# Neutrino Physics with NUCLEUS

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with material from the NUCLEUS collaboration

Austrian Roadmap Round Table Meeting, 10 June 2024 nu cleus EXPERIMENT

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

- ~65 People, 7 institutions, 4 countries
- **Strong Austrian contribution**:
  ~15 people from HEPHY + TU Wien
- Long-Term Goals:
  Use **Coherent Elastic Neutrino-Nucleus Scattering** (CEvNS) as a probe for precision physics and new physics
  HEPHY INSTITUTE OF HIGH ENERGY PHYSICS data analysis, simulation, DAQ + detector development
- (Future) Facility:
  The **Very Near Site** at the nuclear power plant in Chooz, France
- Current Activities:
  **Commissioning** of NUCLEUS at TUM, prepare to move to Chooz
- Synergies:
  Searches for Dark Matter (COSINUS, CRESST), neutron physics, …

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS | TU WIEN | cea | INFN Istituto Nazionale di Fisica Nucleare | MAX-PLANCK-INSTITUT FÜR PHYSIK | SAPIENZA UNIVERSITÀ DI ROMA | Technische Universität München TUM | erc European Research Council Established by the European Commission | SFB 1258 Neutrinos Dark Matter Messengers | FWF Der Wissenschaftsfonds. | P2IO Physique des 2 Infinis et des Origines

# Coherent Elastic Neutrino-Nucleus Scattering

Approximative cross-section

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2 - \frac{MT}{E_\nu^2}\right)$$

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

Coherency typical $E_\nu < 30\ \mathrm{MeV}$:

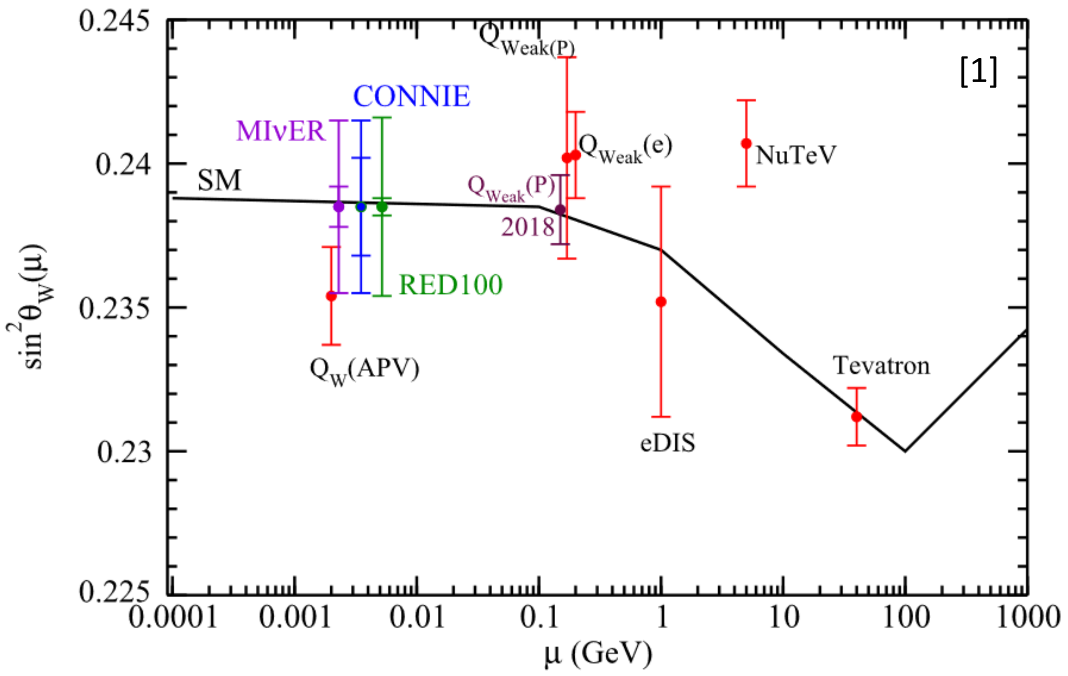
$$F^2(Q) \rightarrow 1$$

$$\frac{d\sigma}{dT} \propto N^2$$

- Weak neutral current process
  → Precisely predicted by the Standard Model (SM)
- **Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)** predicted by D. Freedman[1] in 1974
  → Event signature: **nuclear recoil**
- **No threshold**, unlike inverse beta decay (IBD) that needs at least 1.8 MeV
  → Sensitive to sub-MeV physics
- Observed in 2017 by the COHERENT collaboration[2] with only partial coherency due to $E_\nu < 50\ \mathrm{MeV}$
  → World wide endeavor to use low energy ν from nuclear power plants for **full coherency** and $\boldsymbol{N^2}$ **boost**

[1] D. Freedman, Phys.Rev. D 9.5 (1974) 1389-1392, [2] D. Akimov et al. (COHERENT Collab.), Science 357 (2017) 1123-1126

# Physics Cases



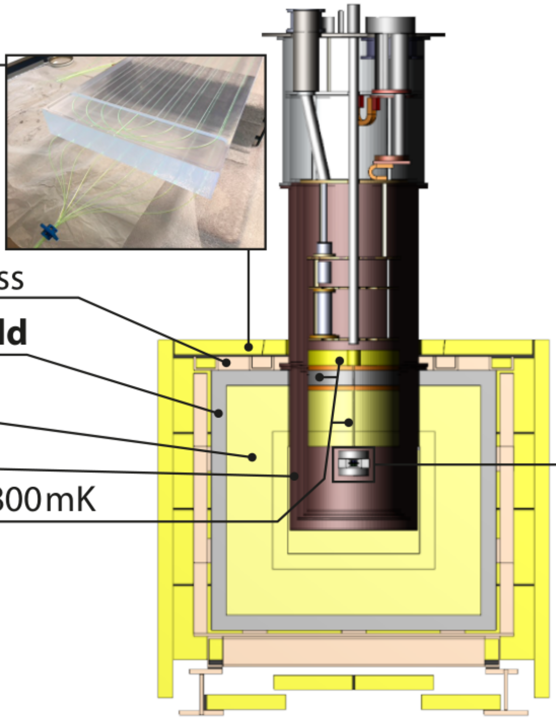

- CEvNS in the SM
  - Electroweak precision tests, *Weinberg angle at low Q*[1], neutron form factors, etc.[2]
- CEvNS beyond the SM
  - Non-standard interactions between neutrinos and quarks
  - New neutrino properties: neutrino electromagnetic properties (magnetic moment, charge radii)
  - Light sterile neutrinos
  - And more[2]

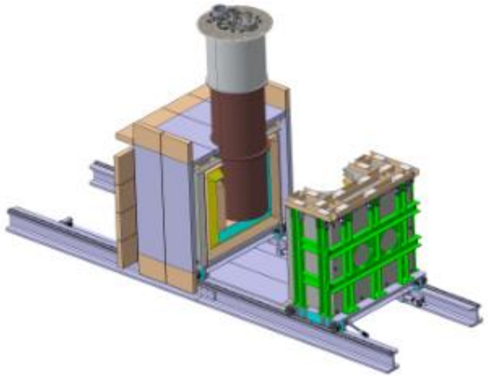
→ **Rich physics cases**

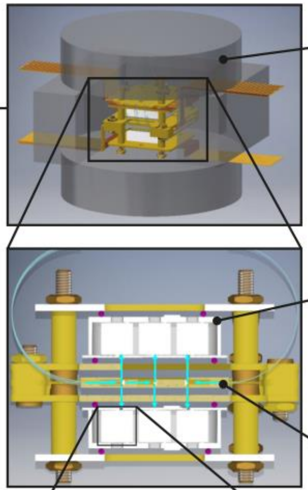
[1] B.C. Cañas et al., Phys.Lett. B 784 (2018) 159-162], [2] M. Abdullah et al., arXiv:2203.07361]

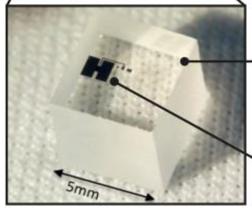
# The NUCLEUS Experimental Setup

- **Muon veto**: 5 cm thick plastic scintillator with SiPM and WLS-fibre read-out, >99% geometric coverage, muon rate ~700 Hz → detector dead time < 10%
- Movable **mechanics** for easy access
- 5…10 cm low radioactivity **Pb shield**
- 20…15 cm borated **PE shield**
- Dry dillution **cryostat**
- **Inner shields and muon veto** @ 800 mK










**Outer Veto** against external γ,n
- active ionizing detectors
- 6 HPGe crystals, each 2.5 cm thick, total mass of 2 kg, O(1 keV) trigger threshold

**Inner Veto** against surface background
- instrumented detector holder
- Transistion Edge Sensor (TES) readout, <1 keV trigger threshold
- UV/VIS **calibration system** (fibres, Ge mirror wafer, collimator)

Cryogenic calorimeter arrays as **targets**
- 3x3 array with $CaWO_4$ (6 g)
- 3x3 array with $Al_2O_3$ (4 g)
- TES with 20 eV trigger threshold

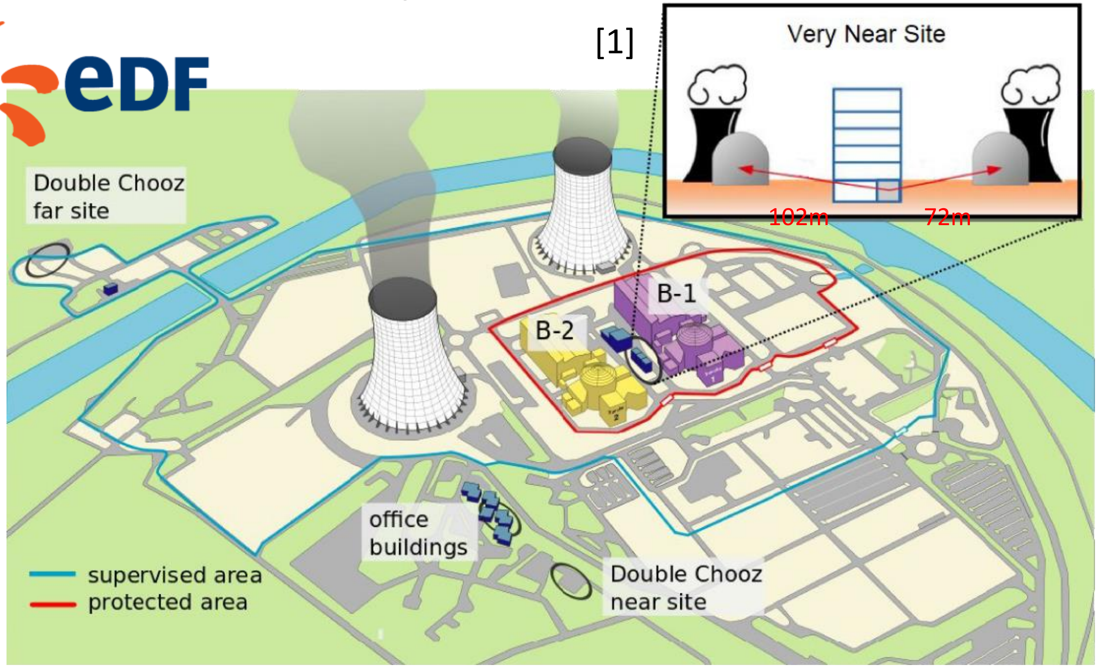
→ **proven** CRESST detector technology

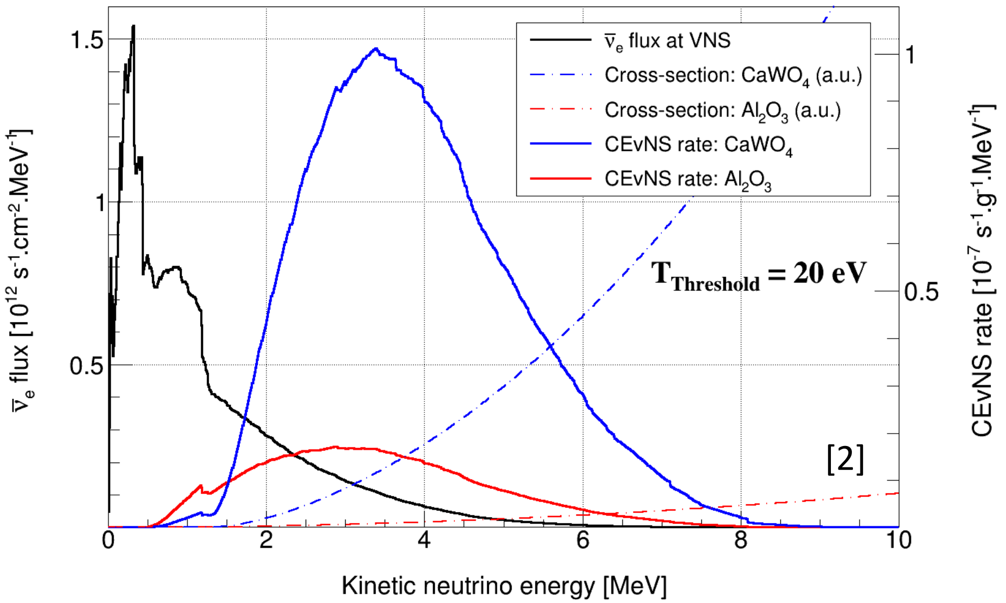
→ DAQ: Vdaq3 @ HEPHY

[H. Kluck et al. (NUCLEUS Collab.), J.LowTemp.Phys. 209 (2022) 936–943]

# The Very Near Site at Chooz

[1]

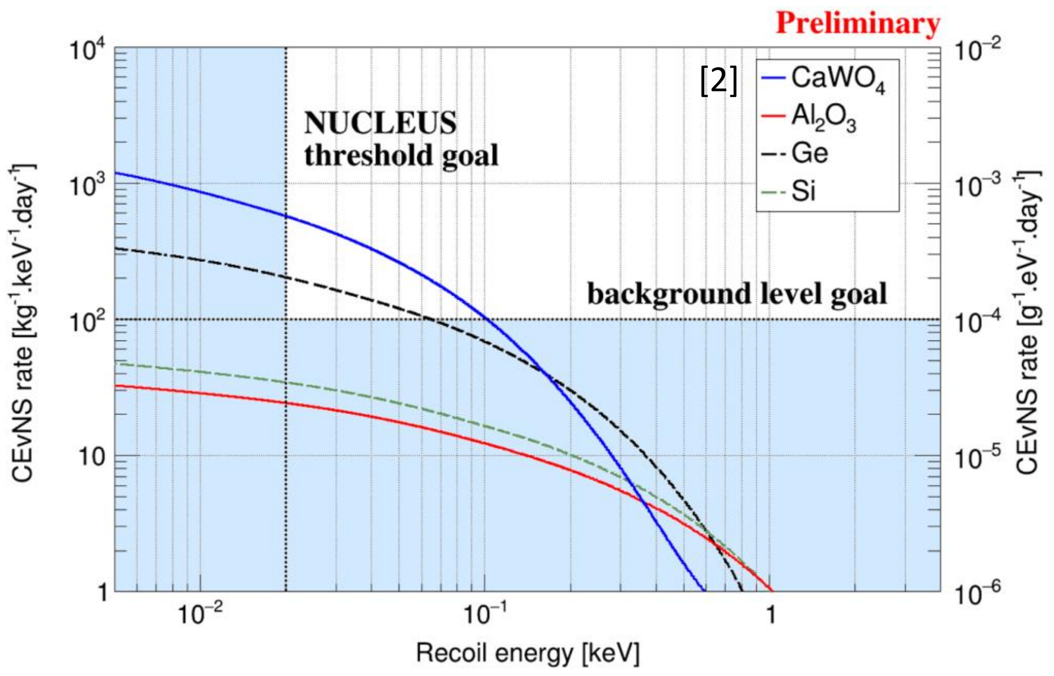



- Very Near Site (VNS):
  - **New experimental site**[1] at EDF nuclear power plant in Chooz, France
  - 24m² basement room between two 4.25 GW reactors
- Antineutrinos from Chooz' reactors[2]:
  - High intensity: $\Phi_{B1+B2} = 1.7 \cdot 10^{12}$ $cm^{-2}s^{-1}$
  - Low energy: $E_\nu < 10$ MeV
    → **full coherency**

[1] G. Angloher et al. (NUCLEUS Collab.), Eur.Phys.J. C **79** (2019) 1018], [2] H. Kluck et al. (NUCLEUS Collab.), J.LowTemp.Phys. **209** (2022) 936–943]

# Signal and Background




- Below ≈100 eV: coherency boost signal above expected background level
  →**Only experiment with proven 20 eV threshold for nuclear recoils**[1]
- Preliminary predicted total background, based on Geant4 simulations[2]: $<100\ kg^{-1}\ keV^{-1}\ d^{-1}$ in [10 eV, 100 eV] for $CaWO_4$
- Validating sub-keV simulations with ELOISE[3]
- Energy calibration with CRAB technique[4]

[1] R. Strauss et al. (NUCLEUS Collab.), Phys.Rev. D 96 (2017) 022009, [2] G. Angloher et al. (NUCLEUS Collab.), Eur.Phys.J. C 79 (2019) 1018,
[3] H. Kluck, SciPost Phys. Proc. 12 (2023) 064, [4] H. Abele et al. (CRAB & NUCLEUS Collab.), PhysRev.Lett. 130.21 (2023) 211802

# Commissioning at TUM

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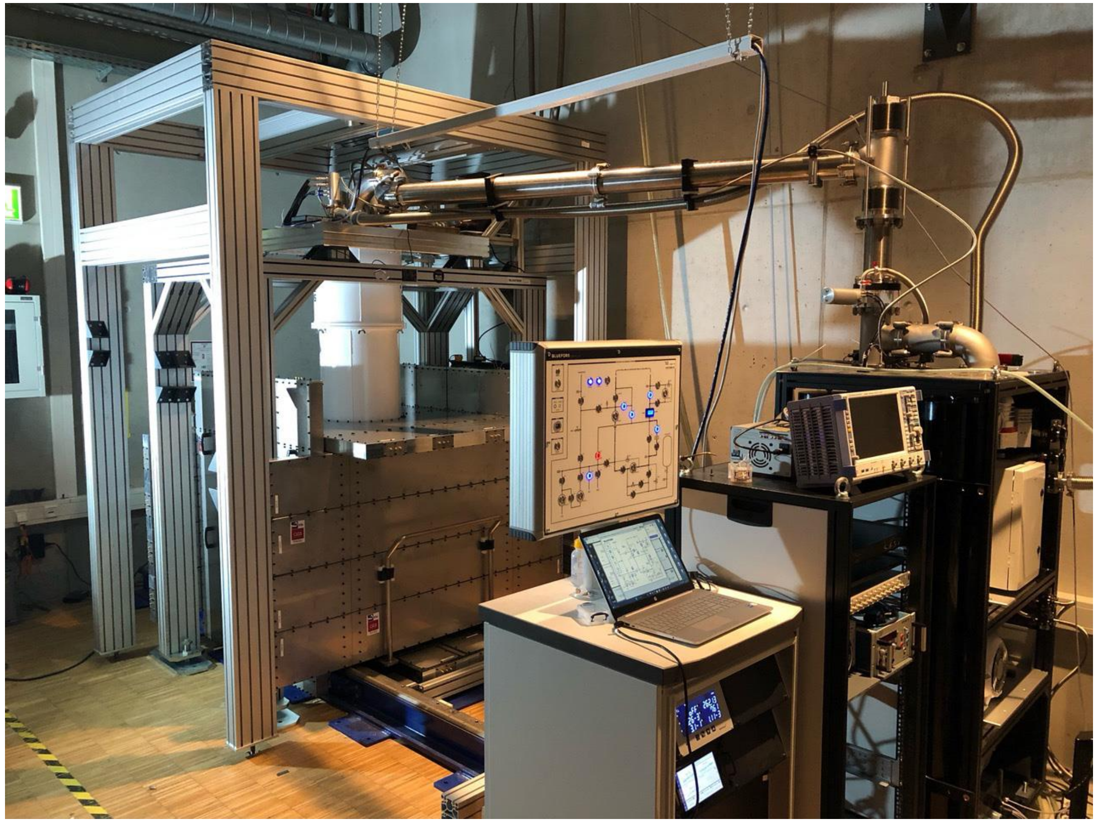

- Since May 2023: commissioning at Underground Lab (UGL) of TUM
  - Blank assembly of cryostat, shields, etc. ✓
  - Integrating of components ✓
  - Synchronizing of DAQ ↺
  - Cryostat + DAQ optimisation ↺
  - Background studies ↺
  - More than **4 weeks of stable data taking** with $CaWO_4$ ✓

→Move to **Chooz in 2025**

→>2025: run with 10 g target

→$\gtrsim$2027: upgrade to 1 kg target

# Synergies

- NUCLEUS' neutrino **physics** has connections to:
  - Dark matter (DM) physics – CEνNS is a background to DM searches (neutrino fog)
  - New physics beyond the SM (incl. DM): CEνNS as low energy-probe for any deviation from the standard model
  - Neutron physics – CEνNS as probe for nuclear structure information
- CRESST, CRAB, COSINUS, and NUCLEUS are using the same **detector technology** in the same energy range, hence similar …
  - Detector development
  - Detector calibration
  - DAQ hardware + software development
  - Background simulation + mitigation

# Summary

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- NUCLEUS will use **CEvNS as a probe for low energy neutrino physics** looking for wide range of phenomena in the SM and beyond
- Only CEvNS experiment with **proven O(20eV) detection threshold** for nuclear recoils → use of full $N^2$ coherency boost
- Established a **new experimental site** at Chooz nuclear power plant
- **Strong connections** to physics beyond the standard model, dark matter physics, and neutron physics
- **Great synergies** with experiments CRESST, CRAB, and COSINUS for detector technology, DAQ hard- and software, simulation
- **High scientific gain** for applying **HEPHY's core expertises**