The **NUCLES experiment**: exploring **C**oherent **E**lastic **N**eutrino-**N**ucleus **S**cattering (CEvNS) with gram-scale cryogenic detectors

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Nicole Schermer (TUM) on behalf of the NUCLEUS collaboration

ICNFP 2024, September 3rd

Exploring Coherent Elastic Neutrino-Nucleus Scattering

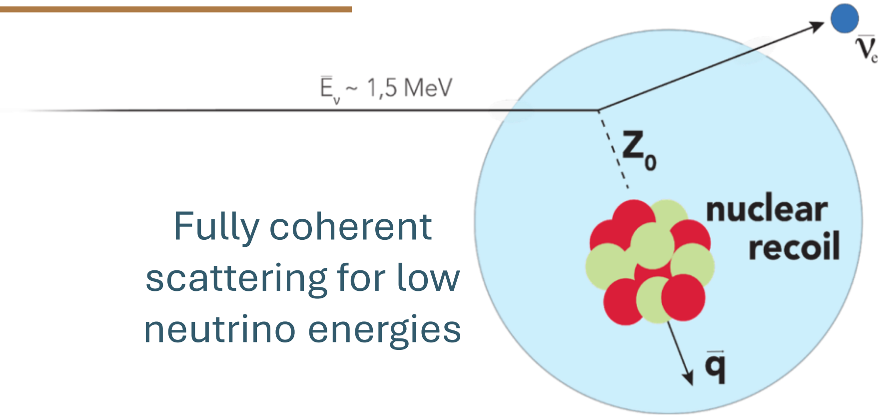
Standard Model prediction: flavor-independent neutrino interaction through exchange of neutral Z-boson

Existence of CEvNS suggested for the first time in 1974

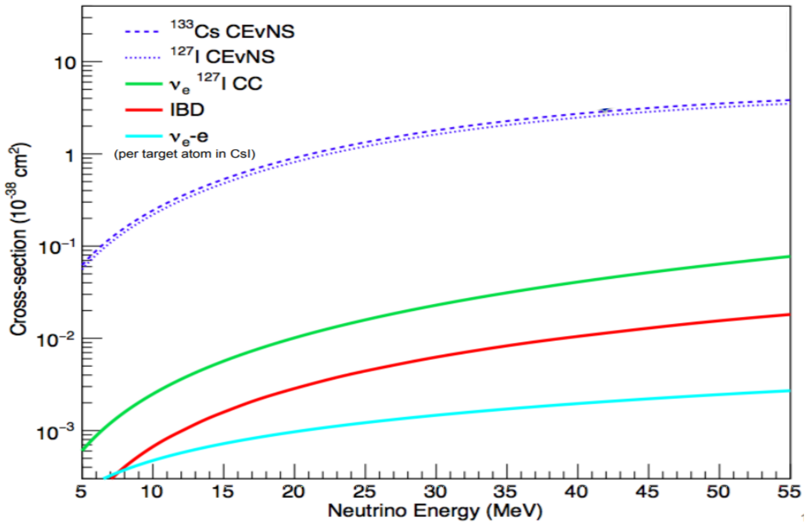
First experimental detection in 2017

the beauty: **high cross-section** $\sigma_{\mathrm{CEvNS}} \sim 10^3 \cdot \sigma_{\mathrm{IBD}}$
the challenge: **small recoil energies** $E_{\mathrm{CEvNS,\ Tungsten}} \sim \boldsymbol{O}(10 - 100\ \mathrm{eV})$
from reactor neutrinos

→ Large cross-section allows to miniaturize target detectors to search at very low energies

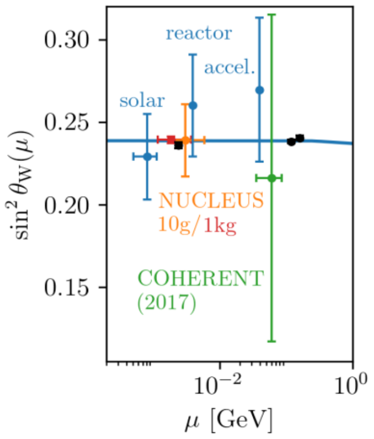


Fully coherent scattering for low neutrino energies

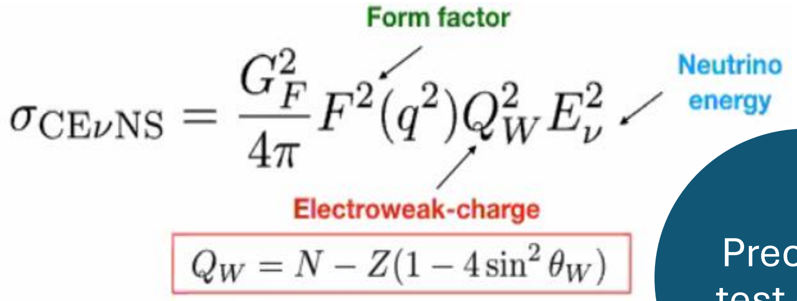


Kate Scholberg, Duke University VIA Seminar December 6, 2017, Observation of Coherent Elastic Neutrino-Nucleus Scattering

Exploring CEvNS as a portal to various fields of particle physics

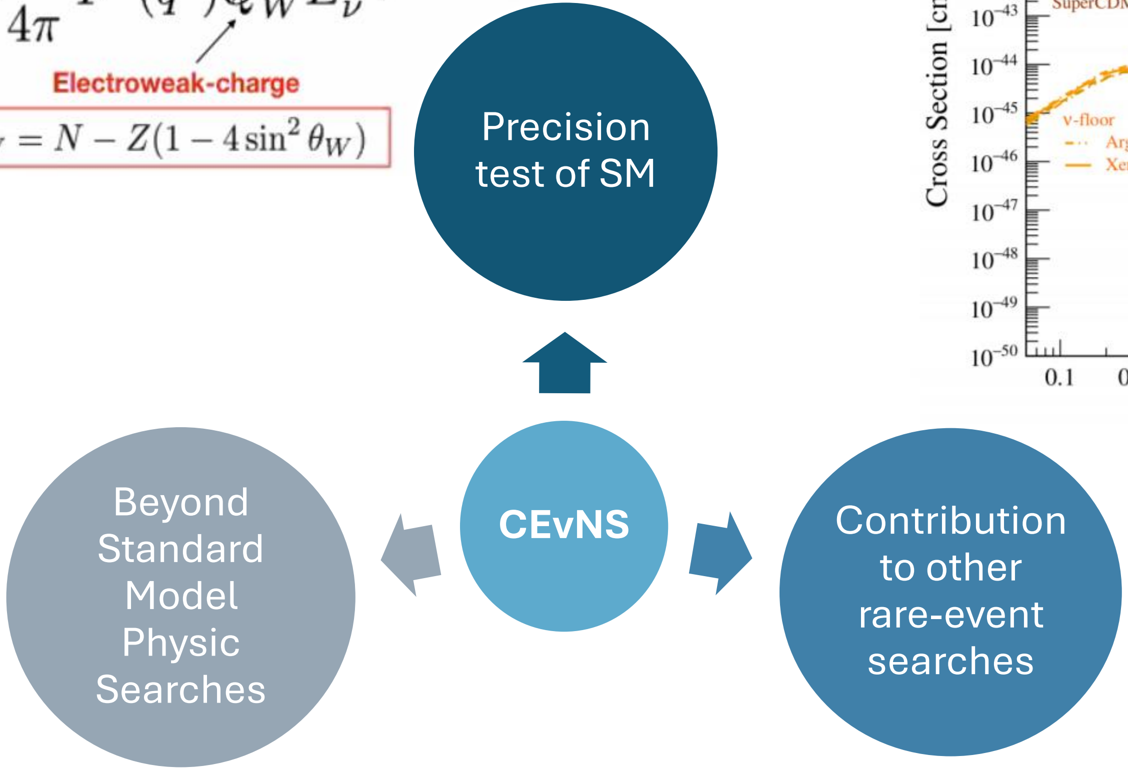


Measurement of the **Weinberg-angle** at low energies



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

$$\boxed{Q_W = N - Z(1 - 4\sin^2\theta_W)}$$

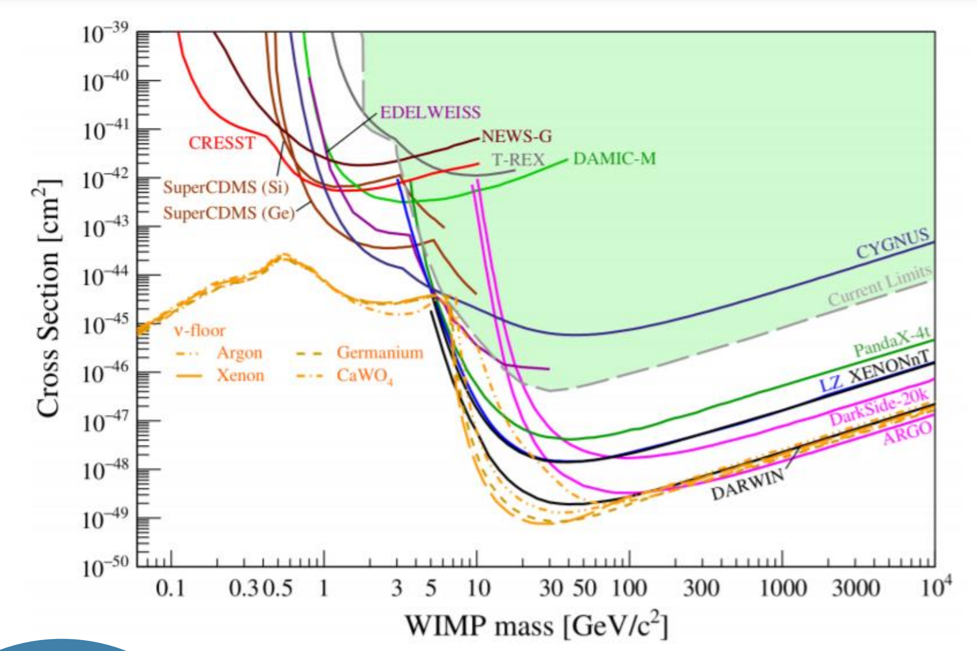


Precision test of SM

Beyond Standard Model Physic Searches

CEvNS

Contribution to other rare-event searches



2021, https://arxiv.org/pdf/2104.07634.pdf/

Additional contribution in CEvNS cross-section, e.g. Measurement of the **neutrino magnetic dipole moment** or **light mediators** would modify the recoil spectra

Neutrino background in **dark matter** search experiments

We are the nucleus

EXPERIMENT

International European Collaboration with ~50 members


Munich, April 2024

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SAPIENZA UNIVERSITÀ DI ROMA

INFN

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

TU WIEN

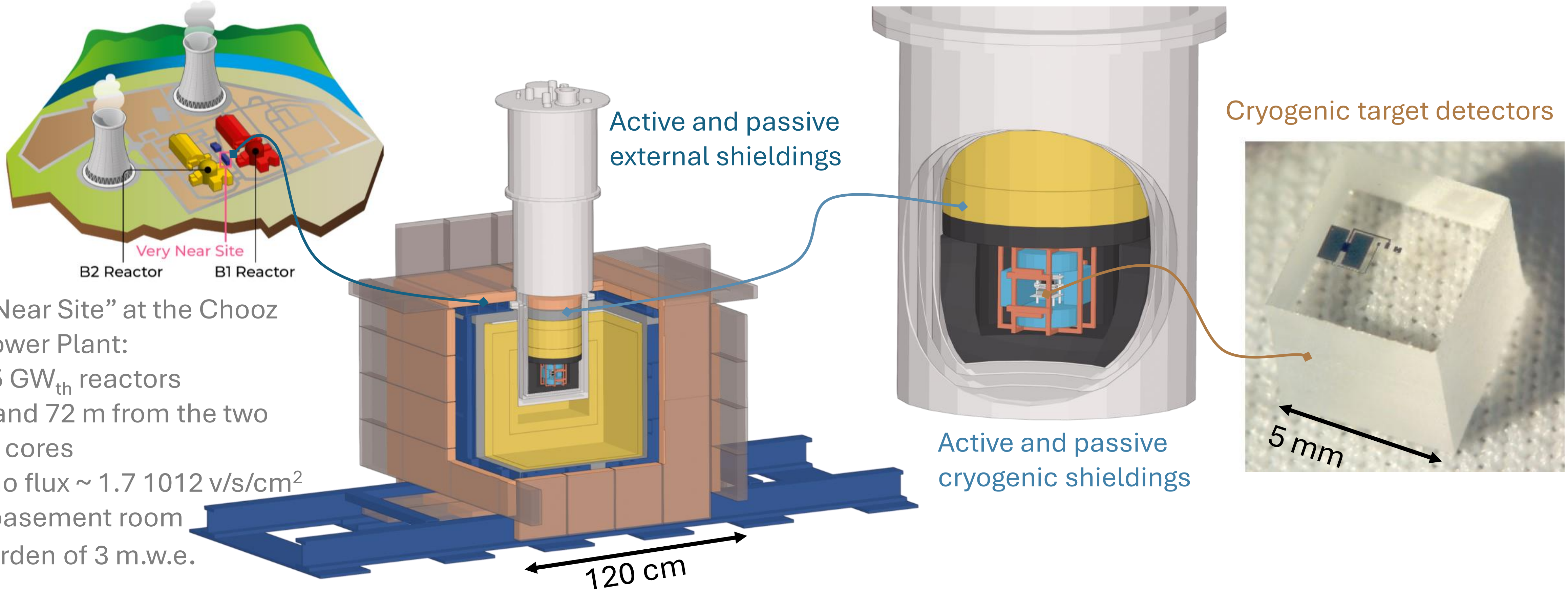
SFB 1258 Neutrinos Dark Matter Messengers

erc European Research Council Established by the European Commission

P2IO Physique des 2 Infinis et des Origines

FWF Der Wissenschaftsfonds.

NUCLEUS concept: measure CEvNS from reactor neutrinos with gram-scale cryogenic detectors



The “Very Near Site” at the Chooz Nuclear Power Plant:

- 2 x 4.25 GW_{th} reactors
- 102 m and 72 m from the two reactor cores
- Neutrino flux ~ 1.7 1012 v/s/cm^2
- 24 m^2 basement room
- Overburden of 3 m.w.e.

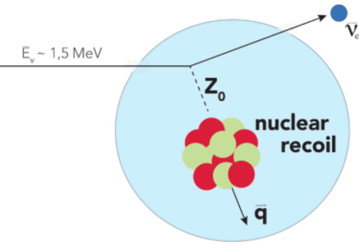
Goal: signal-to-background-rate > 1 (<100 BG counts/keV/kg/day)

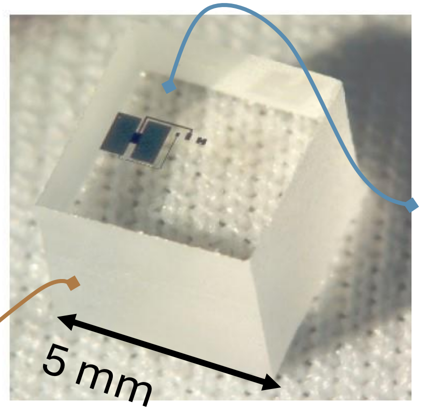
Cryogenic target detectors: Gram-scale calorimeters with Transition Edge Sensors (TES)

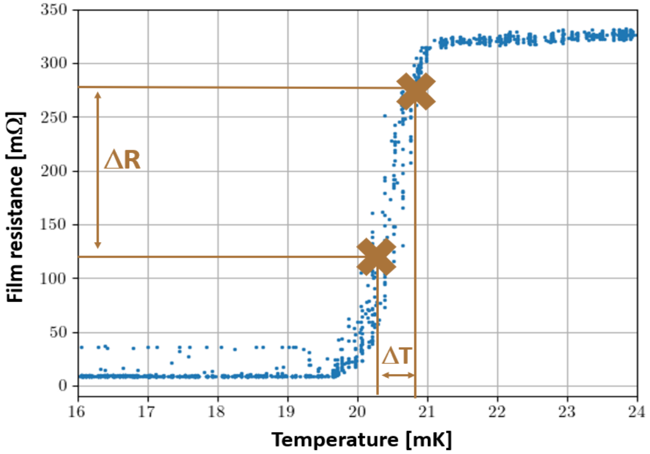
Neutrino scatters off a nucleus in target crystal

Recoiling nucleus leads to temperature rise of cryogenic target crystals

Temperature rise leads to resistance change of superconducting W-film of TES

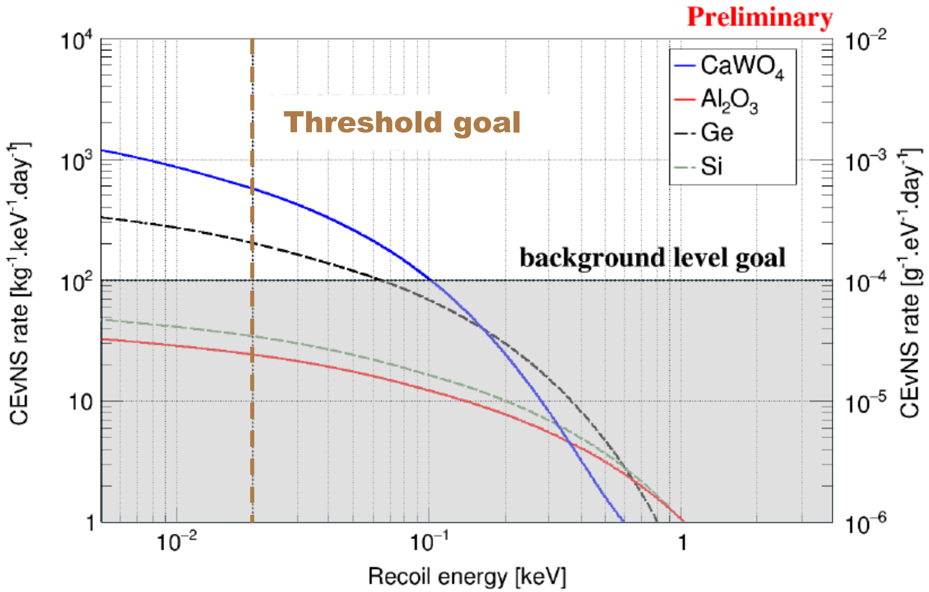






Target crystal equipped with TES, operated at ~20 mK temperatures

- ✓ Allows low threshold & good energy resolution
- ✓ NUCLEUS Al_2O_3 prototype: E_{th}=(19.7 +/- 0.8) eV [*Phys. Rev. D* **96**, 022009 (2017)]
- ✓ Good performances demonstrated over multiple measurements & in ongoing commissioning @TUM



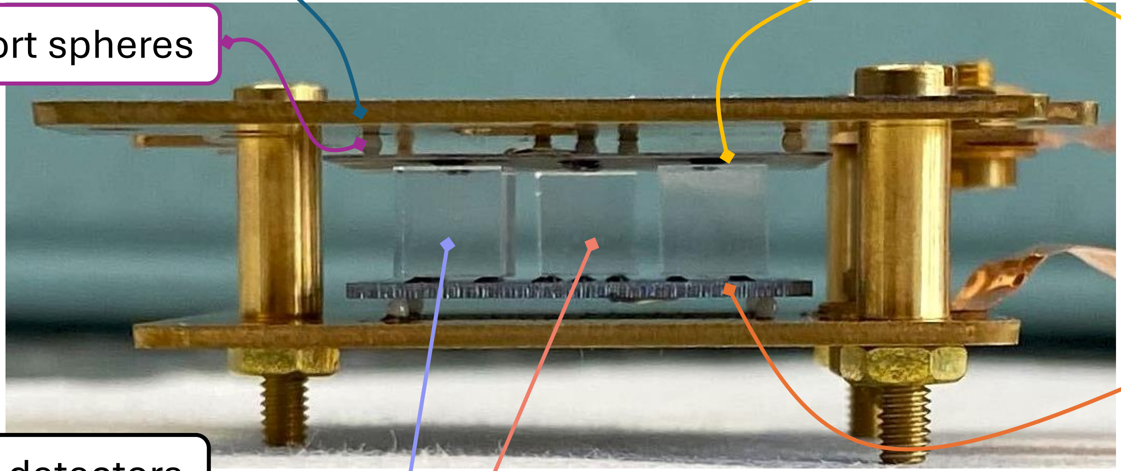
Multitarget approach:

- $CaWO_4$ offers a high CEvNS rate
- Al_2O_3 for in-situ background measurement of neutrons leaving the same experimental signature as CEvNS (nuclear recoil)

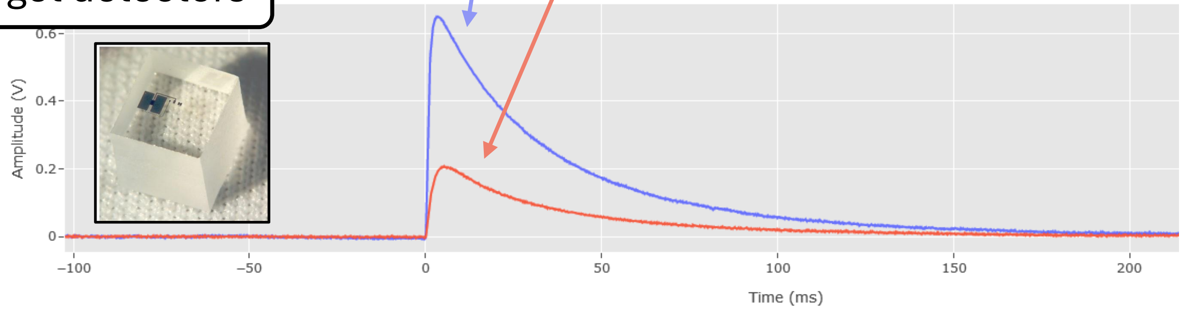
Inner veto module: silicon wafers as instrumented holder for target detectors

Holding plates with electrical & thermal contact

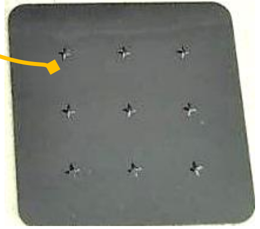
Support spheres



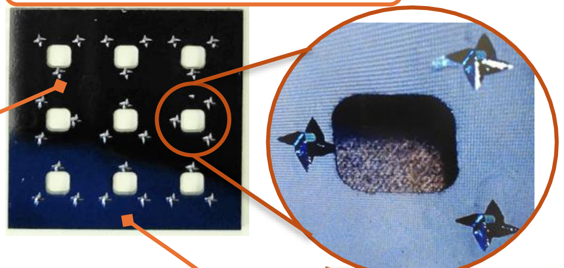
Target detectors



Thin inner veto wafer



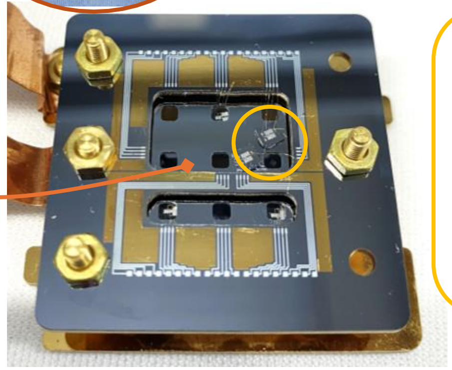
Thick inner veto wafer



Inner veto to reject:

1. Surface events
2. Mechanical stress relaxation-induced events (Low Energy Excess candidate)

Pyramids as point-contact between crystals and silicon wafers for low phonon dispersion

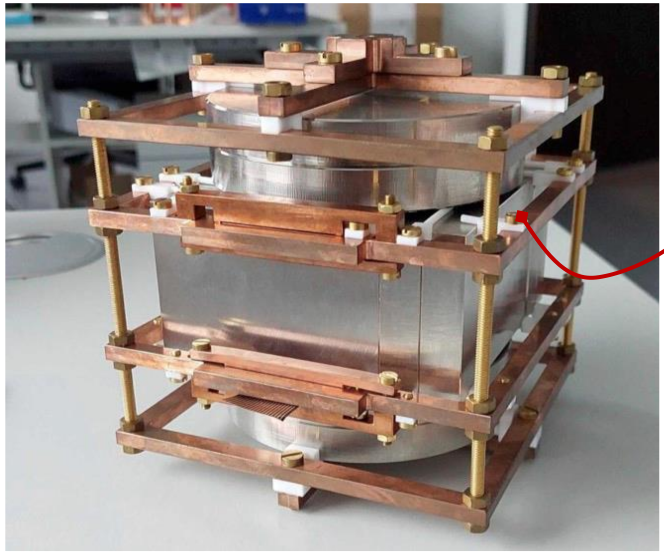


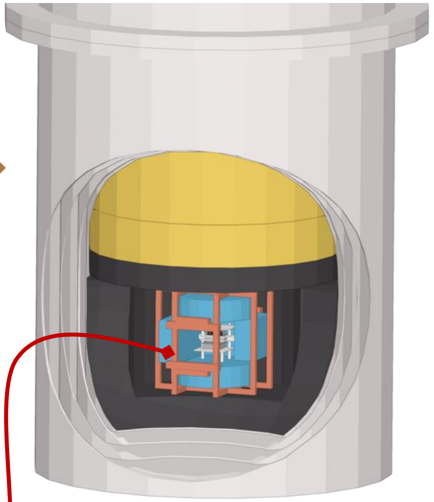
Ongoing: optimization of inner veto TES design & validation of veto capabilities

✓ Good performance of **two target detectors in the inner veto module** demonstrated: 6 eV baseline resolution & no cross-talk between detectors!

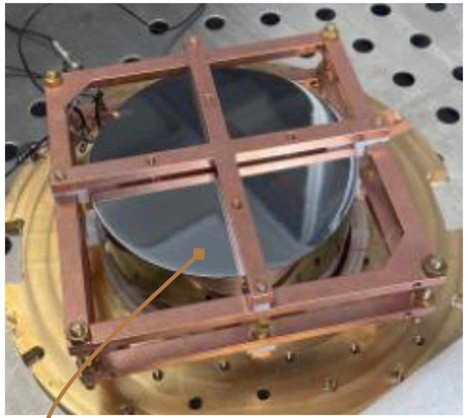
Active cryogenic shielding: germanium outer veto to discriminate external gamma background

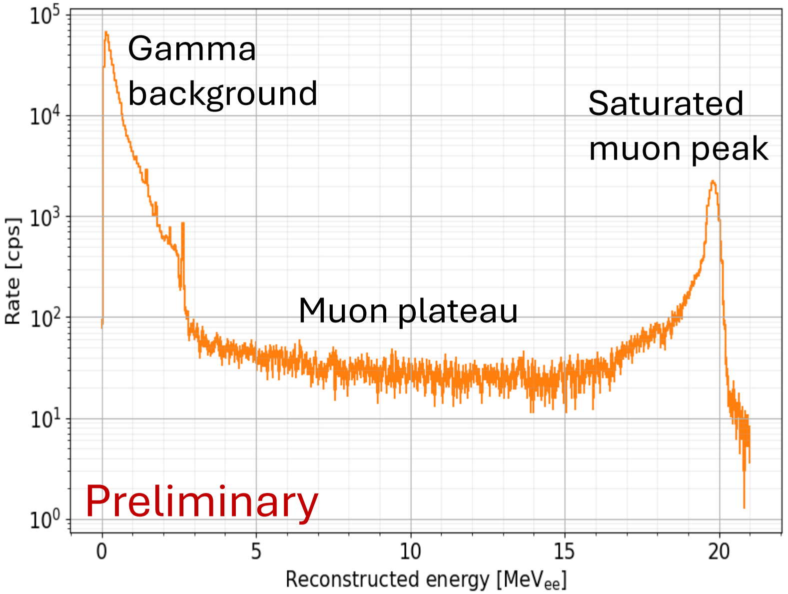
Outer veto goal:
6 High purity Germanium detectors (4 kg, 2.5 cm thickness) with threshold ***O***(1-10 keV)





6 Ge crystals in copper holding structure arranged to cover 4*π* around target detectors





✓ **One cylindrical crystal operated:**
Threshold of ~25 keV achieved with one-electrode readout (improvement to be expected with double-electrode readout)

Next steps:

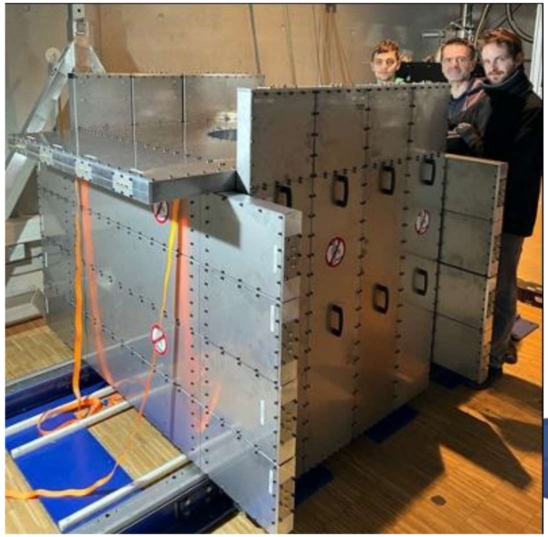
- Test of rectangular crystals (ongoing)
- Scale up to 6 crystals with double-electrode readout

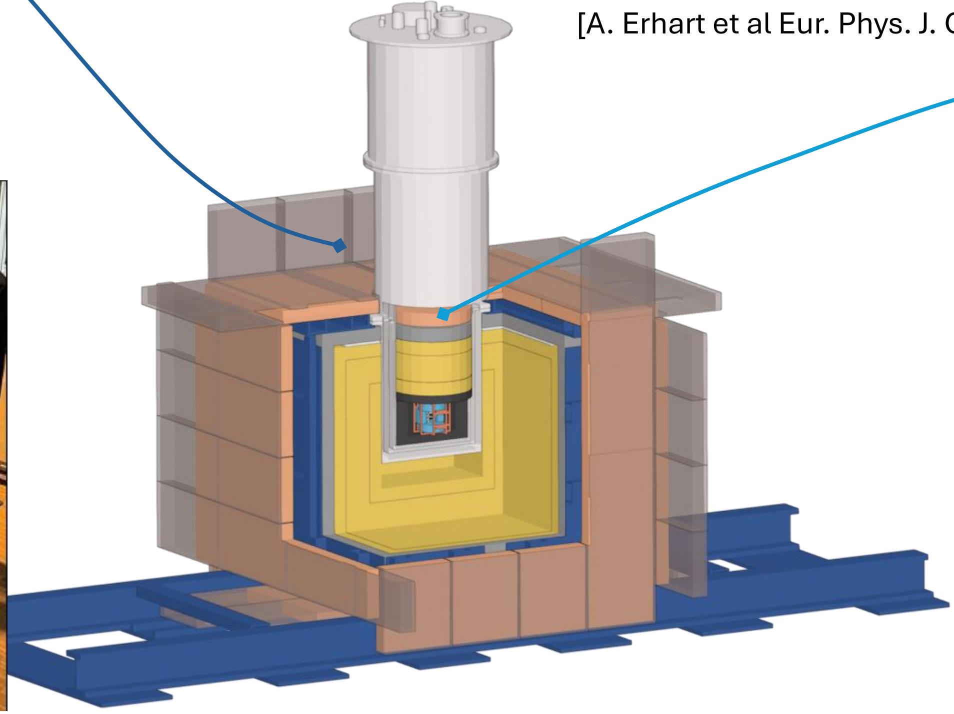
Active muon veto to discriminate muon induced backgrounds

Muon veto

28 x 5cm thick plastic scintillator plates with SiPMs and WLS-fiber readout

[V. Wagner et al 2022 JINST 17 T05020]



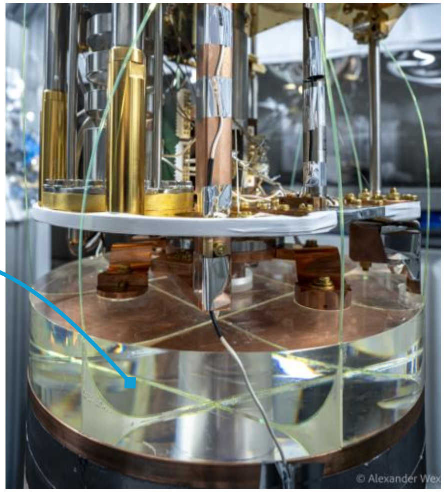


Cryogenic muon veto:

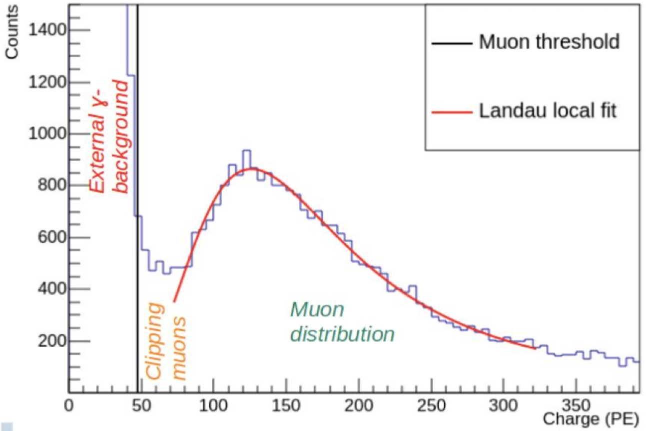
for 4 π coverage

(>99% geometrical efficiency)

[A. Erhart et al Eur. Phys. J. C 84, 70 (2024)]



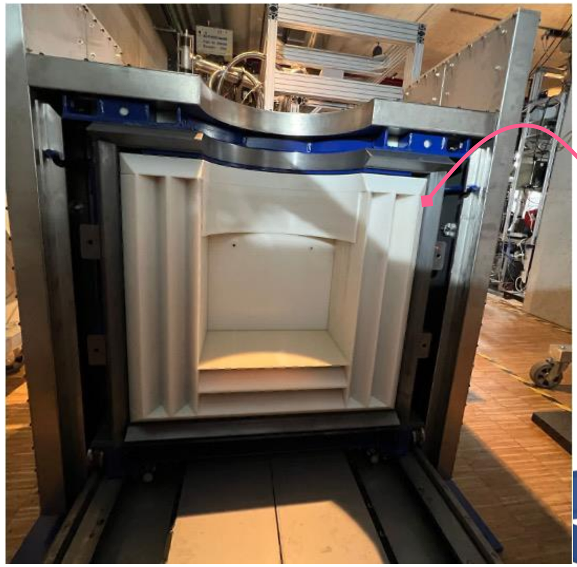
MV charge spectrum



- ✓ **Full Muon Veto in operation** during the commissioning @TUM
- ✓ **Muon Veto fully validated** in terms of rates, spectral shape, calibration, efficiency, dead time

Layered passive shielding to suppress ambient gammas, atmospheric and secondary neutrons

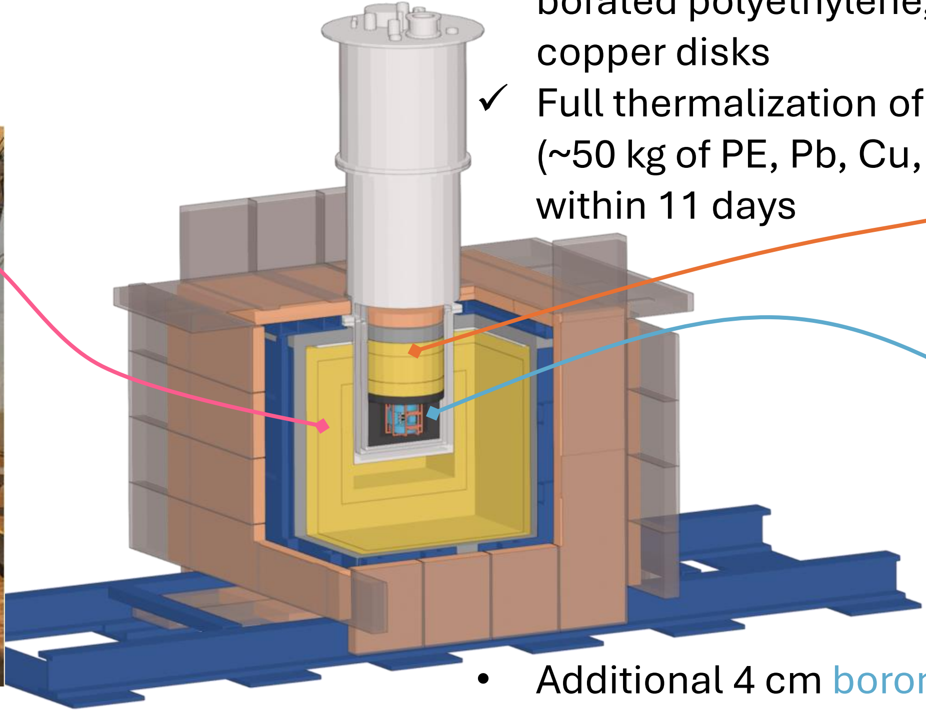
Outer shielding: 5 cm lead + 20 cm borated polyethylene

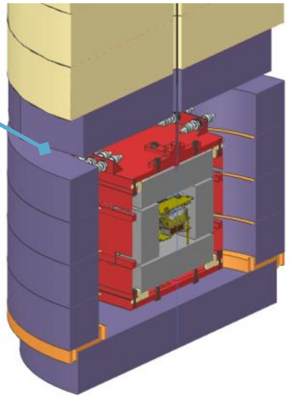


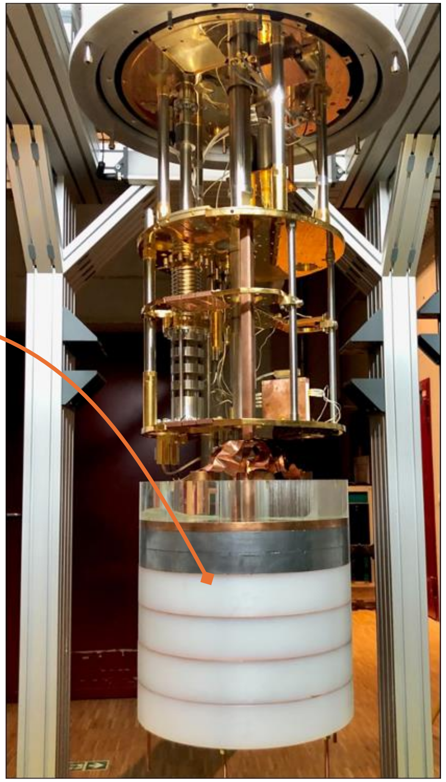
✓ External shielding fully commissioned and in place

Cryogenic inner shielding:

- Extension of the outer shielding inside the cryostat: cryogenic muon veto + lead + borated polyethylene, thermalized by copper disks
- ✓ Full thermalization of inner shielding (~50 kg of PE, Pb, Cu, CMV) achieved within 11 days







- Additional 4 cm boron carbide (B4C) layer around detectors for slow and thermal neutron reduction
- B4C production @Wintrustek (China) ongoing

Vibration decoupling system for continuous cryogenic detector operation in a dry cryostat

Dry dilution refrigerator to avoid handling of cryogenic liquids (BlueFors LD400) with a base temperature of ~10 mK

Pulsed tube cryo-cooler: challenging vibration environment

Custom vibration decoupling system developed and validated [patent protected]

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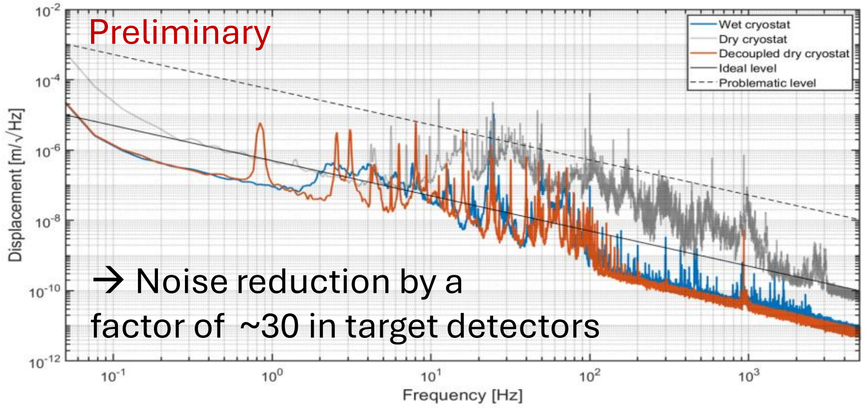
Spring hanging freely from room temperatur ceiling inside cryostat and end of spring thermally coupled to 4K stage of cryostat

Kevlar wire for thermal isolation

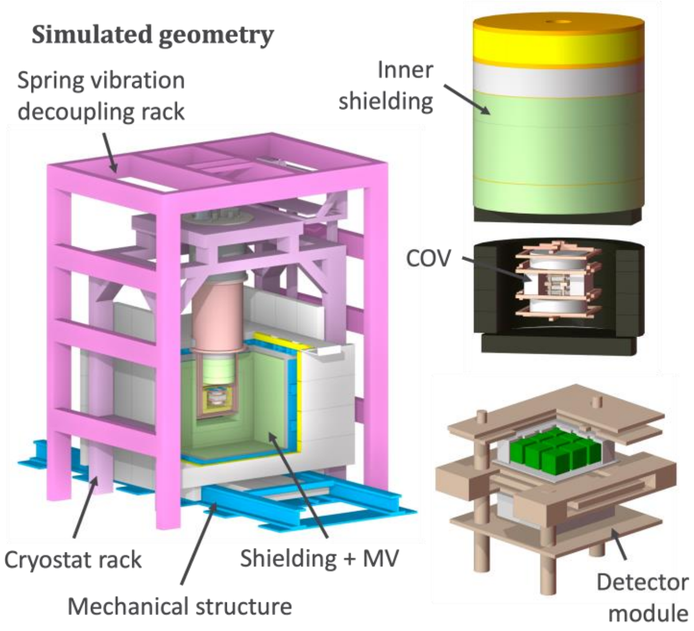
Cryogenic detectors at 10mK



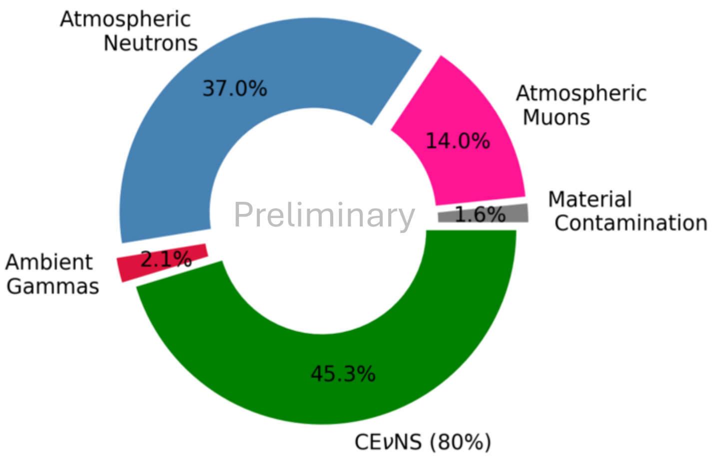
→ Noise reduction by a factor of ~30 in target detectors

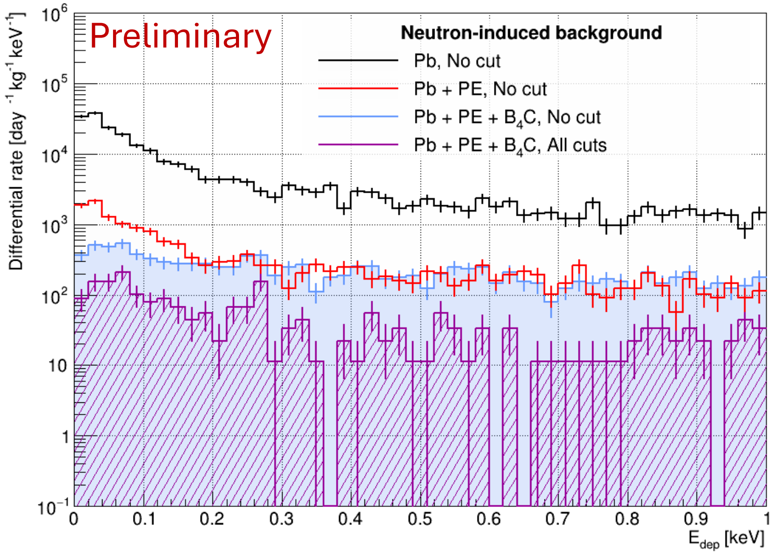
✓ More than 4 weeks of stable continuous operation of cryogenic detectors during the commissioning run mostly independent of Pulse Tube vibrations

Simulations to investigate the background budget and to optimize the shielding strategy



Background and signal budget in $CaWO_4$ in 10-100 eV @Chooz (background upper limits)



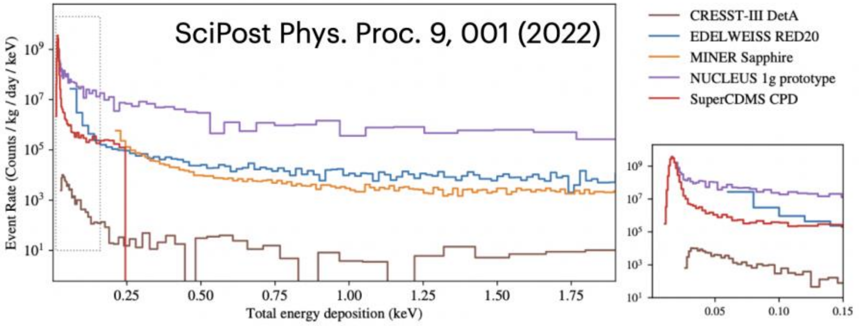


PE shielding: factor 10 reduction in [0-1keV]
B_4C shielding: factor ~3 reduction <200 eV
Ge Outer Veto: add. factor ~3 reduction in [0-1keV] for 1keV threshold

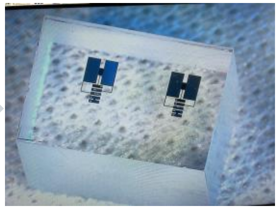
Signal-to-(known)background-ratio of ~1 can be achieved @Chooz! [Publication in preparation]

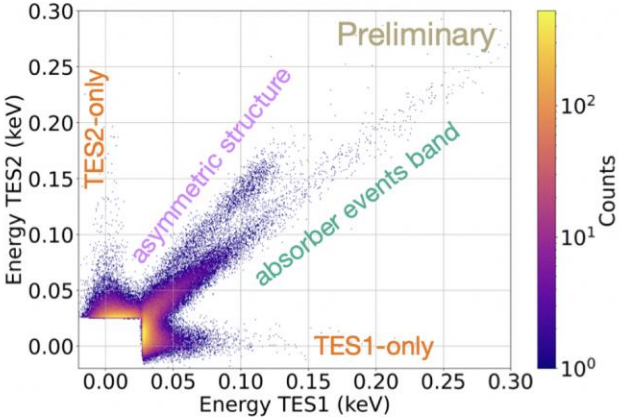
Strategy to target unknow background: the Low Energy Excess (LEE)

Many low-threshold experiments observe rising event rates of yet unknown origins below a few hundred eV and above the background expectation → Significant impact on CEvNS sensitivity



Investigating double-TES readout to reject events not originating in the absorber crystal (TES-only events) [promising measurements ongoing]

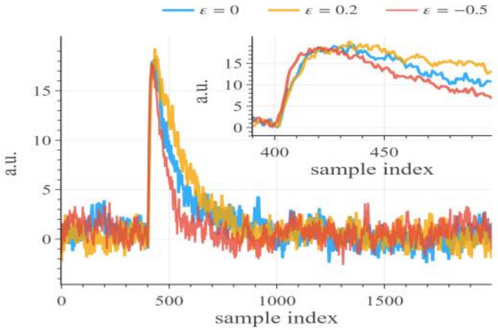




Inner veto can discriminate holder-related stress events [validation ongoing]

Development of new analysis tools for sophisticating pulse shape discrimination: “ASPECT”: a modified matched filter

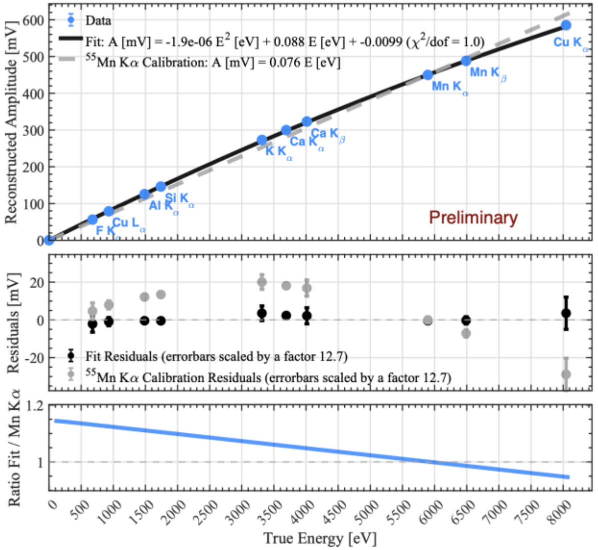
[M. Cappelli *et al* 2024 *JINST* **19** P0603]



Low energy calibration concept

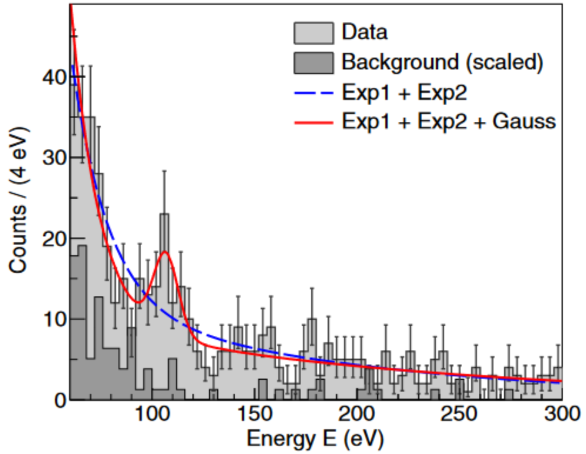
- State-of-the-art: calibration with keV-scale X-rays from ^{55}Fe extended to nuclear recoil signal at eV energies
- Need to investigate detector non-linearities & nuclear recoil/ electron recoil differences

Low energy X-ray source:



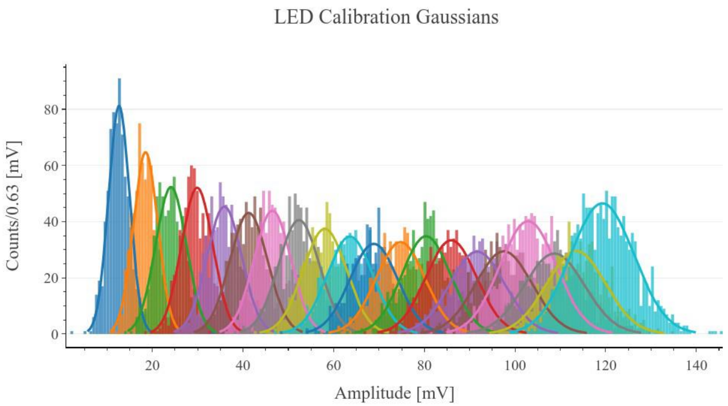
- ✓ Sub-keV **X-ray fluorescence** source used to detect the Fluorine-Kα line **@677 eV** in a single CaWO$_4$ detector cube [Publication in preparation]

Nuclear recoil calibration with CRAB:



- ✓ Nuclear de-excitation **after thermal neutron capture @112 eV** unaffected by quenching effects detected in a single CaWO$_4$ detector cube [Phys. Rev. Lett. 130, 211802]

LED calibration:

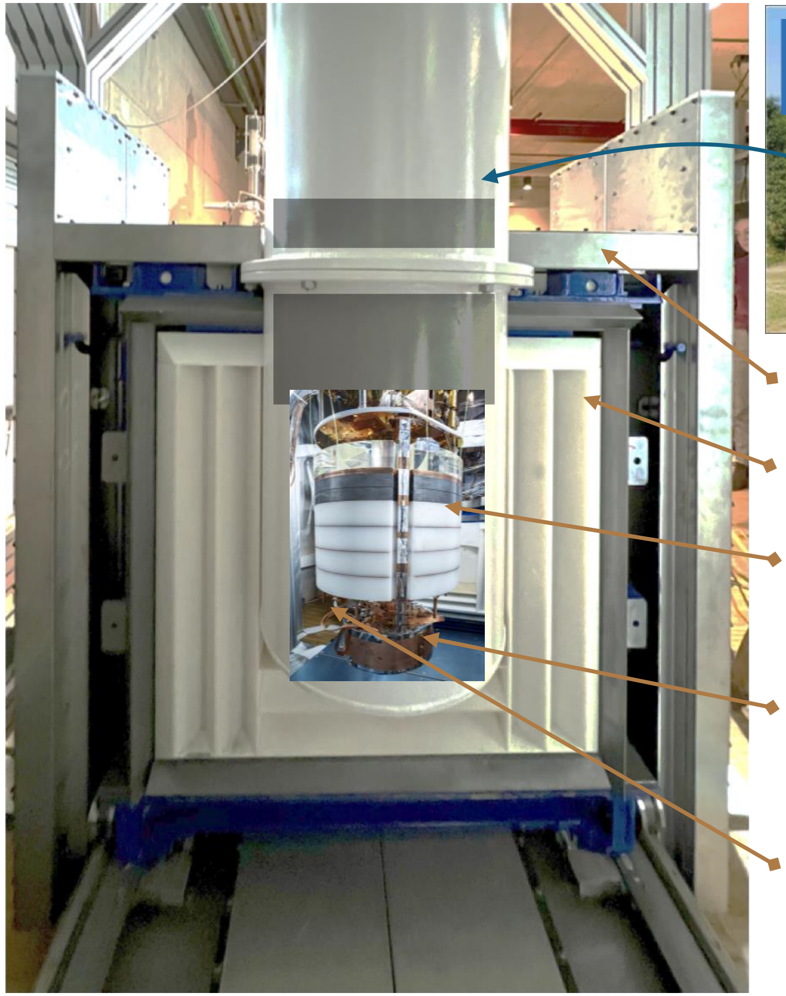


- ✓ Use monochromatic LED shining to detector and phonon statistics to measure the calibration constant
- ✓ In-situ, continuous, sub-keV calibration w/o radioactive sources

Commissioning at the shallow underground laboratory in Munich – the “Long Background Run”

– continuous data taking since August 1st

LIVE



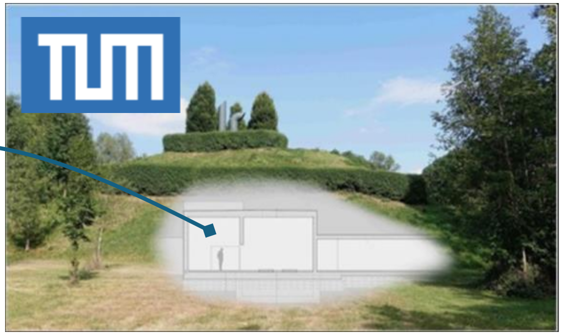
Full Muon Veto

Outer shielding

Inner shielding (w/o B4C)

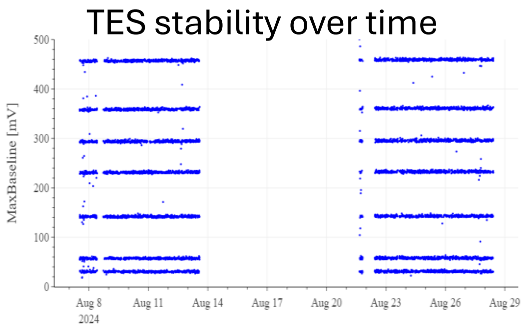
1x Ge Outer Veto detector
2 x $CaWO_4$ detectors
1x Al_2O_3 detector
(with double TES readout)

LED calibration system

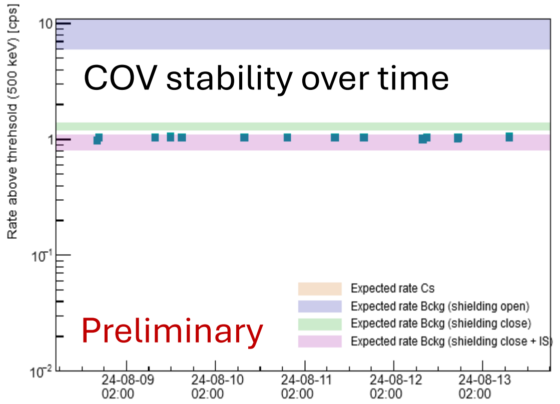


Goals:

- Demonstration of stable detector operation and performance over months-long periods
- Validation of shielding strategy: Background measurement & comparison to simulation


TES stability over time

Preliminary

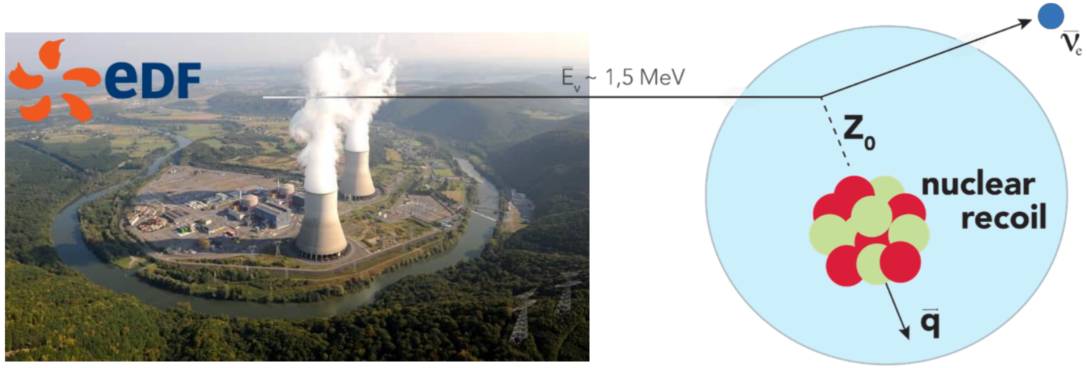

COV stability over time

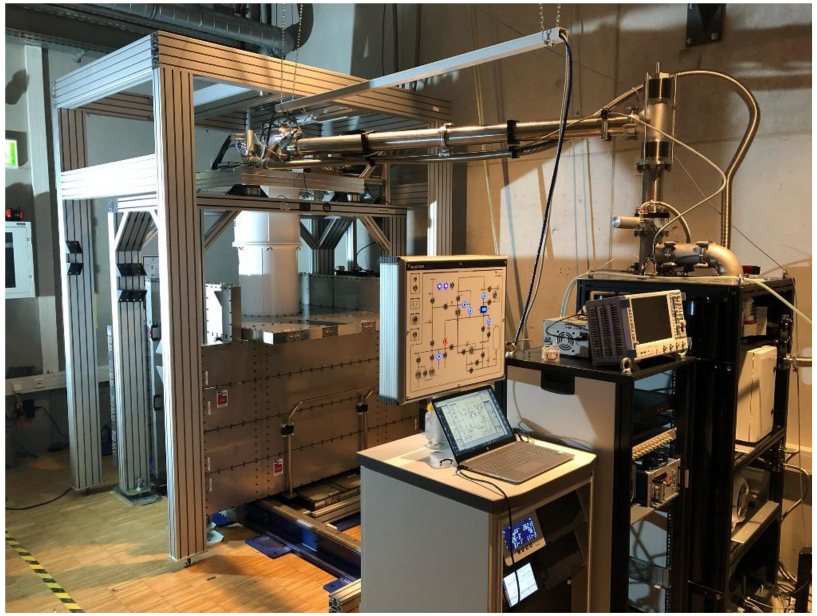
Preliminary

✓ Stability of cryogenic detectors and muon veto over > 4 weeks

Up next: Deployment at Chooz in the beginning of 2025

the “Long Background Run”

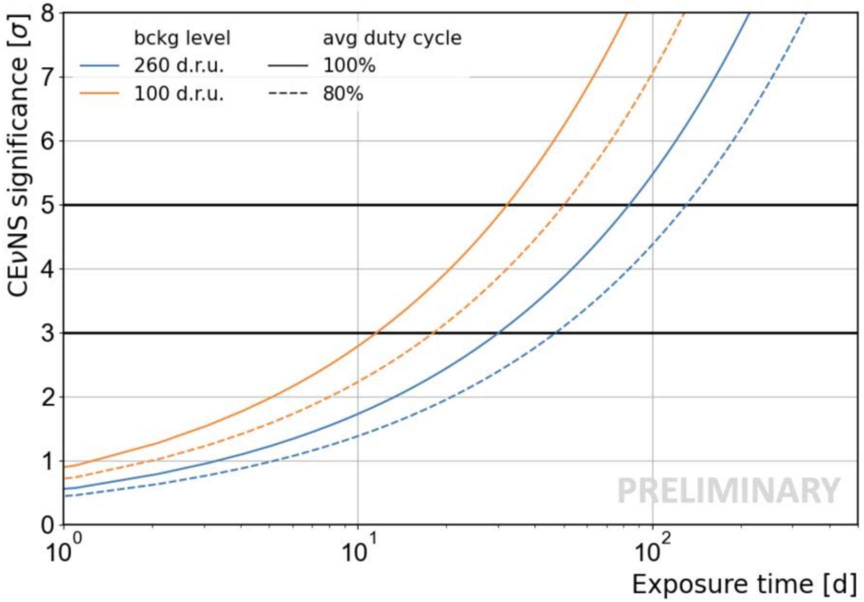




Outlook: expected performance with 10g of target mass (6g of $CaWO_4$ and 4g of Al_2O_3)

Sensitivity to CEvNS observation:

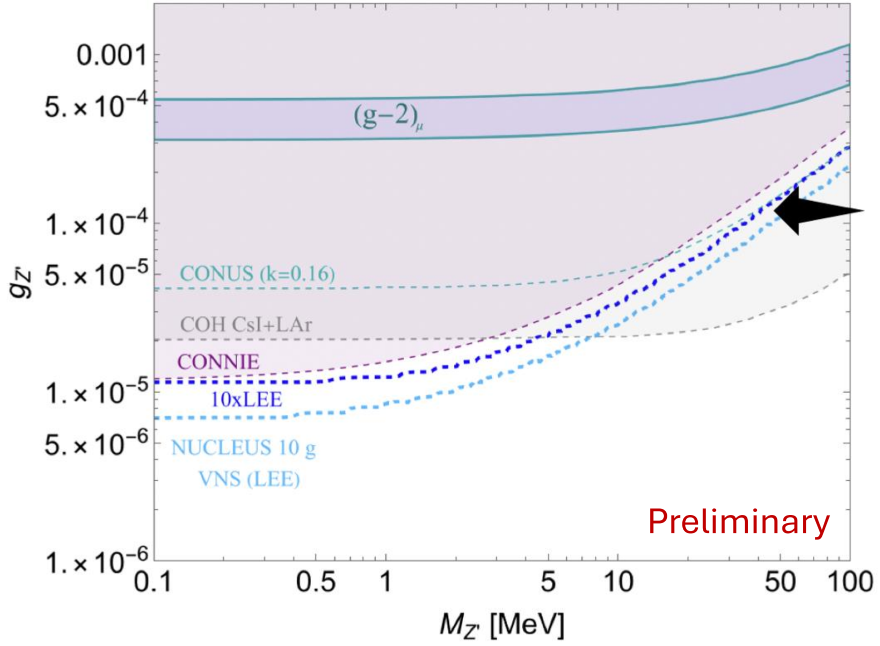
- ~30 counts/kg/day in 10 eV - 1 keV from CEvNS in $CaWO_4$
- With a targeted signal-to-background-ratio of ~1 & flat background (no LEE): **5σ sensitivity in ~150 days** lifetime (after cut efficiency and dead time)



Beyond the Standard Model physics searches:

NUCLEUS sensitivity to light mediators and neutrino EM properties in the presence of the Low Energy Excess: competitive limits due to low threshold

[in collaboration with phenomenologist M. Corona]



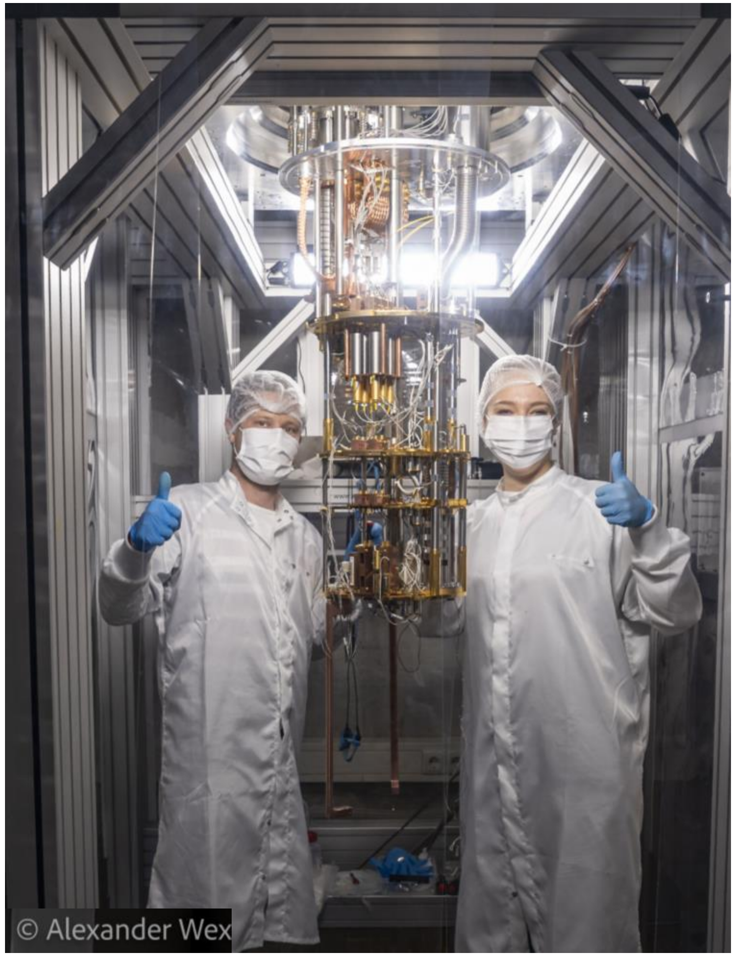
Conclusion

NUCLEUS in the commissioning phase in Munich:

- ✓ External & cryogenic passive & active **shielding** @ TUM **fully in operation**
- ✓ Successful operation of cryogenic detectors
- ✓ **Long background measurement** @TUM with stable conditions ongoing

NUCLEUS future in Chooz:

- ✓ Laboratory at the Chooz nuclear power plant ready to welcome us
- ✓ Simulations and **background budget** for Chooz finalized
- Move to Chooz in 2025 for the **first technical run** with a light version of target detectors!
  → First neutrino data, background measurement, LEE measurement…
- Then: **first physics run**: Upgrade to **10g** of target mass to measure CEvNS from a nuclear reactor and investigate neutrino properties



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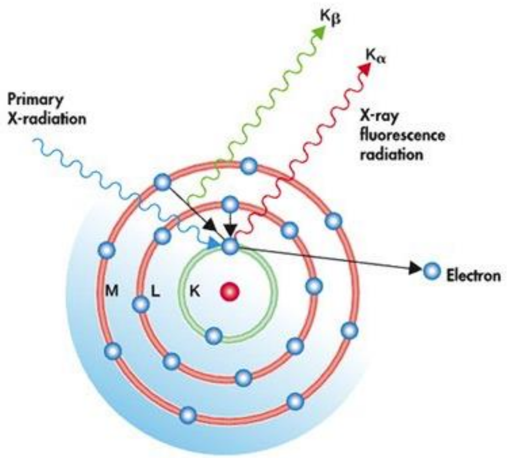
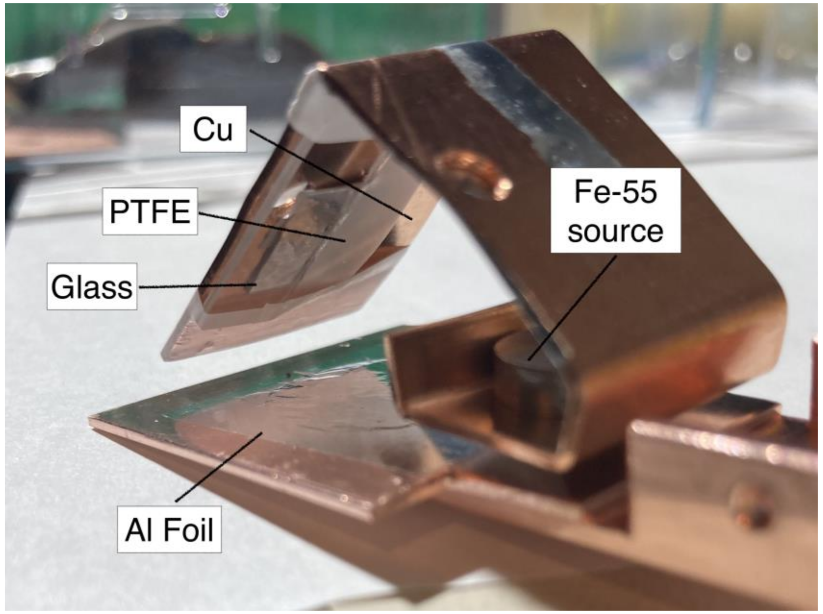
Backup Slides

XRF Calibration

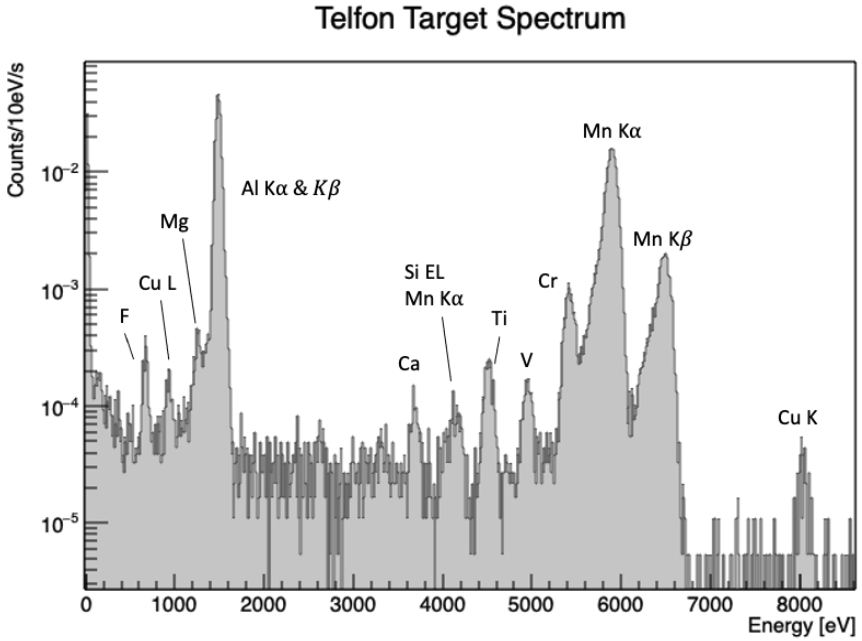
X-Ray fluorescence



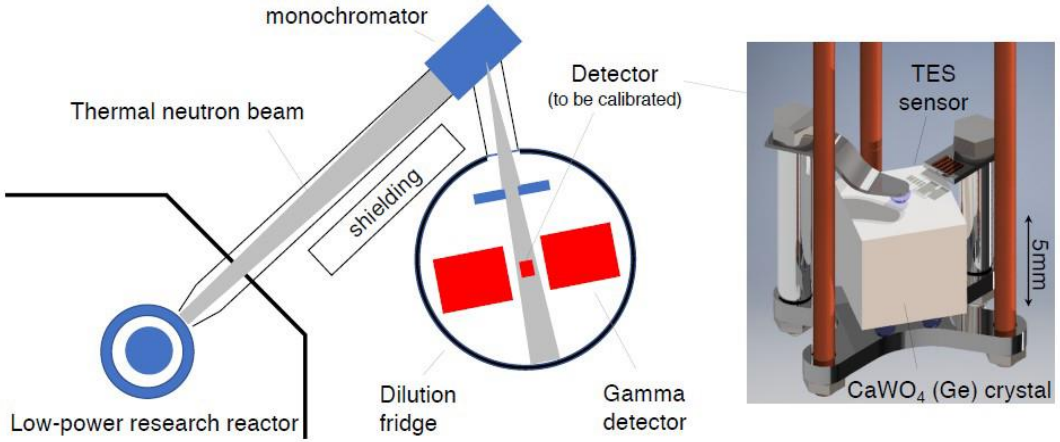
XRF Setup with multiple targets and primary iron source



Spectrum with SDD



CRAB Calibration

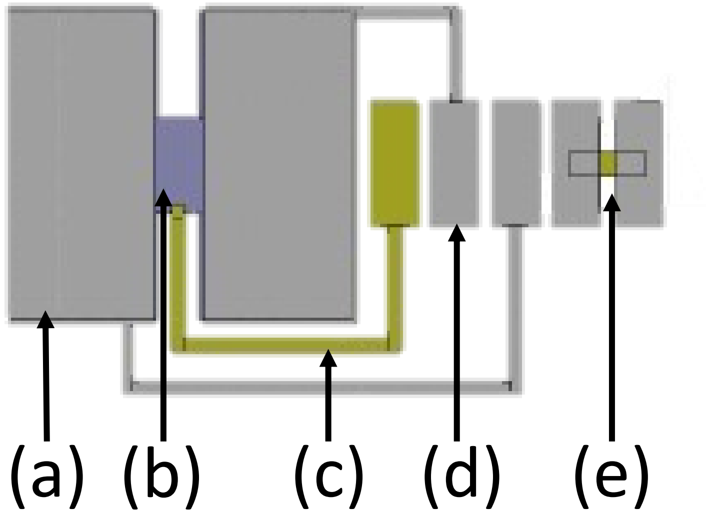


- a thermalized neutron beam originates from a low-power research reactor and enters the dilution refrigerator after being detected by a monochromator
- the neutron capture process excites the nucleus close to the neutron separation energy and decays via the emission of -rays and conversion electrons
- This process can induce a high-energy photon to escape the nucleus inducing nuclear recoils in the 100 eV range for middle and heavy mass nuclei

TES

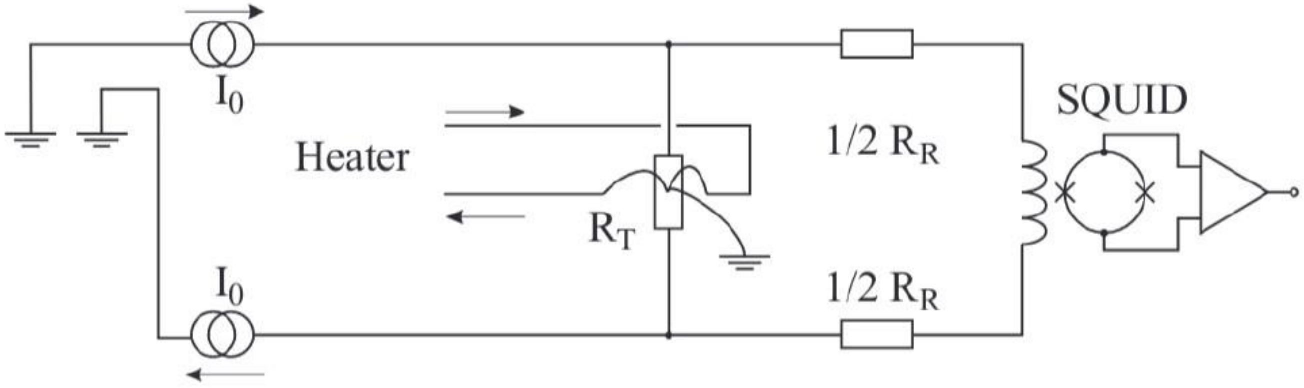
TES consisting of:

- (a) Superconducting aluminum phonon collectors
- (b) Superconducting tungsten film
- (c) Gold thermal link
- (d) Wire-bond pads
- (e) Ohmic heater

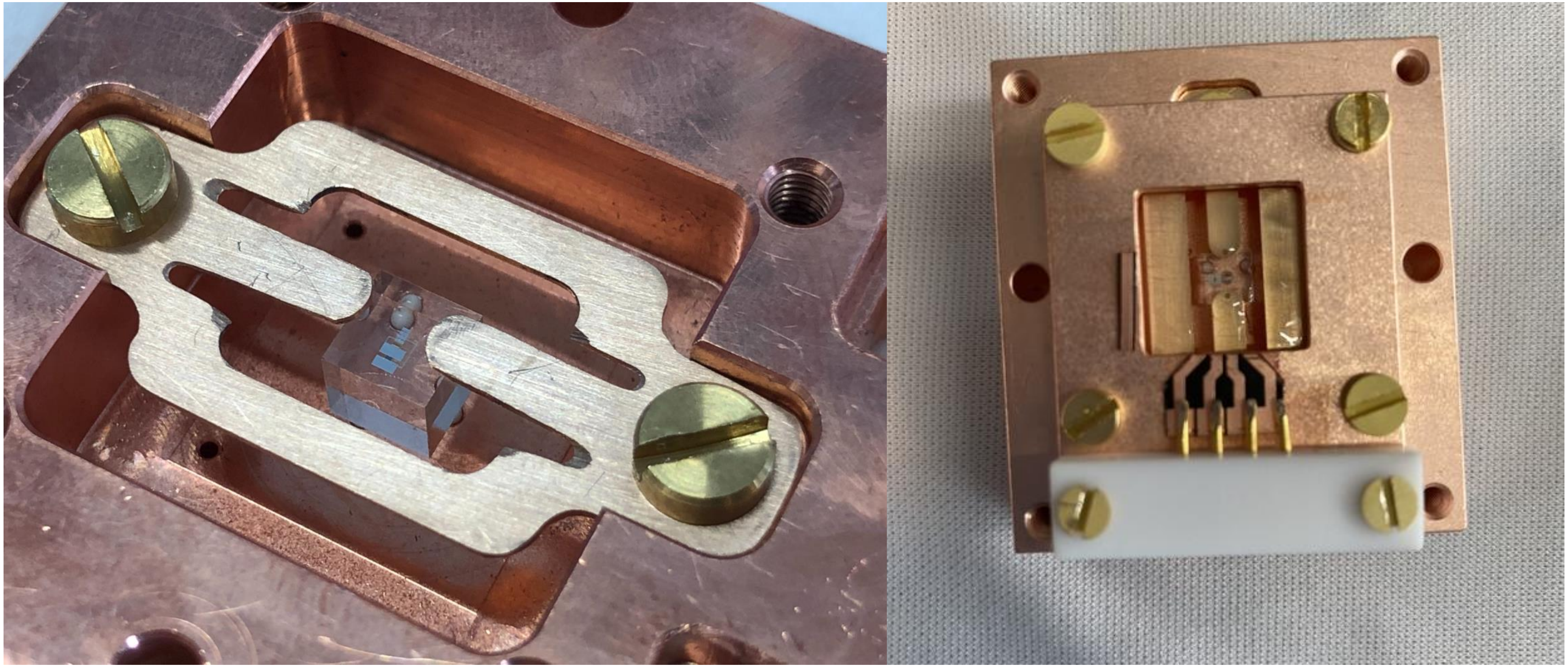


SQUIDs

- The change in resistance of the TES needs to be measured to a very high precision < O(mOhm) while maintaining low readout currents < O(10 A) due to heating constraints
- Superconducting Quantum Interference Devices (SQUIDs) measuring very small changes in magnetic flux
- The TES is operated in a readout circuit, in which its resistance R_T is connected in parallel to a reference resistance R_R and an input coil of the SQUID, the whole circuit is biased with a constant current I_0. When a particle interaction leads to a change in the resistance of the TES R_T, the change in current in the TES branch induces a change of the magnetic field in the input coil of the SQUID.



Target detector holders



COHERENT Results

- General:
  - Oak Ridge, Spallation Neutron Source, pulsed proton beam
  - During the spallation process of protons on a mercury target, pions are generated as a by-product and subsequently decay at rest
  - neutrinos as by-product from pion-deacay-at-rest (pi+ → u+ & u-neutrino (prompt); u+ → e+ & e-neutrino & u-anti-neutrino (delayed))
- 2017: Observation on CsI [doi:10.1126/science.aao0990]
  - Cs(133)I(127)
  - Observed at "6.7σ confidence level, using a low-background, 14.6-kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source"
  - $E\nu \sim$ 30 MeV, CsI[Na]: 6.5 keV
- 2020: Observation on Ar with 3 sigma significance [doi:10.1103/PhysRevLett.126.012002]
  - Ar(40), light element
  - 24kg active-mass Lar scintillator detector, using quenching factor
  - Uses pulse-shape discrimination to suppress ER BG <-> NR
- Cross-section consistent with the SM prediction
- Probing of the N^2 dependence of the cross-section