The NUCLEUS experiment for Coherent Elastic Neutrino-Nucleus Scattering

Matteo Cappelli on behalf of the NUCLEUS collaboration

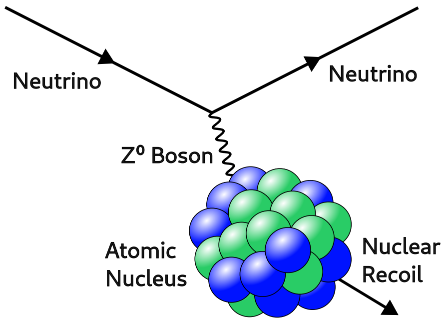
PASCOS 2026 in Sheffield

23/06/2026

Physics case: CEvNS

Coherent elastic neutrino-nucleus scattering

- A neutrino interacts with an entire atomic nucleus via neutral current
- Predicted in 1974 by Freedman Phys. Rev. D 9, 1389
- First detected in 2017 by the COHERENT experiment Science 357(6356), 1123–1126
- Neutrino interaction with the largest cross section at low energies
- No energy threshold on the incoming neutrino

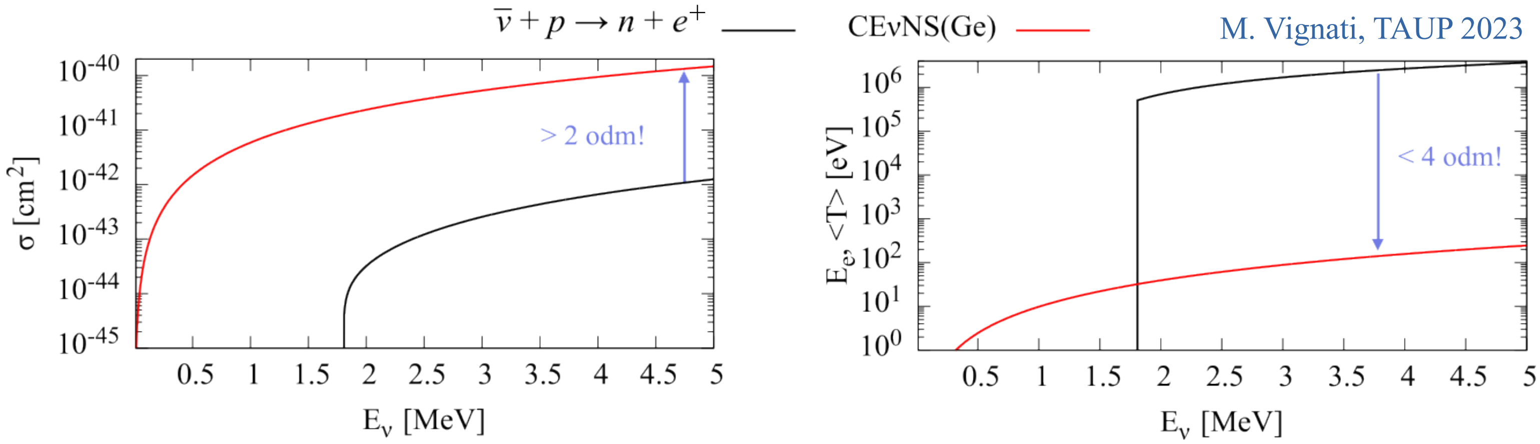


$$\frac{d\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{dT_{\mathrm{nr}}} = \frac{G_F^2 m_N}{\pi}\left(1 - \frac{m_N T_{\mathrm{nr}}}{2E_\nu^2}\right)\left[g_V^p Z F_p(|\vec{q}|^2) + g_V^n N F_n(|\vec{q}|^2)\right]^2$$

nuclear form factors

kinematics

neutrino couplings with protons and neutrons

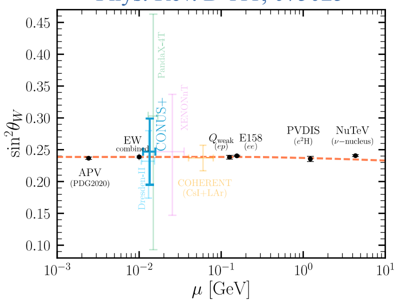


CEvNS: applications

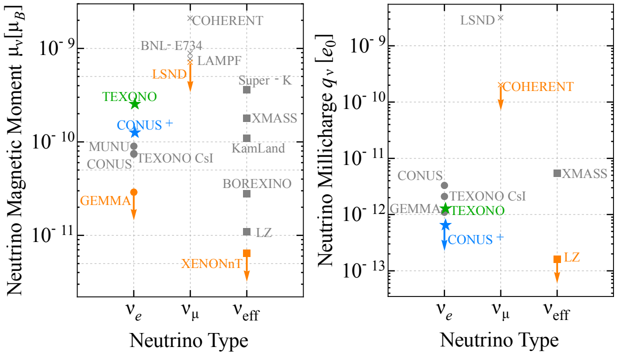
Fundamental physics

- Weak mixing angle θ_W at low energies
- SM: weak couplings, neutrino charge radius, form factors...
- BSM: neutrino magnetic moment, non-standard interactions, light mediators...
- Neutrino fog in DM experiments

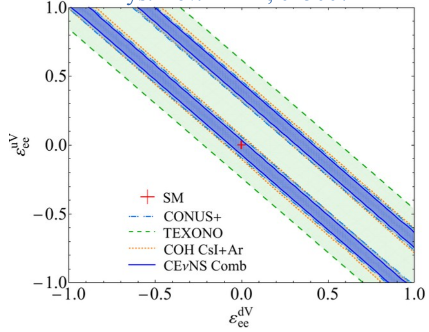
Phys. Rev. D 111, 075025



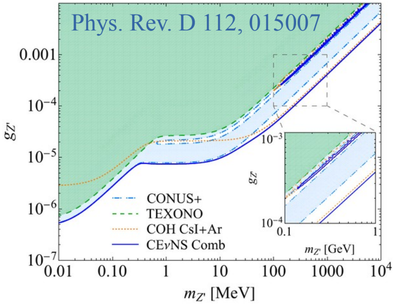
Phys. Rev. D 112, 015007



Phys. Rev. D 112, 015007

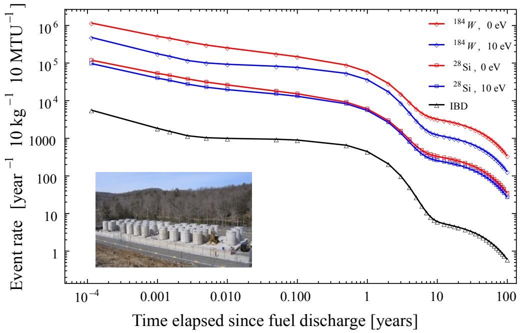


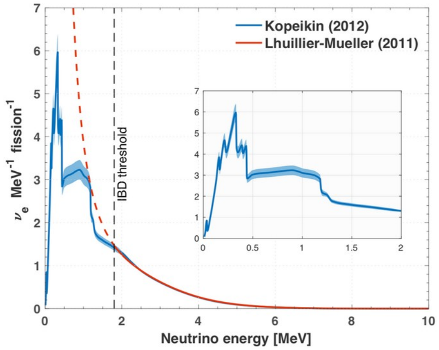
Phys. Rev. D 112, 015007



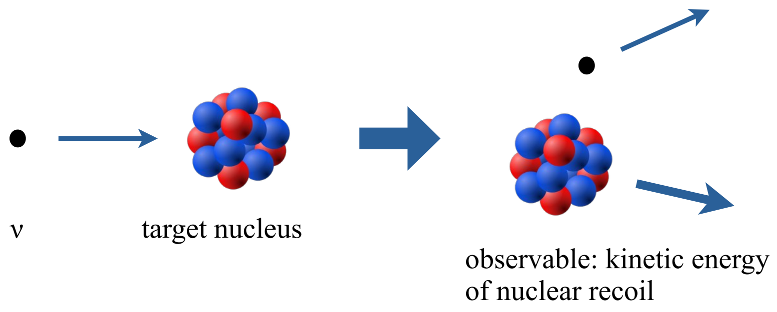
Civilian applications

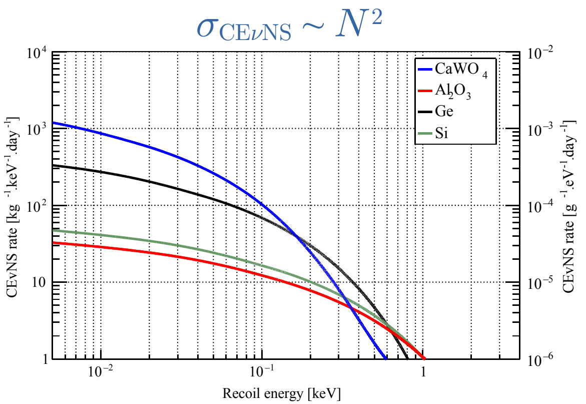
- Monitor of spent nuclear fuel
  Phys. Rev. D 105, 056002
- Nuclear nonproliferation and security
  Rev. Mod. Phys. 92, 011003





Detecting CEνNS

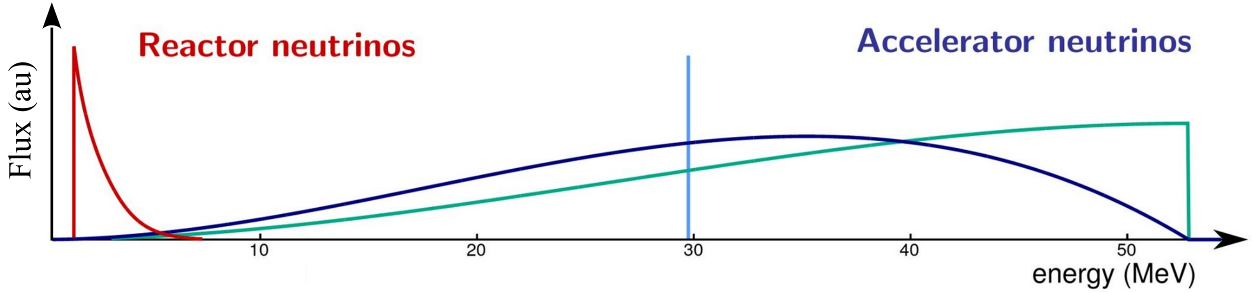




Experimental challenges

- Cross section of ~10^{-40} cm^2: need **large target mass**
- Faint nuclear recoil signals: need **low energy threshold**

Neutrino sources for CEνNS



cross secton $\sigma_{\mathrm{CE}\nu\mathrm{NS}} \sim E_\nu{}^2$ →

recoil energy $<T> \sim E_\nu{}^2$ →

← coherency $F(q^2 \to 0) \to 1$

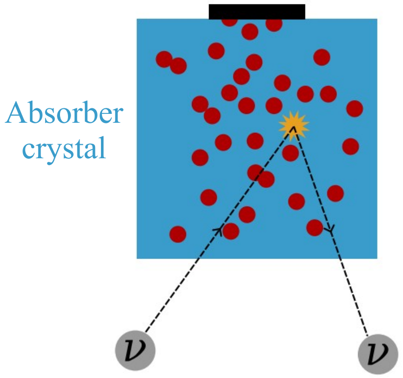
Precision measurements
Nature 643, 1229–1233

Discovery
Science 357(6356), 1123–1126

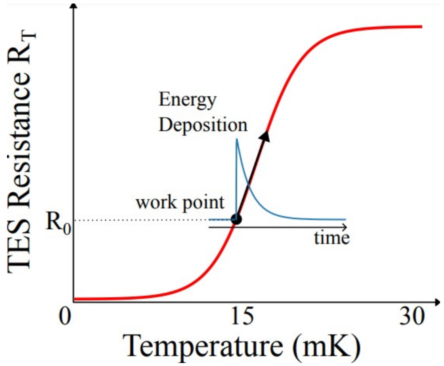
After the discovery in 2017, we aim at **precision measurements** with fully coherent interaction

NUCLEUS: CEνNS with cryogenic calorimeters

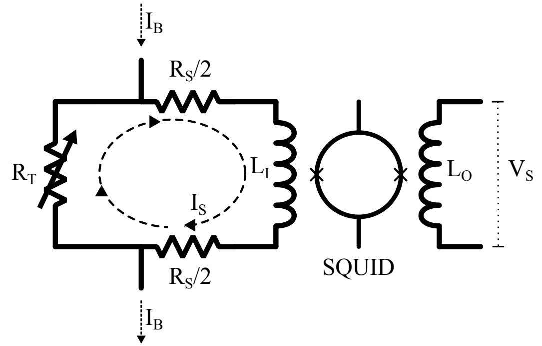
TES sensor



TES: superconductors operated at transition



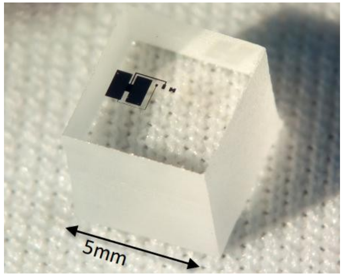
SQUID readout: sensitive magnetometers



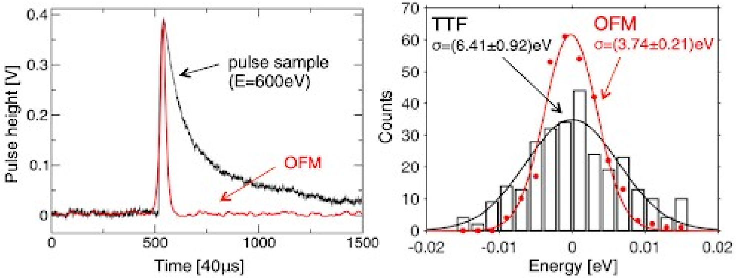
Neutrino interaction inside the absorber at O(10 mK) → Phonon production → Phonon absorption in the TES and resistance change → SQUID readout and voltage signal

NUCLEUS target detectors

- $CaWO_4$ absorbers with TES sensors
- O(10 eV) energy threshold
- Thermalized at O(10 mK) inside a dry dilution refrigerator

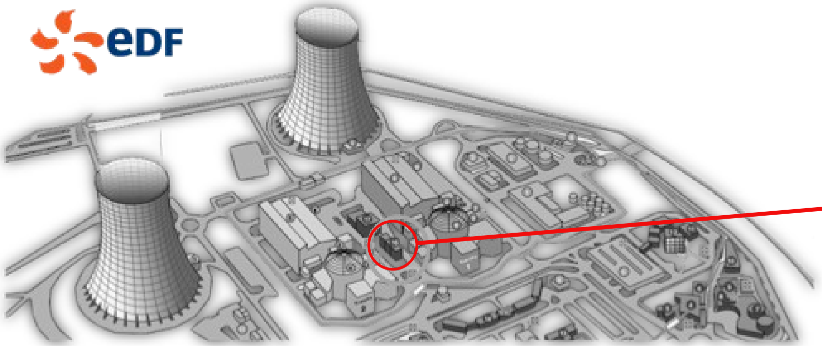


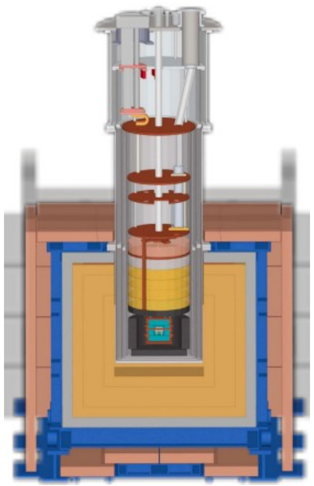
Phys. Rev. D 96, 022009



The NUCLEUS experiment

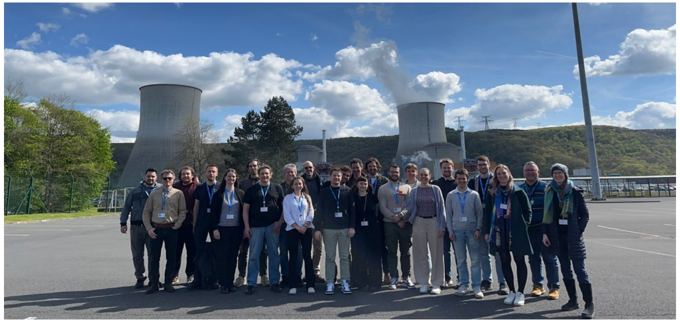
- Antineutrinos from the Chooz nuclear power plant, $2\times$ 4.25 GW_{th} cores
- Experimental room at 102 m and 72 m, $\sim 1.7\cdot 10^{12}$ $\nu/cm^2/s$ flux, 80% duty cycle





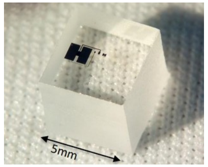
- Dry dilution refrigerator at ~10 mK
- Target detector surrounded by several layers of active and passive shieldings

5 institutions, ~65 scientists

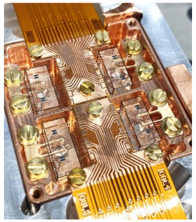


NUCLEUS strategy

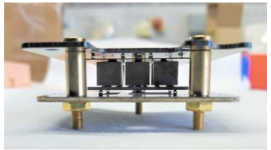
NUCLEUS-1g 2019-today → **Technical run @Chooz (in preparation)** → **Integration with inner veto and physics run**



R&D on detectors with single cubes of gram scale at TUM, Munich

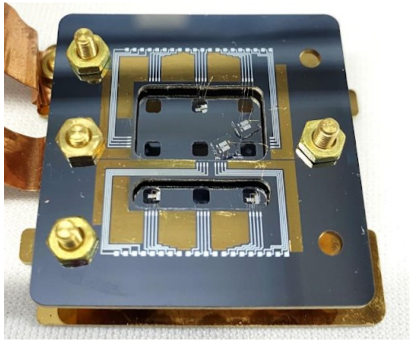


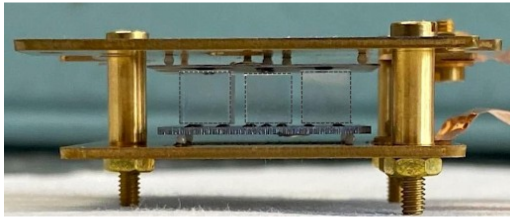
Integration of target detectors with the full shielding



Reduced background and larger mass for a CEνNS cross section measurement

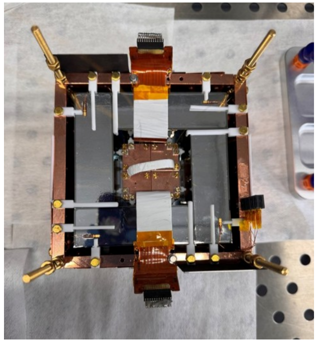
Shielding from background



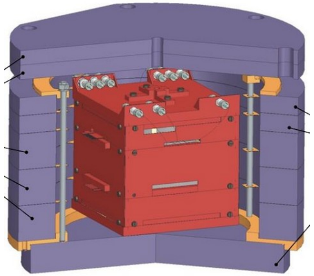


Inner veto: TES on silicon next to the cubes, to reject surface events and mechanical stress againts Low Energy Excess (under development)

Cryogenic outer veto: HPGe detectors for suppression of γ background, 4π coverage. Double readout, O(1-10 keV) energy threshold



B_4C: 4 cm of boron carbide for the reduction of thermal neutrons



Lead + Borated polyethylene: both inside and outside the cryostat. Lead for γ reduction, polyethylene for reduction of atmospheric and secondary neutrons

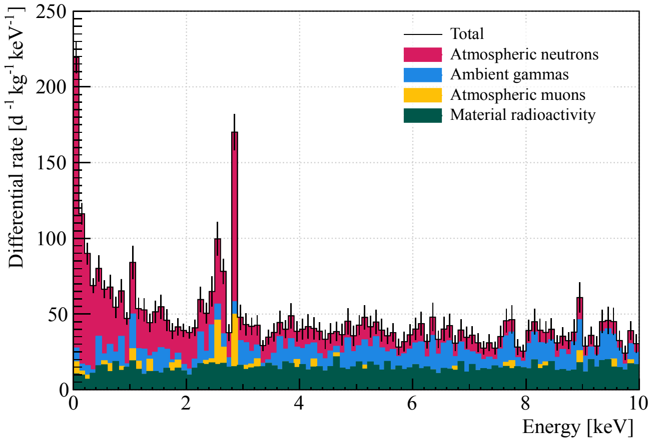
Muon veto: inside and outside the cryostat. Made of 28 plastic scintillator modules with WLS optical fibers and SiPM readout

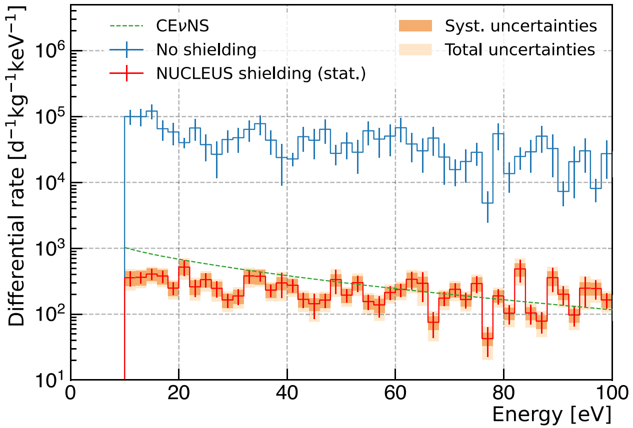
Expected background and sensitivity

Target background: **~100 d.r.u** (counts/keV/kg/day)
Enough to have a Signal/Background ratio of 1-2 in the ROI
Dedicated Geant4 framework

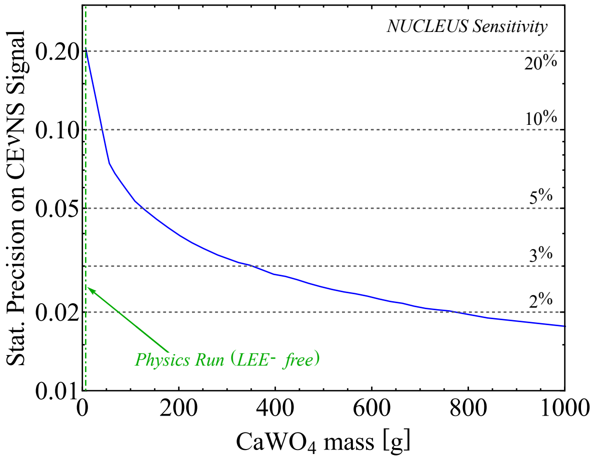
Precision of 10-20% on the cross section for a first physics run with O(10g) target, 20 eV energy threshold and 1 year of exposure.

Eur. Phys. J. C 86, 29 (2026).





arXiv:2603.24450



Low Energy Excess: sharp rise of background events at sub-keV energies, observed by many low-threshold experiments

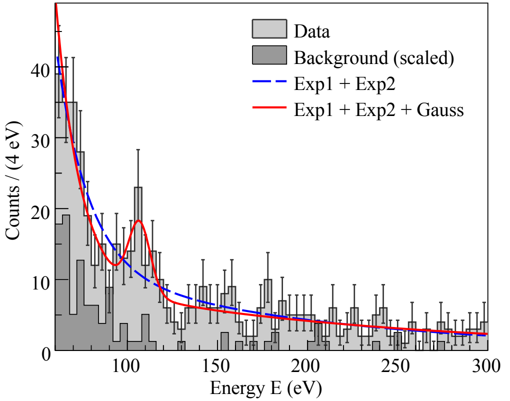
EXCESS workshop

LEE complete **origin** is still **unknown**, and it is limiting the sensitivity of low-threshold dark matter and CEνNS experiments

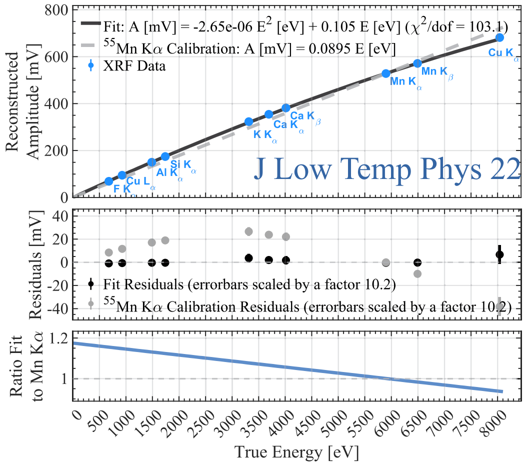
(some) NUCLEUS milestones

Calibration with nuclear recoil peak…

Phys. Rev. Lett. 130, 211802



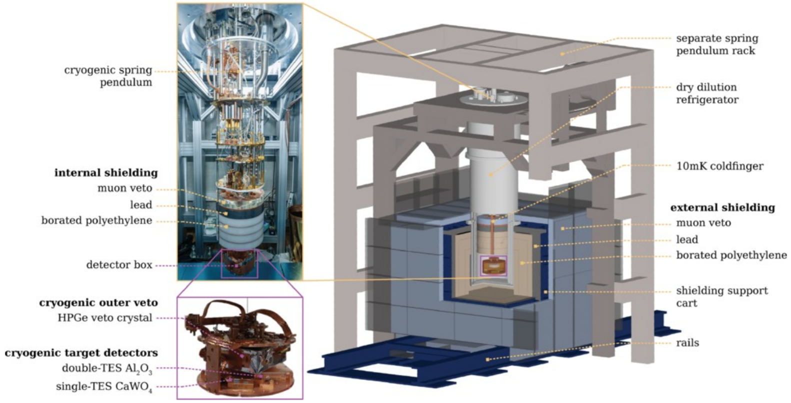
…and with low energy X-ray peaks



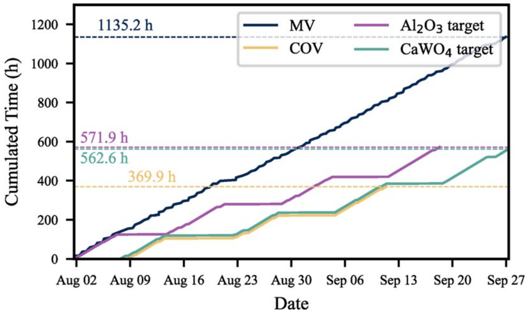
J Low Temp Phys 221, 265–288

Commissioning run at TUM

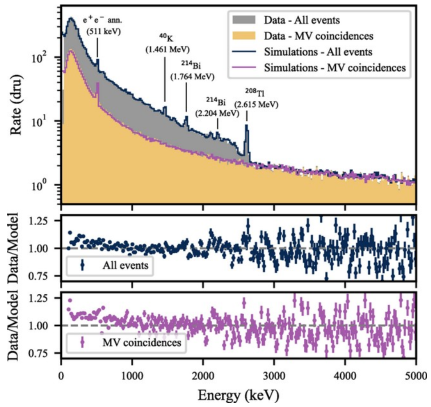
Phys. Rev. D 112, 072013

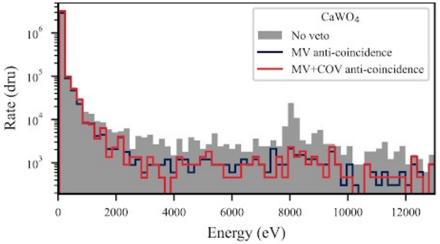


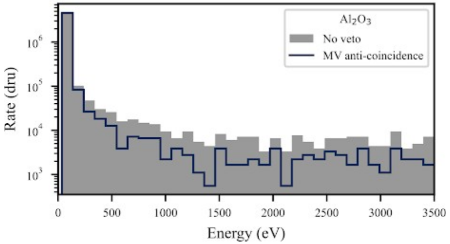
- Demonstrated the stable operation of $CaWO_4$ and Al_2O_3 target detectors, outer veto and muon veto for two months



- First validation of G4-based particle background model



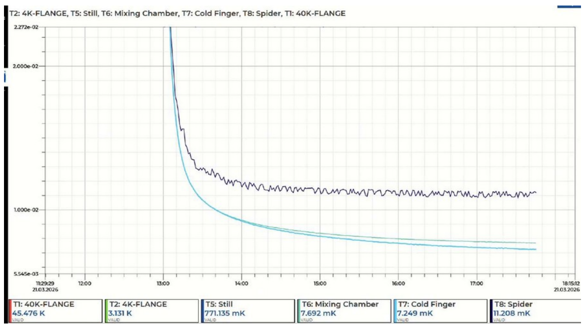




Current status and outlook

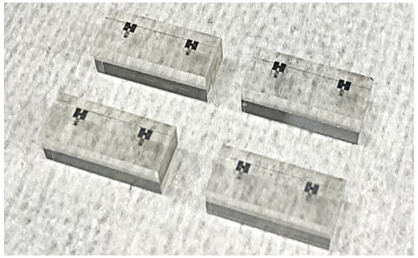
Cryostat relocated at Chooz, now ready for the **technical run**

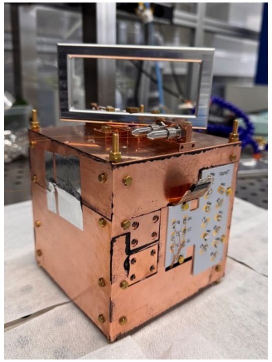
First cooldown performed, base temperature reached



Technical run:

- 4 Double-TES $CaWO_4$ detectors (total mass ~7 g)
- Full germanium veto
- Lead + polyethylene + muon veto



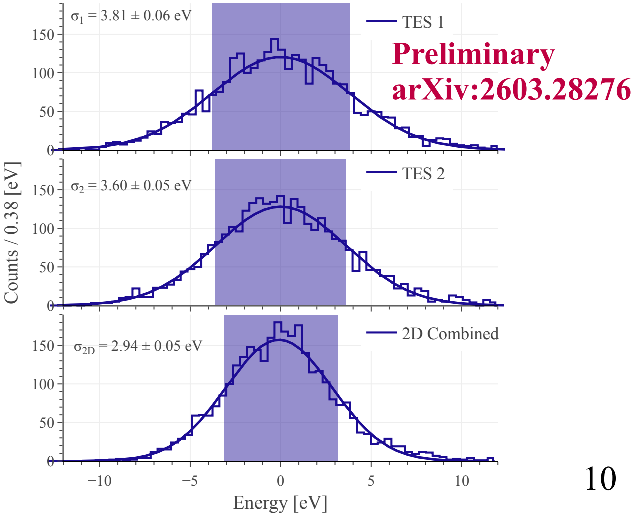


Physics run:

- After technical run
- Integration of the setup with the inner veto for LEE reduction
- 20% statistical precision measurement of the cross section

Several studies and publication foreseen:

- Hardware and software techniques to enhance sensitivity **arXiv:2603.28276**
- Prospects and new physics searches **arXiv:2603.24450**
- Low Energy Excess extensive studies with Al_2O_3 detector **arXiv:2603.07687**



Conclusions

- NUCLEUS will exploit sensitive cryogenic calorimeters and extensive shielding techniques to precisely measure CEνNS at reactors
- Commissioning of an essential version of the experiment completed in 2024 in Munich
- Detector upgrade and experiment relocation at the reactor site completed this year
- Technical run soon to test the setup and measure the background, physics data right after

2024	2025	2026	
Commissioning run @TUM	Relocation @Chooz	Technical run @Chooz	Physics run @Chooz

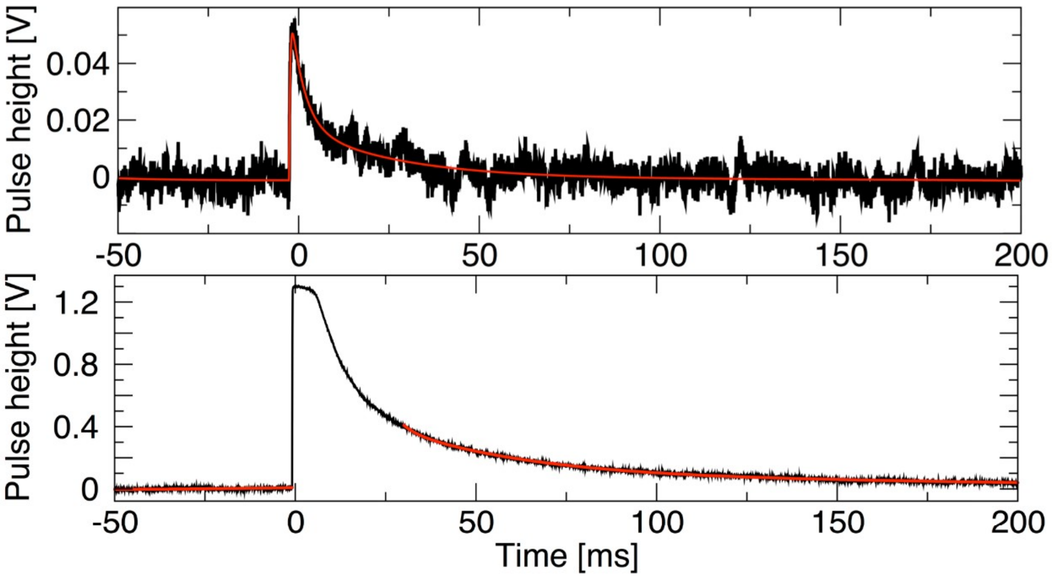
Stay tuned for physics data!

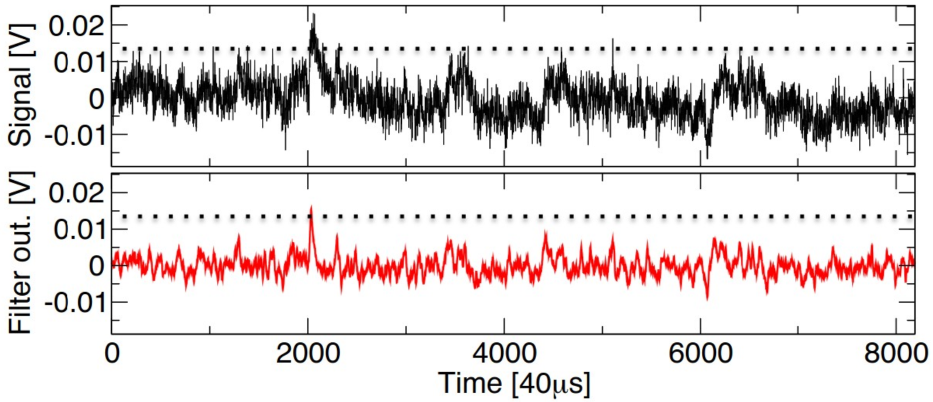
Visit our **website**, with **blog** and **comic**!

credit: Chloé Goupy

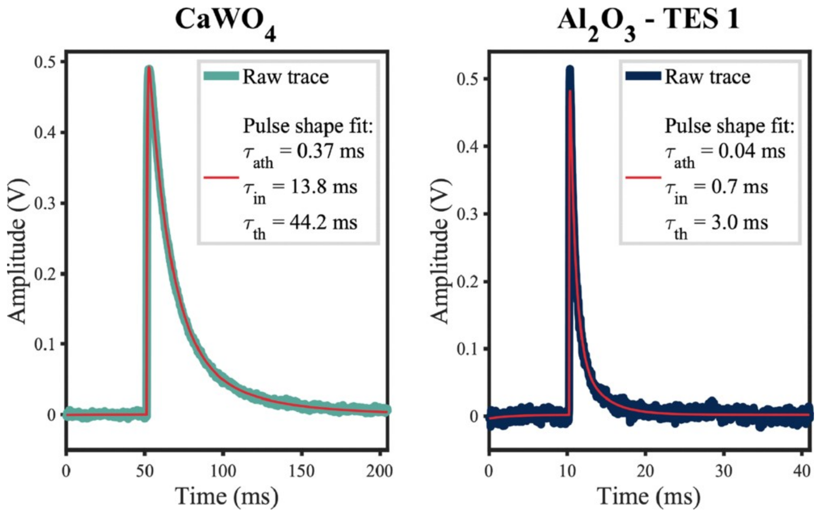
Thanks for your attention!

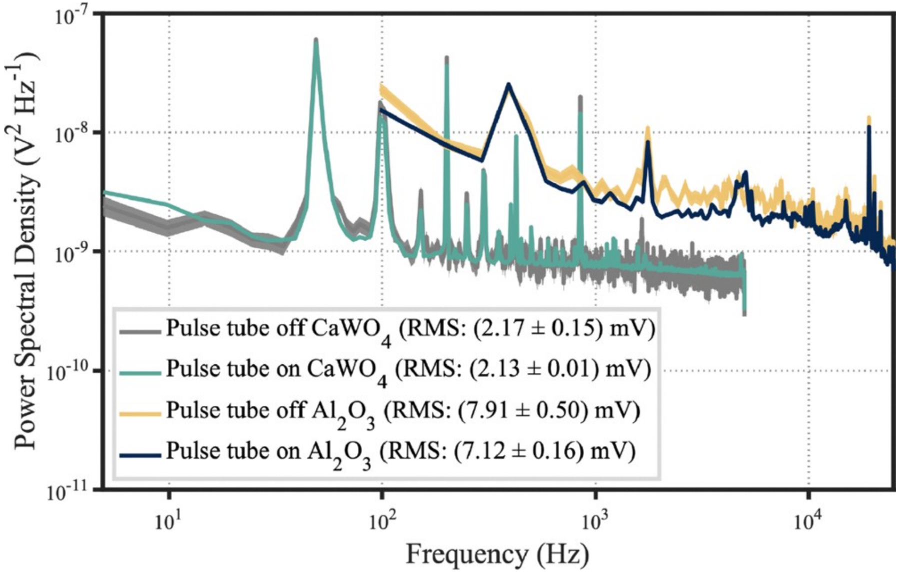
Backup: pulses

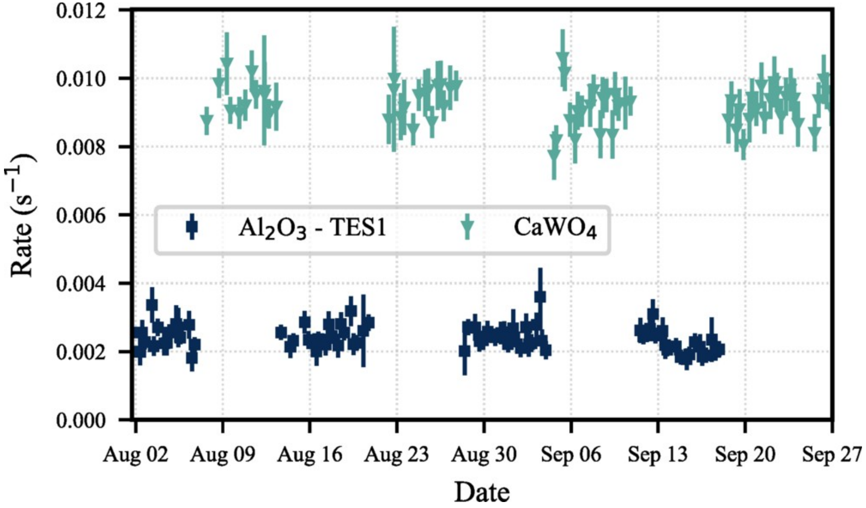


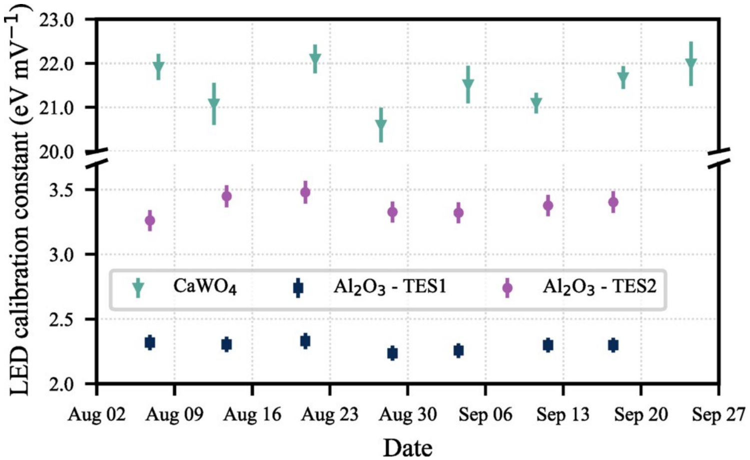


Backup: Commissioning run @TUM

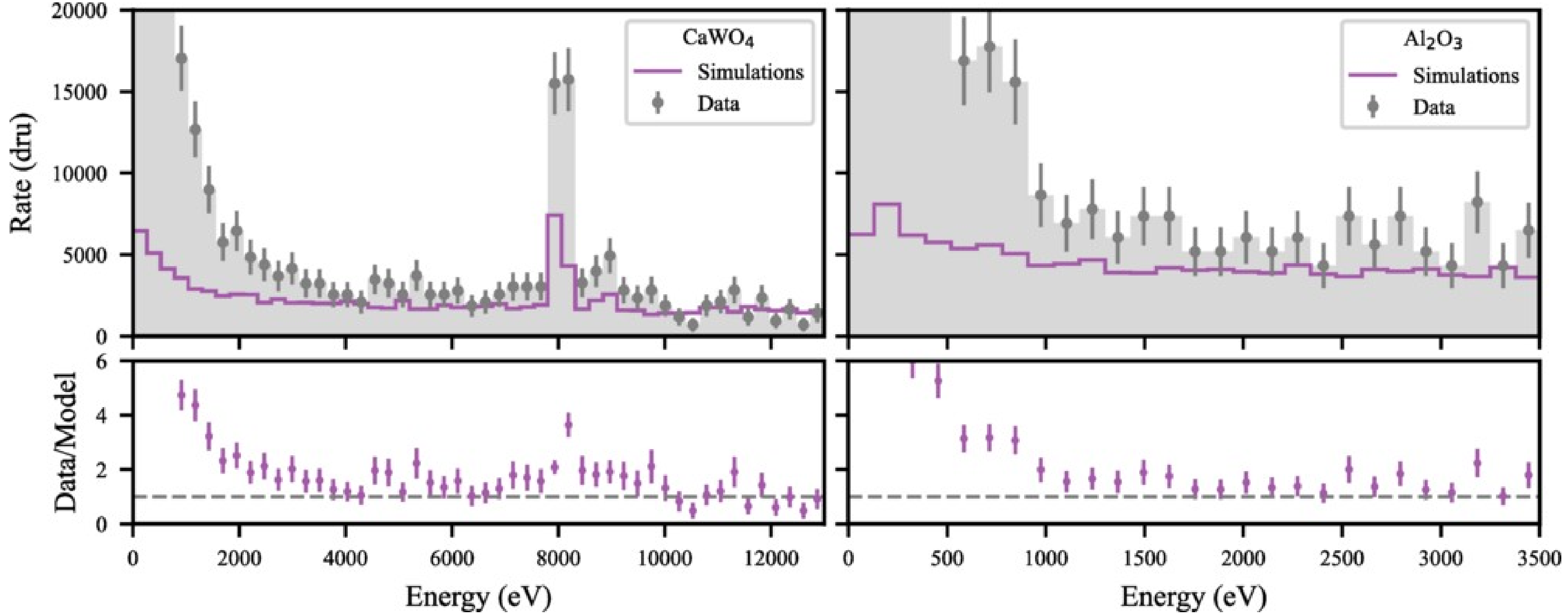




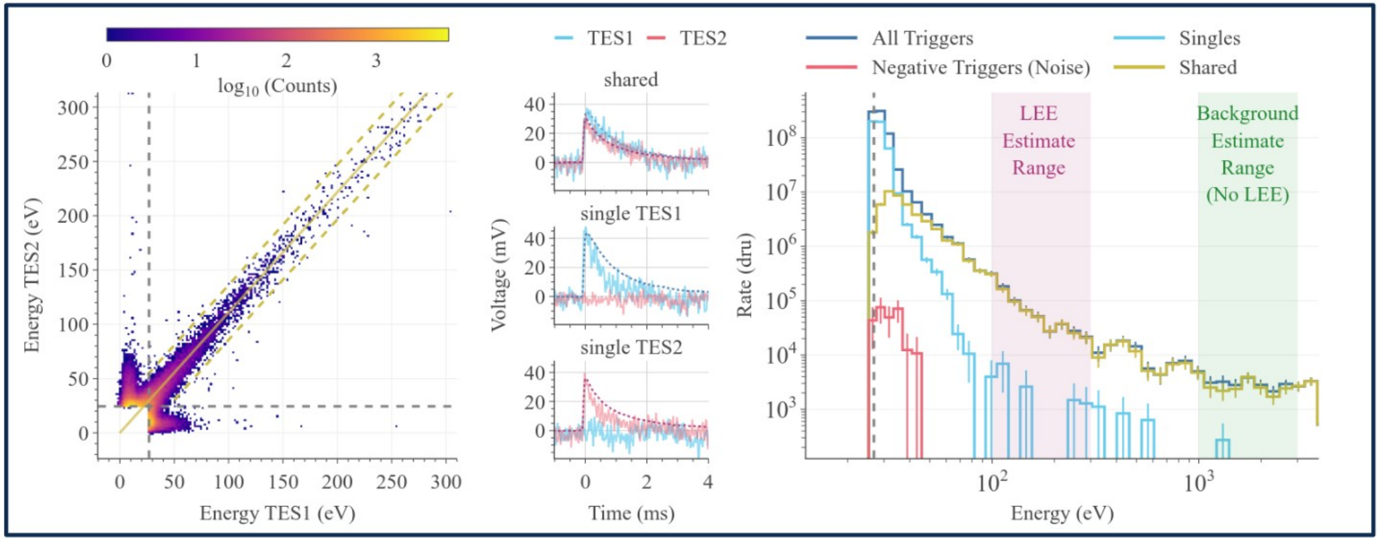


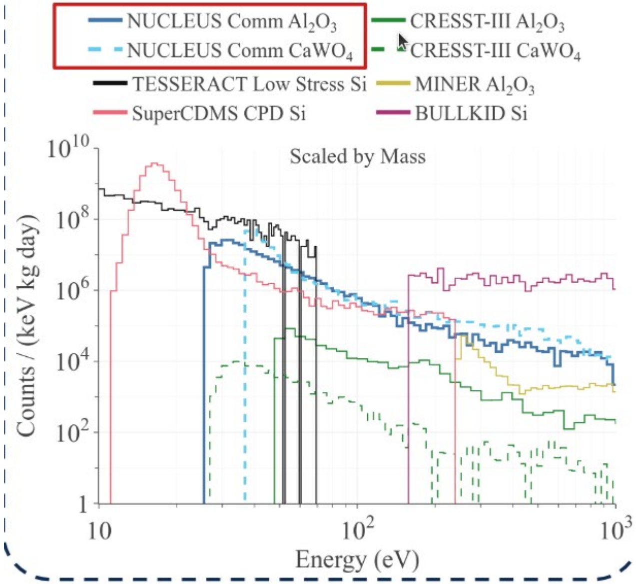


Backup: Commissioning run @TUM



Backup: LEE


log10 (Counts)
0 1 2 3
Energy TES2 (eV)
Energy TES1 (eV)
TES1 TES2
shared
single TES1
single TES2
Voltage (mV)
Time (ms)
All Triggers
Negative Triggers (Noise)
Singles
Shared
LEE Estimate Range
Background Estimate Range (No LEE)
Rate (dru)
Energy (eV)


NUCLEUS Comm Al2O3
NUCLEUS Comm CaWO4
CRESST-III Al2O3
CRESST-III CaWO4
TESSERACT Low Stress Si
MINER Al2O3
SuperCDMS CPD Si
BULLKID Si
Scaled by Mass
Counts / (keV kg day)
Energy (eV)