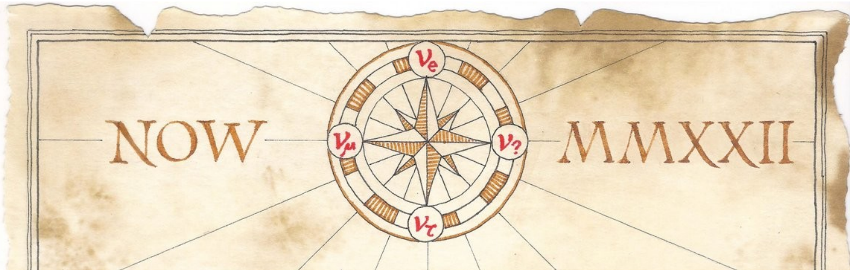
# The NUCLEUS experiment:

# CEvNS with reactor neutrinos and cryogenic detectors

Johannes Rothe,
Technical University Munich

Neutrino Oscillation Workshop 2022
September 10, Ostuni

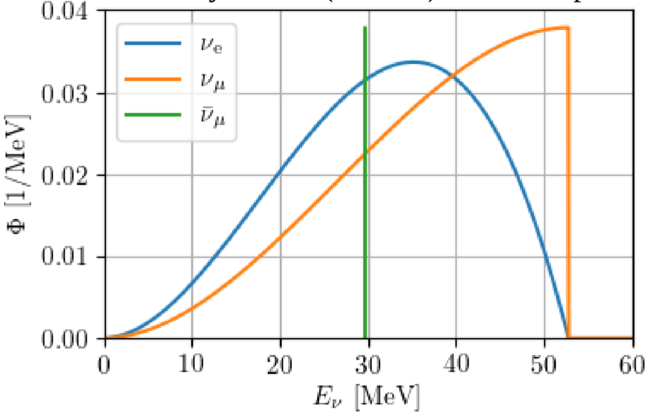



TECHNISCHE UNIVERSITÄT MÜNCHEN

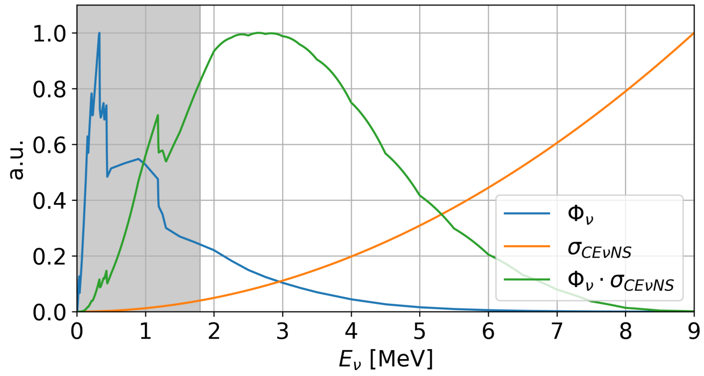
nucleus EXPERIMENT

# CEvNS at Nuclear Reactors

Pion decay-at-rest (π-DAR) neutrino spectrum




Reactor antineutrino spectrum



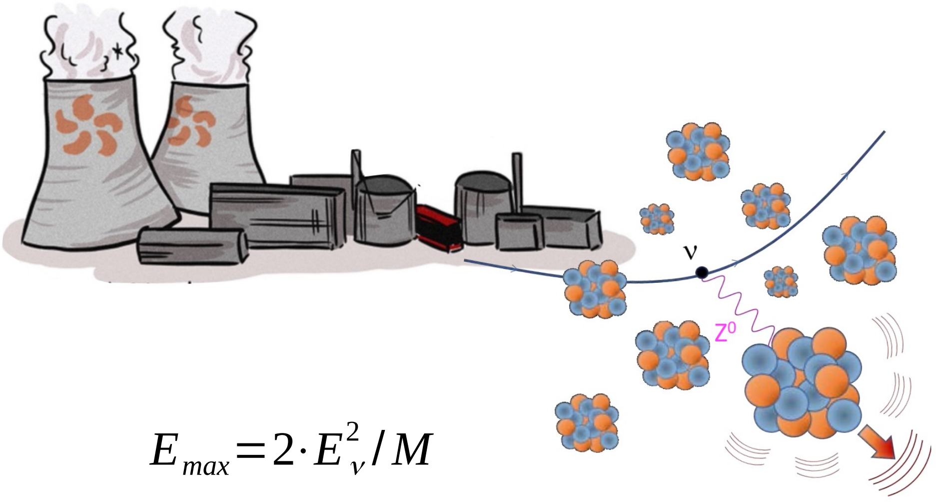

**Taking CEvNS to a nuclear reactor:**

- 10 x lower neutrino energies than π-DAR → full coherence expected
- Several orders of magnitude higher total neutrino flux

- Potential for low-energy precision studies
- Possibility for detector miniaturization and technological application

**Initial goal**: first observation of CEvNS from reactor neutrinos

# Reactor CEvNS: the challenge



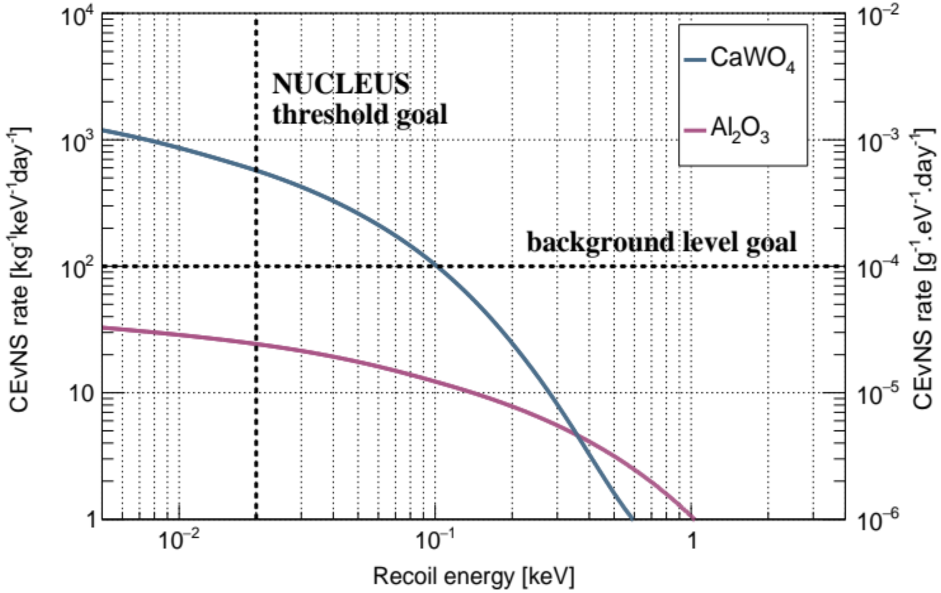

$$E_{max} = 2 \cdot E_\nu^2 / M$$

$$= 2 \cdot (3\,MeV)^2 / (182\,GeV) = 100\,eV$$

→ detection of **sub-keV nuclear recoils** is mandatory

neutrino rate in 10g target: ~0.16 counts/day

→ needs **low background techniques** at a shallow site

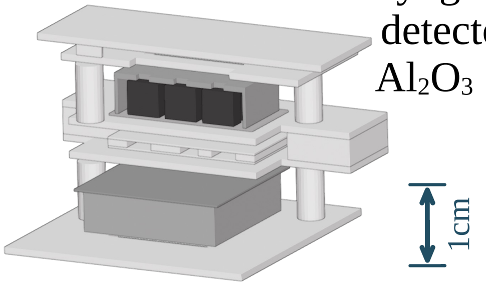


# The NUCLEUS collaboration

~50 members from
institutions in four countries

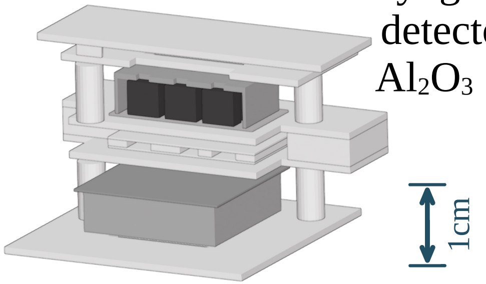
# The experimental setup

Cryogenic target detectors (10g): $Al_2O_3$ + $CaWO_4$

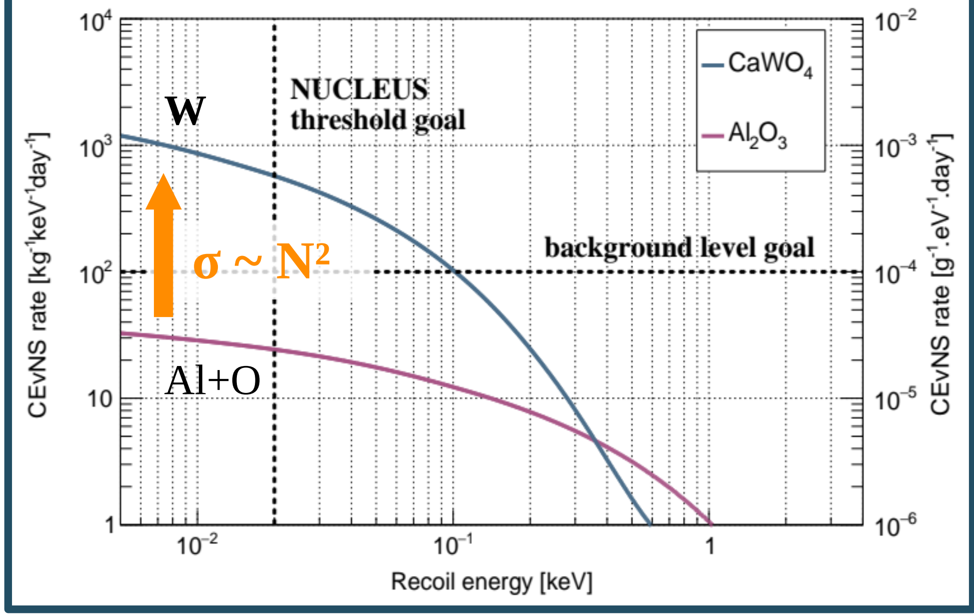



Active and passive external shields

# The experimental setup



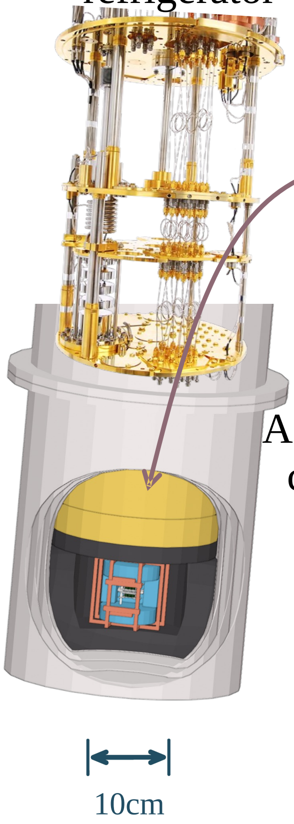

Cryogenic target detectors (10g): $Al_2O_3 + CaWO_4$



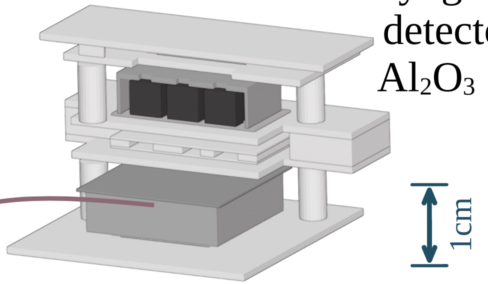

Active and passive external shields

# The experimental setup

$^3He/^4He$ dilution refrigerator

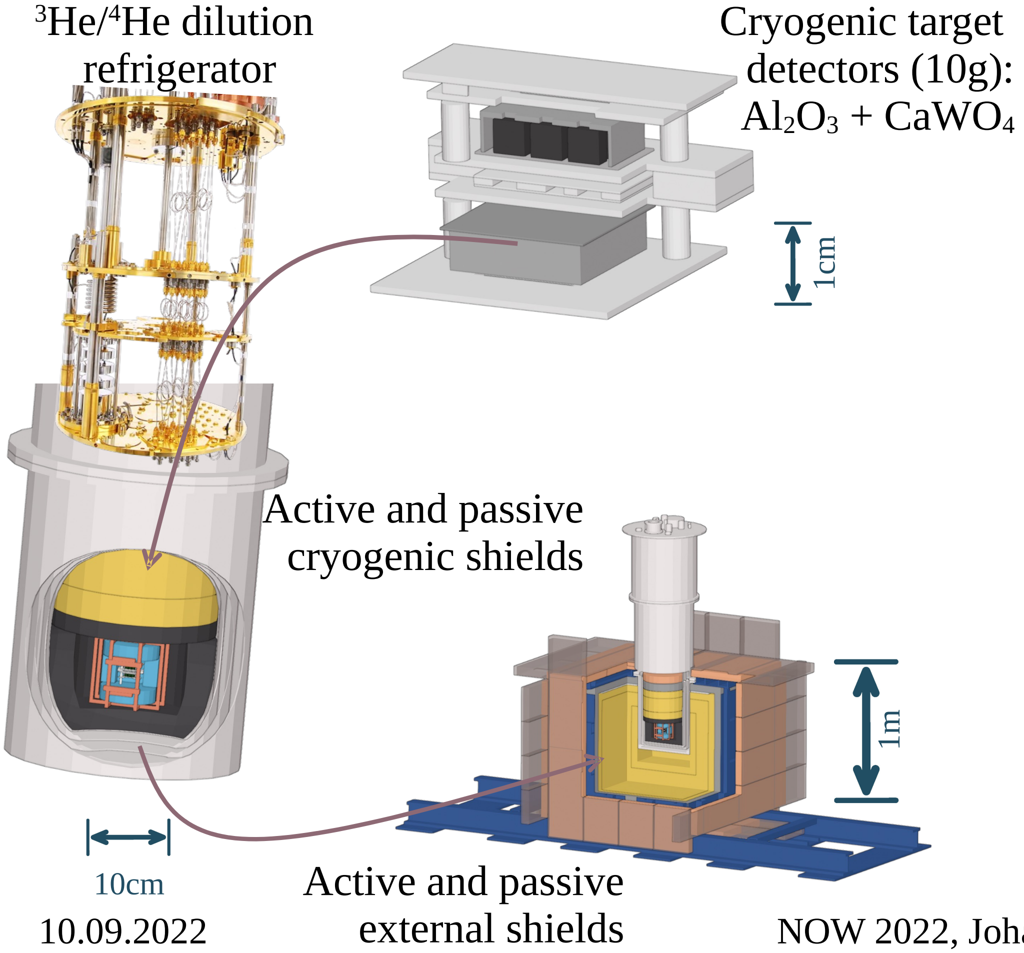



Cryogenic target detectors (10g): $Al_2O_3 + CaWO_4$



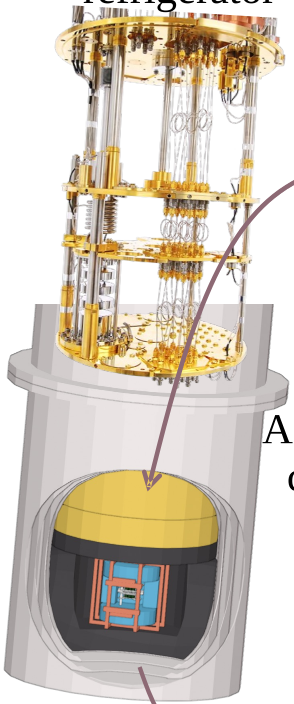

Active and passive cryogenic shields

# The experimental setup



# The experimental setup

$^3He/^4He$ dilution refrigerator



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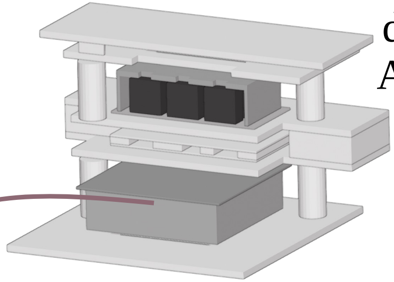
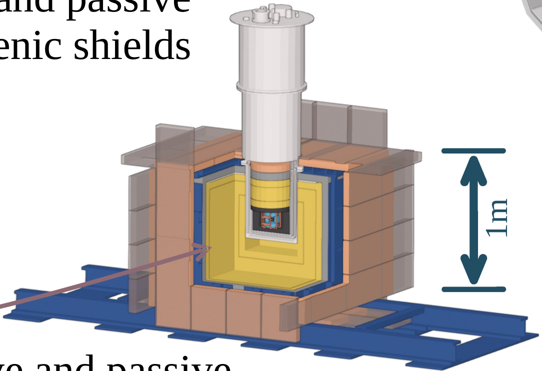


1cm

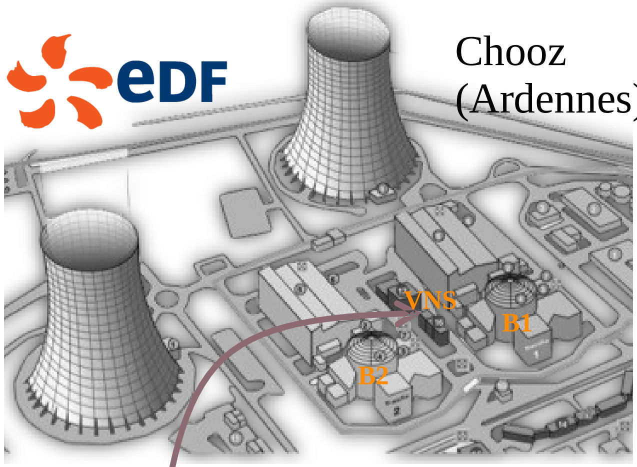
10cm

Active and passive cryogenic shields

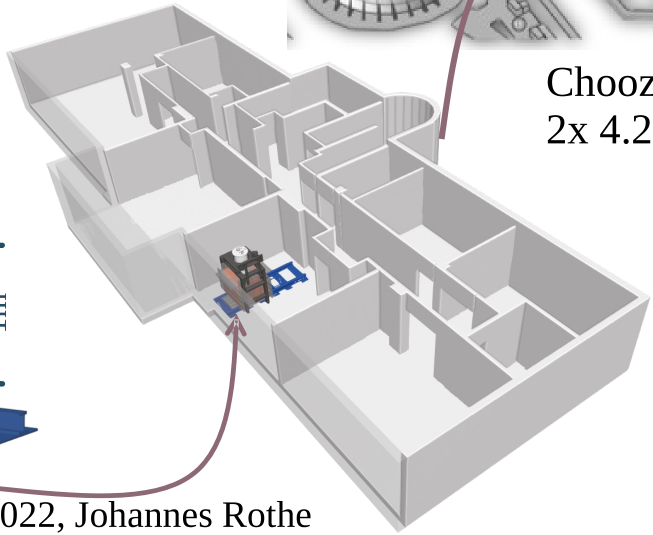


1m

Active and passive external shields




Chooz (Ardennes)



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

Experiment room:
“Very-Near-Site” (VNS)
102 m & 72 m from cores

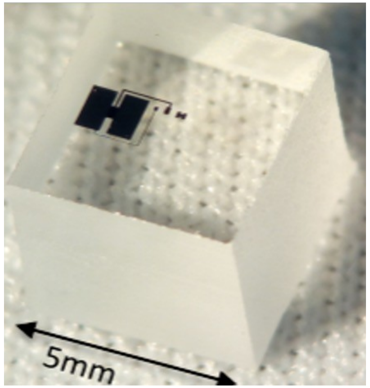
$\rightarrow$ flux $1.7 \cdot 10^{12}\ \nu / s / cm^2$

24 m² (basement),
3 m.w.e. overburden

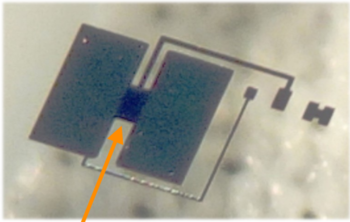
# Gram-scale Cryogenic Calorimeters

Target crystal: Transition edge sensor (TES): SQUID amplifier:

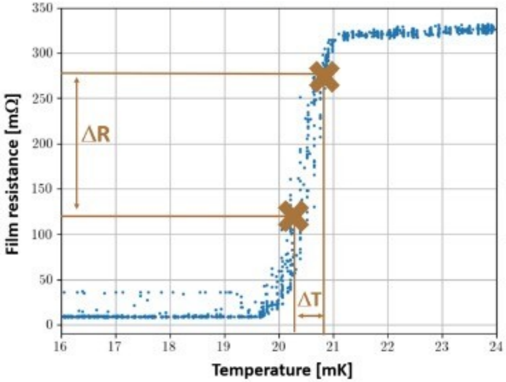
Energy deposition → temperature rise → resistance change → current pulse → magnetic flux signal → voltage output

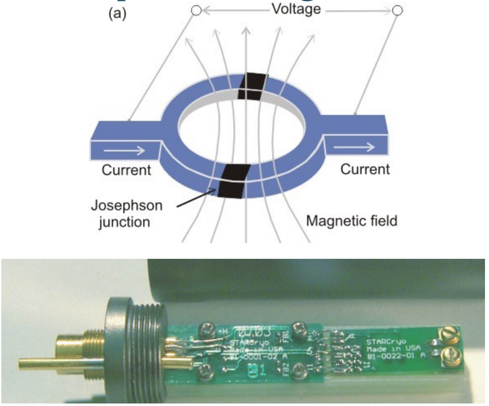


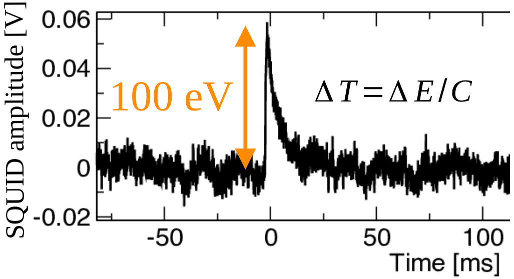

5mm-cube of $Al_2O_3$ or $CaWO_4$



superconducting tungsten film



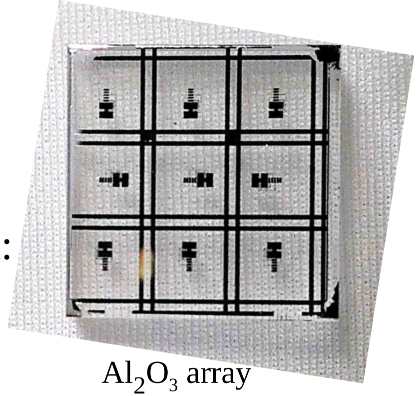




- Operation at mK temperatures
- Excellent energy resolution and threshold (prototype: 20eV)
- Synergy with light dark matter search

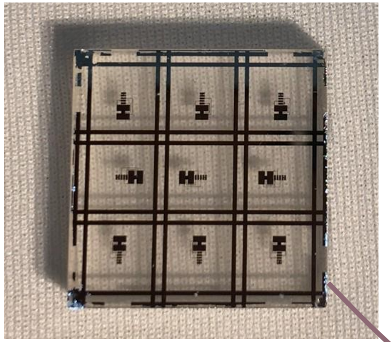
NUCLEUS is based on CRESST technology!

# NUCLEUS target crystals

- Detectors fabricated as 3x3 arrays (two of each material)
- Transition temperatures characterized:
  $T_c$ < 21mK,
  good for high sensitivity



$Al_2O_3$ array

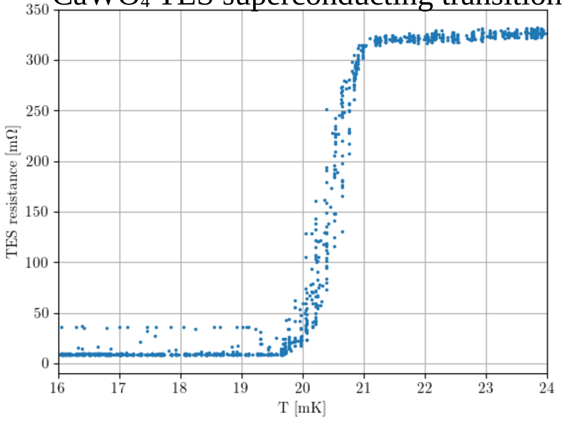


$CaWO_4$ array before dicing

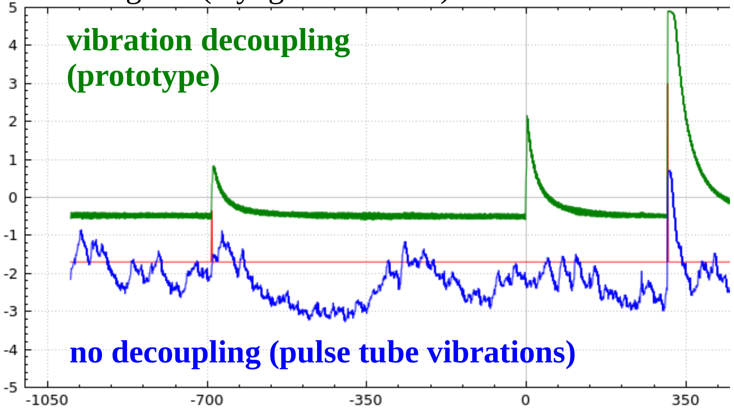
Finished target cubes

- Dicing and polishing in progress
- Cryogenic testing of target cubes ramping up
- Recent breakthrough: cryostat vibration decoupling

$CaWO_4$ TES superconducting transition




TES signals (cryogenic test run)



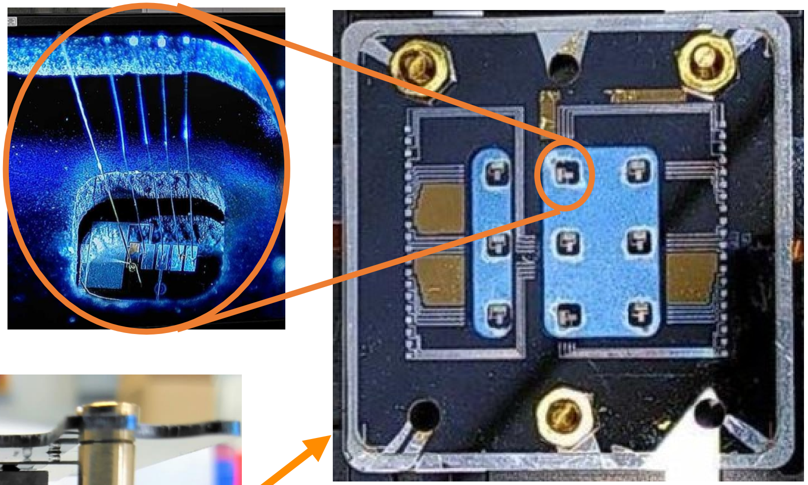
# NUCLEUS inner detector module

Design goal: only **active material** facing the targets
→ no degraded higher-energy events or external backgrounds

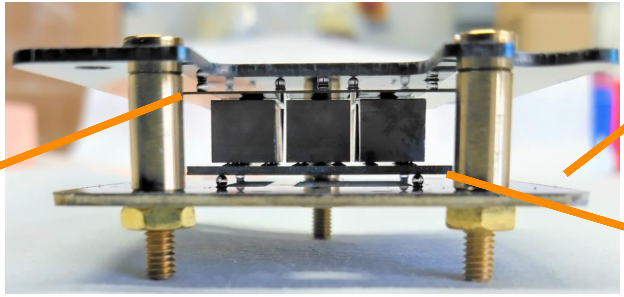
- Thermal and electrical lines on **silicon support wafers**

- Instrumented detector holding structure: **“inner veto”**
  - Top: Si wafer with flexible contact points to target cubes
  - Bottom: rigid wafer → Silicon beaker

- Fast and easy mounting procedure
  → Design verified by cycling to < 0.01 K
  → ready for test with active target cubes

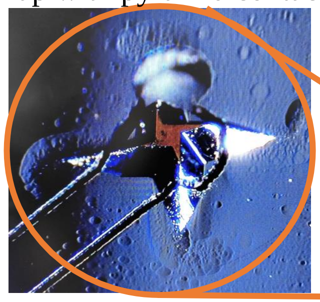


Support wafer and connections

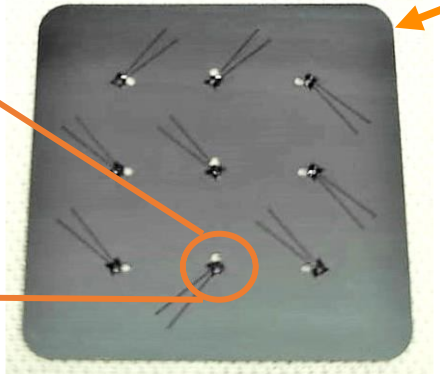


Inner detector module: side view

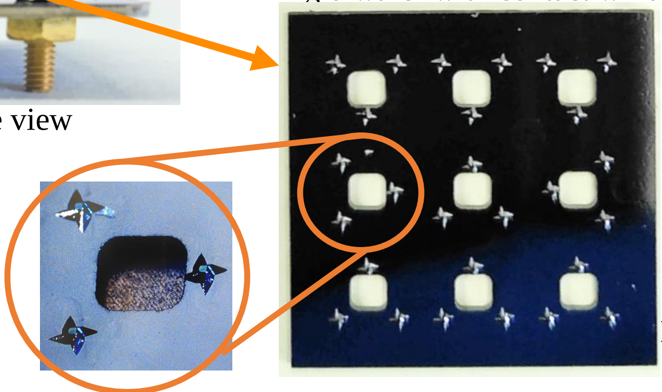
Flap with pyramid contact



Inner veto flexible wafer



Rigid wafer with contact windows

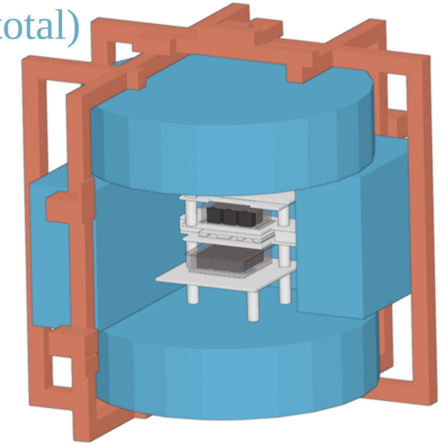


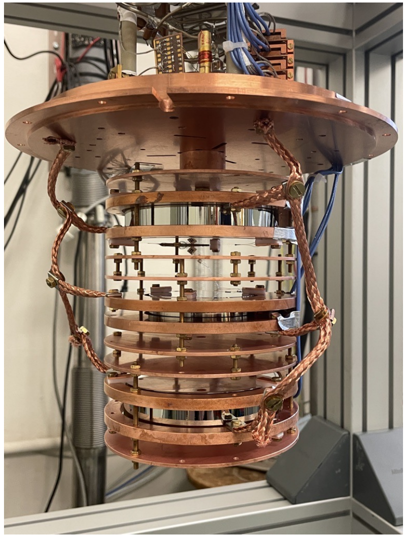
# Cryogenic Outer Veto

**6 high purity Germanium crystals** (2.5cm, 4kg total)

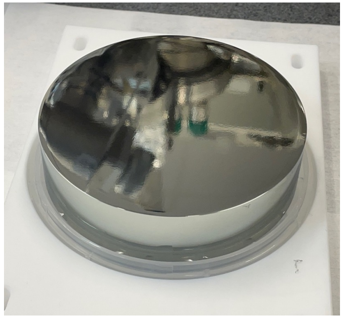
Active shielding against external backgrounds

- ionization readout
- fully surrounding inner cryodetector
- fast response for anti-coincidence operation
- few keV threshold
  → >90% rejection of ambient γ events

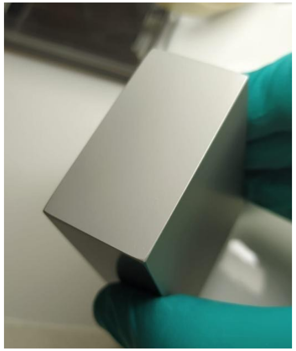




2x cyl. crystals during cryogenic performance test



2x cylindrical detectors completed and validated



4x rectangular detectors in production

Cu holding structure: mechanical demonstrator

# Plastic Scintillator Muon Veto

**External muon veto**

28 plastic scintillator slabs (5cm) read out with WLS fibers and Silicon PhotoMultipliers (SiPM)

- Geometrical efficiency 99%
- Prototype characterized (*JINST* **17** T05020 (2022))
- Modules in production

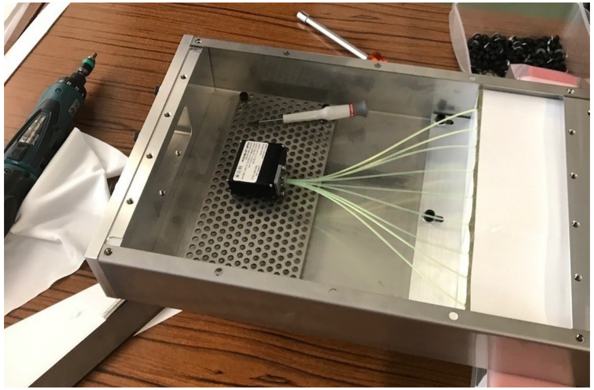
**Cryo muon veto**

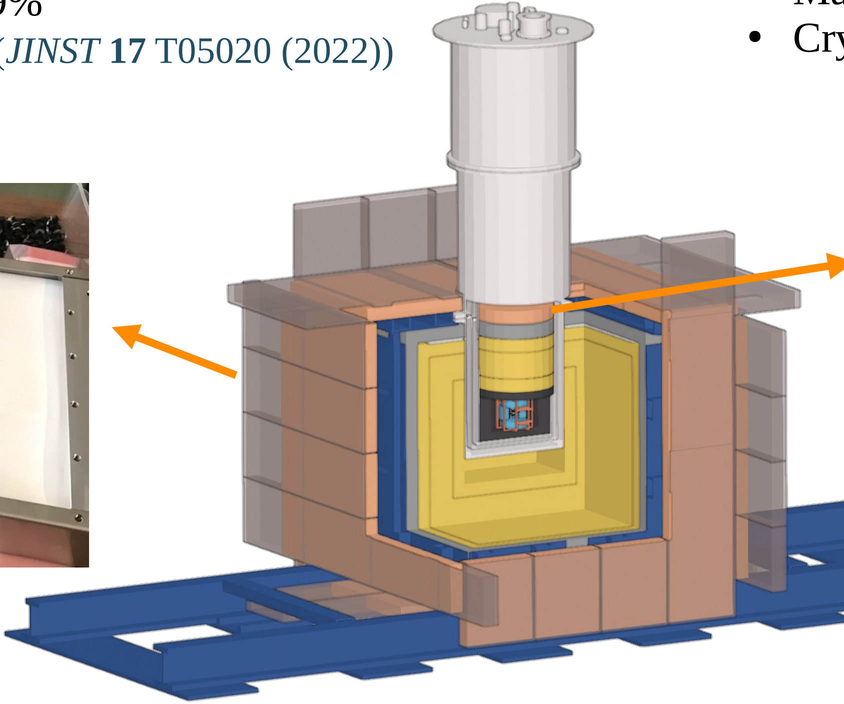
Disk thermalized at 0.7 K

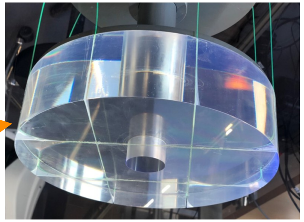
Read by a SiPM at 300 K

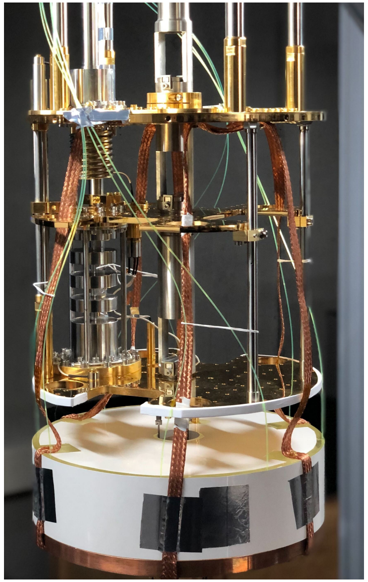
- Mandatory for solid-angle coverage
- Cryogenic operation demonstrated

(arXiv:2205.01718)









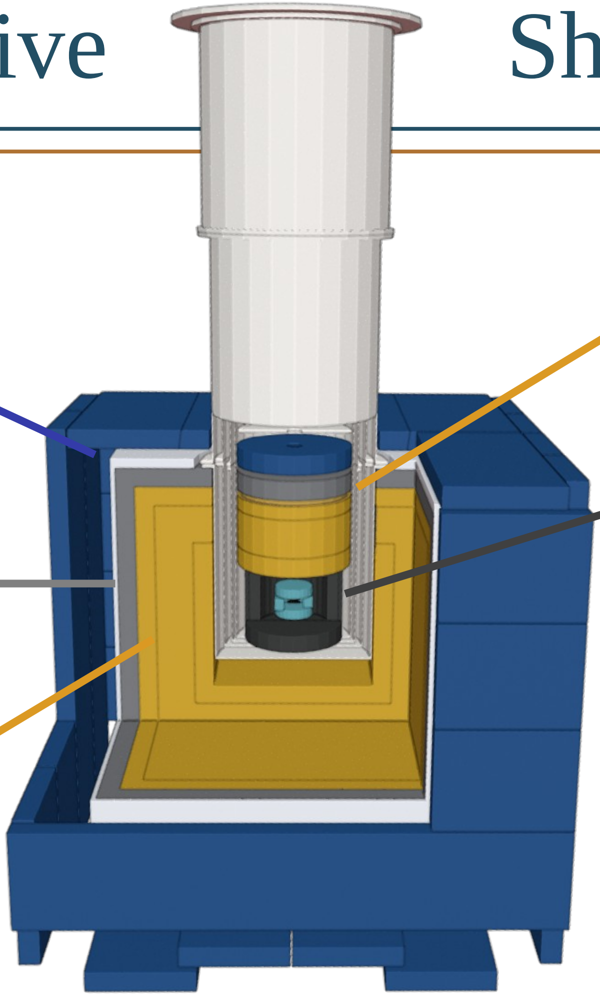
# Compact Passive Shielding

Low-background conditions with a compact (m³) shielding:

**Support frame on rails**
→ movable structure for easy access to the cryostat

**5cm lead**
→ shields against ambient gamma radiation

**20cm polyethylene, 5% borated**
→ reduces the impact of secondary neutrons
→ moderates and attenuates atmospheric neutrons

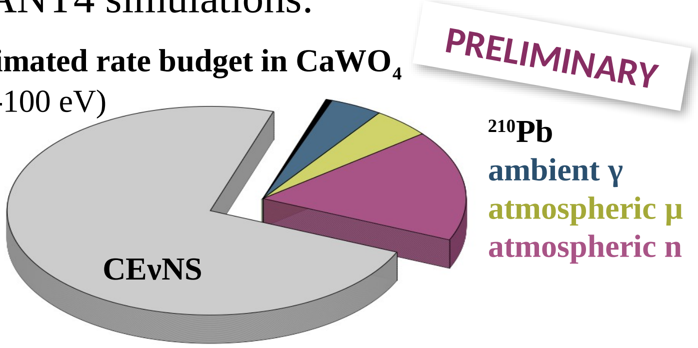


**Cold shield**
→ mounted below cryostat base plate
→ thermalized to 0.7 K

**4cm boron carbide**
→ directly around the cryodetectors
→ captures slow & thermal neutrons reaching the central volume

Configuration optimized using extensive GEANT4 simulations:

**Estimated rate budget in $CaWO_4$** (10-100 eV)

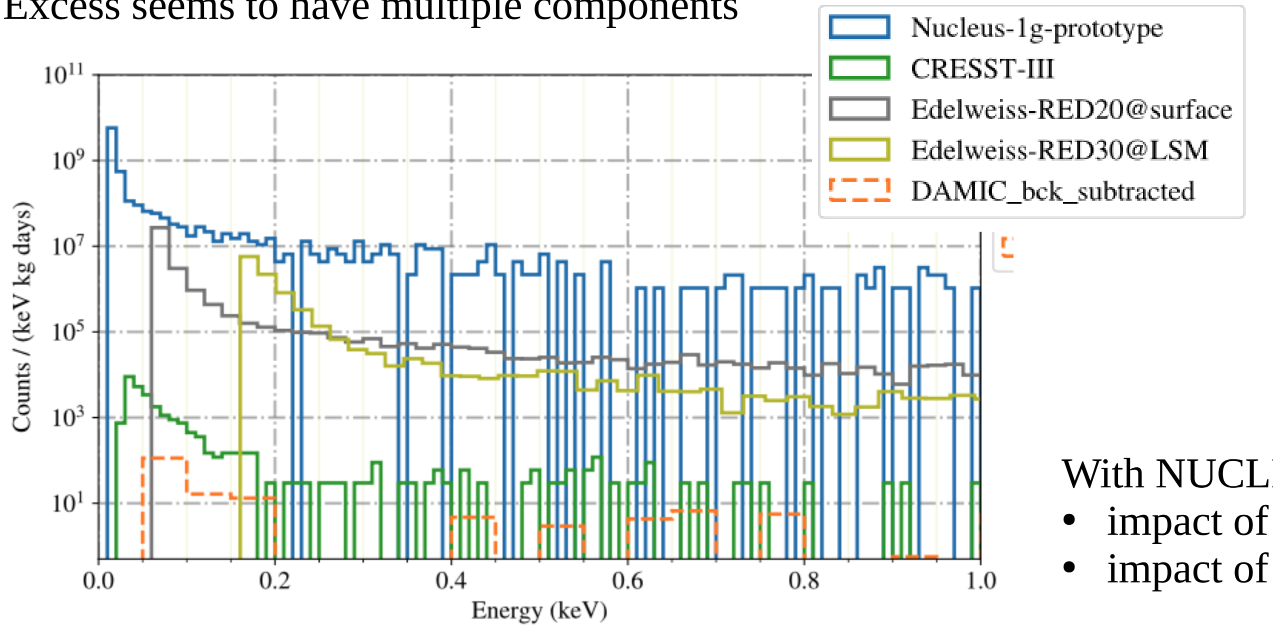



O(100 counts/(keV kg day)) seems achievable.

# The Low-Energy Excess

Many rare-event searches observe a low-energy excess of unknown origin

- Events have particle signature (not necessarily particle origin)
- Excess seems to have multiple components




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

A. Fuss, et al. arXiv:2202.05097, scipost.org/SciPostPhysProc.9.001


https://indico.cern.ch/event/1117540/contributions/

**EXCESS workshop**: multi-collaboration effort.
two editions so far, up next: satellite of TAUP23

With NUCLEUS' veto systems we plan to investigate:

- impact of atmospheric muon secondaries
- impact of detector holder-related events

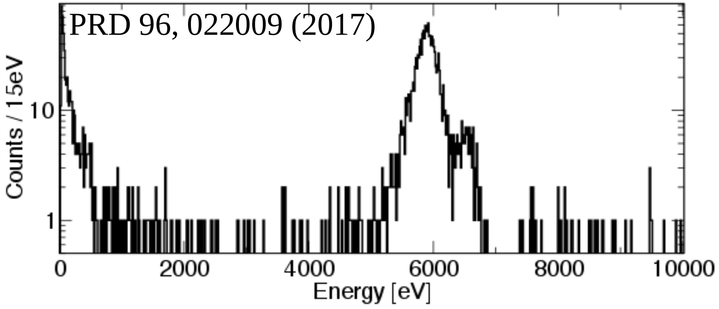
# Calibration techniques

NUCLEUS aims to observe a broad nuclear-recoil spectrum < 100 eV

**Calibration "state-of-the-art":**

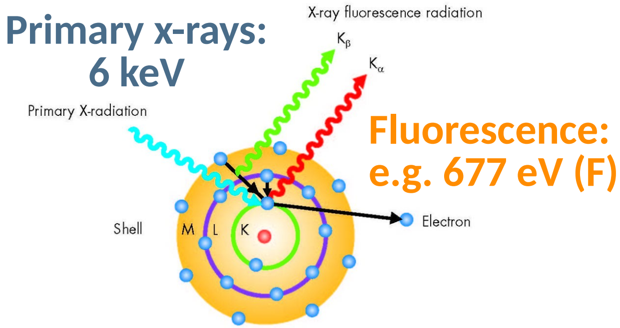
- $^{55}Fe$ source (5.9/6.5 keV x-rays)
- heater pulses to map linearity of detector response

→ extrapolation over two orders of magnitude
→ electron-recoil calibration / nuclear-recoil signal




**Improvements planned for NUCLEUS-10g:**

1) ER calibration at lower energies (XRF)
   - Cryo-compatible source developed @TUM
   - $^{55}Fe$ source + Al/Cu/PTFE targets → dense line spectrum down to sub-keV




2) Mapping detector response with artificial particle events (LED calibration)
3) Cross-calibration with sub-keV monoenergetic nuclear recoils (CRAB project)

# Calibration: photon statistics

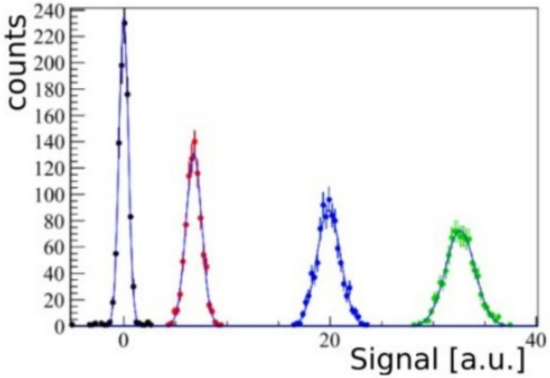
Light bursts from room-temperature LED via optic fibers:

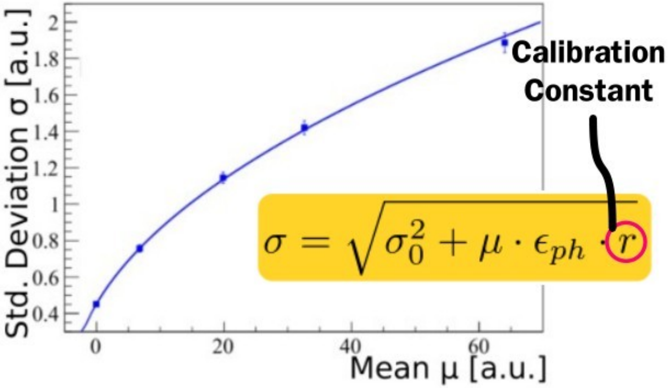
- fast (µs) LED flashes → detector signals with controllable average photon number
- Poissonian photon statistics reveal true injected energy! (photon energy is known)

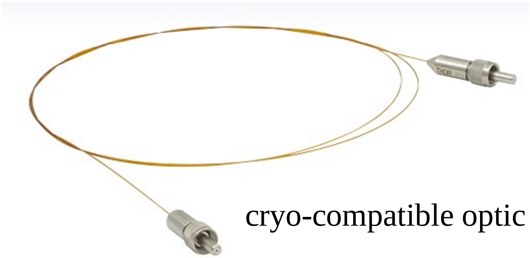
→ absolute calibration + injection at tunable energies (down to threshold!)

- NUCLEUS-10g will be integrated with optic fibers on each target
- Two-fiber prototype system operational

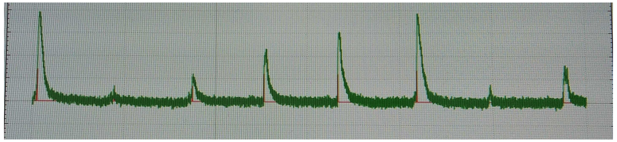
L. Cardani et al, Supercond. Sci. Technol. 31 (2018)



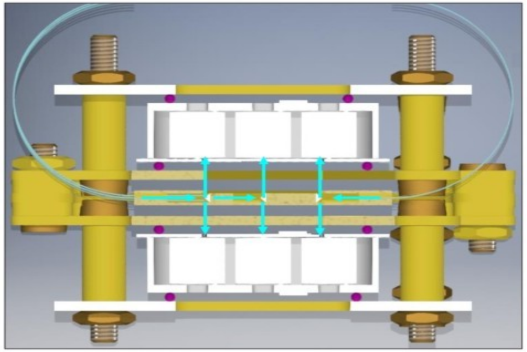



cryo-compatible optic fiber



photon bursts on a cryodetector



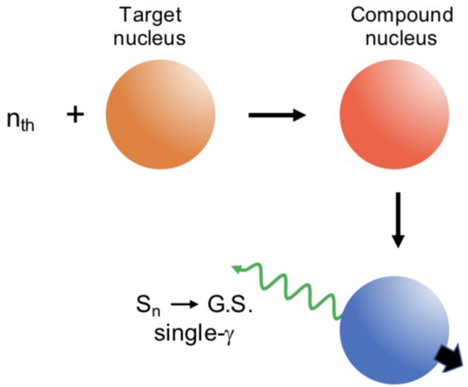
Optic fibers in NUCLEUS-10g

# Calibration: nuclear recoils

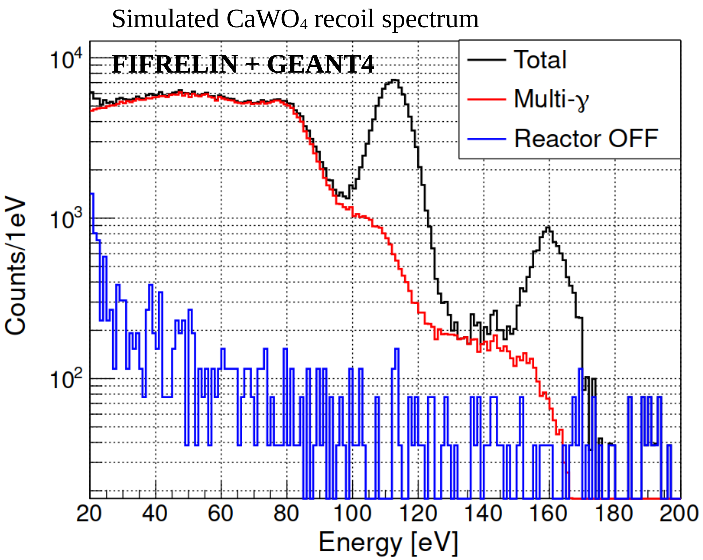
Typical nuclear recoil spectra are continuous (free scattering angle)

The **CRAB** idea: mono-energetic recoils following neutron capture

L. Thulliez, D. Lhuillier *et al* 2021 *JINST* 16




$$E_{NR}=E_{\gamma}^{2}/(2M)$$




**Calibrated Recoils for Accurate Bolometry**

$^{182}$**W**: 14% single γ emission,

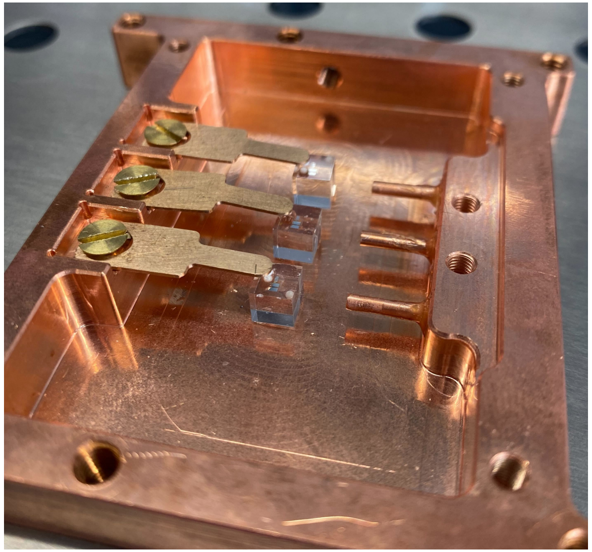
$$E_{\gamma}=6.2\,MeV \;\rightarrow\; E_{NR}=112.5\,eV$$

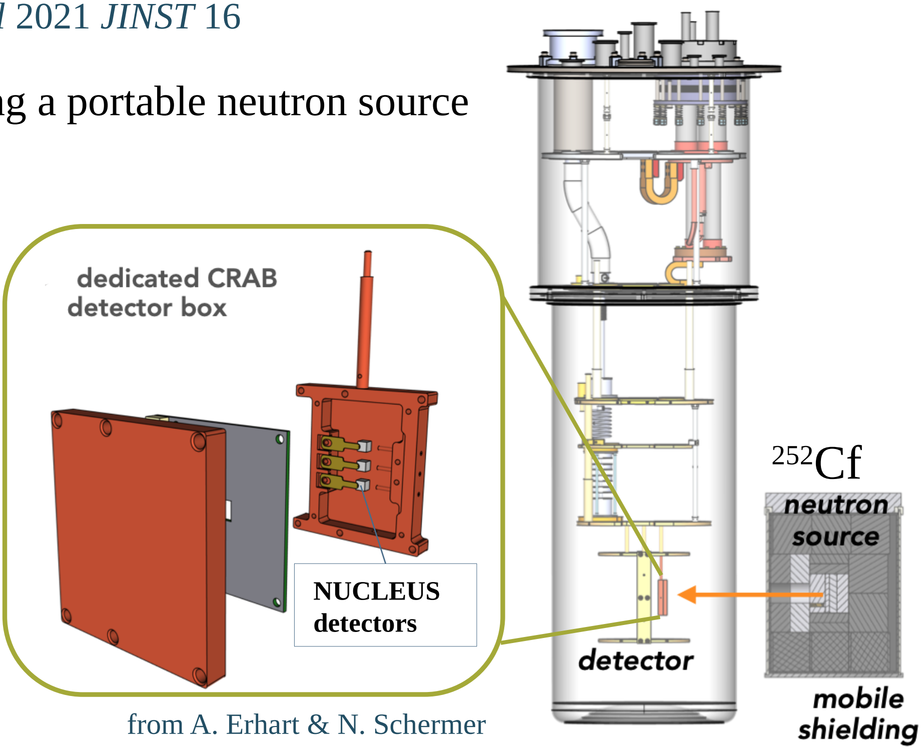
# Calibration: nuclear recoils

The **CRAB** idea: mono-energetic recoils following neutron capture

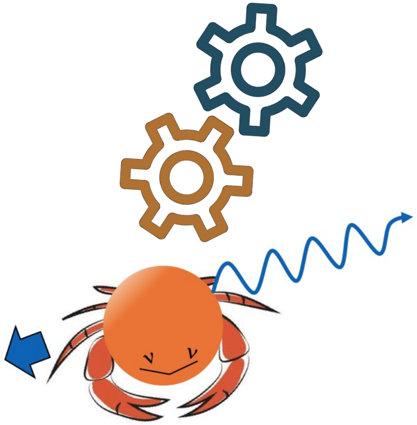
L. Thulliez, D. Lhuillier *et al* 2021 *JINST* 16

Working on a first measurement using a portable neutron source






from A. Erhart & N. Schermer

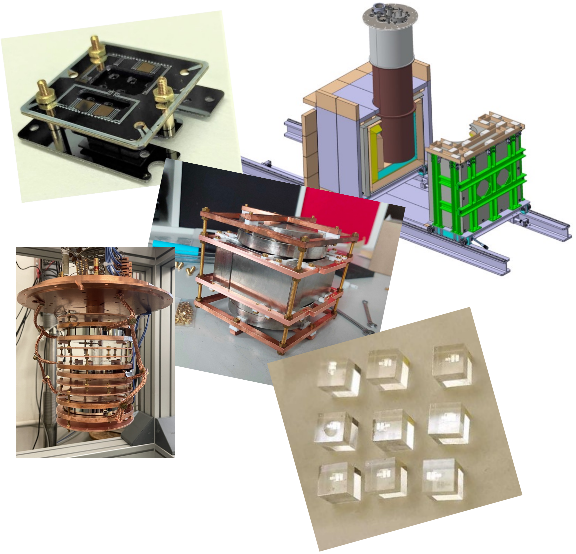


**C**alibrated **R**ecoils for **A**ccurate **B**olometry

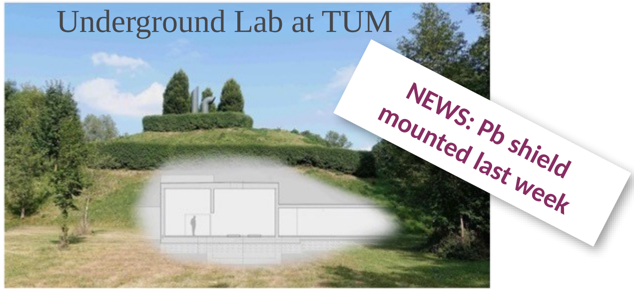
# NUCLEUS Status & Schedule

Sep 2022 — Late 2023

## Design & production phase



## Blank assembly & commissioning

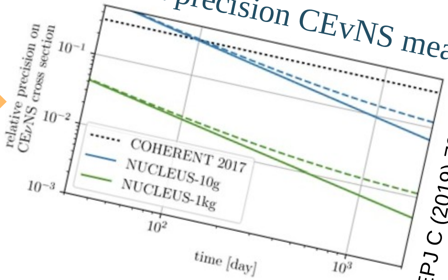



- full mechanical integration
- detector performance tests
- sub-keV calibration campaigns
- extensive background characterization

## On-site installation


Preparations ongoing:
- Background measurements (gamma, neutrons)
- Site characterisations (acoustic, magnetic)
- Installation of infrastructure at VNS

potential precision CEvNS measurement




EPJ C (2019) 79: 1018

2024

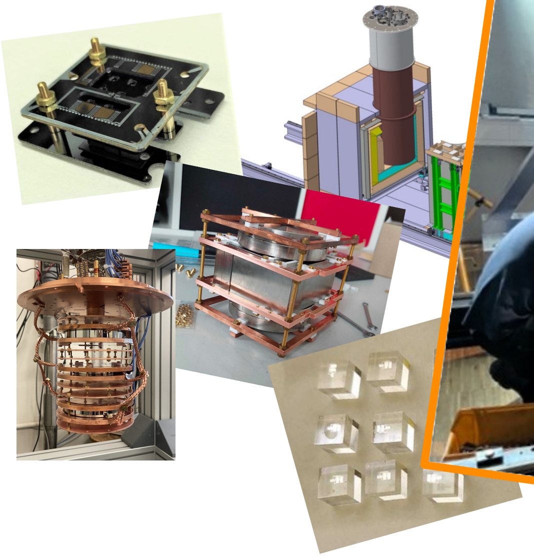
NUCLEUS-10g physics run
Phase 1: observe CEvNS

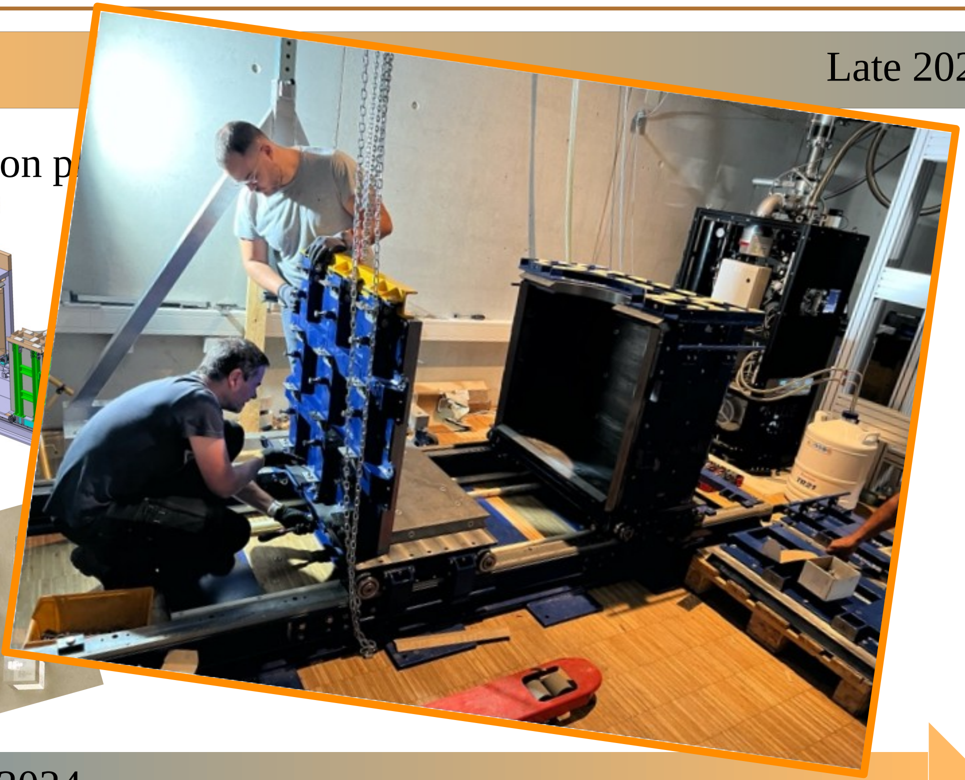
Towards NUCLEUS-1kg
Phase 2: CEvNS at few-% level

# NUCLEUS Status & Schedule

Late 2023

Design & production p

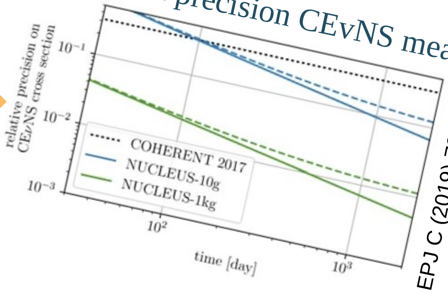




On-site installation


Preparations ongoing:
- Background measurements (gamma, neutrons)
- Site characterisations (acoustic, magnetic)
- Installation of infrastructure at VNS

potential precision CEvNS measurement

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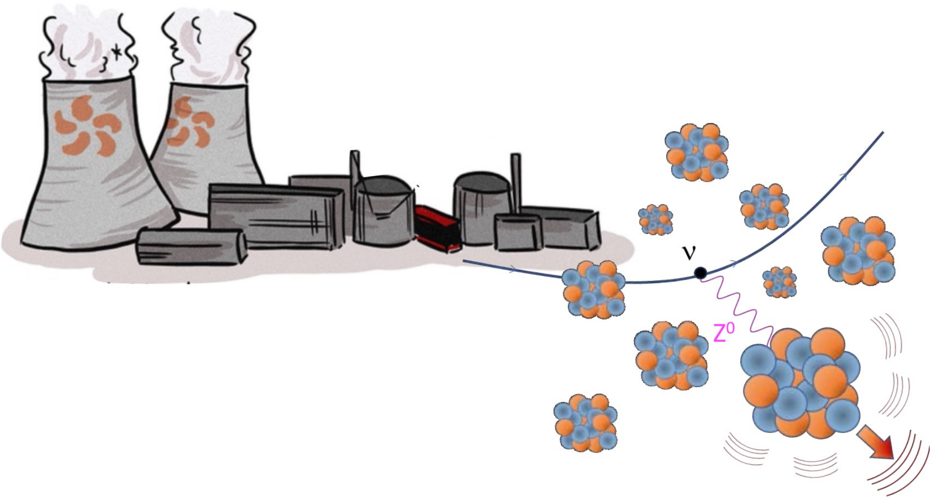
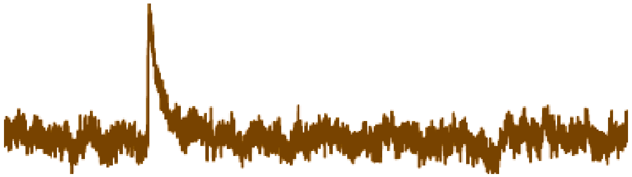
2024

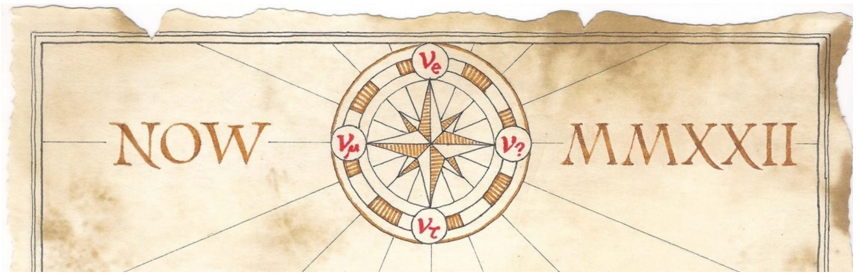
NUCLEUS-10g physics run
Phase 1: observe CEvNS

Towards NUCLEUS-1kg
Phase 2: CEvNS at few-% level

# Thanks for your attention



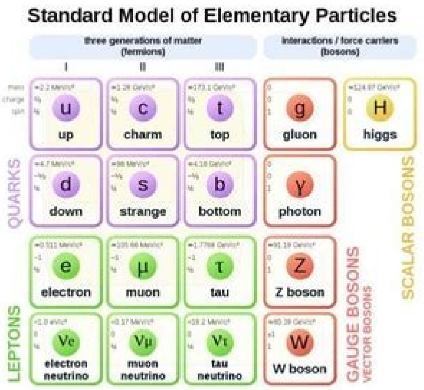






Neutrino Oscillation Workshop 2022
September 10, Ostuni

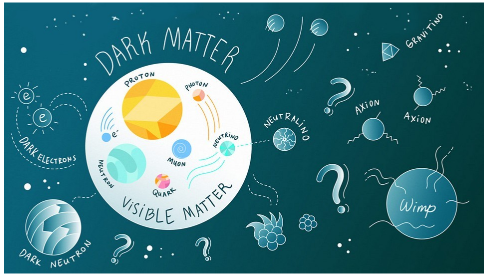
# CEvNS applications

SM / BSM tests of neutrino interactions at low energies




Input to supernova modeling

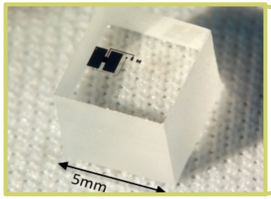
Irreducible background to WIMP searches (neutrino floor)



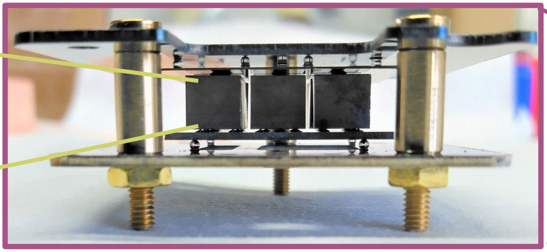

Non-invasive nuclear reactor monitoring (with small detectors)

# The fiducialized cryogenic detector

**Target crystals:**
Two 3x3 arrays,
6g ($CaWO_4$) + 4g ($Al_2O_3$)
simultaneous measurement of CEvNS
and a background-only reference




**Inner veto:**
**TES-instrumented holder**
to reject surface backgrounds
and holder-related events



**Germanium outer veto:**
for active γ/n background rejection