The NUCLEUS experiment

Concept and status

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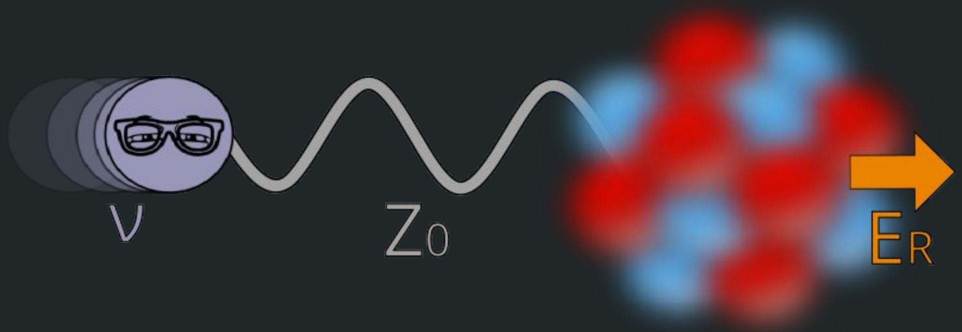
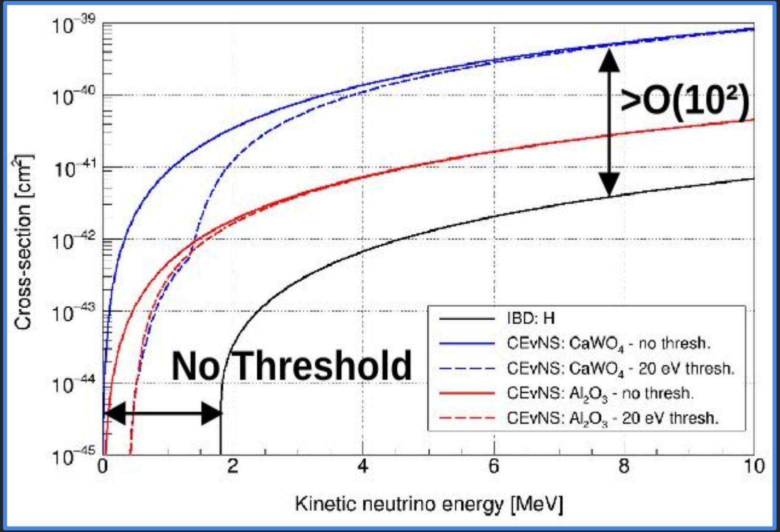
CEvNS - a brief overview



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

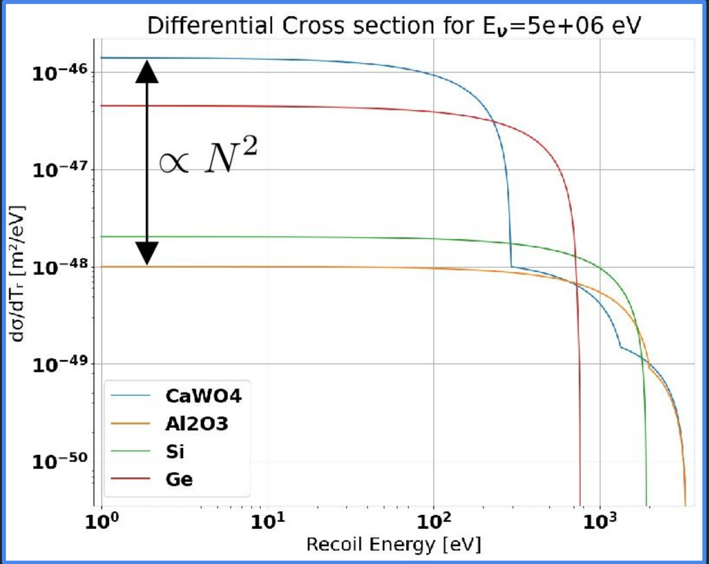
$$\text{Coherent:} F(q^2) \approx 1$$
$$\Downarrow$$
$$q \cdot R_N \ll 1$$
$$\Downarrow$$
$$E_\nu^{max} \approx 20\text{MeV [He]} \div 70\text{MeV [U]}$$

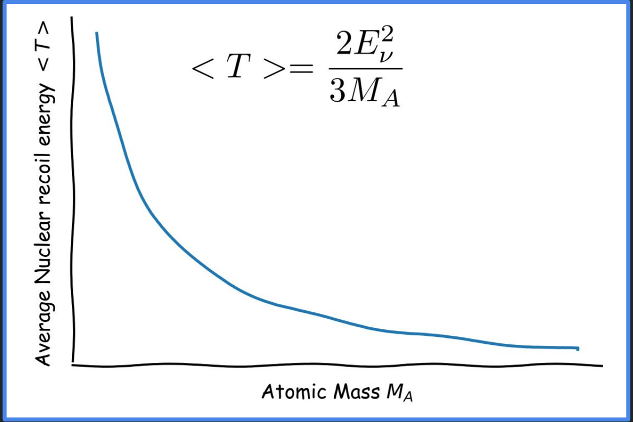


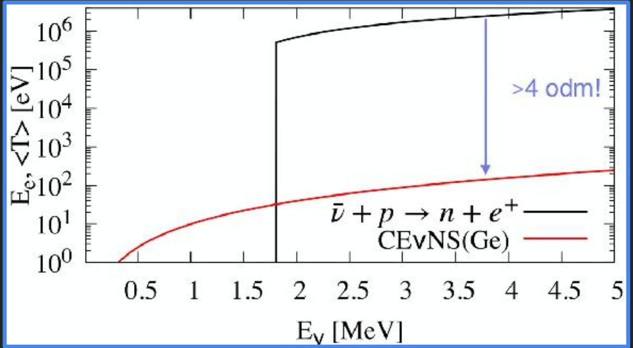
CEνNS - a brief overview

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

$$Q_W = N - P(1 - 4\sin^2\theta_W) \approx N$$







The NUCLEUS collaboration

nucleus EXPERIMENT

NUCLEUS collaboration:

- ~50+ members
- ~7 institutions
- 4 countries

Aims:

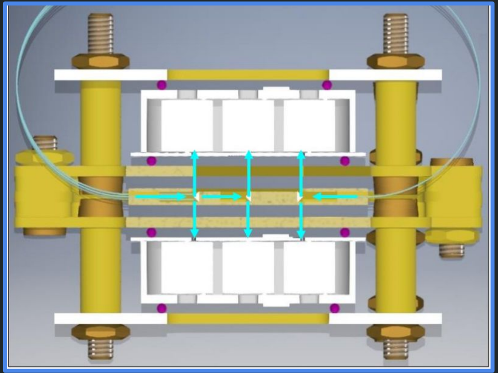
- Develop **new detection methods** for reactor antineutrino
- **Precision measurement** of CEvNS with reactor antineutrinos **at lowest energies** (< 1.8 MeV)

Location:

Chooz-B nuclear power plant in the French Ardennes (EDF site):

- 2×4.25GW_{Th} reactors, 72m and 102m away ➔ $\mathbf{\Phi_{\nu}=1.7\times10^{12}\ \nu\cdot cm^{-2}s^{-1}}$
- Shallow depth ➔ **~3 m.w.e. overburden**

Cryogenic target detectors: TES

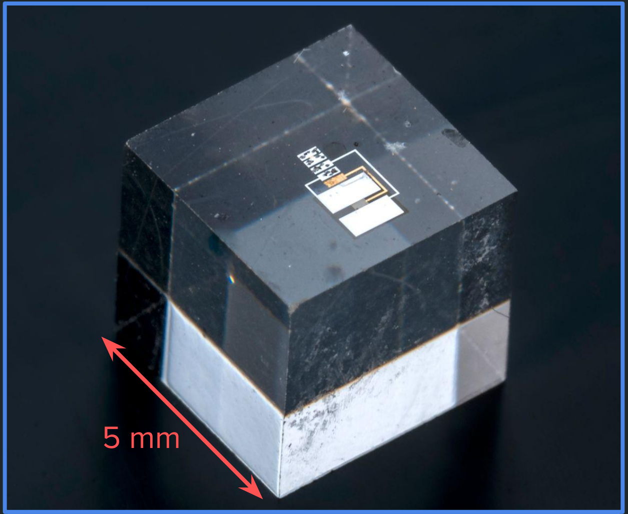


Mockup of final NUCLEUS setup

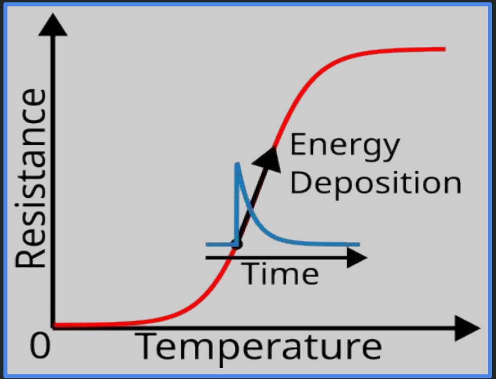
NUCLEUS detector setup:

3x3 array of $CaWO_4$ cubes
→ CEνNS interaction

3x3 array of Al_2O_3 cubes
→ Background measurement



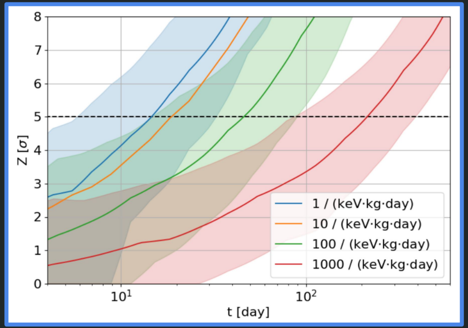
Single NUCLEUS instrumented detector cube



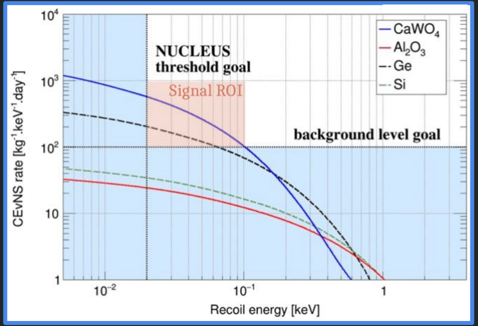
TES measurement principle

Particle interaction → Phonon production → Heating of TES film → Change in resistance

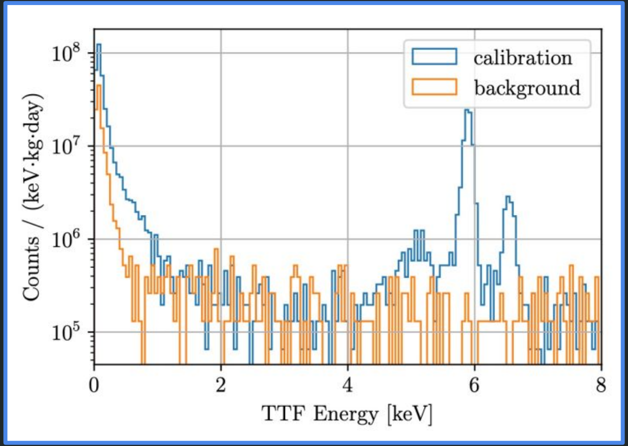
Above ground experiment: backgrounds & sensitivity



Statistical significance of CEvNS observation in NUCLEUS based on exposure time for different background rates



NUCLEUS performance targets



Background for unshielded single NUCLEUS cube with Fe calibration source

Expected CEvNS rate in NUCLEUS: ~30 cts/kg/day in 10 eV to 1 keV ROI.

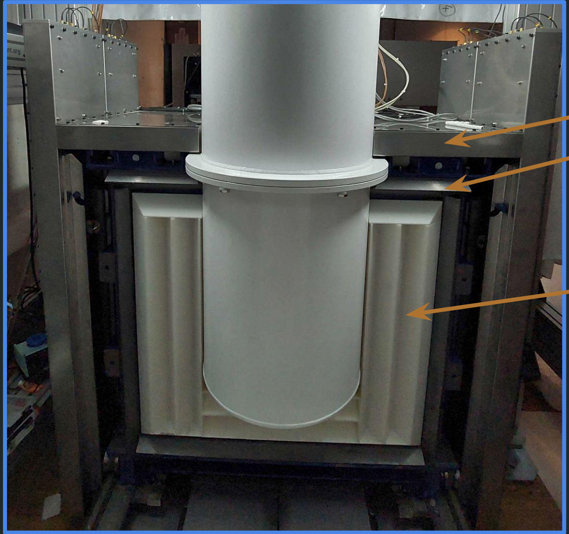
With 100 dru bckg: 5σ significance in observation in a few weeks

Need to decrease background by $O(>10^4)$

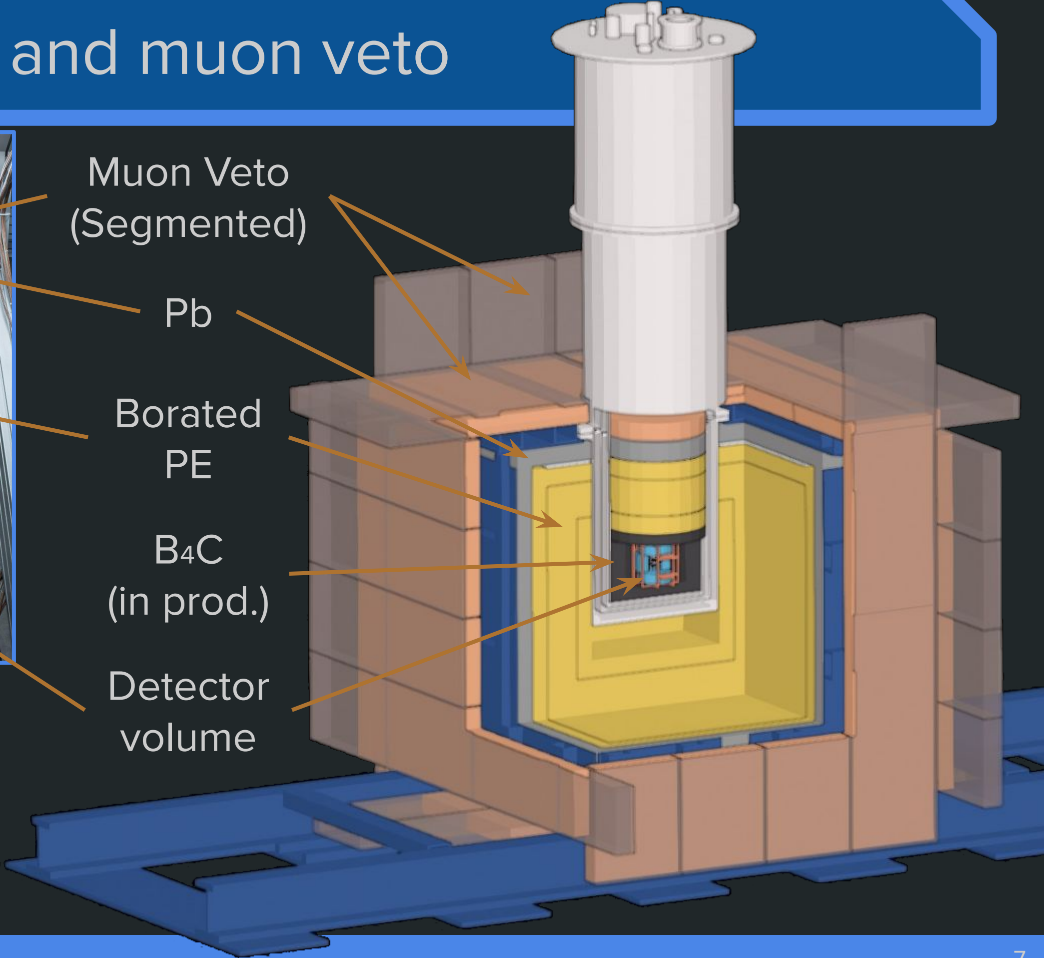
➔ Highest background contributions:

- Ambient γ (measured on site): $\Phi_\gamma = 3.9\ cm^{-2}s^{-1}$
- Atmospheric μ: $\Phi_\mu = 0.02\ cm^{-2}s^{-1}$
- Atmospheric n: $\Phi_n = 0.013\ cm^{-2}s^{-1}$

Shielding and muon veto


Cryostat with half-closed outer shielding


Long Background Run cryogenic setup



- Muon veto tags particle events caused by μ
- Lead strongly attenuates ambient γ
- Polyethylene moderates neutrons
- B_4C absorbs moderated neutrons

Cryo-shield allows full solid angle coverage

Active veto cryogenic detectors

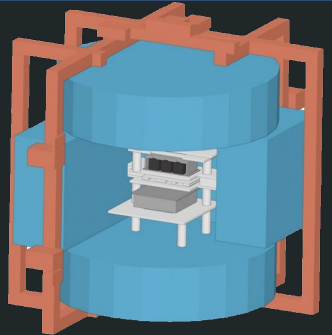


Diagram of CEvNS detectors inside of Inner and Outer vetoes

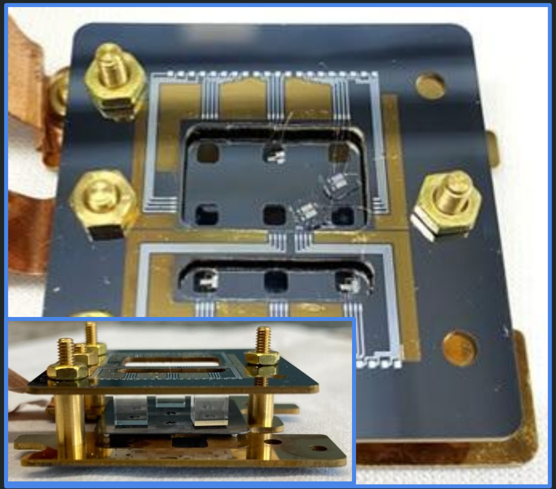
COV detectors in detector cage

Shielding significantly decreases background, but ambient γ needs to be decreased further.

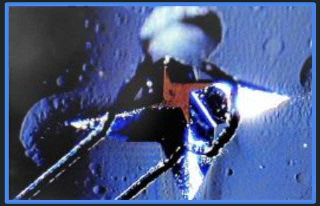
➜ Double cryogenic veto setup:

- Outer veto: High Z detector with low threshold
  ➜ HPGe semiconductor detector (threshold < 10 keV achieved)

- Inner veto: Si holder with TES readout (to be operated)



IV detector holder mechanical mockup

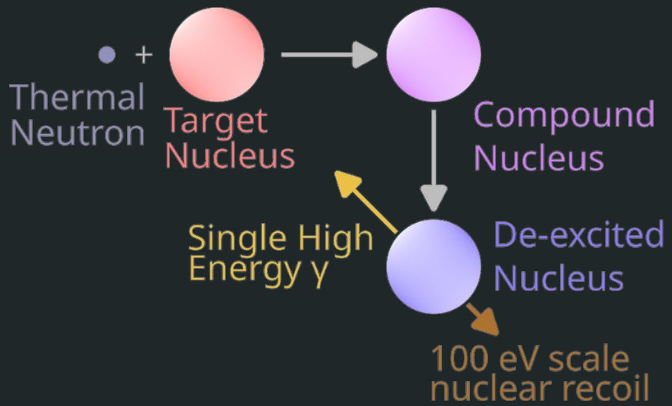


Macro-photo of Si spring clamp of detector cubes holder

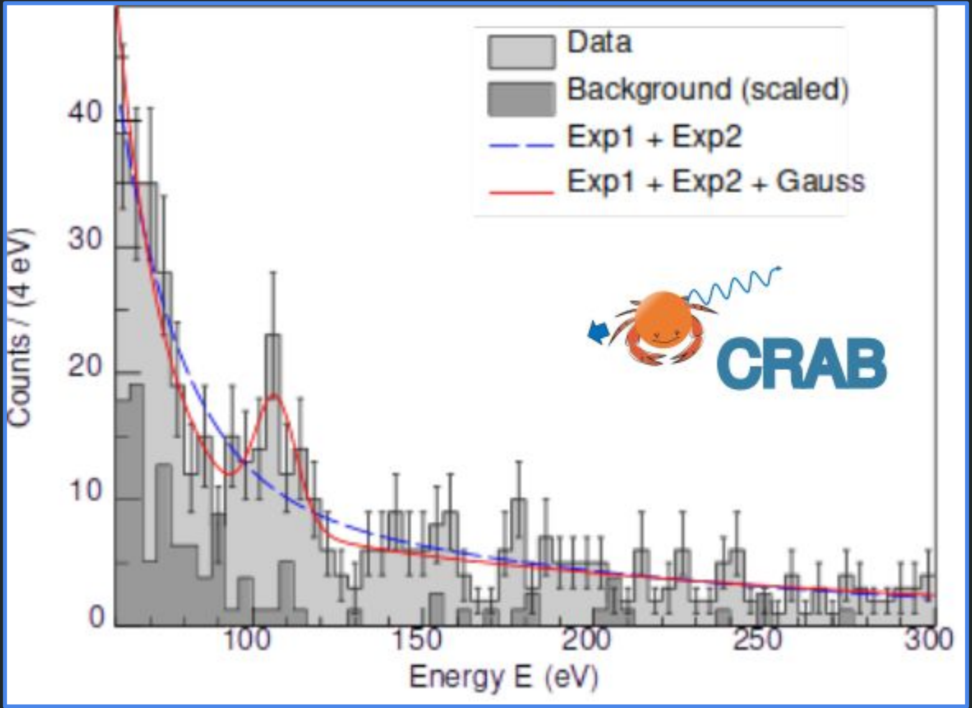
Calibration Recoils for Accurate Bolometry (CRAB)

Beyond γ and LED calibrations, we validate our detector calibration by observing monochromatic nuclear recoils:

The CRAB calibration relies on nuclear recoils of known energy, caused by γ emission following neutron absorption.



Schematic representation of CRAB calibration

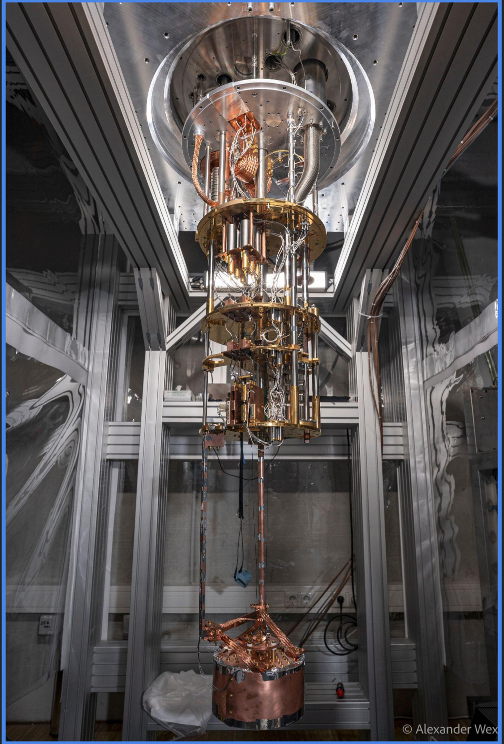


Observation of CRAB peak

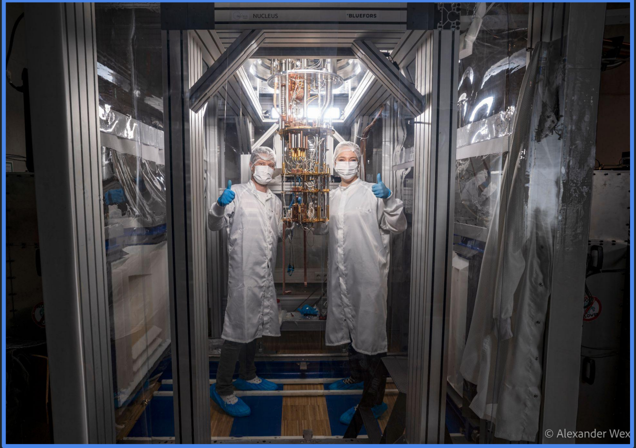
Cryostat Commissioning

Cryostat in TUM (Munich, Germany) shallow underground lab was commissioned:

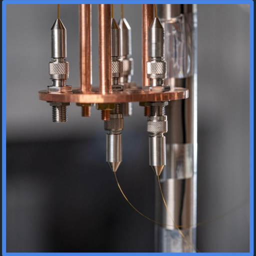
- Installed SQUIDs for TES readout
- Installed vibration decoupling system
- Installed LED calibration fibres & warm electronics
- Installed COV multichannel electronics
- Set up clean-room protocols for cryostat



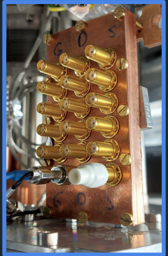
Full vibrationally-decoupled cryogenic detector setup (without cryogenic shielding)



Cryostat clean room



LED calibration fibres



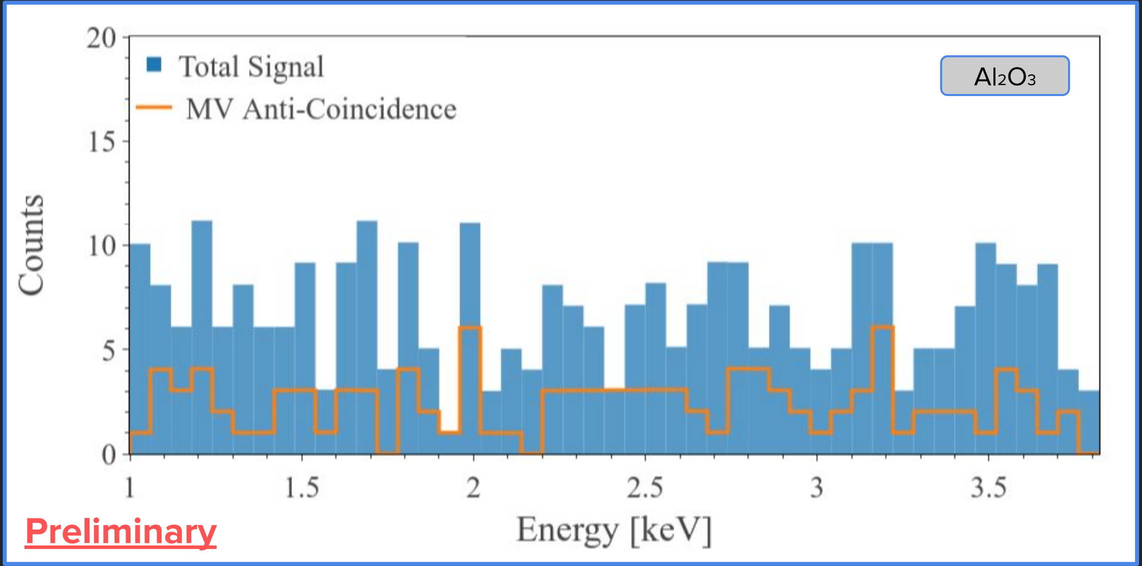
COV multi-channel cryo electronics

Vibration decoupling spring

Current Status: Long Background Run

Long Background Run:

- 2 months from cooldown to warmup
- **~1100h of stable TES + Muon Veto data**
- **Several triple-coincidence (TES+COV+MV) tests**
- Analysis of ROI ongoing



Al_2O_3 background energy spectrum (Above ROI)

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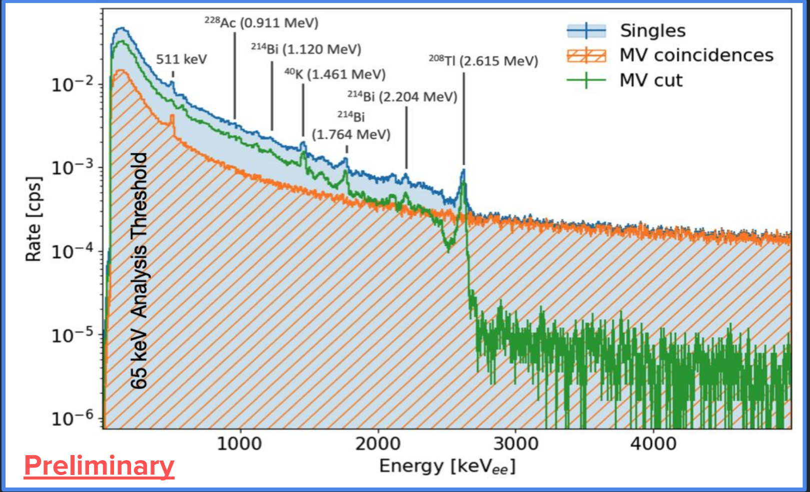
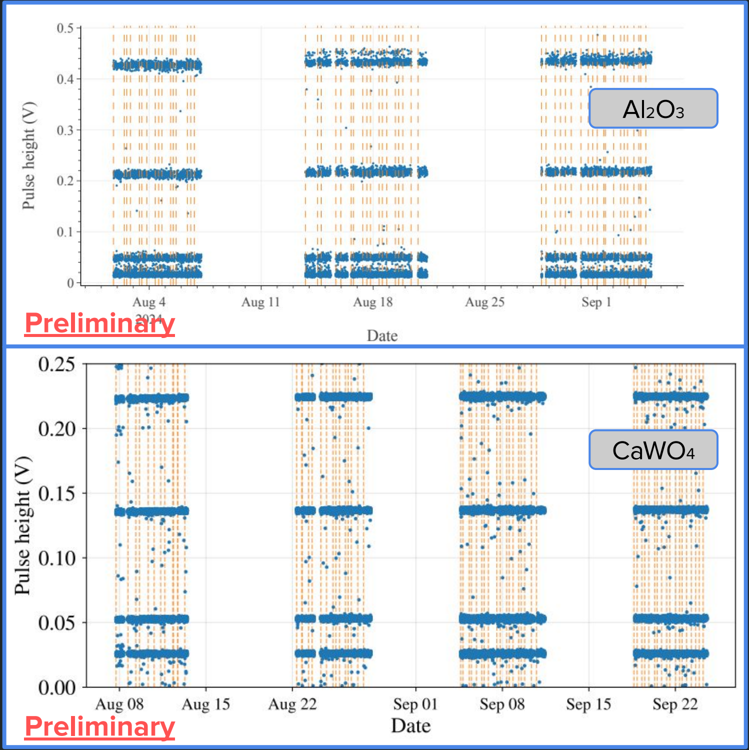


COV energy spectrum

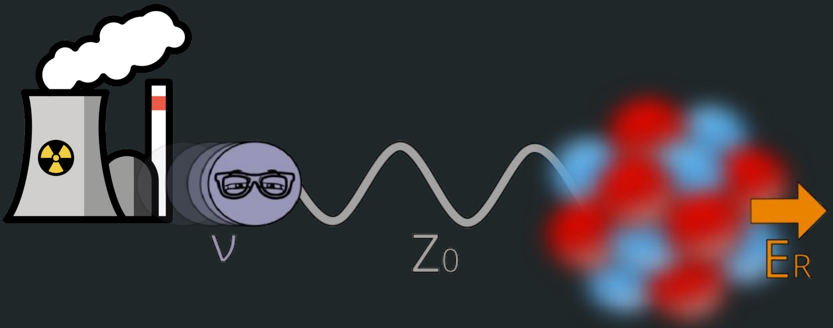


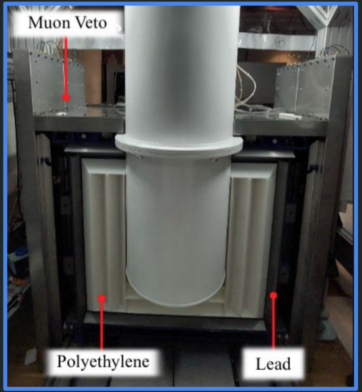
TES stability over Long Background Run

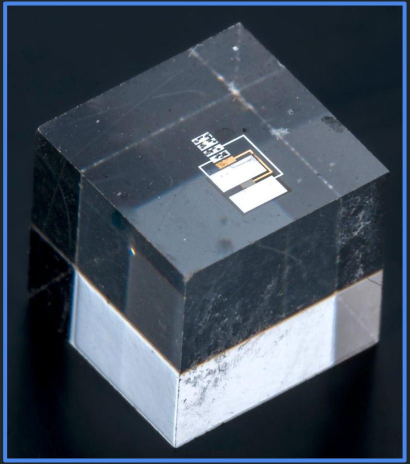
Conclusion & next steps

NUCLEUS in brief:

- CEνNS interaction for enhanced σ_ν
- Gram-scale cryogenic bolometer
- Multi-layer, full solid angle shielding
- 3 layers of veto (Inner, Outer & Muon)



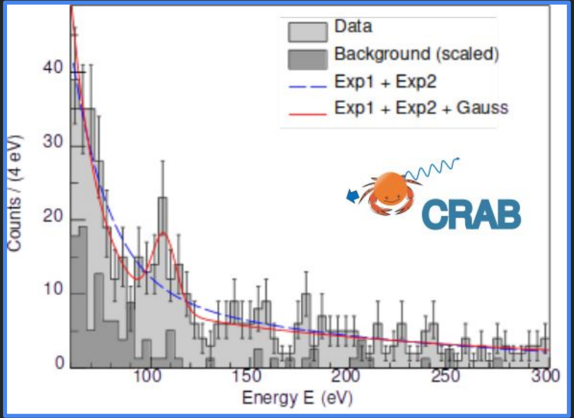


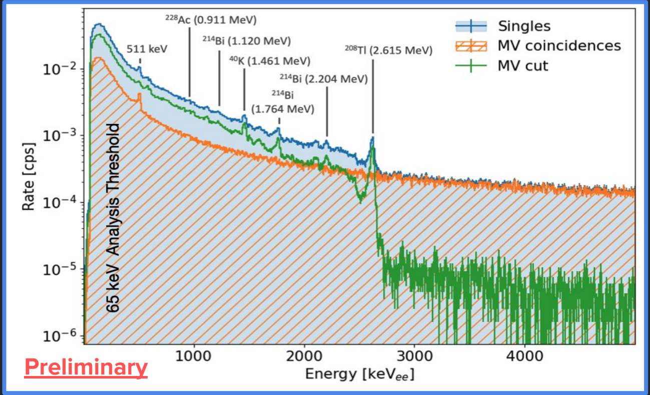


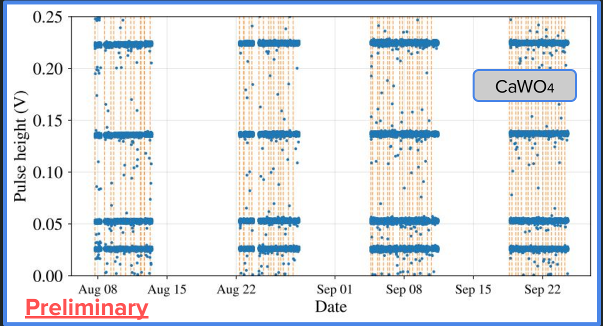
Conclusion & next steps

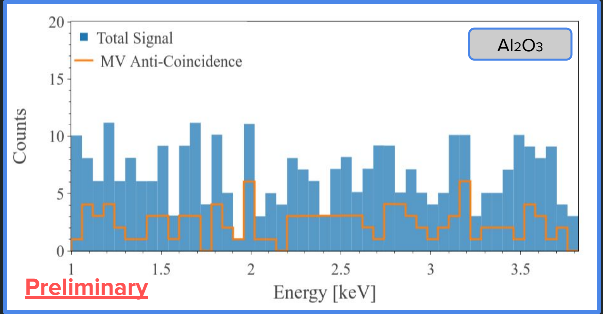
Current demonstrated capabilities:

- Calibration (γ, optical & nuclear recoils)
- Synchronous operation of detectors
- Analysis integrating multiple data streams
- Months-long stable cryogenic operation





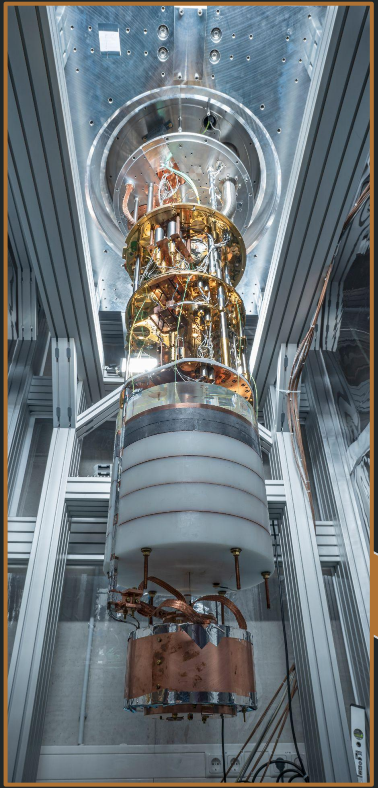


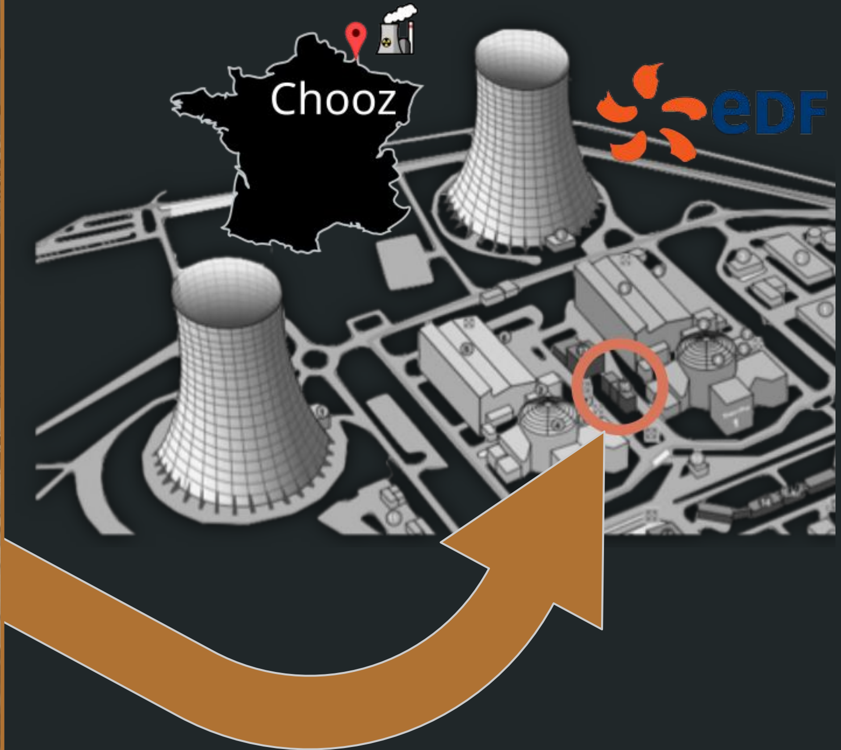


Conclusion & next steps

Next steps:

- Commissioning a technical demonstrator at Chooz
- Optimising performance of working elements
- Implementing further planned improvements to setup
- 2026: Start ν observation @ Chooz





Thank you for your attention.

References:

1 - Angloher, G., Ardellier-Desages, F., Bento, A. et al., Exploring CEνNS with NUCLEUS at the Chooz nuclear power plant. Eur. Phys. J. C 79, 1018 (2019)

2 - R. Strauss et al. The v-cleus experiment: A gram-scale fiducial-volume cryogenic detector for the first detection of coherent neutrino-nucleus scattering. Eur. Phys. J., C77(8):506, 2017

3 - H. Abele et al. (CRAB Collaboration, NUCLEUS Collaboration), Observation of a Nuclear Recoil Peak at the 100 eV Scale Induced by Neutron Capture. Phys. Rev. Lett. 130, 211802 – Published 26 May 2023

4 - J. Rothe et al., NUCLEUS: Exploring Coherent Neutrino-Nucleus ScaQering with Cryogenic Detectors. J. Low Temp. Phys.199 (2020) 433-440.

Backup

LED Calibration

Basic concept: Poisson statistics

(Assuming only linear E dependence)

$$\mu = r \cdot N_{ph} \quad \Rightarrow \quad \sigma^2 = \sigma_0^2 + r \cdot \mu$$

$$\sigma = \sqrt{N_{ph}} \cdot r \qquad \sigma_0 = \text{Detector Resolution}$$

$$= \sqrt{\mu \cdot r} \qquad r : \frac{\text{mV}}{\text{photon}}$$

$$\Rightarrow k = \frac{\text{photon energy}}{r} \left[\frac{\text{eV}}{\text{mV}}\right]$$

Benefits:

- **Low energy (calibrating in ROI)**
- Electronically controlled
- External trigger → high S/B
- Several detector & analysis characterisations possible