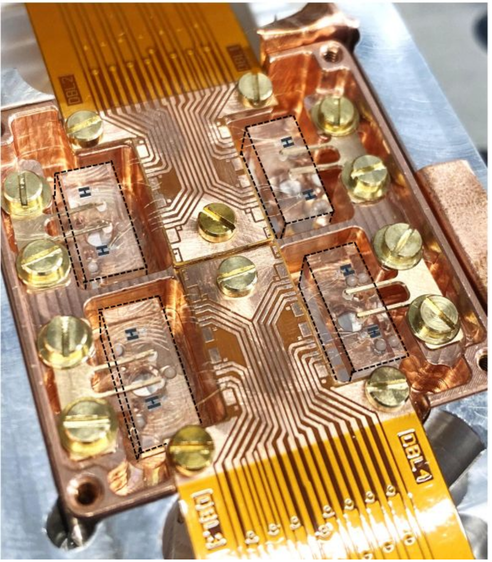




**All 6 COV crystals working together and on specs**; tests concluded 2 weeks ago (no detector module inside)

## V2: in production and to be assembled

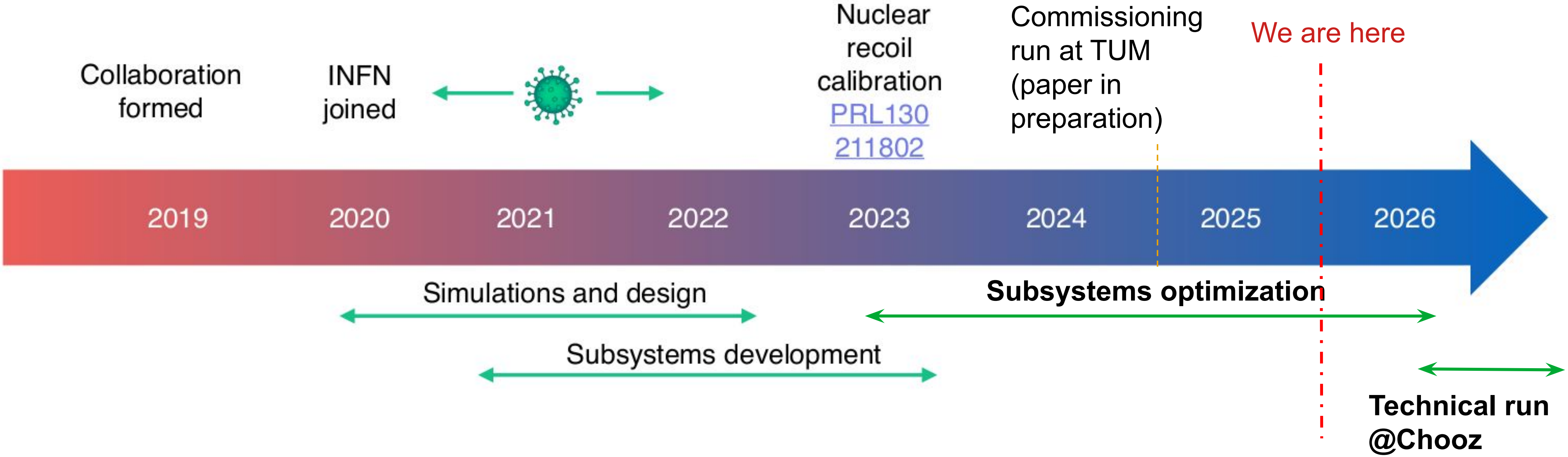




COV cage V2 mockup assembled; **the real V2 cage will be produced soon**

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

# NUCLEUS Timeline



Collaboration formed

INFN joined

Nuclear recoil calibration [PRL130 211802]

Commissioning run at TUM (paper in preparation)

We are here

2019 2020 2021 2022 2023 2024 2025 2026

Simulations and design

Subsystems development

**Subsystems optimization**

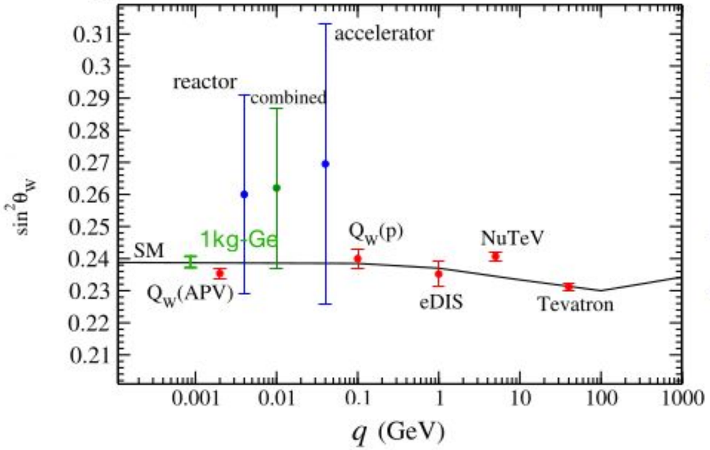
**Technical run @Chooz**

# Thank you for your attention!

# Backup: CEvNS Applications

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

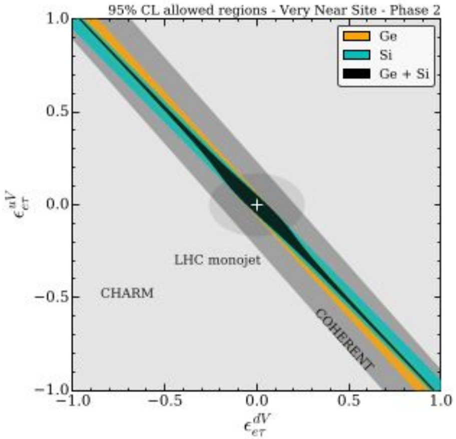
$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2 \qquad Q_W = N - Z(1 - 4\sin^2\theta_W) \sim N$$



Adapted from B.C. Cañas, et al., Phys. Lett. B 761 (2016) 450

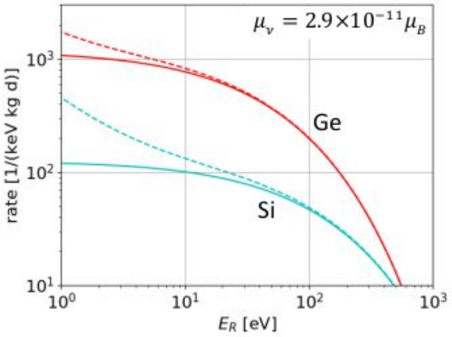
## Non standard interactions (NSI)

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



J. Billard, J. Johnston and B.J. Kavanagh, JCAP 1811 (2018) 016

## magnetic dipole moment of neutrino

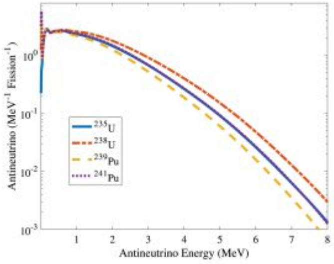


Additive component to CNNS cross-section:

$$\frac{d\sigma_{EM}}{dE_R} \sim \mu_\nu{}^2 \left(\frac{1 - E_R/E_\nu}{E_\nu} + \frac{E_R}{4E_\nu^2}\right)$$

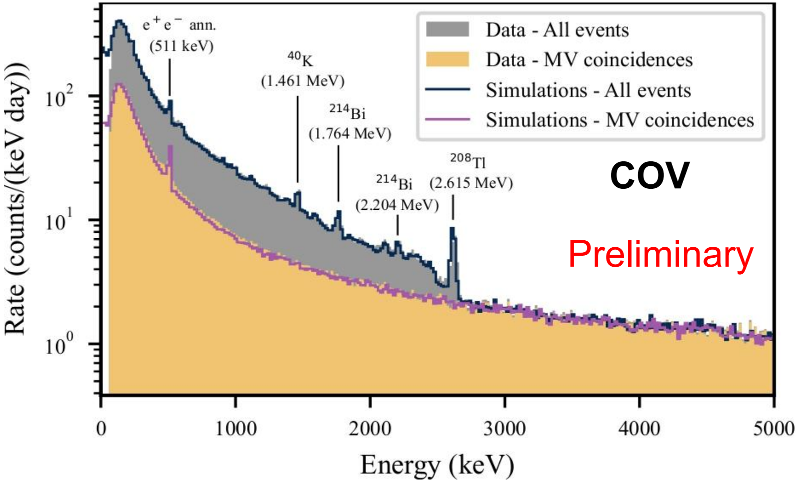
A.B. Balantekin, N. Vassh, Phys. Rev. D **89** (2014) no.7, 073013

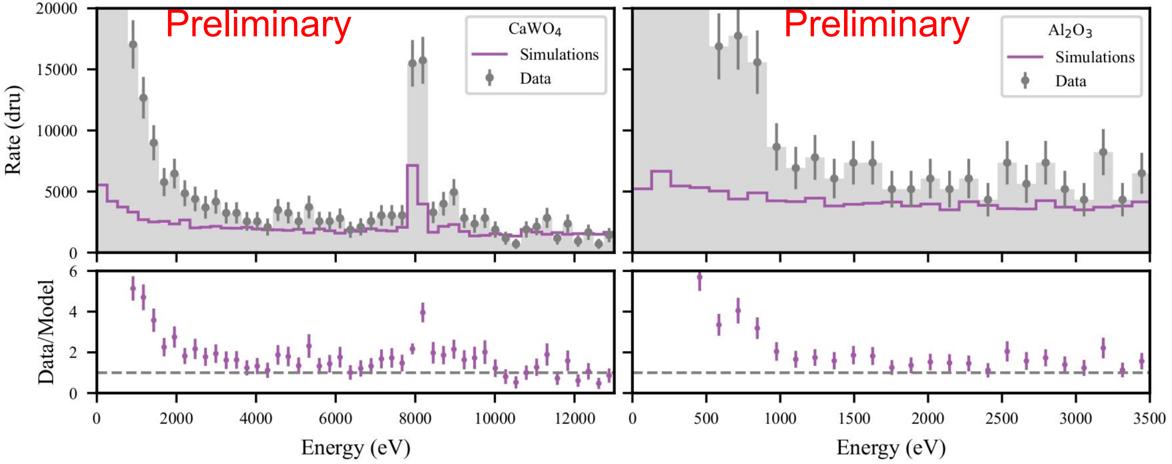
## reactor and nuclear waste monitoring



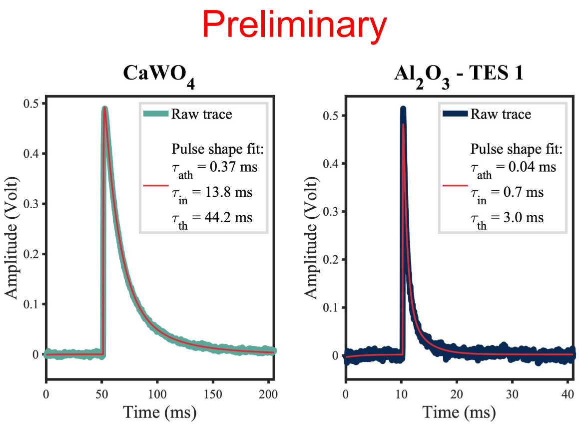
Adam Bernstein et al.: Colloquium: Neutrino detectors as tools for nuclear security
Rev. Mod. Phys 92 (2020) 011003

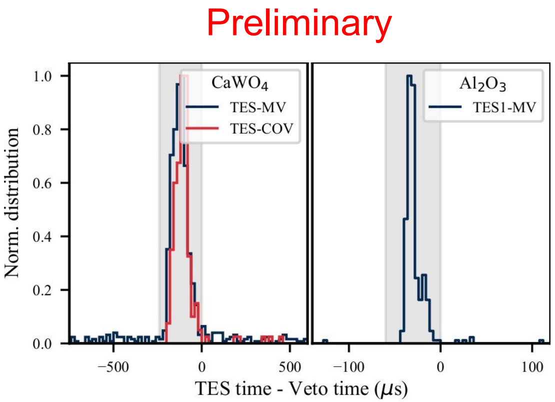
# Backup: Commissioning Run at TUM

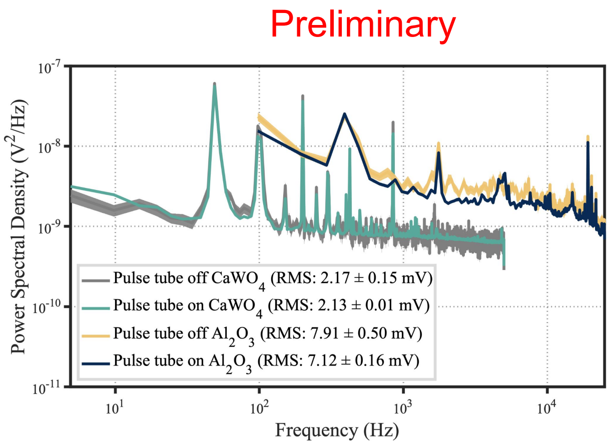




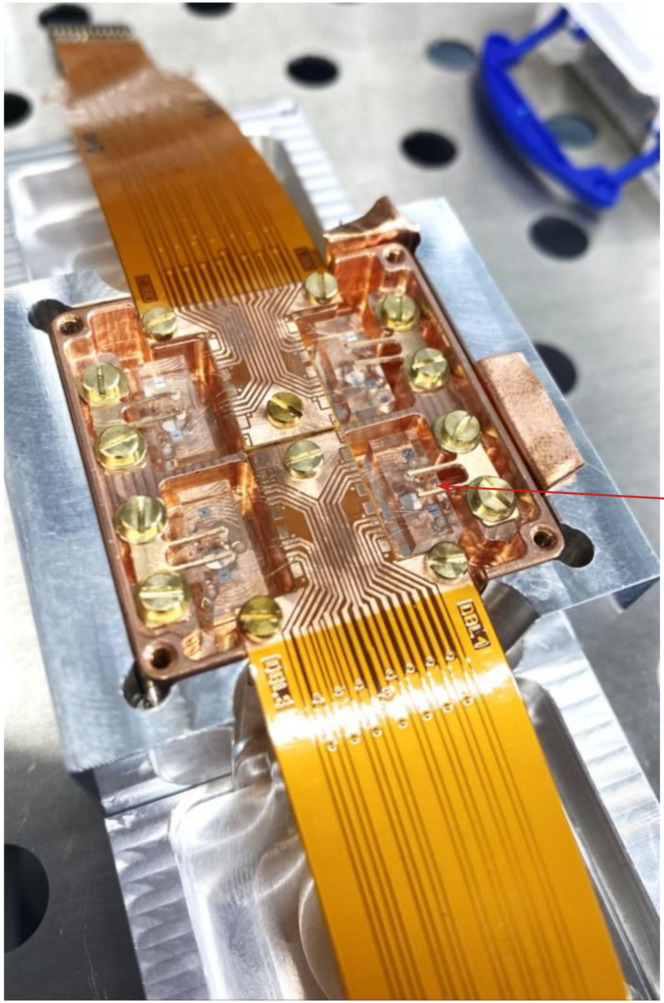
**NB: UGL is at ≈ 15 m.w.e. depth**



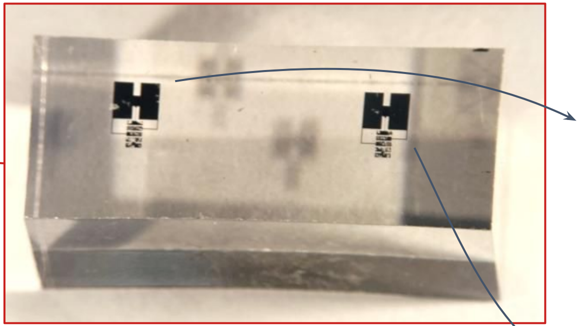


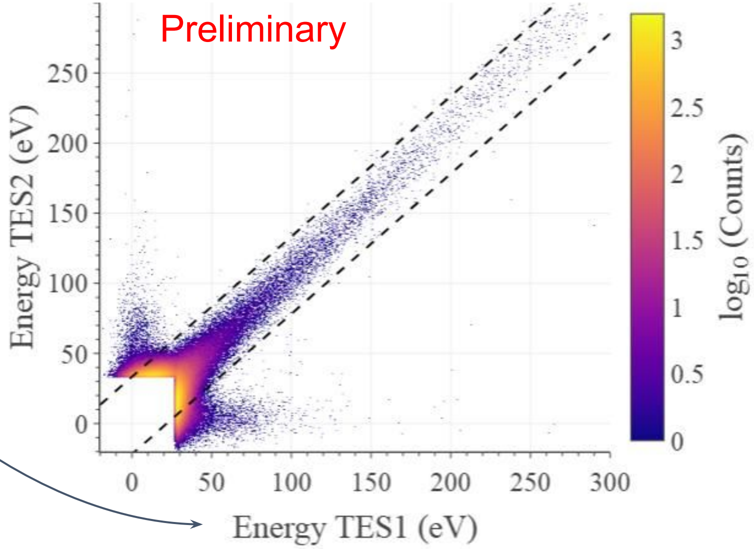


# Backup: Minimal Detector Module



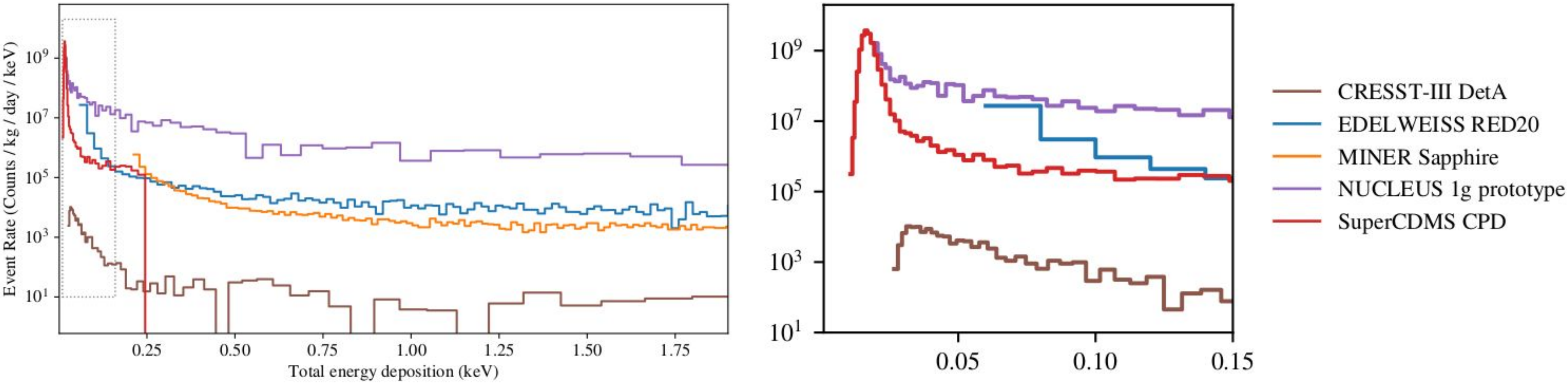
- **4 x $CaWO_4$ detectors with double-TES**, inside minimized copper encapsulation (**compatible with technical run @Chooz**)





**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