# Exploring Coherent Neutrino-Nucleus Scattering with the NUCLEUS Experiment

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NUCLEUS Coll.: 7 Institutions, 40 members

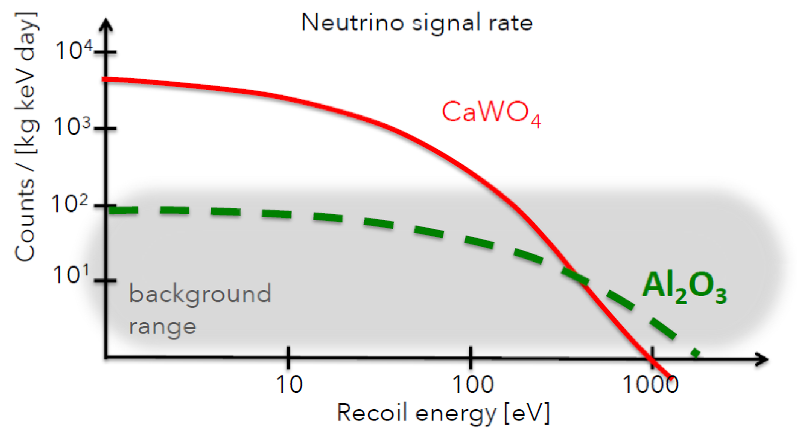
## Coherent Elastic Neutrino-Nucleus Scattering: The Potential of NUCLEUS

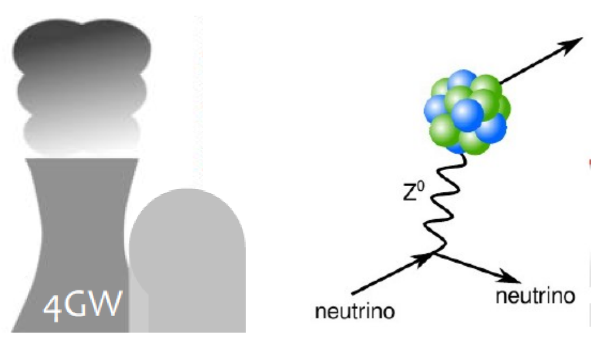
A precision measurements of the Coherent Elastic Neutrino-Nucleus Scattering (CE$\nu$NS) cross-section offers a unique way to study neutrino properties and to search for new physics beyond the Standard Model.

The NUCLEUS experiment will study CE$\nu$NS profiting from the following features:

Source: antineutrinos from nuclear reactors
- ⇒ Low energy
- ⇒ High intensity

Detector: gram-scale cryogenic calorimeter
- ⇒ Ultra-low energy threshold ($E_R \approx$20 keV in prototype)
- ⇒ Low systematics



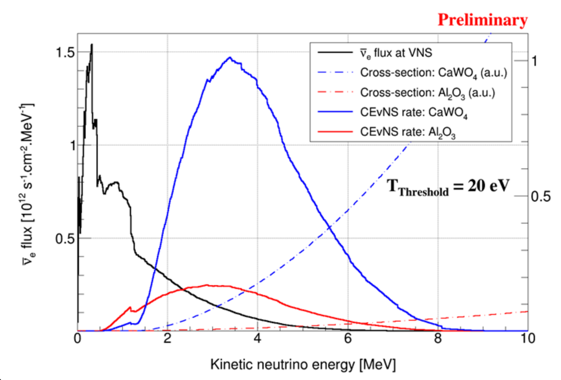



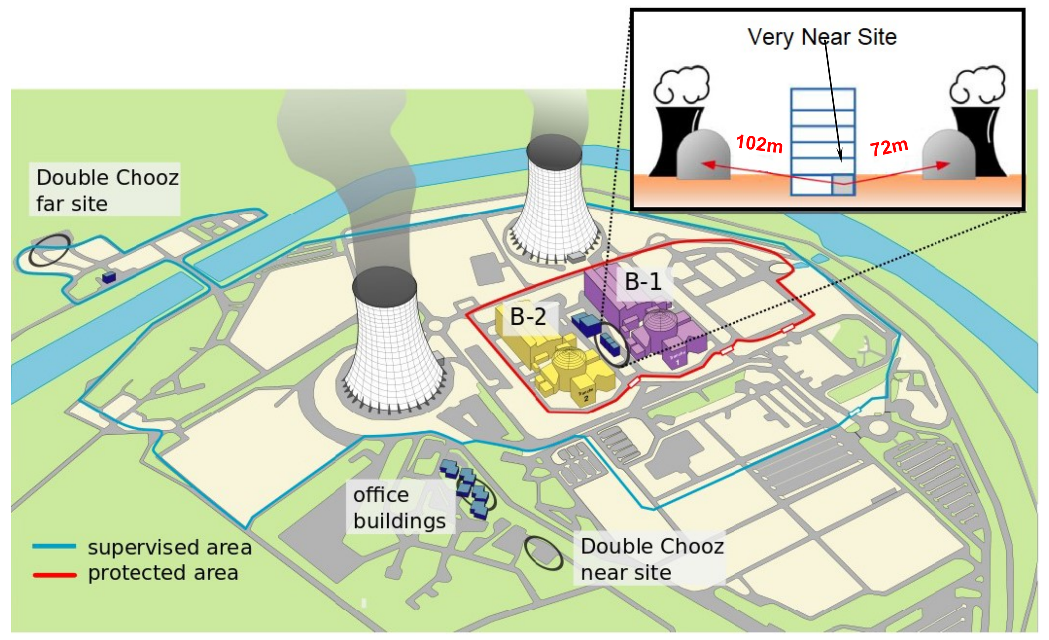

Multi target with CaWO$_4$ and Al$_2$O$_3$ crystals:
- ⇒ Smoking gun signal
- ⇒ Background discrimination
- ⇒ Test N$^2$ dependency

Target background level in [20 eV, 1 keV]: 100 cpd/kg/keV

## The Experimental Site @ VNS of CHOOZ Nuclear Power Plant

- 24m$^2$ basement room (~3 m.w.e.) in administrative building between two 4.25 GW$_{th}$ reactors
- Distance to reactor core: 72 m to B-1 and 102 m to B-2
- $\Phi_\nu$ = 1.7 ×10$^{12}$ $\nu$/cm$^2$/s; $E_\nu$ < 10 MeV
- 30% reduction of the cosmic $\mu$
- Environmental $\gamma$, n and Rn measured:
  $\Phi_\gamma \approx$ 3 $\gamma$/cm$^2$/s
  $\Phi_n \approx$ 5×10$^{-3}$ n/cm$^2$/s
  Rn ≈ 30 Bq/m$^3$
- Vibration measurement performed

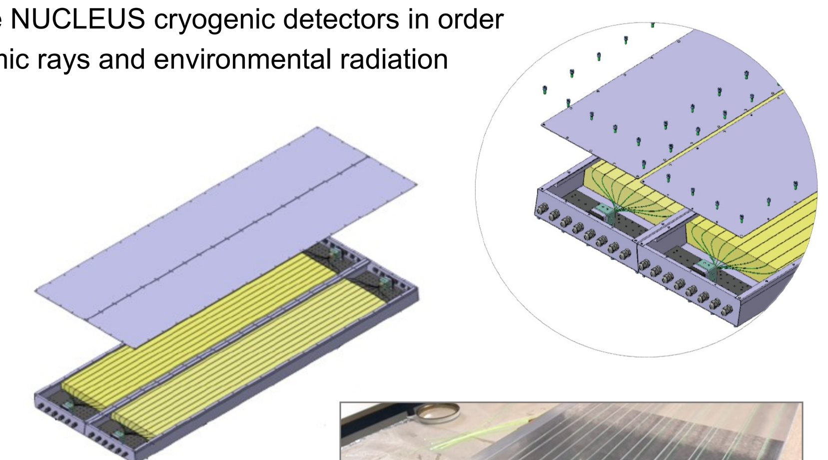


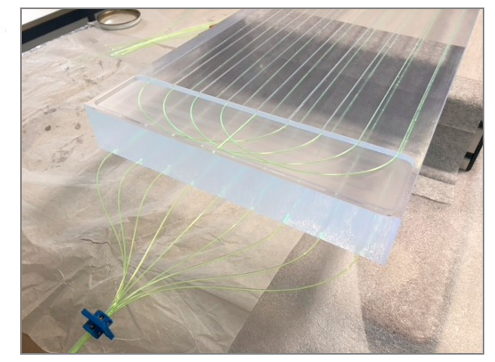

## The Muon Veto and the Passive Shield

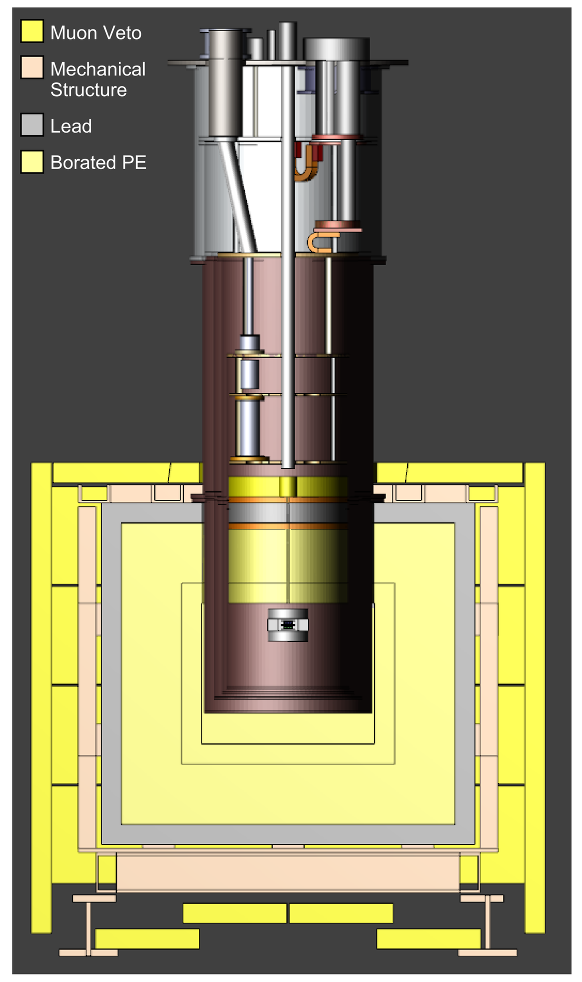
An active muon veto and a passive shield surround the NUCLEUS cryogenic detectors in order to minimize the contribution to background due to cosmic rays and environmental radiation

Main background sources
- Cosmic-rays and $\mu$-induced secondaries in VNS building and setup components
- Environmental gammas
- Environmental neutrons
- Radioactive contaminants in the setup materials



Muon Veto
- 5 cm thick plastic scintillator plates
- SiPM & WLS-fiber based read-out system
- ≈4$\pi$ coverage of the set-up (> 99% geometrical efficiency)
- Expected count rate of cosmic muons ~700 Hz
  ⇒ detector dead time < 10%

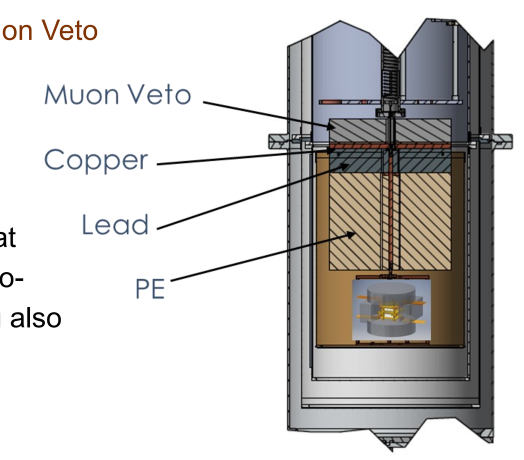





Passive Shield

Extensive Geant4 simulation campaign to optimize the passive shield design:
- External layer: 5/10 cm low radioactive lead to reduce ambient $\gamma$'s (external position reduces the production of $\mu$-induced neutrons near detectors)
- Inner layer: 15/20 cm borated PE as low-Z material to reduce neutrons
- Movable mechanical structure to allow easy opening/closing procedure

Inner Cold Shield and Cryogenic Muon Veto
- Placed inside the cryostat, just above the cryogenic detectors
- Aligned with external shield
- Consists of cryogenic muon veto (plastic scintillators characterized at sub-Kelvin temperatures), low radio-active lead, copper support (acting also as thermal contact), borated PE
- Thermalized at 800 mK



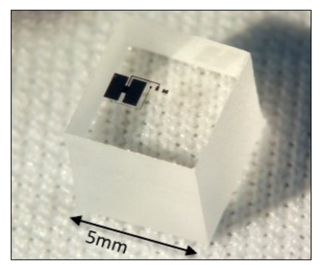

Radiopurity of Materials
- Screening of setup materials with HPGe detectors is ongoing
- Evaluation of tolerance levels in setup materials with Geant4 simulations is also ongoing: e.g., upper limits for $^{210}$Pb level in lead of passive shield and for contaminants in cryostat vessels have been used to select the materials

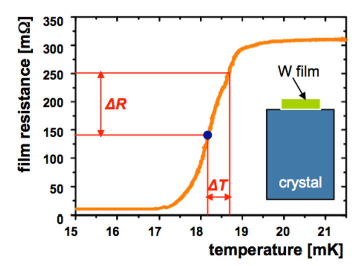
## The NUCLEUS Cryogenic Detectors

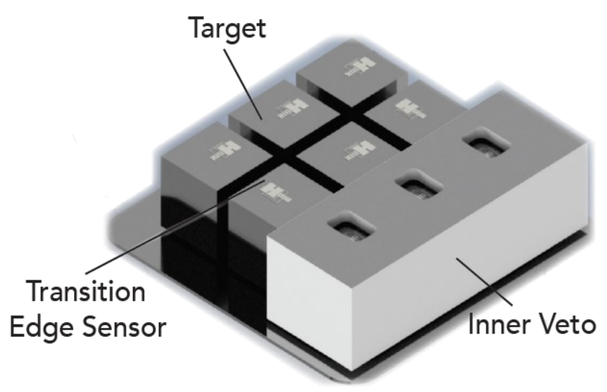
The NUCLEUS cryostat will hold a system of nested cryogenic detectors that will allow the reduction of the background counting rate thanks to the anticoincidence technique

Target detectors

Gram-scale cryogenic calorimeters based on CRESST technology
- Equipped with thin-film tungsten transition edge sensors as highly sensitive thermometers
- Optimized to reach at least 20 eV energy threshold
- 3x3 array with CaWO$_4$ (6g)
- 3x3 array with Al$_2$O$_3$ (4g)

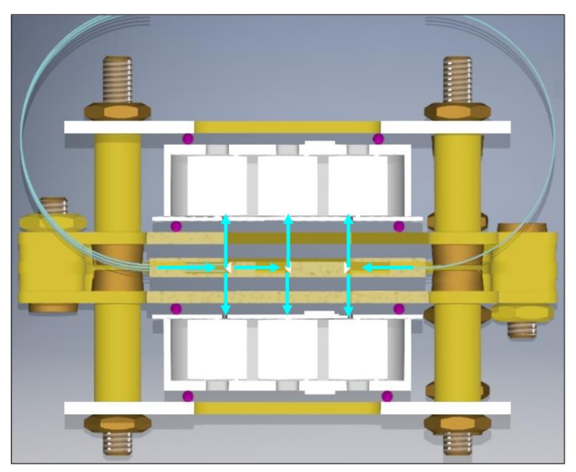


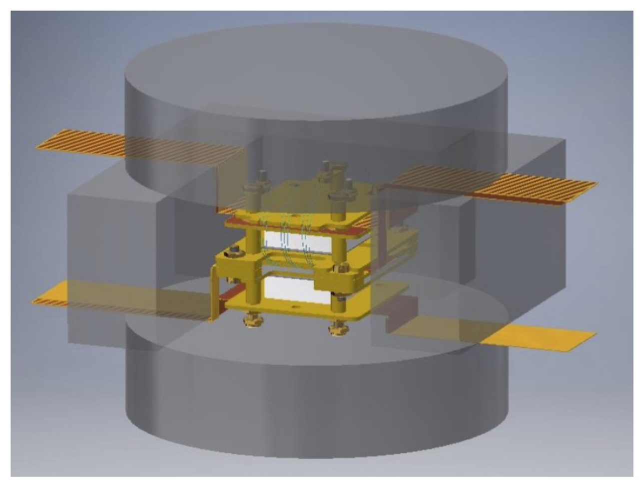

Inner Veto

It has the dual role of instrumented holder for crystal arrays and veto against $\alpha/\beta$ surface contaminations:
- Made of silicon beaker and wafer to fully encapsulate the crystal arrays
- Act as sub-keV threshold cryogenic detector
- Readout by transition edge sensors



Calibration system

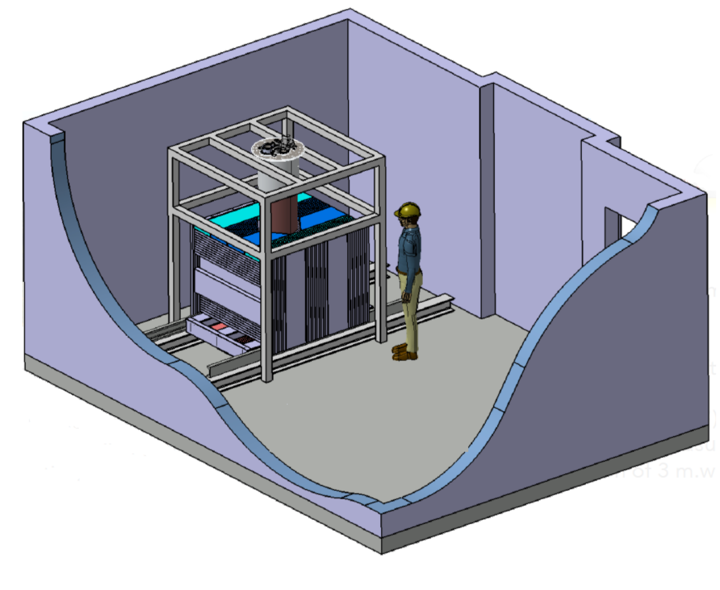
A system of optical fibers, Ge mirror wafer and collimators is used to illuminate the target detectors with UV-VIS light

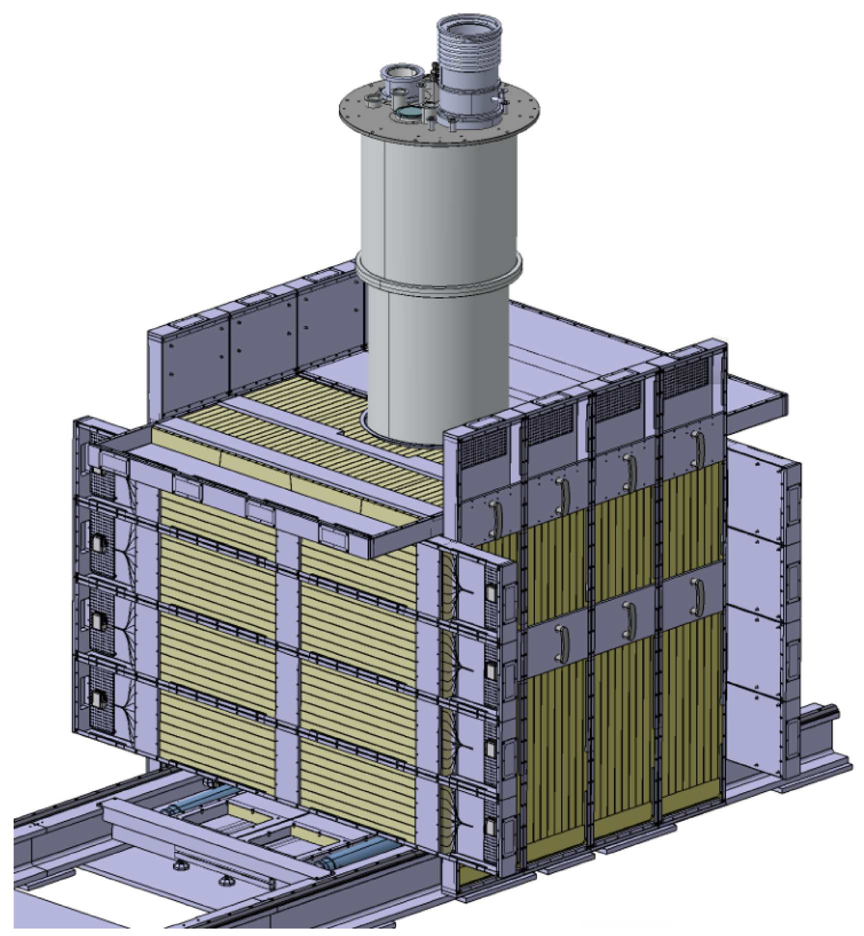


Outer Veto

For reduction of external gamma and neutron background
- Active ionizing detectors
- 2 kg and 2,5 cm thickness in 6 HPGe crystals
- Enclosing inner veto and target detectors with 4$\pi$ coverage
- Energy thresholds of O(1 keV)
- Further effective background reduction for secondary particles produced by undetected muons

Cryostat: a "dry" dilution refrigerator is used to avoid handling of cryogenic liquids. It has been commissioned in May 2020. The base temperature is of O(10 mK). A dedicated work on vibration decoupling is ongoing.





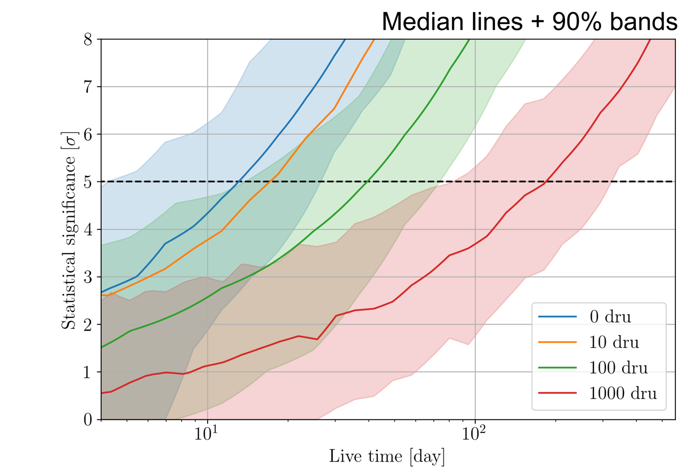
Preliminary views of the experimental setup to be installed at the Very Near Site of the Chooz nuclear power plant

The design of some components of the setup (as e.g. the passive shield and the vibration decoupling system) still has to be finalized

Simulation studies are in in progress to determine the best configurations

## NUCLEUS 10g Sensitivity

Sensitivity to CE$\nu$NS signal for the following assumptions:
- 20 eV energy threshold
- VNS neutrino flux at 80% reactor power
- Flat background




5σ observation of a CE$\nu$Ns signal achievable in ~40 days of measurement time for a flat background of 100 cpd/kg/keV

## A Two Phase Project

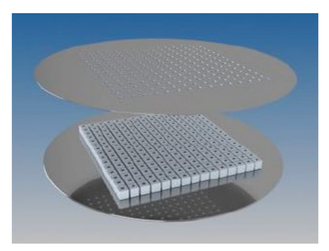
Phase 1

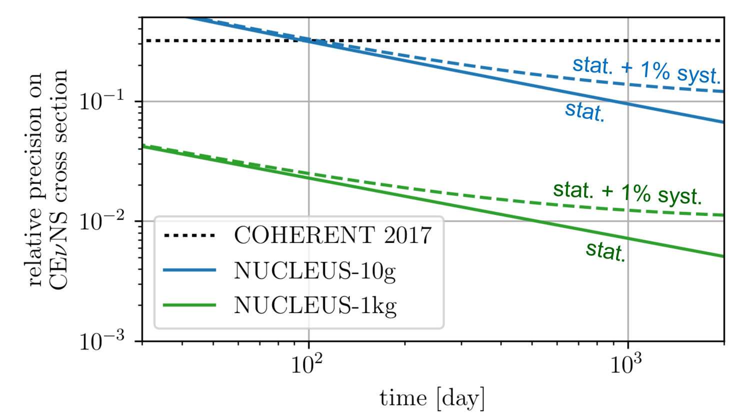
10g target detector: detection of coherent neutrino scattering

2021 - Commissioning at TUM
2022 - Installation at Chooz
2022 - Start data taking

Phase 2 (2024)

1 kg scale: high-precision measurement






1$^{st}$ phase: stat limited

2$^{nd}$ phase: syst limited

Main NUCLEUS papers:

[1] R. Strauss et al., *The ν-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.

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