Exploring coherent elastic neutrino-nucleus scattering with the NUCLEUS experiment

Rencontres du Vietnam,

30th anniversary

Windows on the Universe

6-12 August 2023

Chloé Goupy, on behalf of the NUCLEUS collaboration

IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

The NUCLEUS collaboration

nucleus EXPERIMENT

≈ 50 members

TUM

cea

EDF

INFN

SAPIENZA UNIVERSITÀ DI ROMA

TU WIEN

MAX-PLANCK-INSTITUT FÜR PHYSIK

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

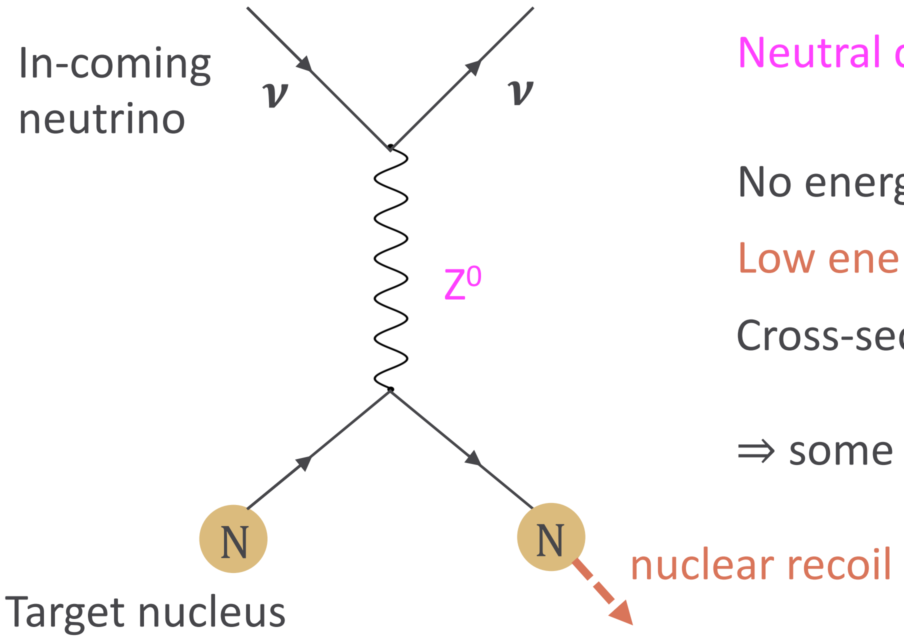
TUM LMU ORIGINS Excellence Cluster

SFB 1258 Neutrinos Dark Matter Messengers

erc European Research Council Established by the European Commission

P2IO Physique des 2 Infinis et des Origines

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)



Neutral current interaction
→ flavor independent

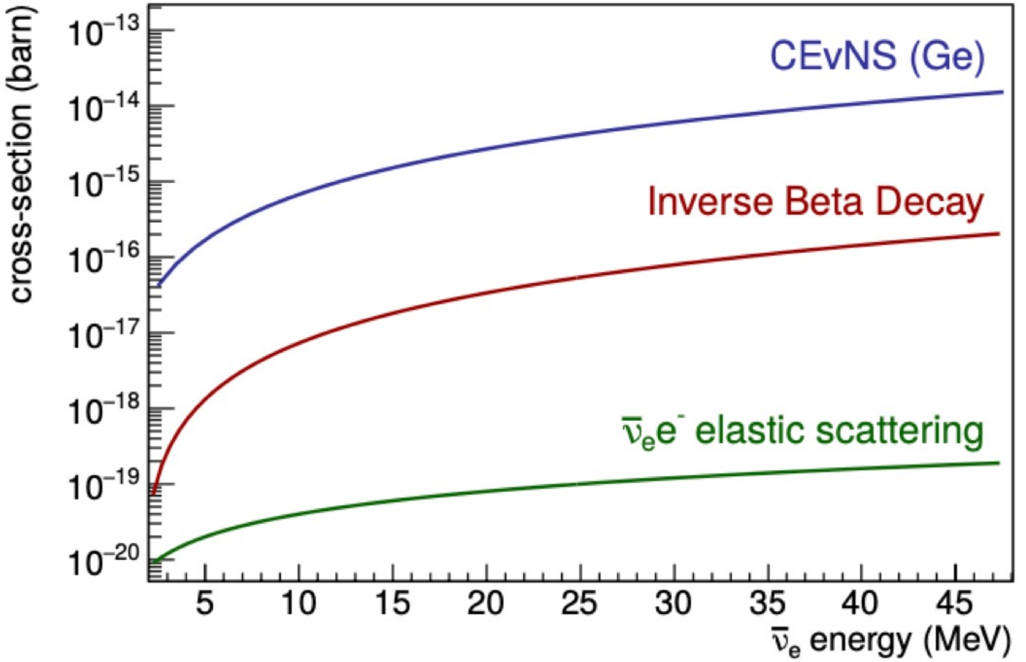
No energy threshold

Low energy nuclear recoils

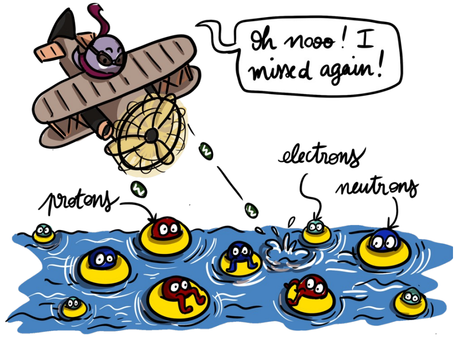
Cross-section proportional to N^2
→ 10 to 1000x larger than IBD
⇒ some kg/g-scale detectors

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_w^2 F^2(q^2) m(Z,N)\left(1 - \frac{E_r}{E_{r,max}}\right)$$

From J. Billard - BSM-Nu workshop 2022



Elastic scattering/IBD

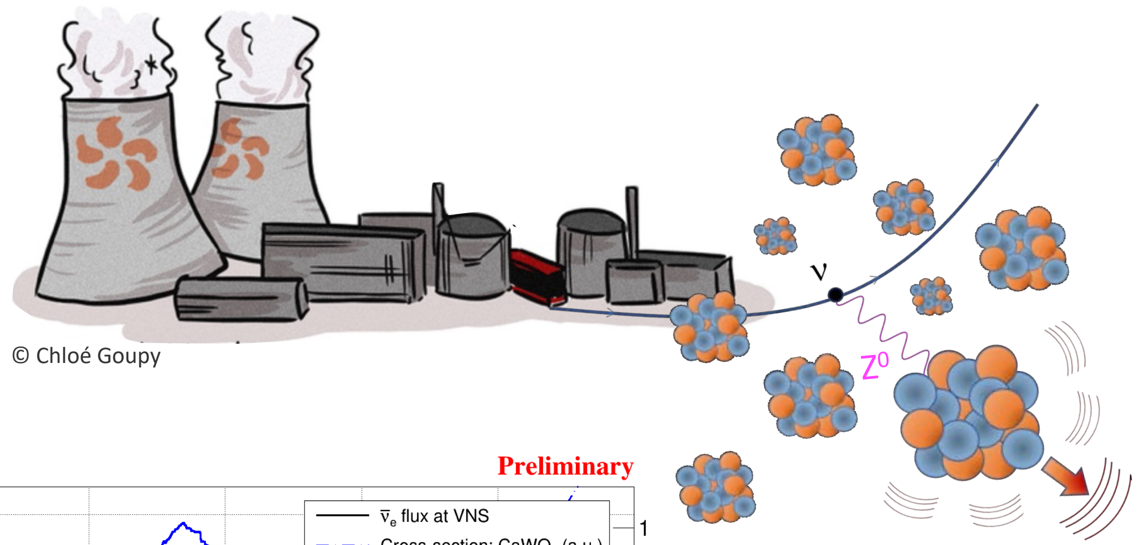


CEνNS

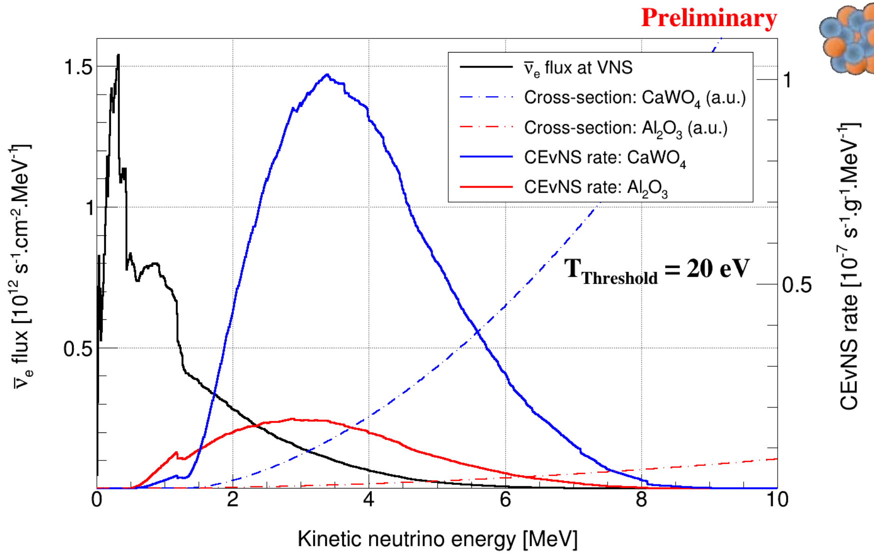
From Nucleus comic (nucleus-experiment.org)

CEνNS from reactor (anti-)neutrinos

Coherent Elastic Neutrino-Nucleus Scattering



© Chloé Goupy



Nuclear reactors: intense sources of $\bar{\nu}_e$

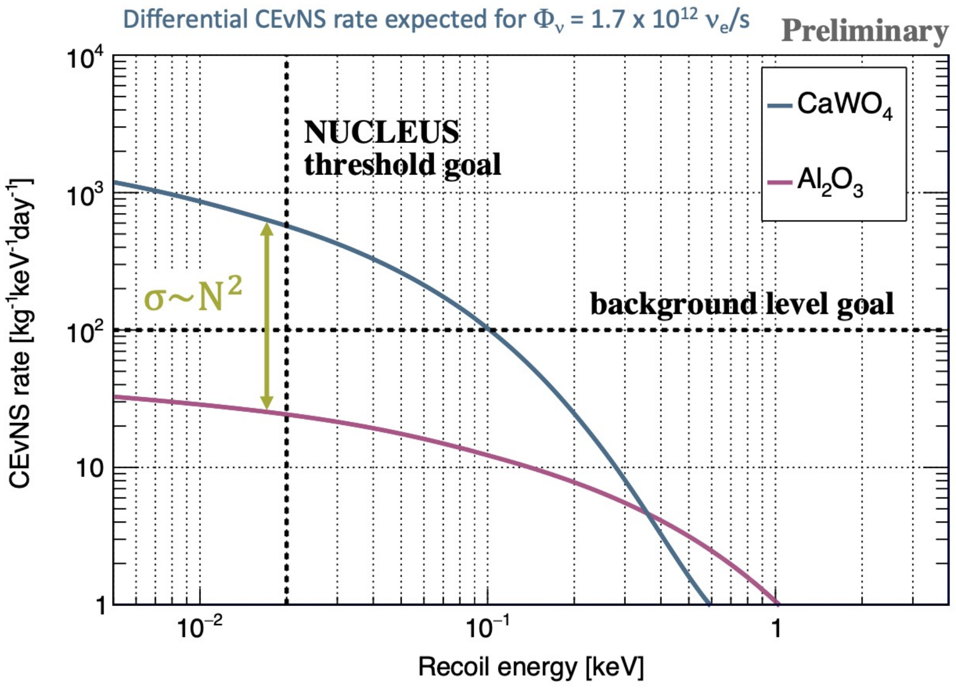
E_ν < 10 MeV → fully coherent regime

⇒ **sub-keV recoils**

Trade-off between cross-section and nuclear recoil energy

⇒ Low thresholds detectors and low background counting rate required

NUCLEUS @Chooz

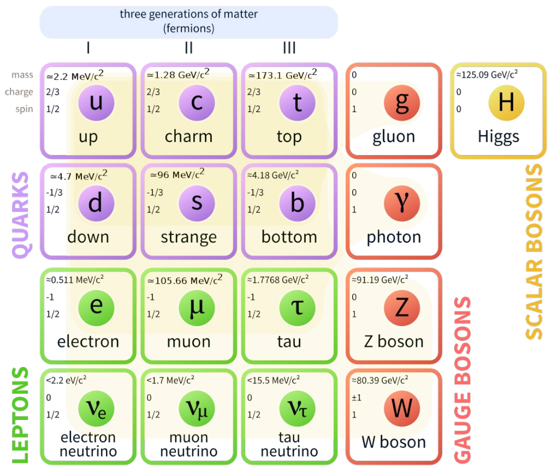


CEνNS, what for?

1- New probe for Standard Model (SM)

CEνNS cross-section is a clean standard model prediction

Standard Model of Elementary Particles



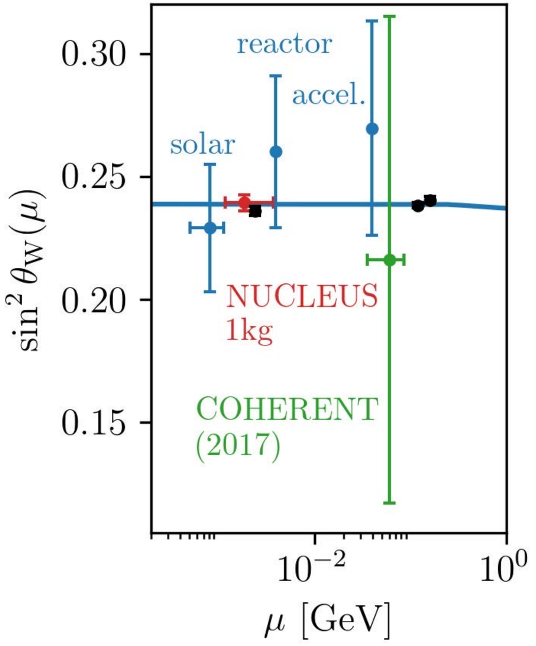
If deviations wrt SM

2- Beyond the SM

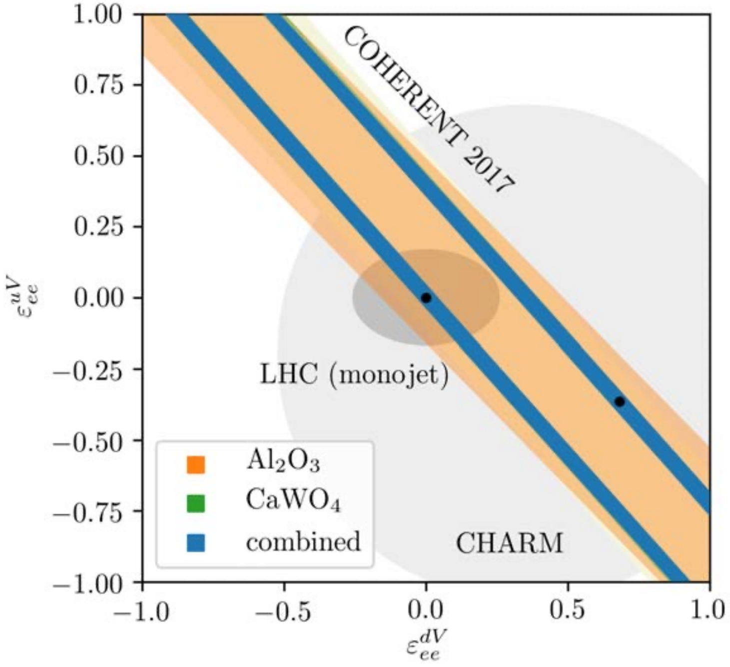
Sterile neutrino

Neutrino electro-magnetic properties (e.g. magnetic dipole moment)

Weinberg angle at low momentum transfer



Non-standard interactions



3- For Dark matter experiments:

CEνNS of solar or atmospheric neutrinos: irreducible background for experiment looking for WIMPs

⇒ “neutrino floor”

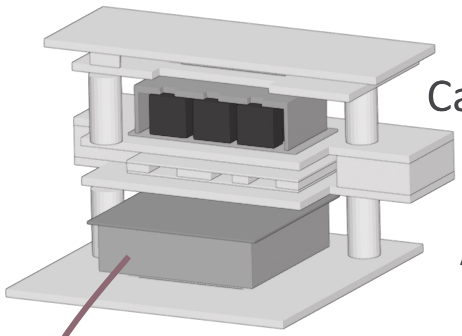
… and more!

Long range detection:

- Supernovae neutrinos
- Solar neutrinos
- Reactor monitoring

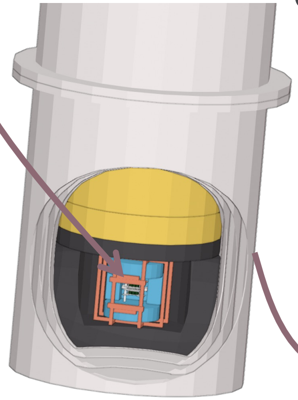
The NUCLEUS Experiment

The cryogenic target detectors (10g)

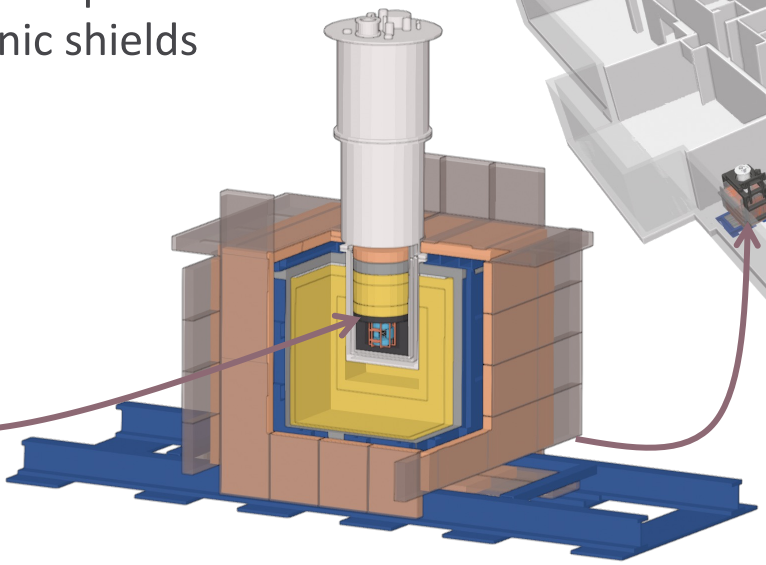


$CaWO_4$

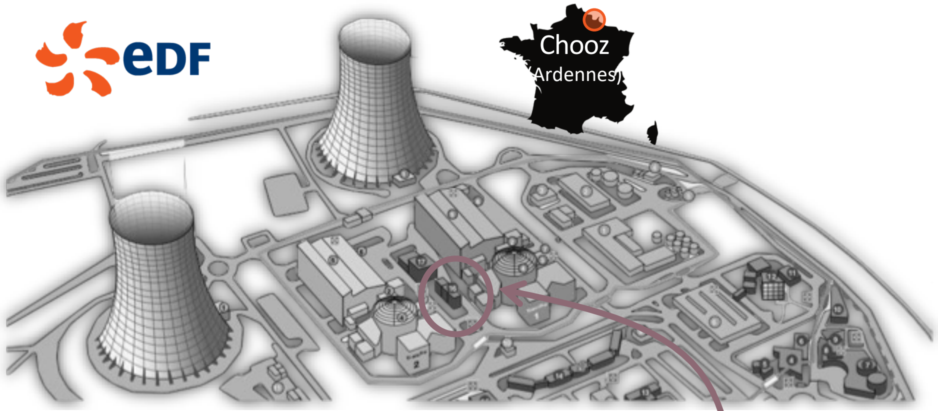
Al_2O_3

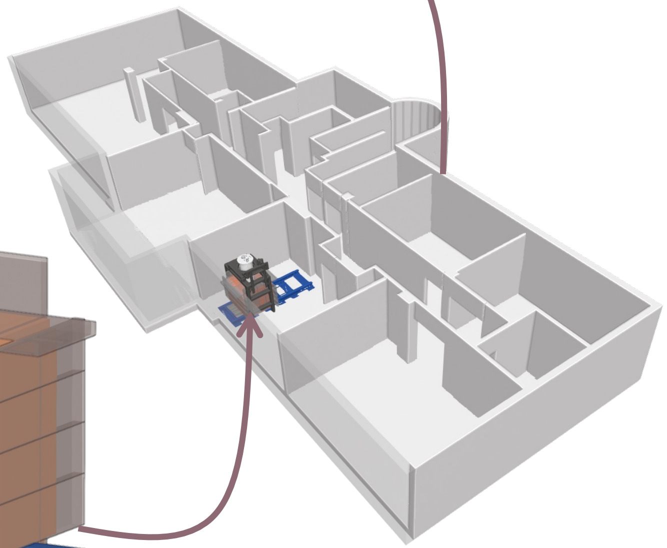


Active and passive cryogenic shields



Active and passive external shields





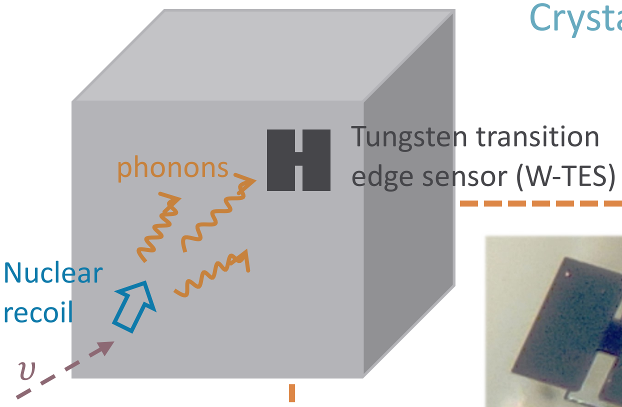
Chooz B nuclear power plant:
Thermal power of 2 x 4.25 GW_{th}

Experimental site: the "Very Near Site" (VNS)
102m and 72m from the two reactor cores
Excepted neutrino flux : $1.7{\times}10^{12}\ \overline{\upsilon}\ /(s.cm^2)$

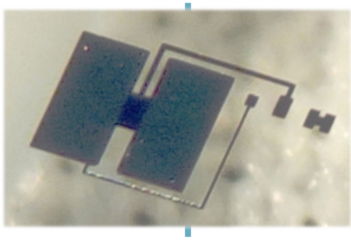
24 m^2 room in the basement of a tertiary building
overburden of 3 meters water equivalent
⇒**Ready to welcome the experiment**

Gram-scale cryogenic calorimeters

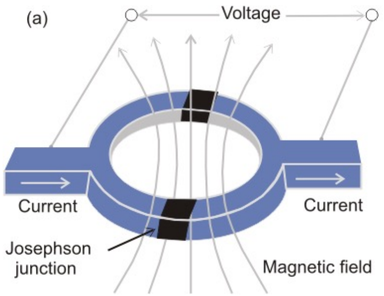
Crystal



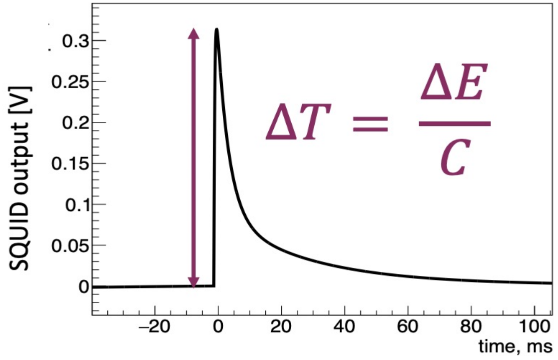
W-TES



SQUID readout



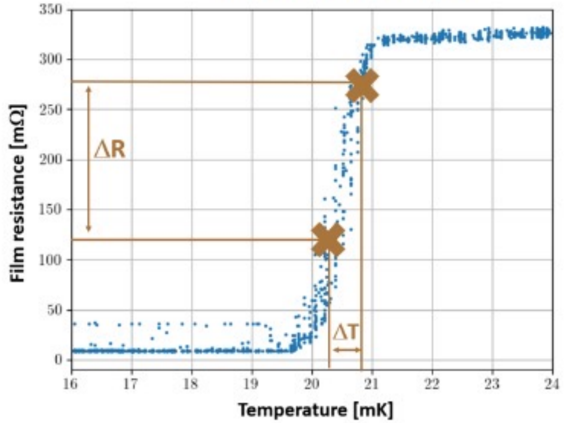
Heat pulse measured with tungsten transition edge sensors (W-TES)



$$\Delta T = \frac{\Delta E}{C}$$

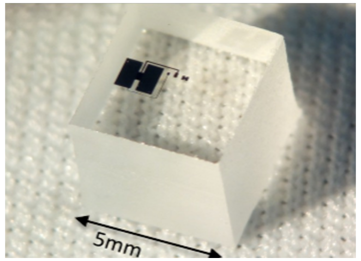
Energy (E) → Temperature (T) → Resistance (R) ↔ Current (I) → Flux (ϕ) → Voltage (V)

Transition of W-TES



→ operated at mK temperatures
→ very low threshold (20 eV) and excellent energy resolution
→ synergy with light dark matter search: NUCLEUS is based on CRESST technology

Al_2O_3 prototype with threshold
E_{th} = (19.7 ± 0.8) eV_{nr}



Phys. Rev. D **96**, 022009 (2017)

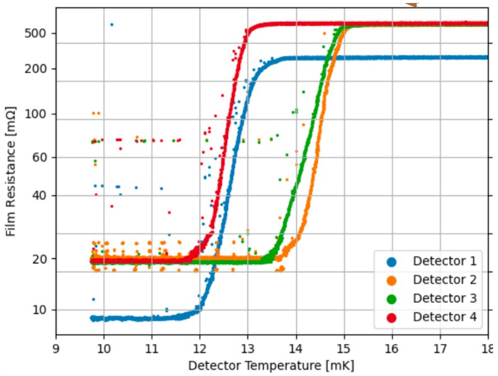
The NUCLEUS target detectors

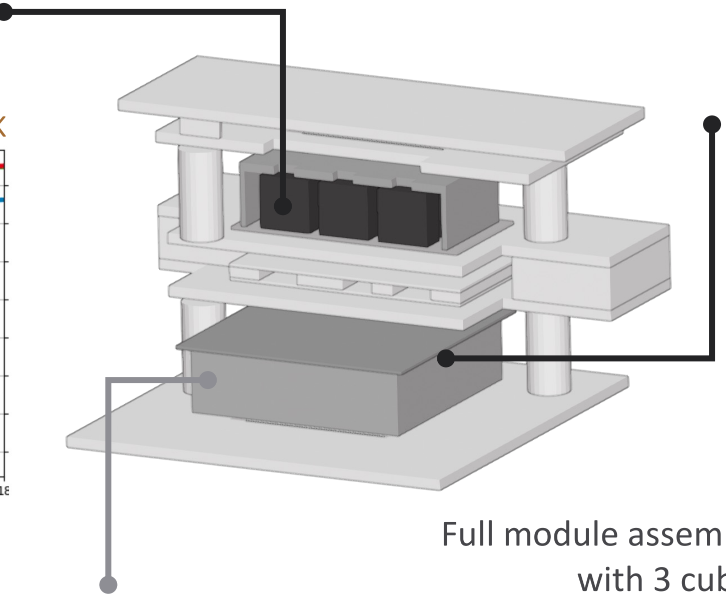
Multi target approach

3x3 array of $CaWO_4$ (6g): Background + CE𝝂NS

18 $CaWO_4$ crystals equipped with W-TES have been tested

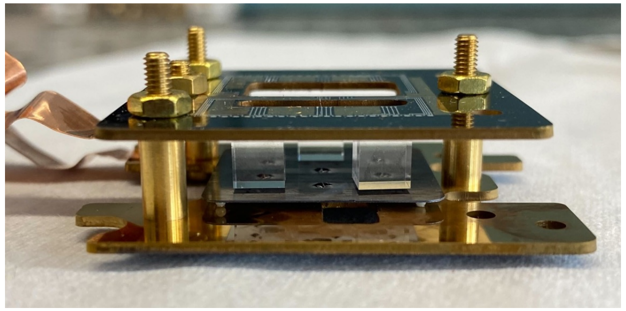
W-TES on CaWO4 detector with transition temperatures of 12-15 mK

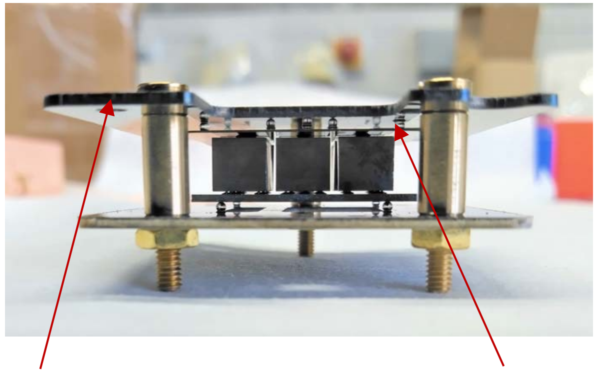




3x3 array of Al_2O_3 (4g): essentially background

Full module assembly with 3 cubes





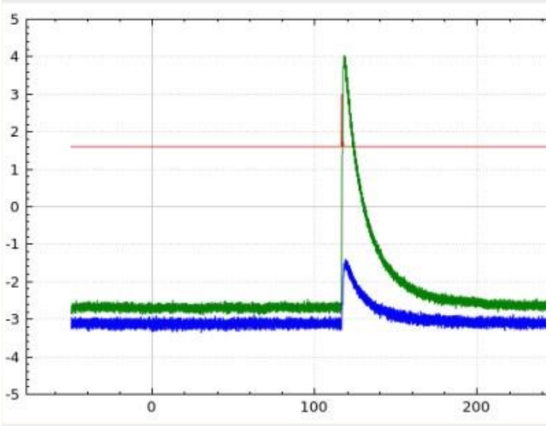
Holding plates (electrical & thermal contacts)

Si wafer

Inner veto

Instrumented Si holder

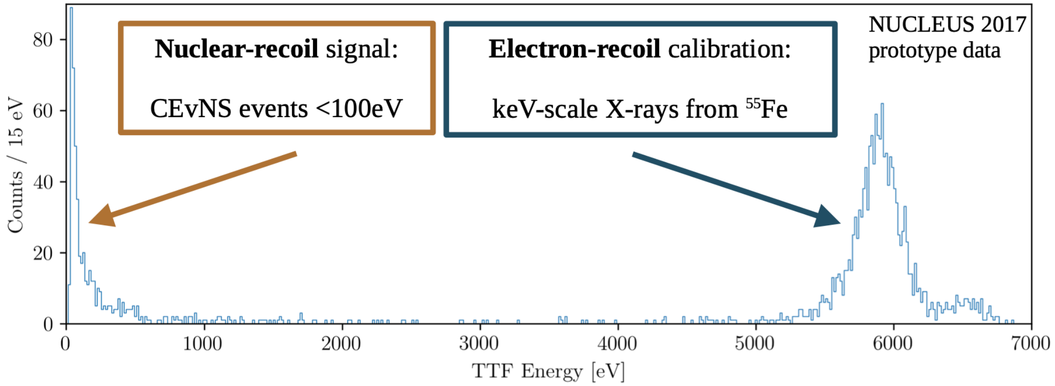
→ Si wafers equipped with TES
→ Reject surface events
→ Reject mechanical stress relaxation-induced events



- Nominal energy baseline resolutions achieved on single detector cubes:
  - 4eV (Al_2O_3)
  - 6eV ($CaWO_4$)
- Two detector cubes successfully operated in silicon holder

Low energy calibration

State-of-the-art



Assumptions to extend it to eV energies:

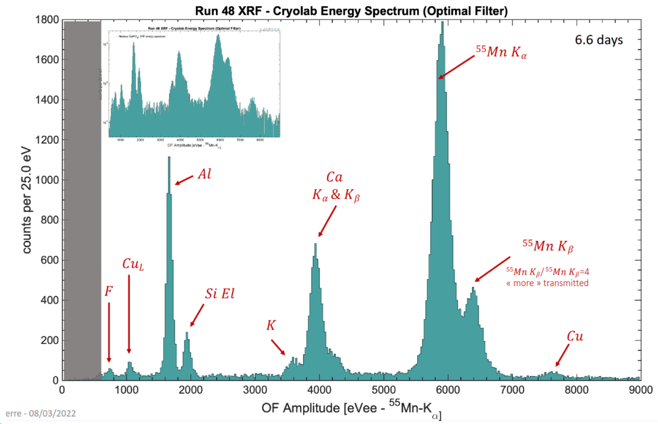
- Detector linearity
- No difference between NR/ER

⇒ New low energy calibration methods developed in the scope of NUCLEUS

Low energy X-ray source

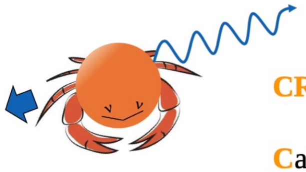
2-stages X-ray fluorescence source
→ Successful sub-keV calibration

(publication in preparation)



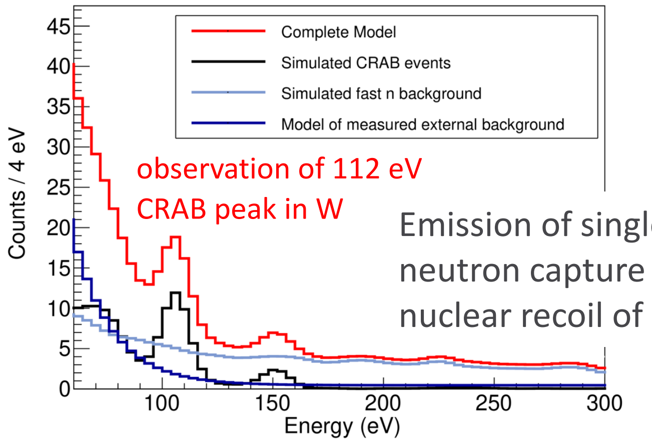
CRAB calibration

*(JINST **16** P07032 (2021)*
PhysRevLett.130.211802 (2023))



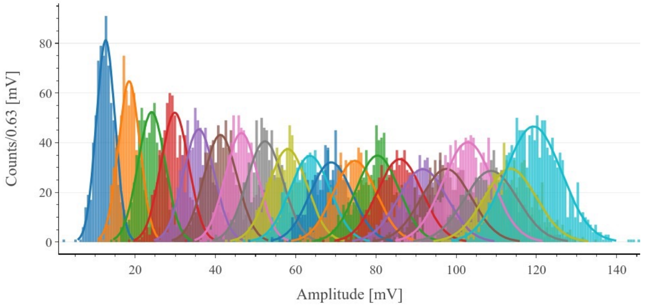
CRAB:

Calibrated
Recoils for
Accurate
Bolometry



Emission of single gamma after neutron capture produces a nuclear recoil of ~100 eV

In-situ LED calibration



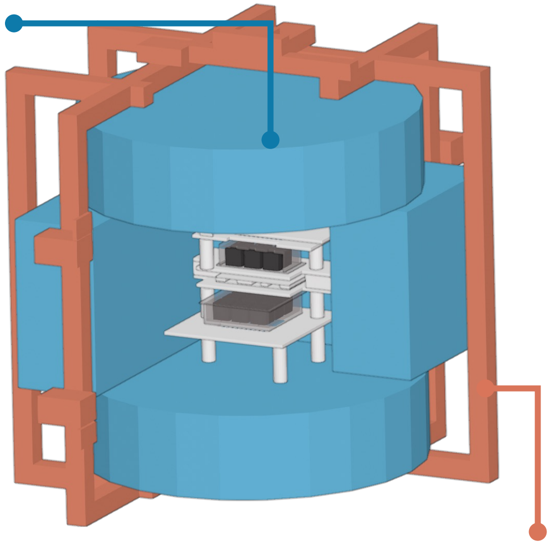
- monochromatic LED shines to detector
- photon-statistics allows to measure calibration constant
→ In-situ continuous stability monitoring of detectors during operation

High purity Germanium Cryogenic Outer Veto

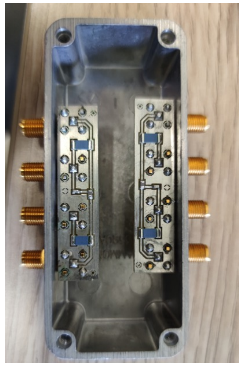
2.5-cm thick six high purity Germanium Crystals (4kg)

Active shielding against external backgrounds

- Read-out in ionization mode
- 4π-coverage active veto
- Fast detector response
- Anti-coincidence with bolometric detectors
- 1-10keV threshold

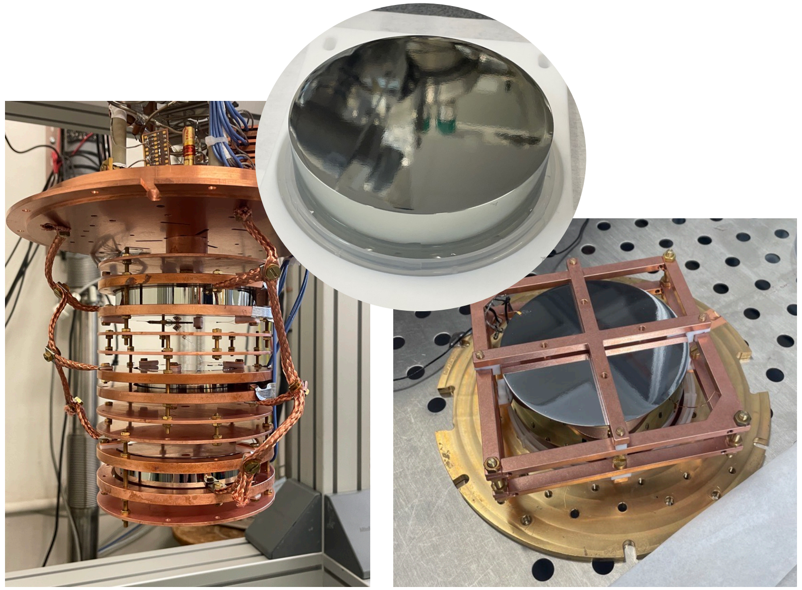


Cold and warm acquisition electronic



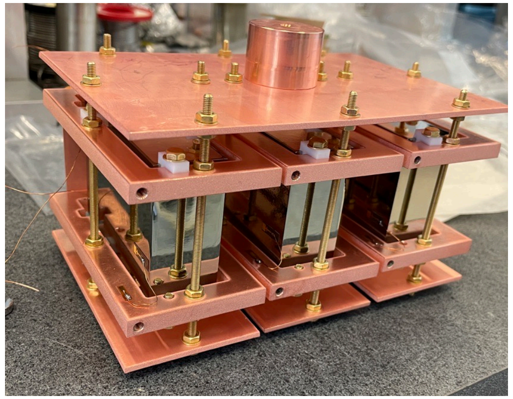
- Cold J-FET-based pre-amplification (300K) + low noise cold electronics (4K)
- Warm amplification with AMPTEK A250

Holding structure



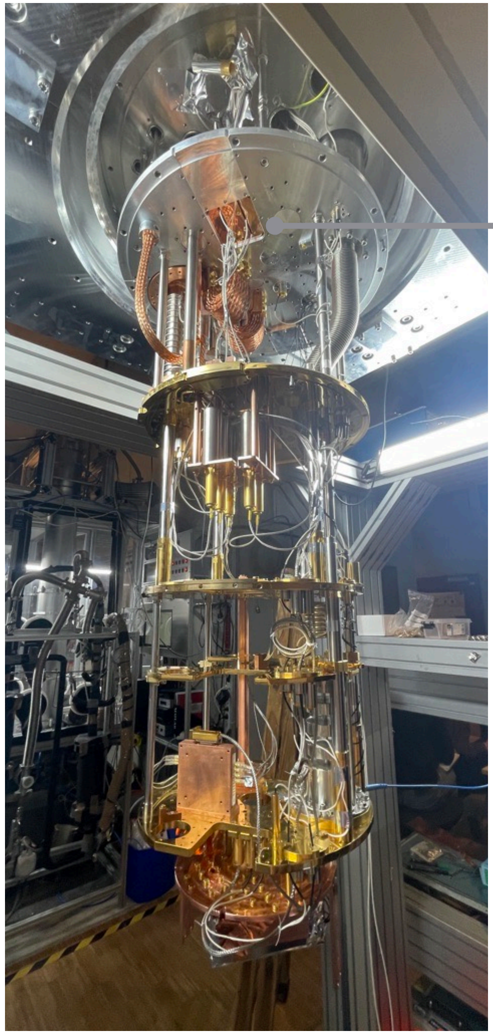
Cylindric crystals tested and validated, under integration at the commissioning site

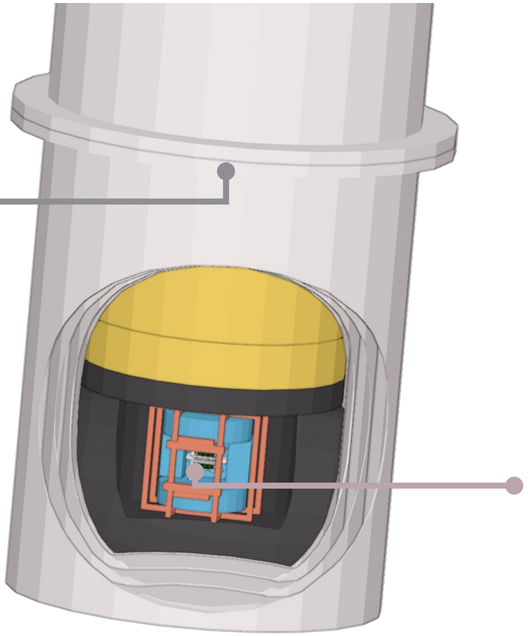
Rectangular crystals under tests



Cage structure mock-up ready for mechanical tests

Cryogenic detector operation

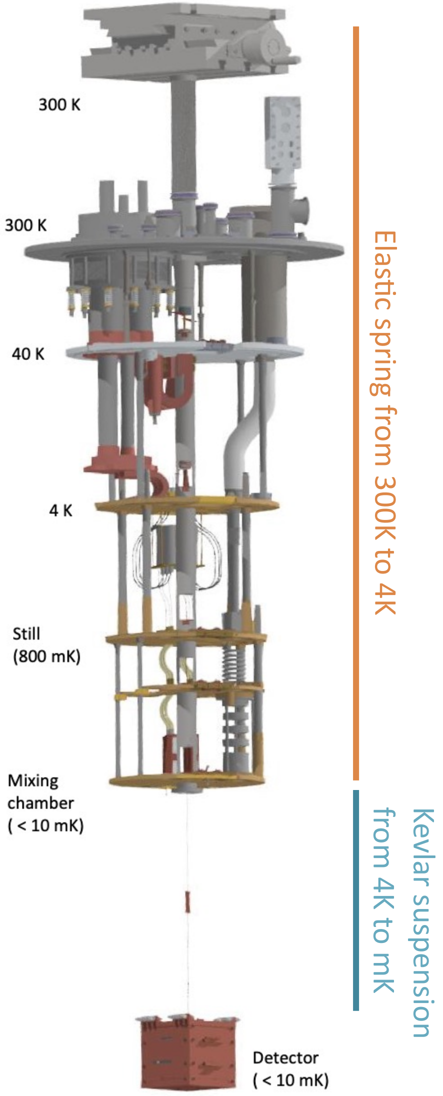




Dry dilution refrigerator

→ O(10 mK) base temperature for detector volume

→ Challenging vibration environment (Pulsed Tube cryo-cooler)

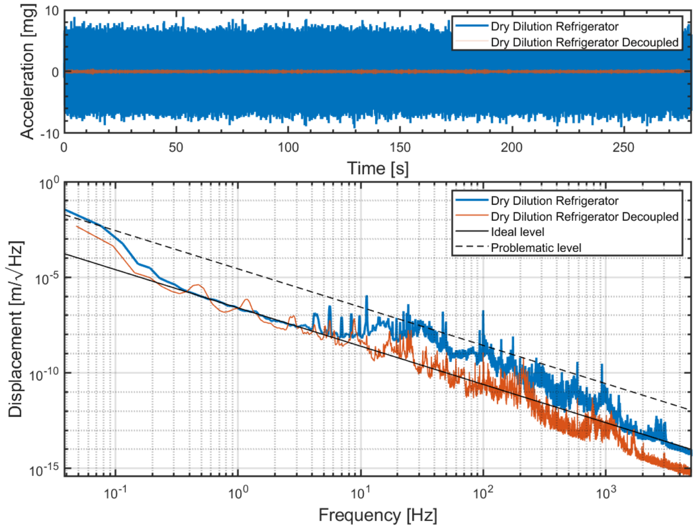


Dedicated vibration decoupling system

Alexander Wex, PhD student, TUM

(patent pending)

- > 4 weeks continuous operation of cryogenic detector with 6 eV baseline resolution achieved using a NUCLEUS $CaWO_4$ crystal
- Detector operation largely independent of pulse tube vibrations
- Successful cooldown of full system to base temperature achieved repeatedly
- RMS reduced by a factor of 30

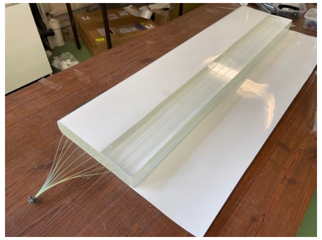


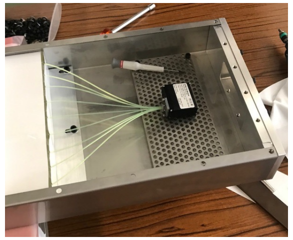
Plastic scintillator based Muon Veto

External muon veto

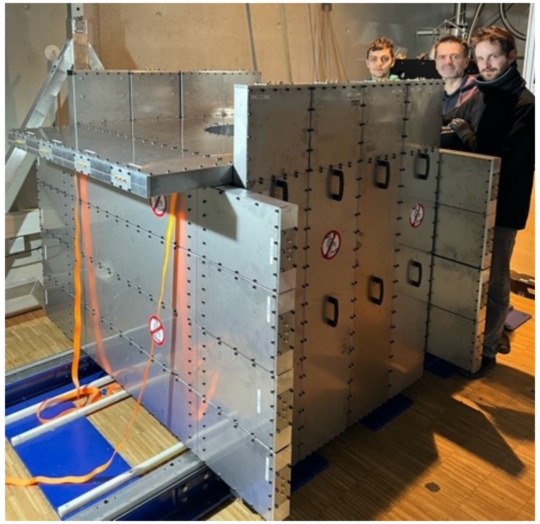
28x 5-cm thick scintillating plastics read out with WLS-fibers and Silicon PhotoMultipliers

- Data acquisition with struck FADC module
- SiPM control voltage controlled via arduino

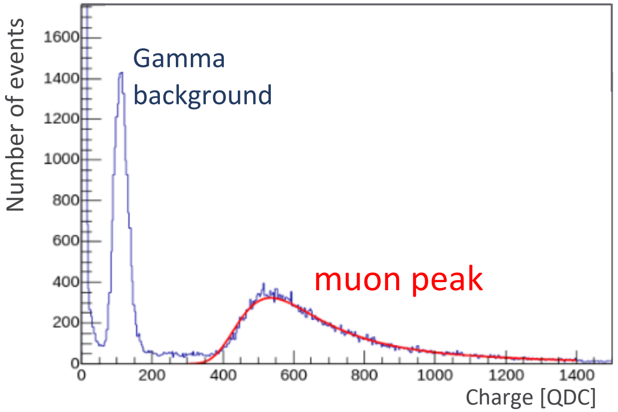


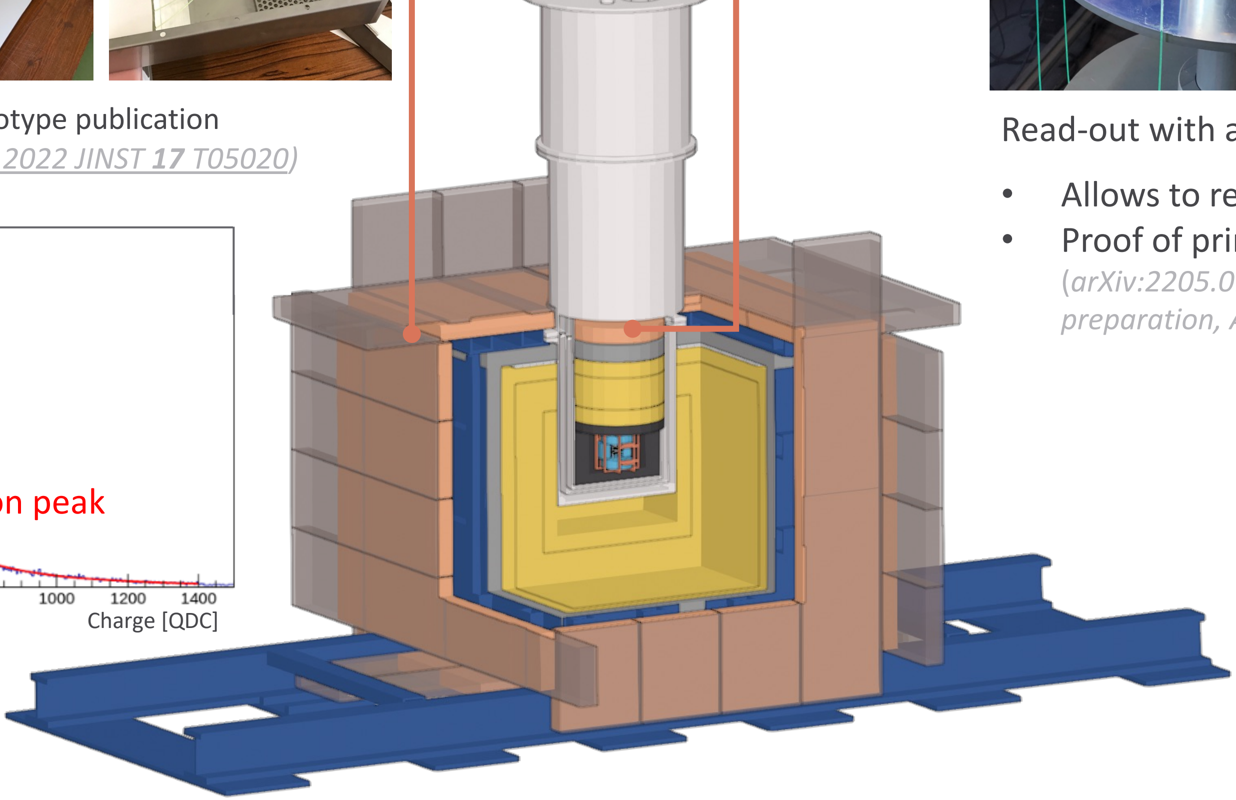


Muon veto prototype publication
*(V. Wagner et al 2022 JINST **17** T05020)*



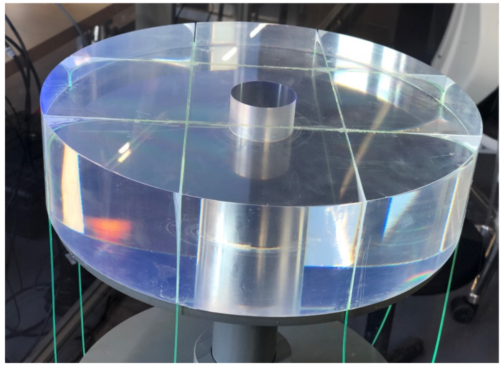
Muon Veto assembled and commissioned at TUM





Cold muon veto

@800mK



Read-out with a SiPM at 300K

- Allows to reach a 4π-coverage
- Proof of principle
  (arXiv:2205.01718, publication in preparation, A.Erhart et al.)

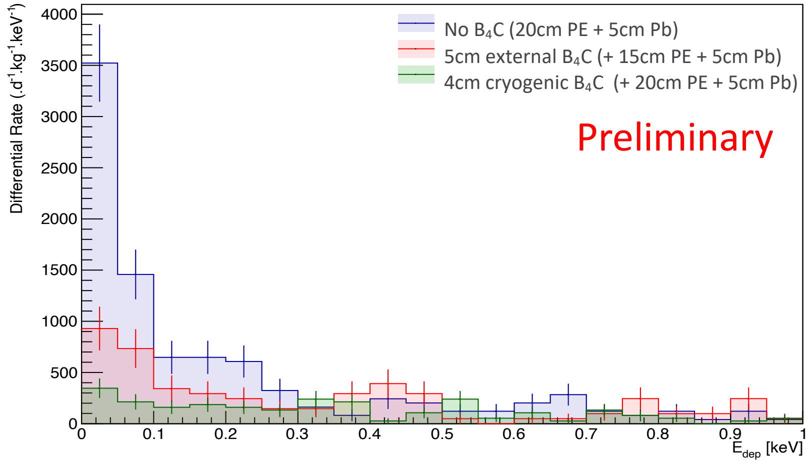
Passive shielding layers

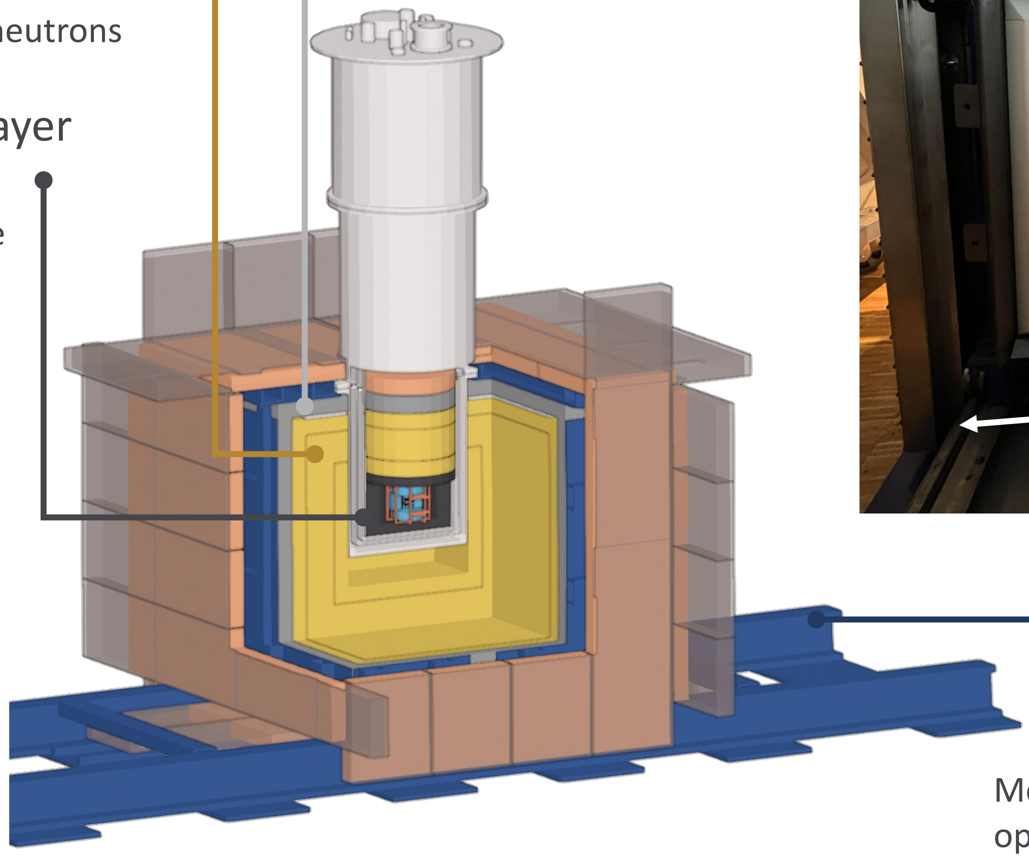
5cm-thick lead
→ Shields against ambient gammas

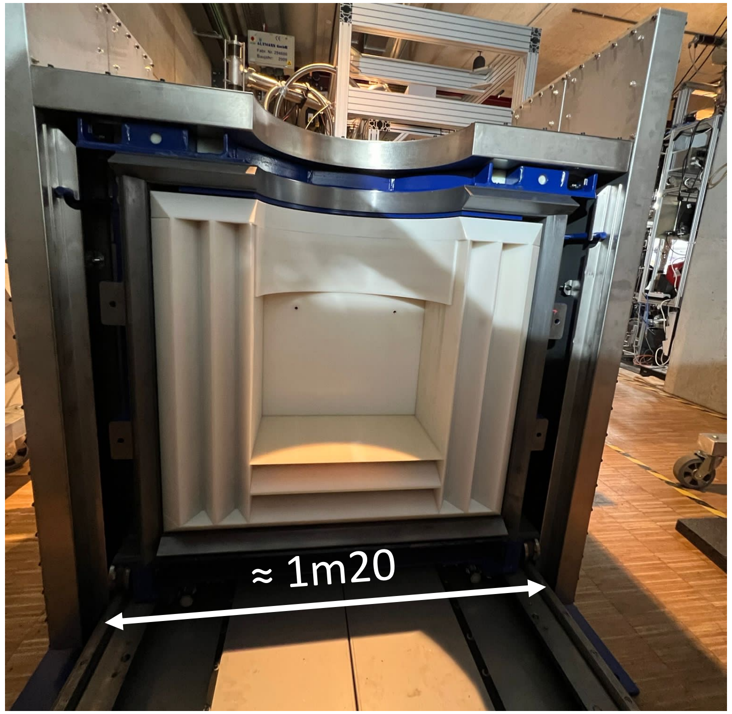
20cm-thick 5% borated polyethylene
→ Reduces the impact of secondary neutrons
→ Moderates and attenuates atmospheric neutrons

≈ 4cm-thick boron carbide layer
→ Inside the cryostat
→ Captures slow & thermal neutrons reaching the vicinity of the target detectors

B_4C shielding impact on the expected neutron-induced background





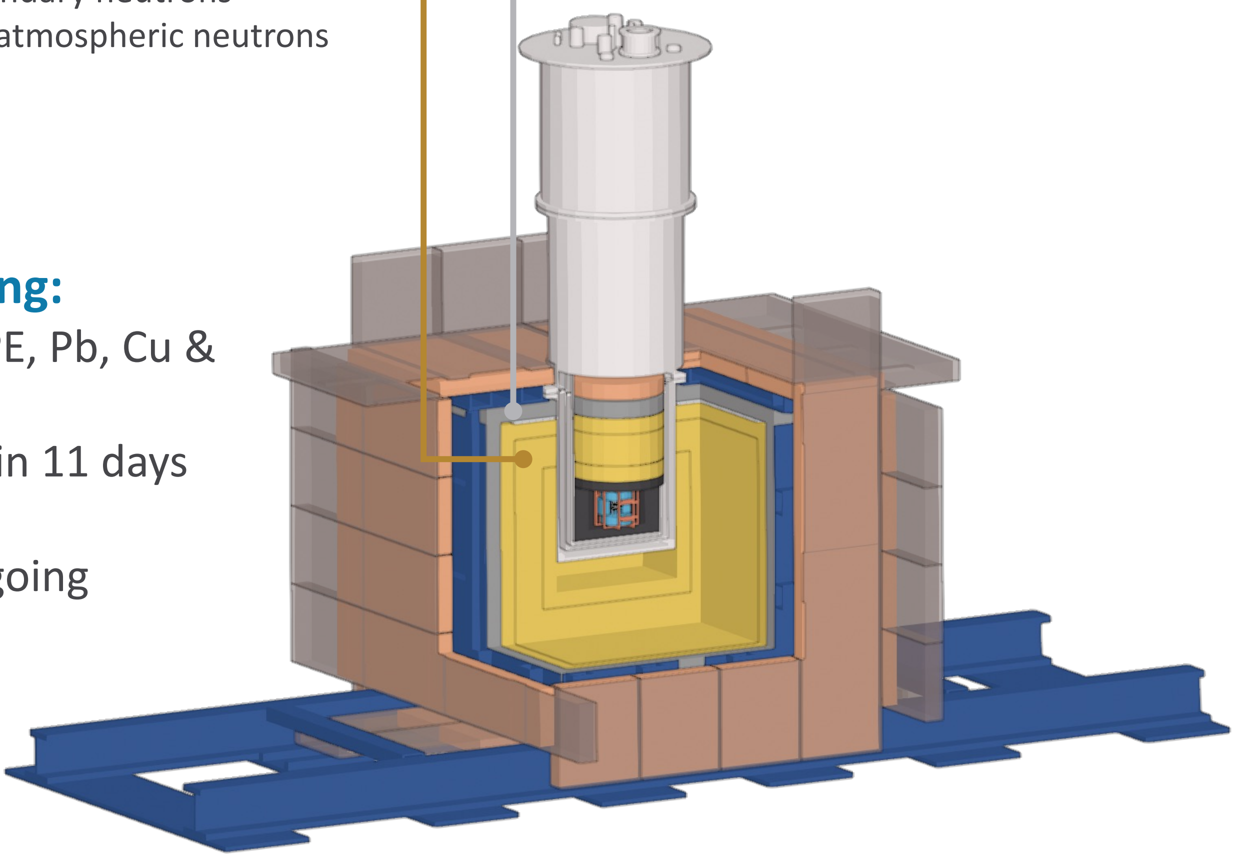


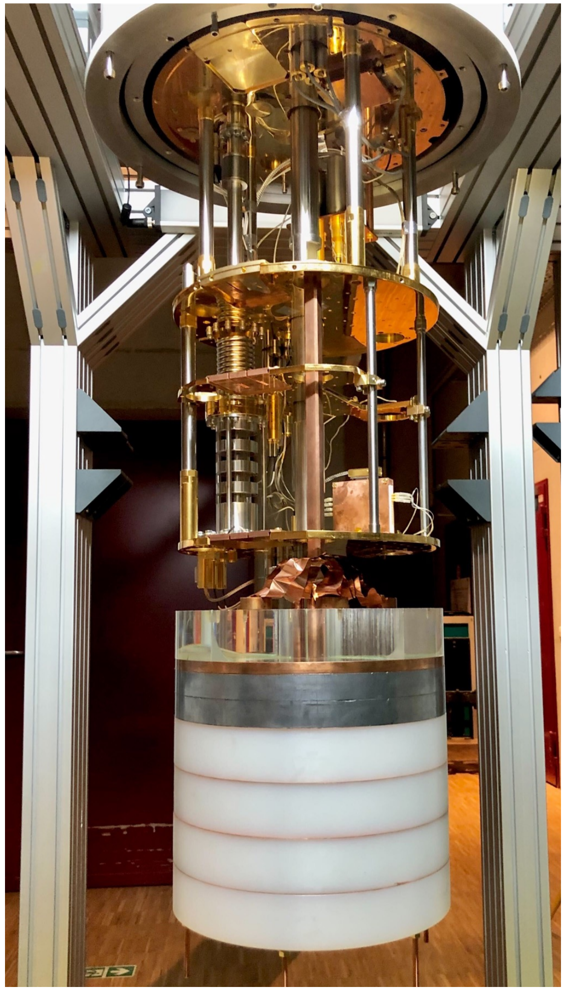
Support frame
Movable structure for easy opening/closing and access to the cryostat

Cryogenic shielding

5cm-thick lead
→ Shields against ambient gammas

20cm-thick 5% borated polyethylene
→ Reduces the impact of secondary neutrons
→ Moderates and attenuates atmospheric neutrons



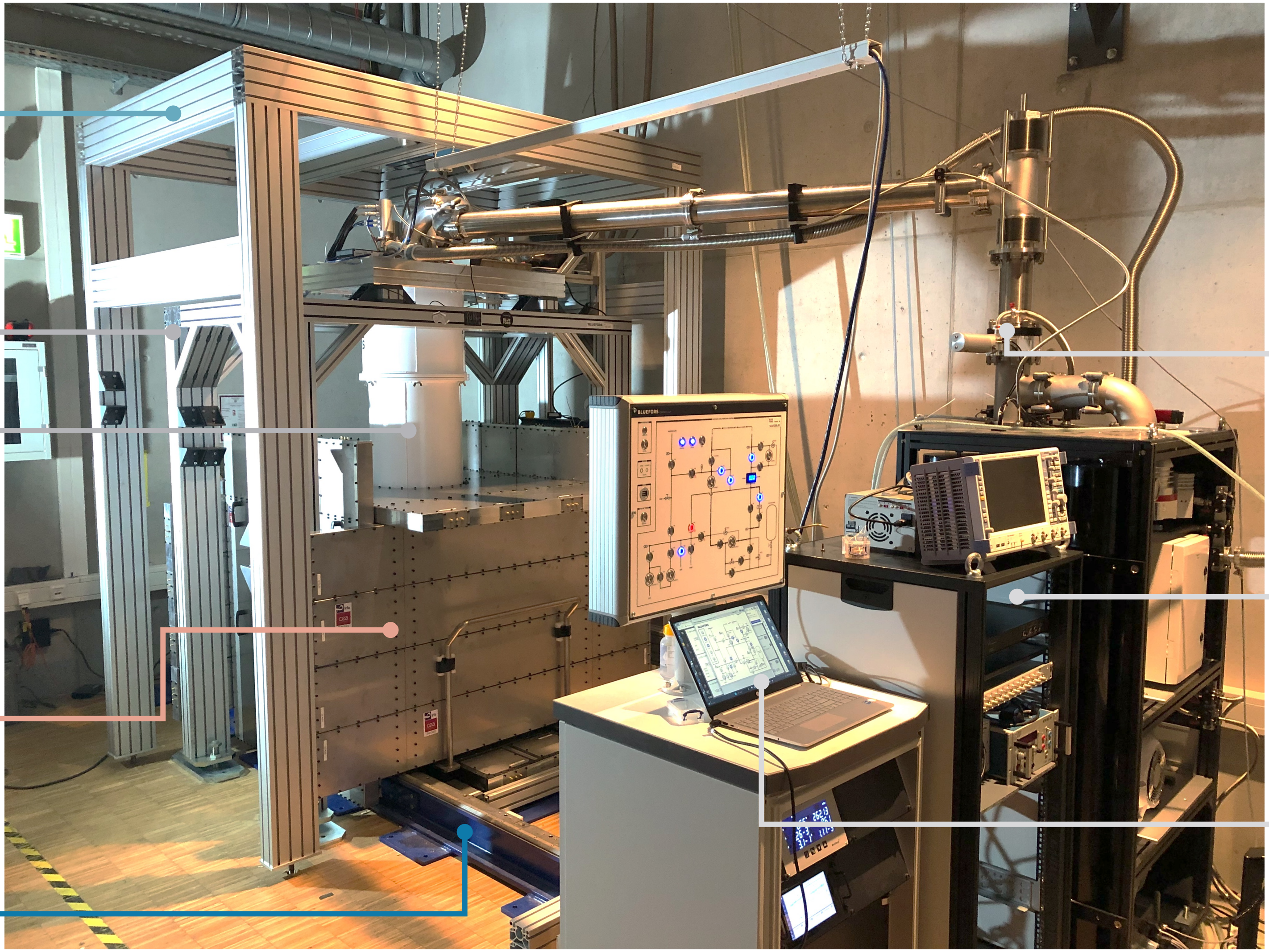


Cryogenic passive shielding:

- **Successful cooldown** of PE, Pb, Cu & Muon Veto (≈ 50 kg)
  → Thermalized to 0.8K in 11 days

- B4C shielding design on-going

Commissioning on-going at TUM underground lab



Vibration decoupling rack

Cryostat rack

Dry dilution refrigerator

Muon Veto and passive shielding

Support frame

Gaz handling

Data acquisition

Cryostat control

Background estimate through Geant4 simulations

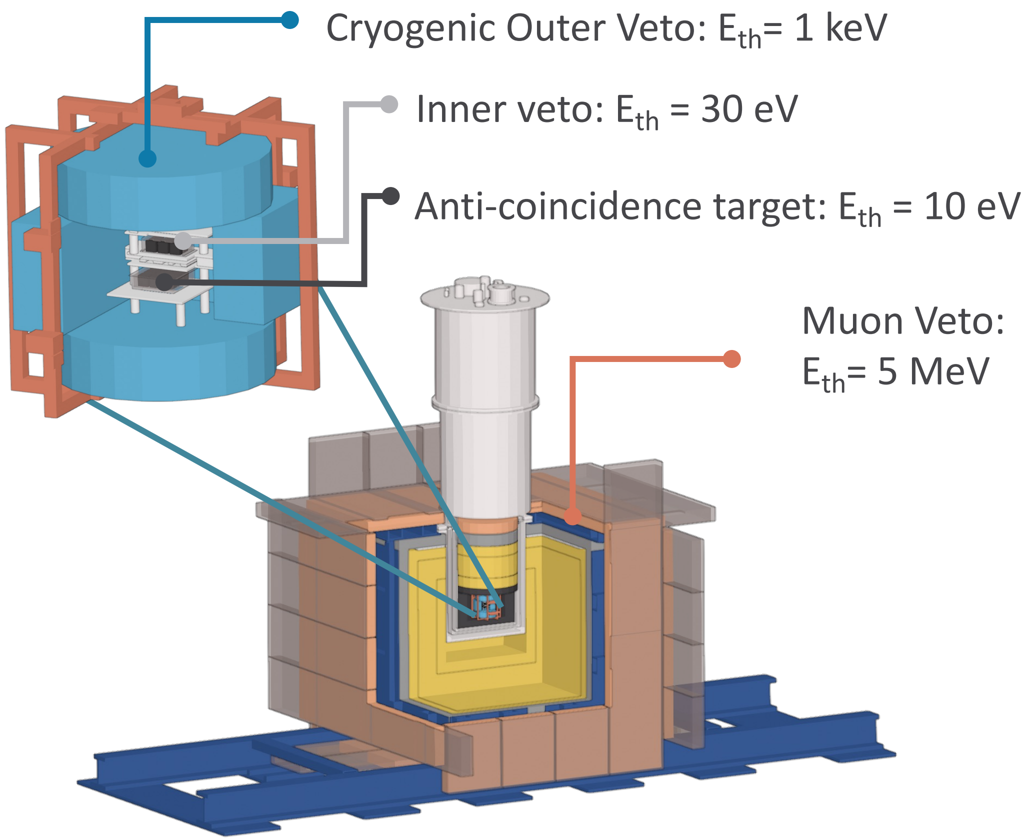
From simulation:

Background contribution Rates in kg^{-1} d^{-1} ***(Preliminary)***	$CaWO_4$ array		
	10-100 eV	100 eV – 1 keV	1 keV – 10 keV
Ambient gammas[1]	$0.5^{+0.9}_{-0.3}$	$4.1^{+1.7}_{-1.4}$	92 ± 7
Atmospheric muons[1]	$1.2^{+0.9}_{-0.8}$	$2.7^{+1.3}_{-1.1}$	9.3 ± 1.9
Atmospheric neutrons[1,2]	5.6 ± 2.0	14.7 ± 5.3	57 ± 20
Total	$\mathbf{7.3^{+2.3}_{-2.2}}$	$\mathbf{21.5^{+5.7}_{-5.6}}$	**158 ± 21**
CEνNS signal	≈ 30	≈ 9	-

[1] *From measured gamma, muon, neutron fluxes*

[2] *Considering the measured high energy neutrons attenuation* of $6.63^{+3.15}_{-1.65}$ from the building

Veto cut applied



Goal of background level of 100 counts/(keV kg d) in reach

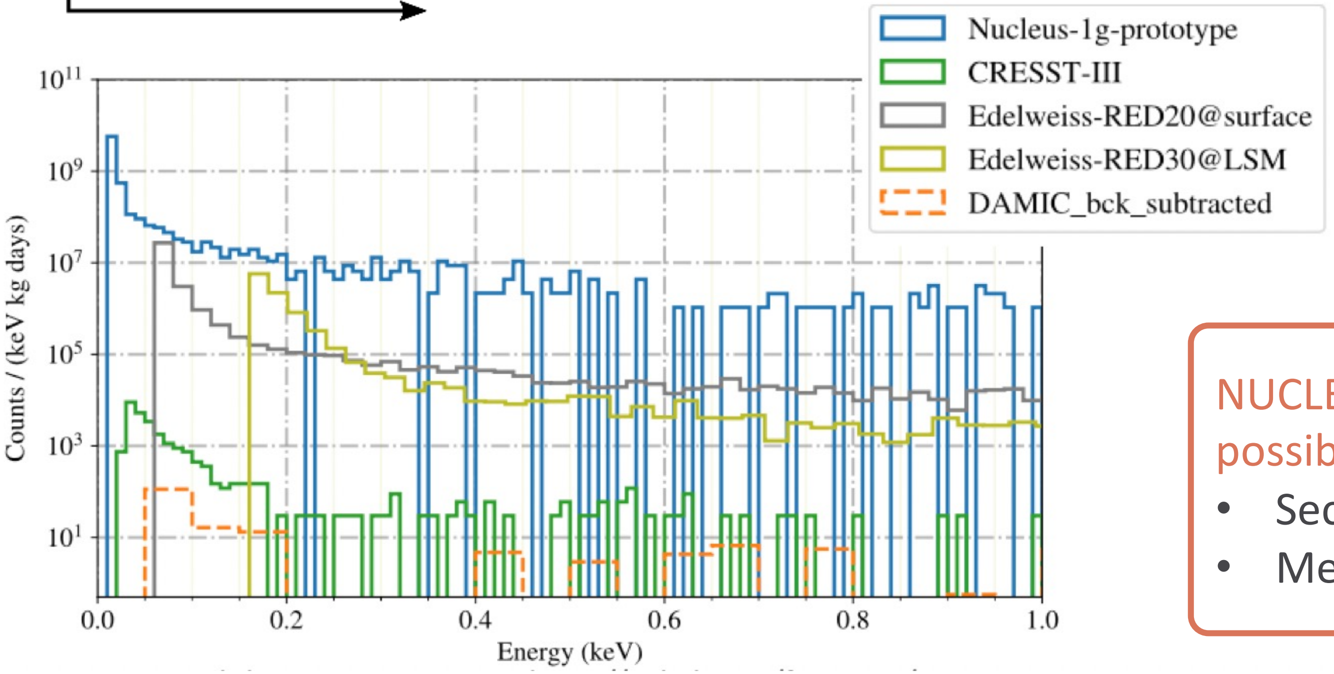
⇒ What about the unknown background(s)?
Excess in the low energy range ?

Investigate the low energy excess?

A. Fuss, et al. arXiv:2202.05097

Many rare event search experiments observe excess at low energies of unknown origin

- Events have particle signature
- Background seems to have multiple components



EXCESS Workshop, Data Repository, https://github.com/fewagner/excess

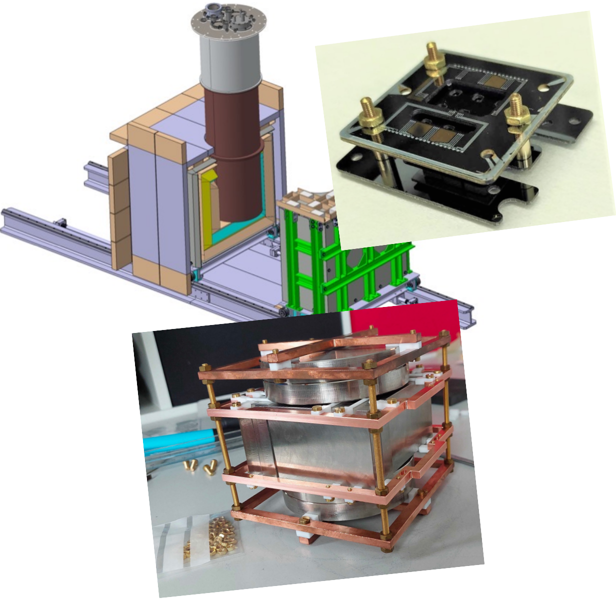
NUCLEUS' various veto systems allows to investigate possible components of the background:

- Secondaries from atmospheric muons (muon-veto)
- Mechanical stress relaxation-induced events (inner veto)

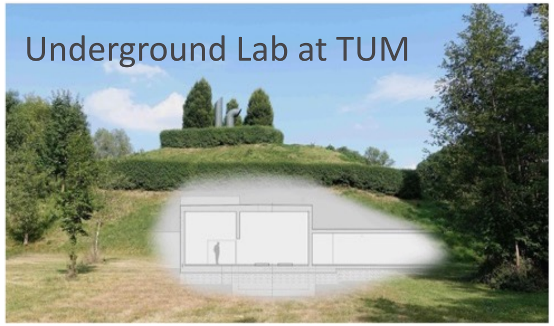
From blank assembly towards on-site installation

2022 → Beginning 2024

Design phase

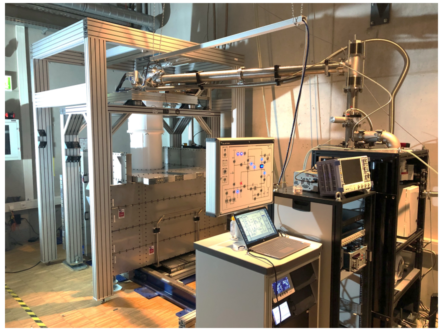


Blank Assembly & commissioning



→ Mechanical integration tests
→ Calibrations at sub-keV energies
- LED
- XRF
- Neutrons with CRAB

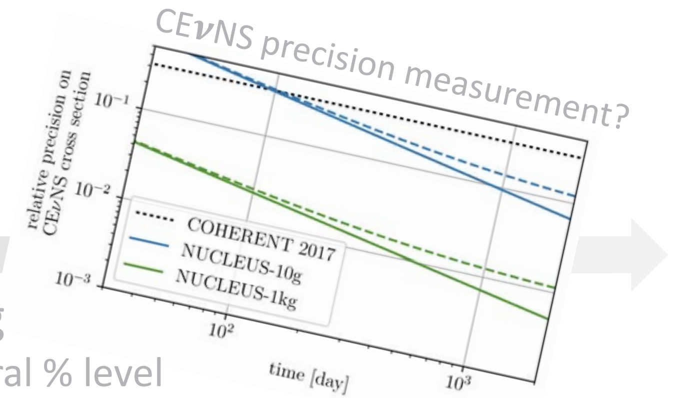
→ Detector performances



Long run measurement

→ Background studies at sub-keV (EXCESS)
→ Validate background strategy

On-site installation



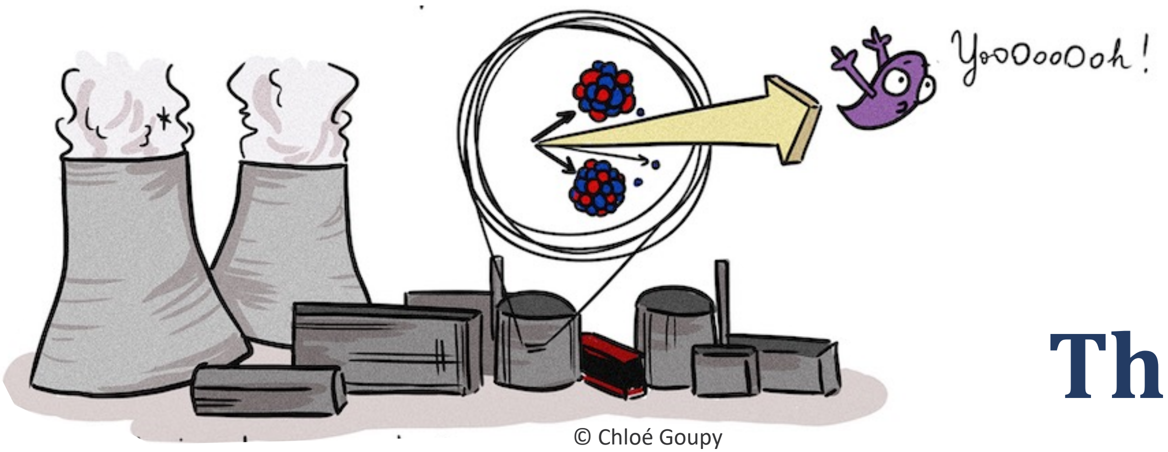
2024 → 202…

NUCLEUS-10g physics run

Phase 1: observe CEνNS

Towards NUCLEUS-1kg

Phase 2: measure CEνNS at the several % level



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Thanks for your attention

nucleus

EXPERIMENT

https://nucleus-experiment.org

Rencontres du Vietnam,

30th anniversary

Windows on the Universe

6-12 August 2023