The NUCLEUS experiment: a search for coherent elastic neutrino-nucleus scattering with reactor antineutrinos

Anthony Onillon *on behalf of the NUCLEUS collaboration*

anthony.onillon@tum.de

NUCLEUS collaboration: 7 Institutions, 40 members

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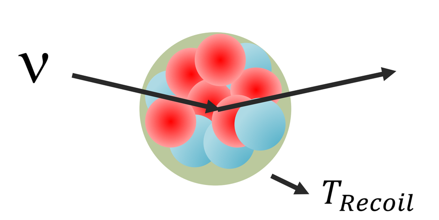
The NUCLEUS experiment 1

NUCLEUS is designed to measure precisely the coherent elastic neutrino-nucleus scattering (CEνNS) cross-section using low energy reactor $\bar{\nu}_e$.

CEνNS

- Neutral current process: first predicted in 1974 by Freedman, Kopeliovich and Frankfurt
- No energy threshold / insensitive to ν flavor
- For low energy (≤ 50 MeV) nucleus seen as a whole rather than a set of individual nucleons
  ↳ Boost in cross section, up to a factor 10^3



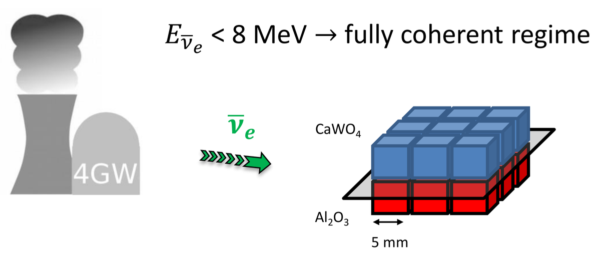
Cross section proportional to N^2…. but low recoil energy

⇒ **Experimental challenge; hard to discriminate against backgrounds**

First detection in 2017 at SNS by COHERENT

NUCLEUS experimental principle

10 g multi target cryogenic detector
- Al_2O_3: essentially background-only measurement
- $CaWO_4$: background + CEνNS



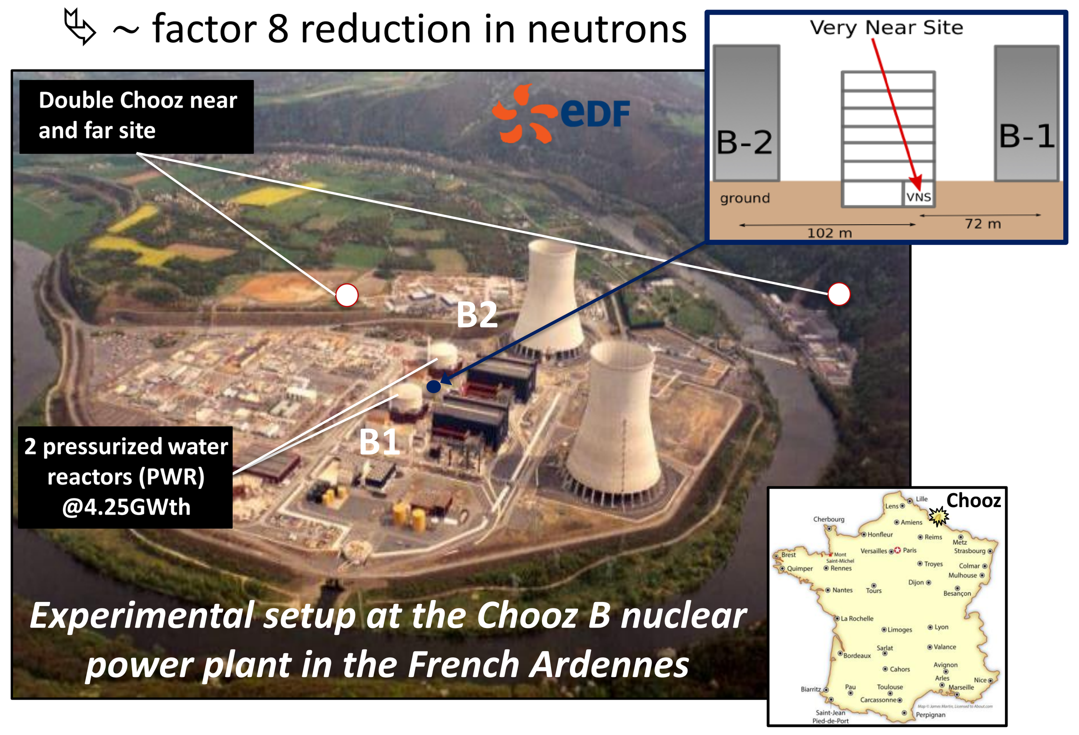
⇒ **Improved signal identification and background discrimination**

Standard Model probe & search for new physics at low energies

Experimental site and expected signal 2

Very Near Site (VNS):

- 24 m³ basement room at the Chooz B nuclear power plant (3 m.w.e.). Between two 4.25 GWth reactors.
- At VNS compared to the surface
  ↳ ~0.7 relative reduction of the atmospheric muon flux
  ↳ ~ factor 8 reduction in neutrons



Experimental setup at the Chooz B nuclear power plant in the French Ardennes

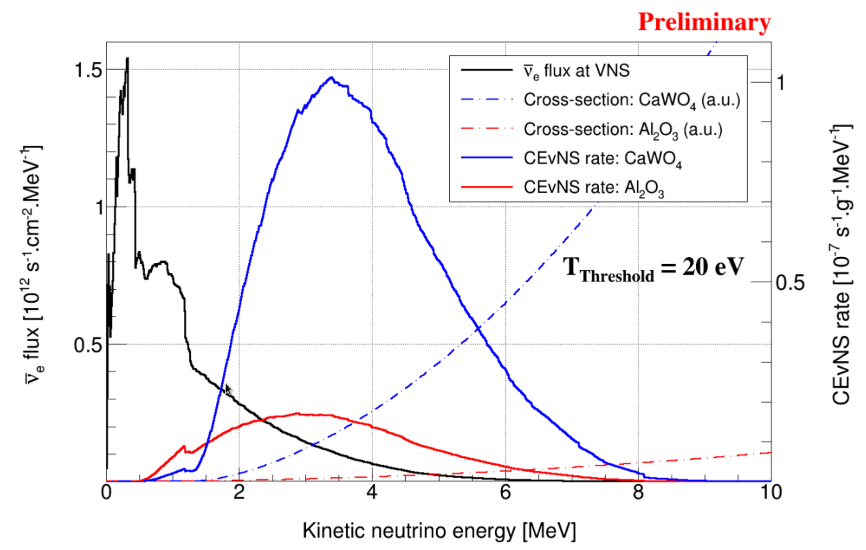
- Pure $\bar{\nu}_e$ source from:
  - fission of ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu
  - activation of fuel materials: ^{239}U and ^{239}Np

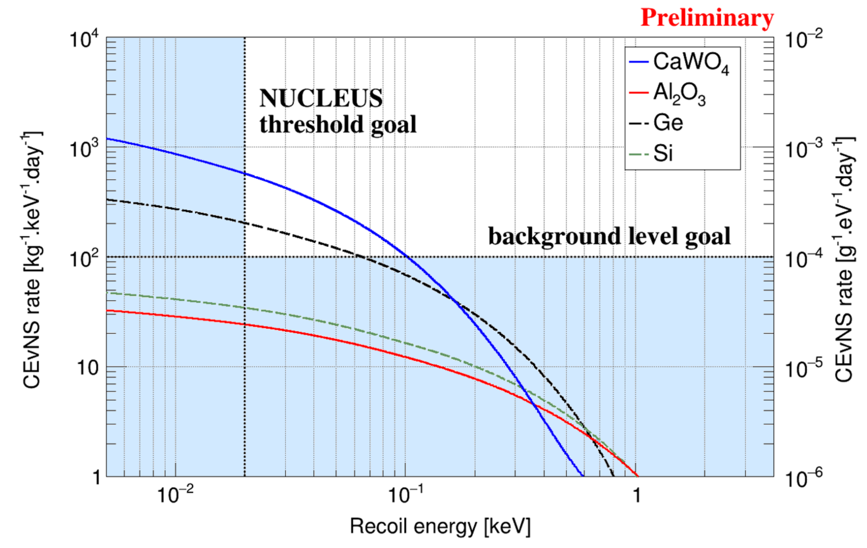
$$\begin{cases} \langle E_{\bar{\nu}_e} \rangle \approx 1.3 \text{ MeV} \\ \langle E_{recoil} \rangle^{CaWO_4} \approx 60 \text{ eV} \\ \langle E_{recoil} \rangle^{Al_2O_3} \approx 410 \text{ eV} \end{cases}$$

- High $\bar{\nu}_e$ luminosity @VNS:
  $\bar{\Phi}_{B1+B2} \approx 1.7 \times 10^{12}\ \text{cm}^{-2}\text{s}^{-1}$

⇒ **Recoil energy threshold goal: 20 eV**

⇒ **Targeted background level: ≤ 100 cpd/kg/keV**



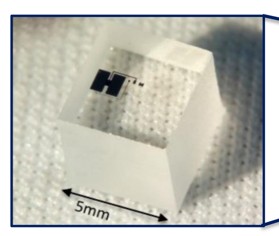


NUCLEUS experimental apparatus 3

Target

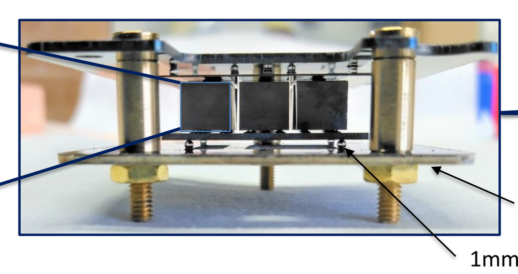
Cryogenic calorimeter arrays
- 3x3 array of $CaWO_4$ (6 g)
- 3x3 array of Al_2O_3 (4 g)
- Transition Edge Sensor (TES)
- 20 eV threshold

Successful Al_2O_3 prototype with demonstrated threshold of E_{th} = 19.7 ± 0.8 eV



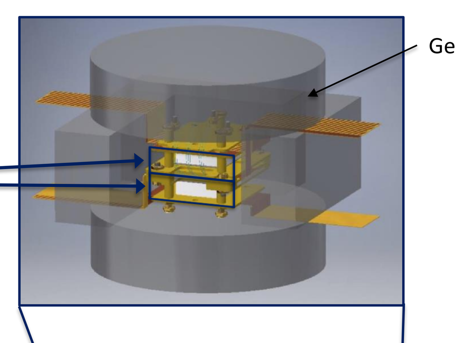
Inner veto

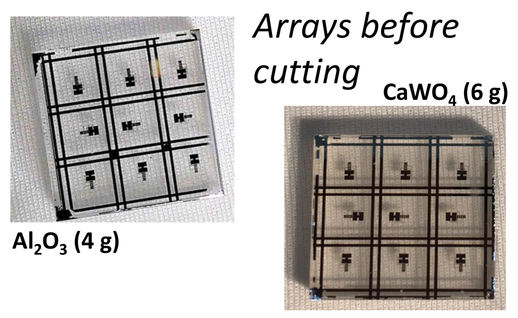
Against surface α,β backgrounds
- Instrumented detector holder
- TES readout, <1 keV trigger threshold
- UV/VIS calibration system (fibres, Ge mirror wafer, collimator)



Outer veto

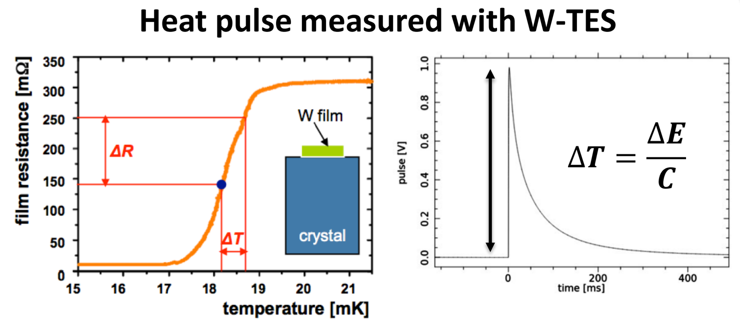
Against external γ,n
- Active ionizing detectors
- 6 HPGe crystals (2.5-cm thick), total mass of ~3.5 kg, couple of keV threshold



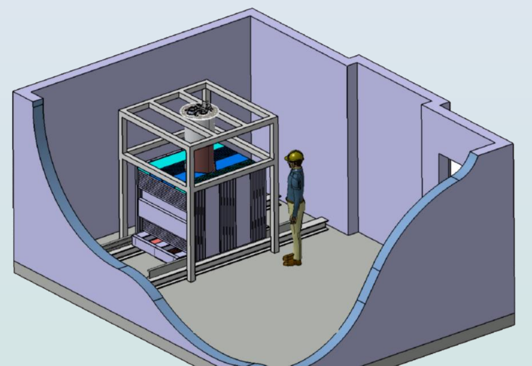


Arrays before cutting

Equipped with thin-film tungsten transition edge sensors as highly sensitive thermometers

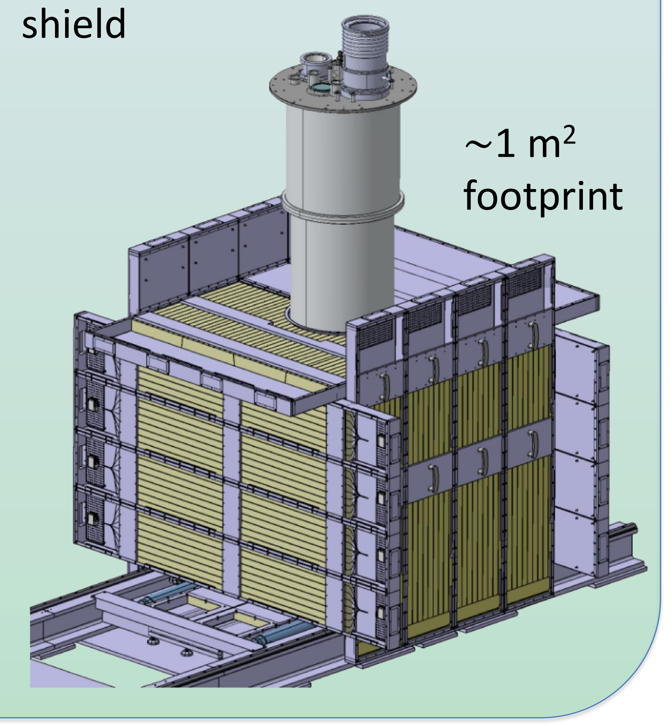


NUCLEUS mechanical setup



- Bluefors cryostat with pulse tube dilution refrigerator @10 mK
  ↳ *Commissioned in May 2020*
- Set-up openable in two parts through translation in a railway
- Close to 4π Muon Veto active shield

~1 m² footprint

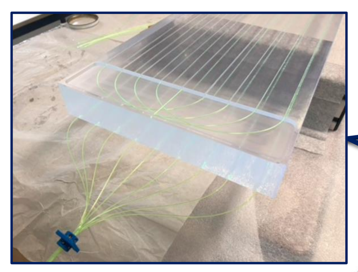


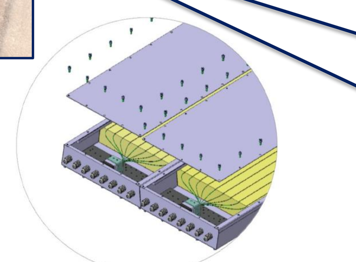
Preliminary views of the experimental setup to be installed at the VNS

↳ *Final design nearly completed. Best configuration being defined through extensive G4 simulations.*

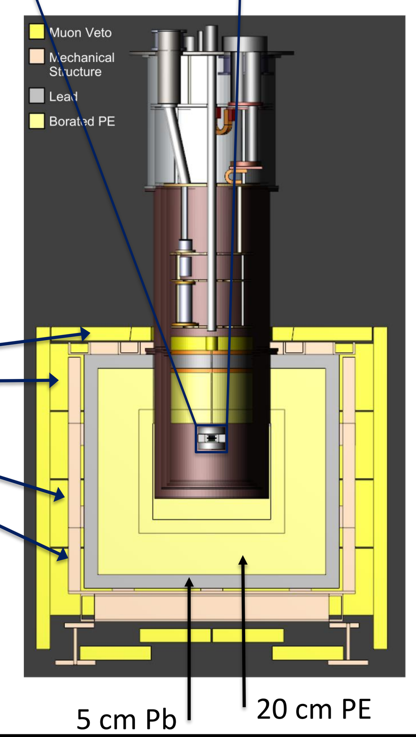
Muon veto

- >99% geometric coverage
- 5-cm thick plastic scintillators with SiPM and WLS-fibre read-out





⇒ **Preliminary expected muon rate: ~700 Hz**
↳ **cryogenic detector dead time < 10%**

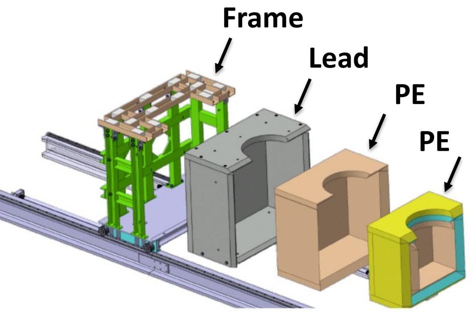


Shielding

External passive Shield

Graded layers of lead and borated PE against ambient γ and neutrons

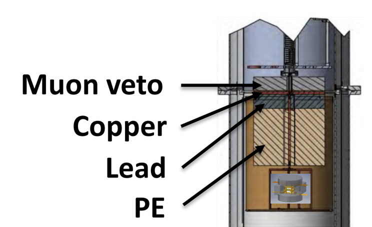
↳ *Setup optimized to minimize production of secondary particles induced by muon*

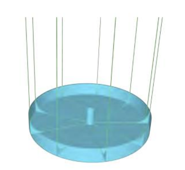


"Cold" passive shield

Above the detectors to close the external shield

↳ *Thermalized at ~800-900 mK*





Cryogenic Muon veto

Successful measurements with first protoype

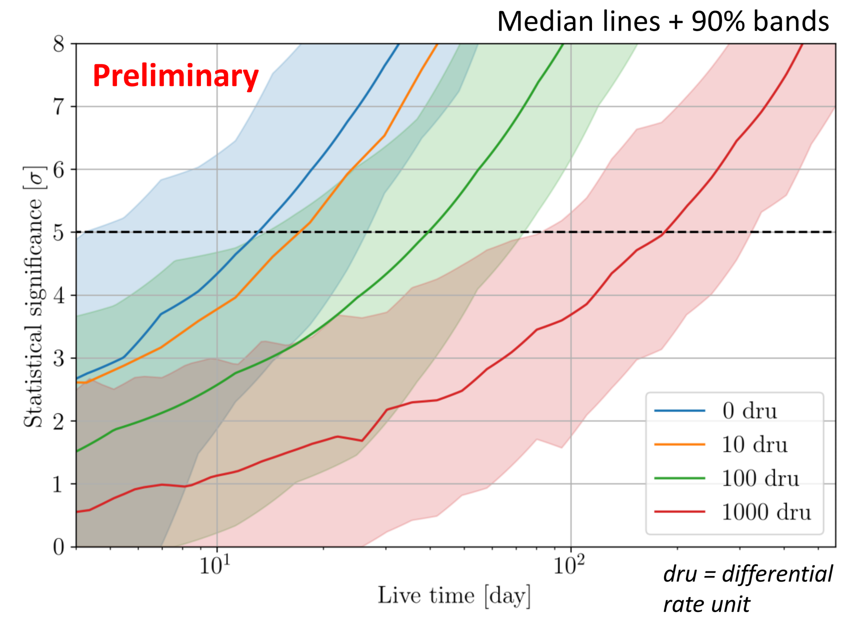
Sensitivity 4

NUCLEUS: a two-phase project

- **1st phase:** 10 g target detector

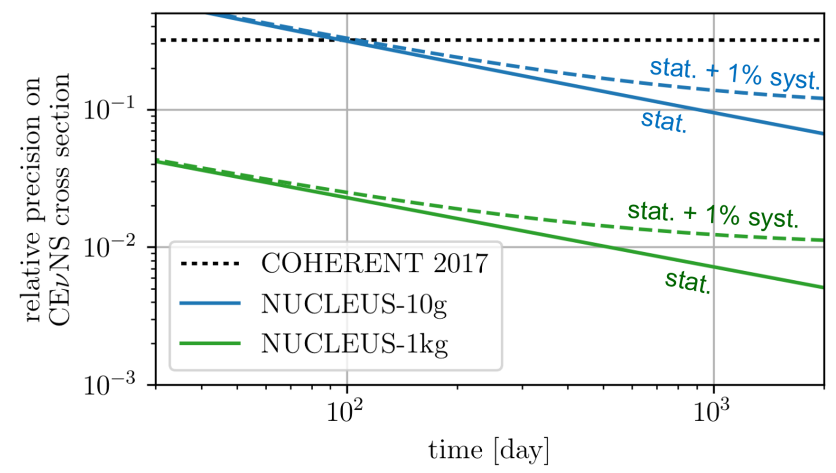
2022	2023	2023
Commissioning at TUM →	*Installation at Chooz* →	*Start data taking*

CEνNS sensitivity as a function of live time for NUCLEUS-10g for a flat background
- Energy threshold: 20 eV
- $\bar{\nu}_e$ flux: - 80% of full reactor power



dru = differential rate unit

⇒ **5σ observation of a CEvNS signal achievable in ~40 days of measurement assuming an optimistic flat background of 100 cpd/kg/keV.**



- **2nd phase:** 1 kg target detector

High-precision measurement (2024)

⇒ **Achievable precision limited by the systematic associated to the $\bar{\nu}_e$ flux prediction. High potential to explore physics beyond SM**

NUCLEUS references

[1] R. Strauss et al., The nu-cleus experiment: a gram-scale fiducial-volume cryogenic detector for the first detection of coherent neutrino–nucleus scattering. Eur. Phys. J. C 77 (2017) 506.
[2] R. Strauss et al., Gram-scale cryogenic calorimeters for rare-event searches. Phys. Rev. D 96 (2017) 022009.
[3] G. Angloher et al., Exploring CEνNS with NUCLEUS at the Chooz nuclear power plant. Eur. Phys. J. C 79 (2020) 1018.
[4] J. Rothe et al., NUCLEUS: Exploring Coherent Neutrino-Nucleus Scattering with Cryogenic Detectors. J. Low Temp. Phys. 199 (2020) 433-440.