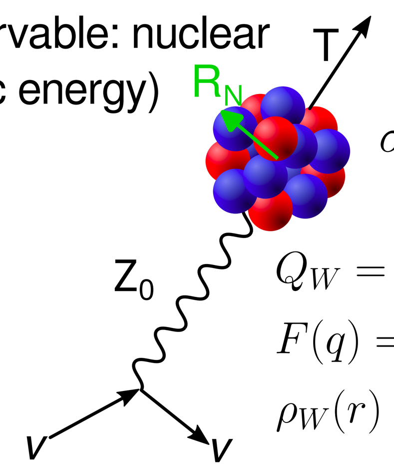
Searching for Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) with the NUCLEUS detectors

Author: Giorgio Del Castello on behalf of the NUCLEUS collaboration

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

Nuclear Recoil (observable: nuclear kinetic energy)



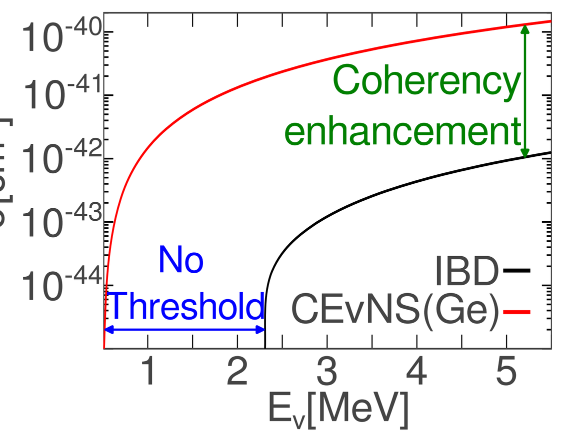
Neutrino Energy | Nuclear Form-Factor | Weak Charge

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

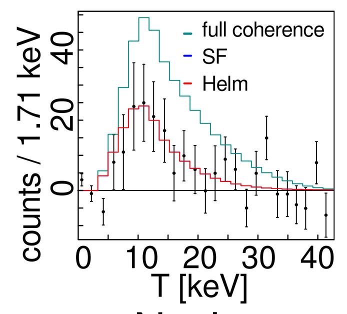
$$Q_W = N - P(1 - 4\sin^2\theta_W)$$

$$F(q) = \frac{1}{Q_W}\int_0^{R_N} \rho_W(r)\frac{\sin(qr)}{qr}dr$$

$$\rho_W(r) = \rho_N(r) - (1 - 4\sin^2(\theta_W))\rho_P(r)$$



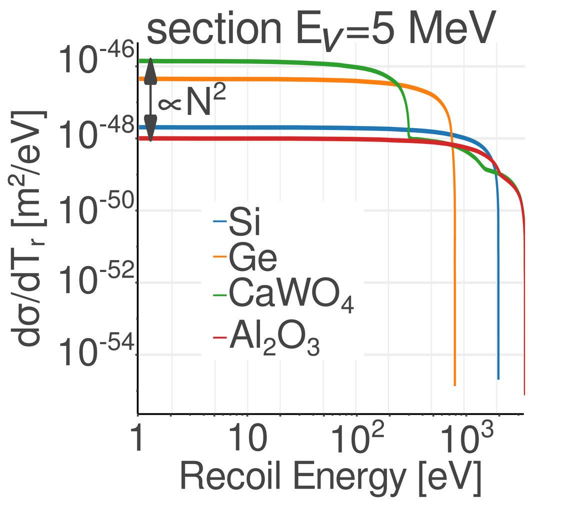
A **precision measurement** of the **CEvNS cross-section** offers a unique way to study many neutrino properties and to search for new physics beyond the Standard Model.



Nuclear form-factor

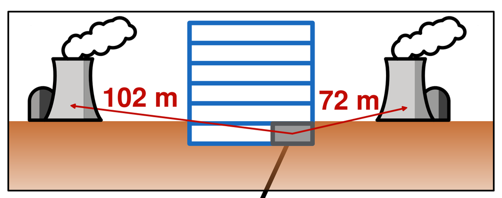
Monitoring of reactors and nuclear waste

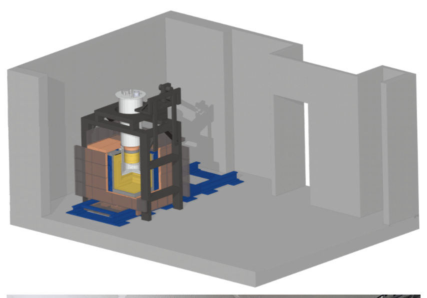
Differential CEvNS Cross section E_ν=5 MeV



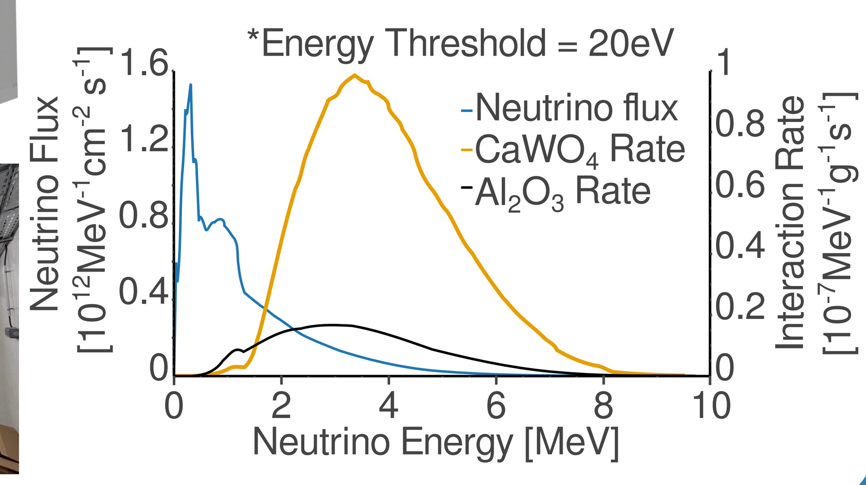
The Experimental Site: VNS at Chooz Nuclear Power Plant

Very Near Site (VNS):
- 24 m² basement room (~3 m.w.e. overburden)
- 30% Muon Attenuation, factor 5 neutron attenuation
- Two 4.25 GW_{th} reactors
- Anti-Neutrino Flux: $\phi_\nu = 1.7\times10^{12}$ ν/cm/s



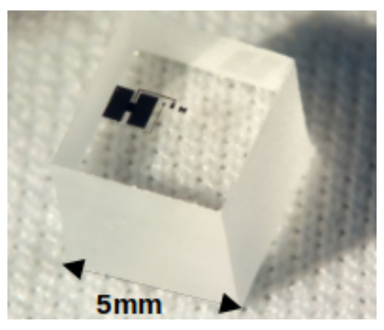


Neutrino Flux and Interaction rate at VNS

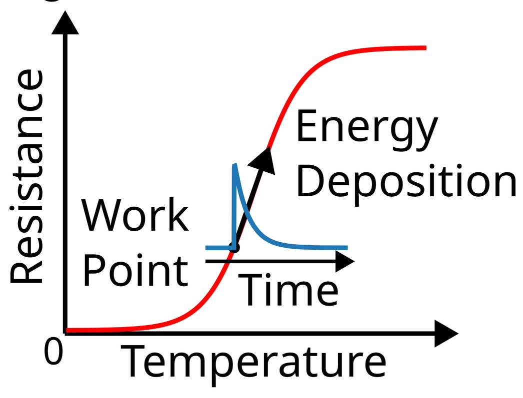


Cryogenic Target Detectors

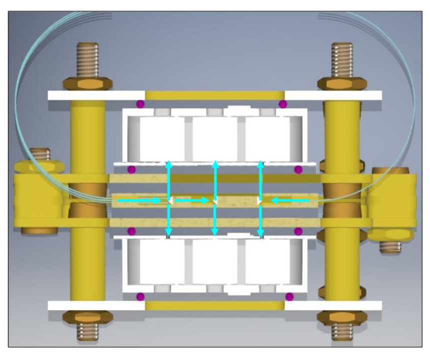
Gram-scale cryogenic calorimeters equipped with thin-film tungsten transition-edge sensors as highly sensitive thermometers.
Optimized to measure energies under a few keV.



Absorber crystal cube coupled with



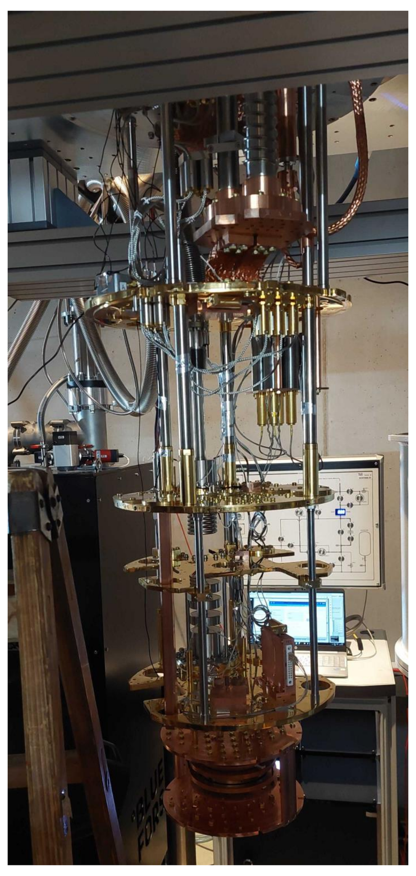
Transition-Edge Sensor (TES): superconductive film operated on the onset of the transition (operated at ~10mK)



Two 3x3 matrices of target detectors.
Multi-target approach:
- Al_2O_3: for background measurement
- $CaWO_4$: high CEvNS rate

Particle Interaction → Phonon Production → TES Heating → Resistance Change

Cryogenic System



Internal stages of the NUCLEUS cryostat

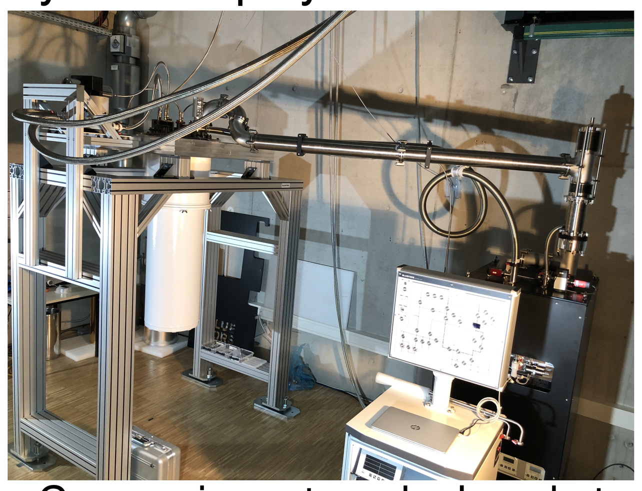
"Dry" Dilution refrigerator to avoid handling of cryogenic liquids. The base temperature reached is below 7mK.

Model: BlueFors LD400 cryogen-free dilution refrigerator
Cooling Power: >500 μW at 100mK

✓ Custom Vibration decoupling system deployed and in use (patent protected)

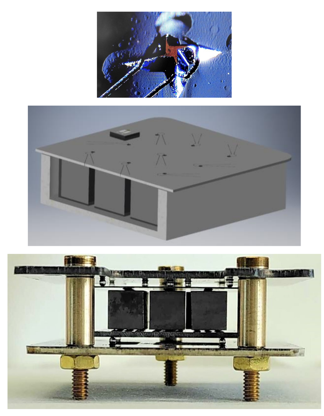
○ Installation of read-out electronics under commissioning

○ Installation of calibration electronics under commissioning



Cryogenic system deployed at TUM's (Munich, Germany) shallow underground laboratory

Active Vetos and Shielding

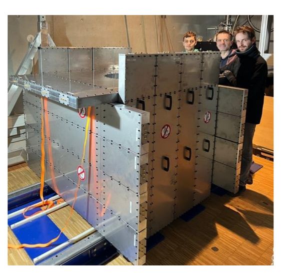


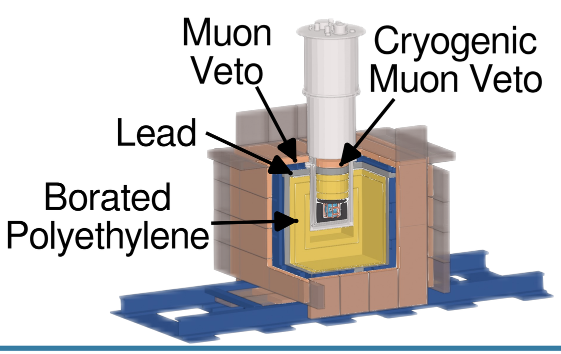
Inner Veto:
- Instrumented holder for target detectors:
  - Sub-keV cryogenic detector with TES readout
- Vetos against
  - Mechanical stress events
  - "EXCESS"
  - Surface contamination

Cryogenic Outer Veto (COV):
- Active ionization detectors
- Reduction of external γ
- 4 kg of 2.5 cm thickness in 6 HPGe crystals (4π coverage)
- Threshold <10 keV

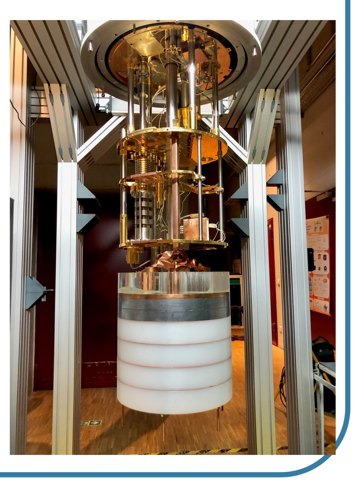
Muon Veto (MV) :
- 5 cm thick plastic scintillator plates
- SiPMs & WLS-fiber readout
- 4π coverage with cryogenic muon veto
- Threshold ~ 5 MeV

External Shielding:
- Lead and Polyethylene





Inner Shielding:
- Lead, Copper, PE, B_4C
- Shielding against neutrons and ambient gammas



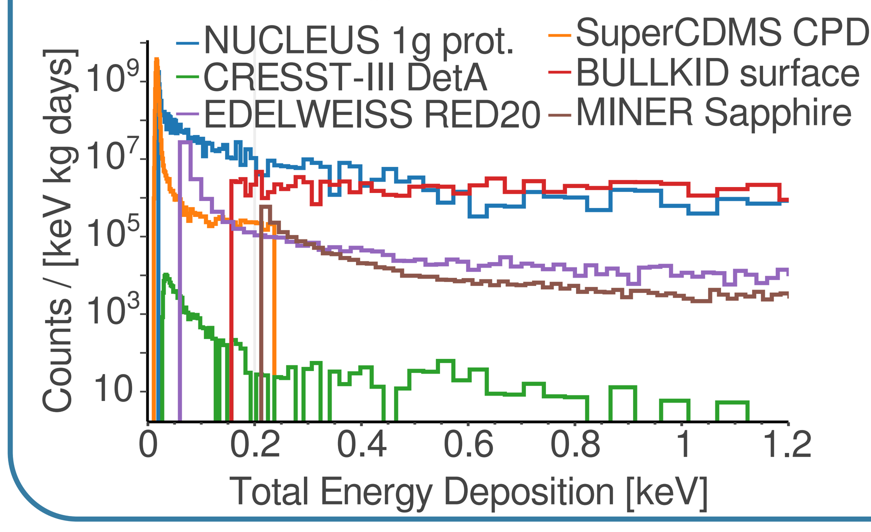
Sensitivity and Simulations

Preliminary

Source	Flux [s^{-1} cm^{-2}]	Rate [counts/kg/day] 10-100 eV	0.1-1 keV	1-10 keV
Ambient γs	3.937	< 1.2	3.2±1.3	51.4±8.4
Atmospheric muons	0.019/1.4	< 7.9	<3.6	10.5±3.5
Atmospheric neutrons	0.0134/5.0	20.9±0.6	39.4±0.9	116.1±1.5
Material Contamination	*(sum)*	0.91±0.18	11.47±0.65	133.8±2.21
Sum		**25.8±2.2**	**55.4±2.1**	**311.8±9.4**

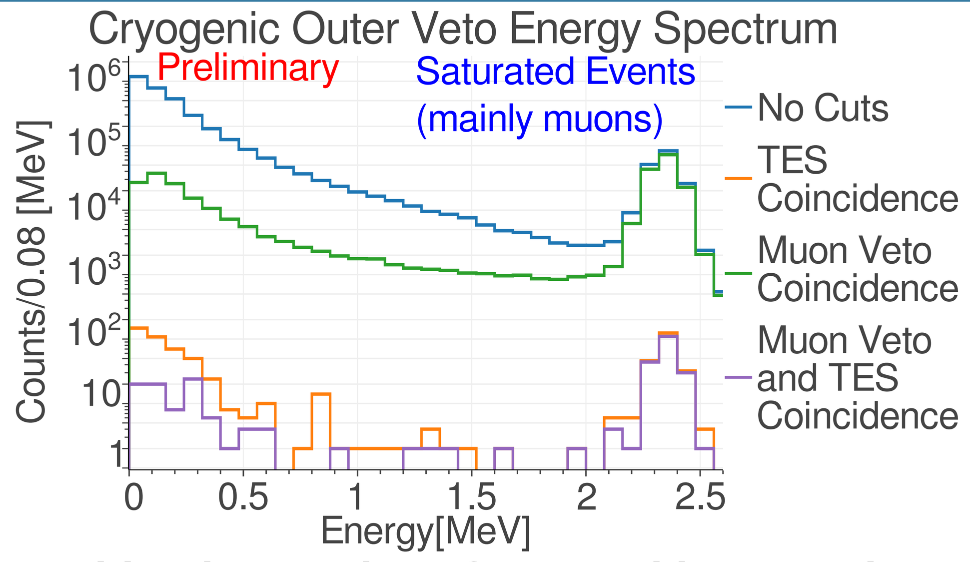
Known Backgrounds:
- Expected CEvNS rate:
  - ~30 counts/kg/day in the 10eV-1keV recoil energy range
- Targeted Signal/Background ≥ 1
- With 100 dru flat background and full setup:
  - 5σ significance in few weeks of live-time
  - 10% uncertainty on CEvNS

Low Energy EXCESS Spectra



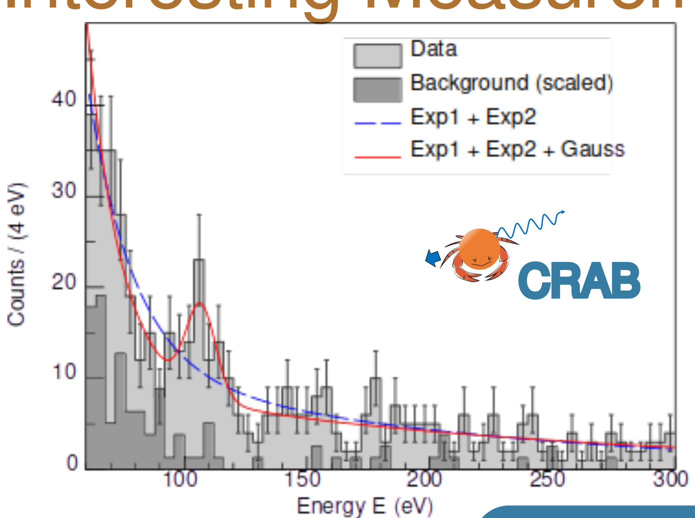
Unknown Background "Low energy EXCESS":
- Unexplained exponential rise of counting rate at low energies (similar to reactor CEvNS)
- With "EXCESS" competitive limits can be set on new physics models (light mediators or neutrino EM properties)

Cryogenic Outer Veto Energy Spectrum

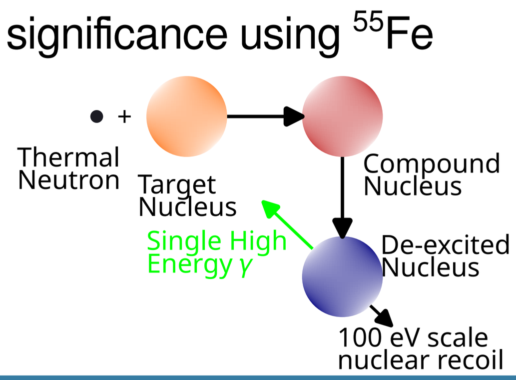


First combined operation of vetos with target detectors
- Muon Veto + One COV crystal + One Al_2O_3+TES crystal cube
- For ~40h of data expected 3-fold coincidences in low background environment (~15 m.w.e):
  - few direct muons and accidentals (very few in CEvNS's R.O.I)

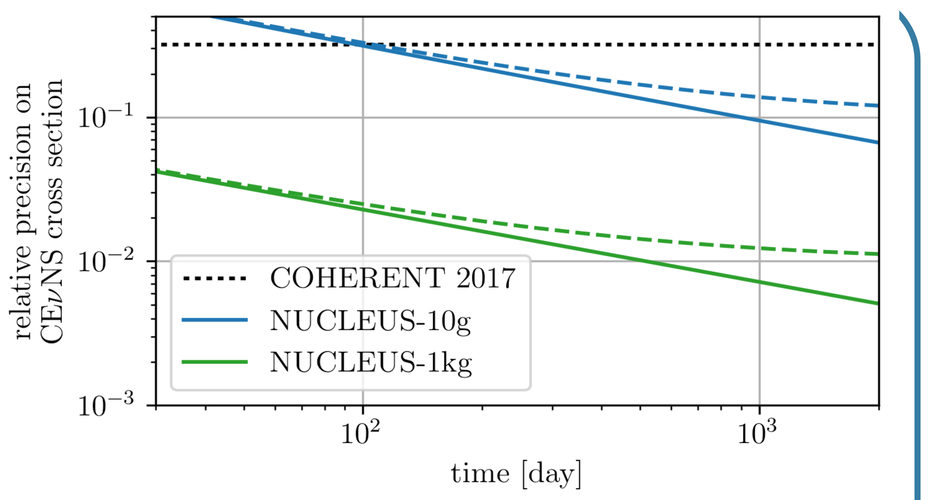
Interesting Measurements and future plans



Direct calibration of nuclear recoils
- Neutron absorption followed by de-excitation with high energy γ emission and nuclear recoil.
- Nuclear recoil on $CaWO_4$ expected at 112 eV
- Seen with 3σ significance using ^{55}Fe calibration



Contacts, References, and Poster Download



NUCLEUS status and future developments:
- Experimental setup being deployed at TUM (Munich, Germany) in shallow underground laboratory for final testing and background validation
- 2025: setup deployment at Chooz

Giorgio Del Castello - Ph.D. Candidate - Università di Roma "Sapienza" - giorgio.delcastello@roma1.infn.it