nucleus

EXPERIMENT

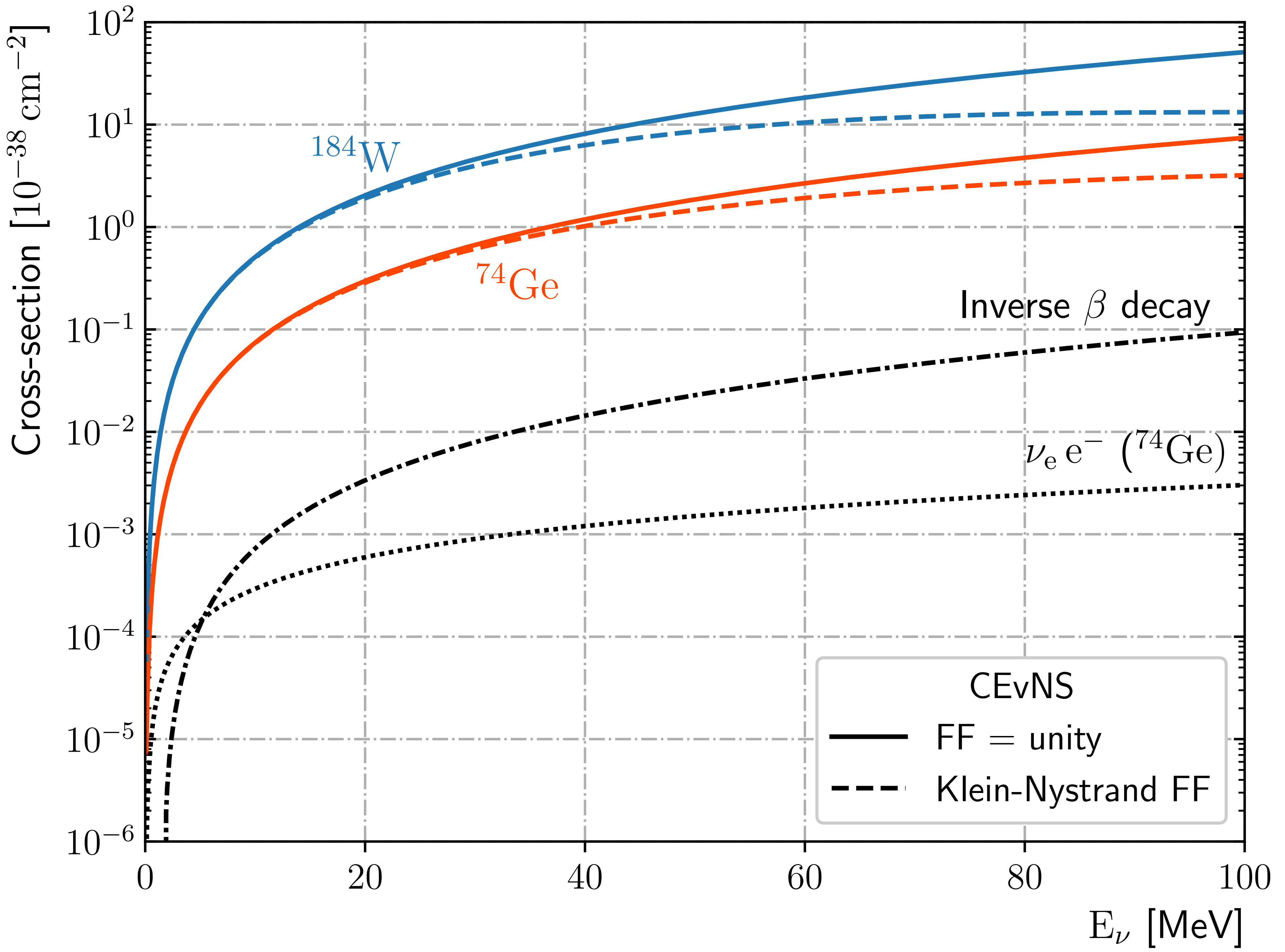
# Latest developments and next steps

Matthieu Vivier, on behalf the NUCLEUS collaboration

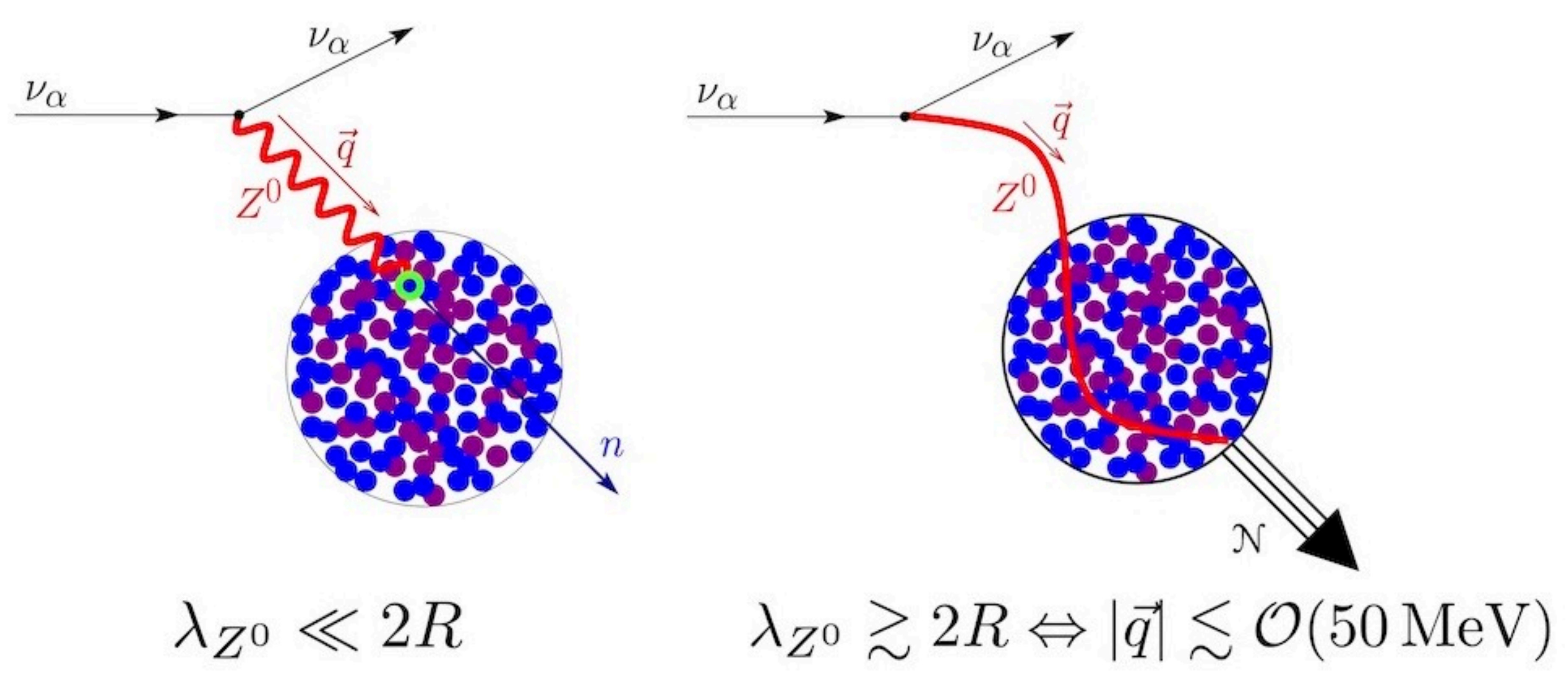
IRN neutrino meeting, June 13th 2025

# Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- Standard model prediction (Freedman, 1974): neutral current and flavor blind process
- Coherent interaction over a nucleus as a whole
  - High cross-section: ~ 10-1000 x IBD
  - Small recoil energies: O(1 keV) for reactor antineutrinos



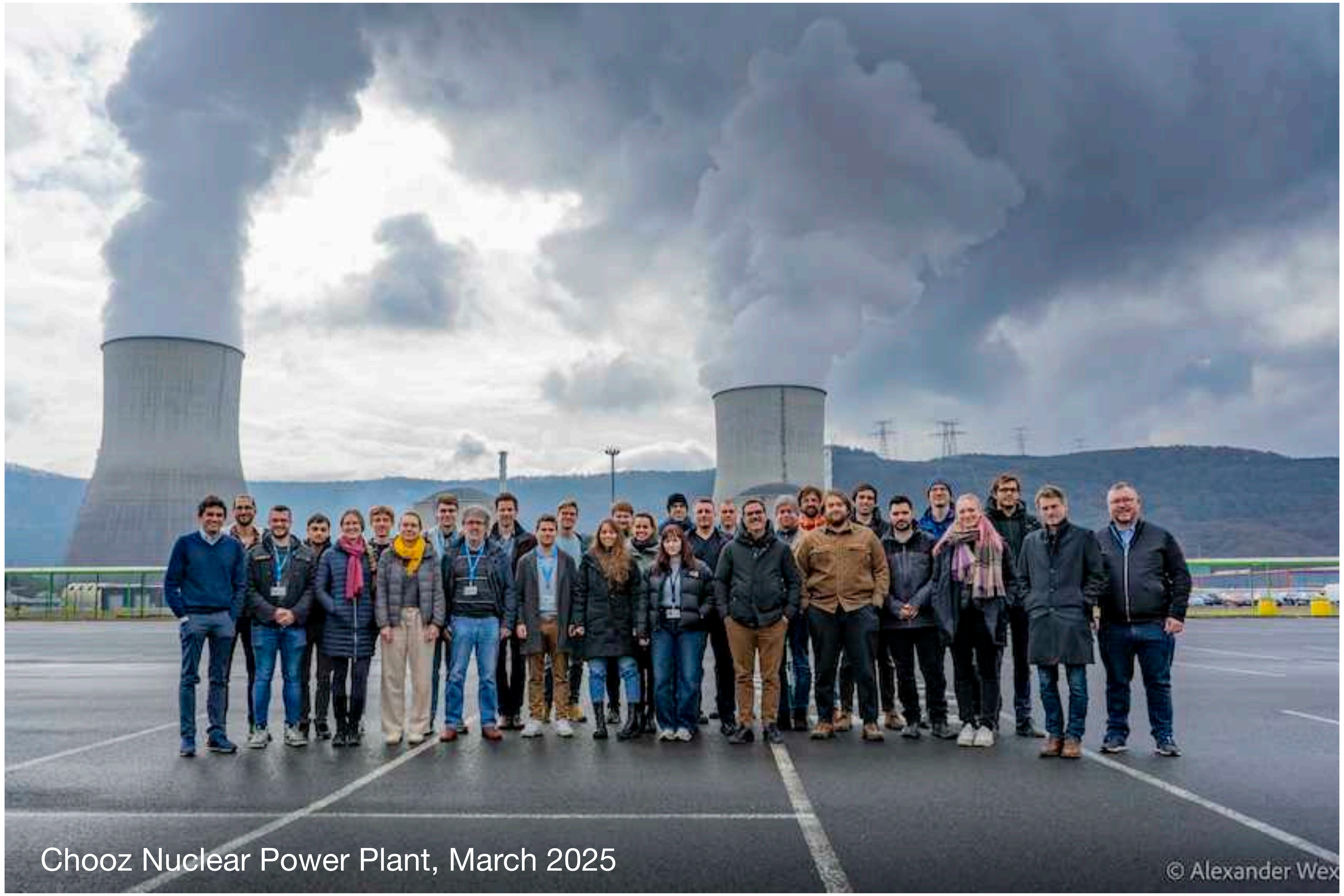

Adapted from Cadeddu, et al. (2023)




- New technique for the detection of low energy neutrinos with potentially much smaller payloads
- New probe for nuclear matter (neutron distributions)
- Electroweak physics and BSM searches at the very low energy frontier

# Collaboration

~ 50 members spread among Austria, France, Germany & Italy




Core & associated institutions

MAX-PLANCK-INSTITUT FÜR PHYSIK
TUM
EDF
cea
SAPIENZA UNIVERSITÀ DI ROMA
INFN
HEPHY INSTITUTE OF HIGH ENERGY PHYSICS
TU WIEN

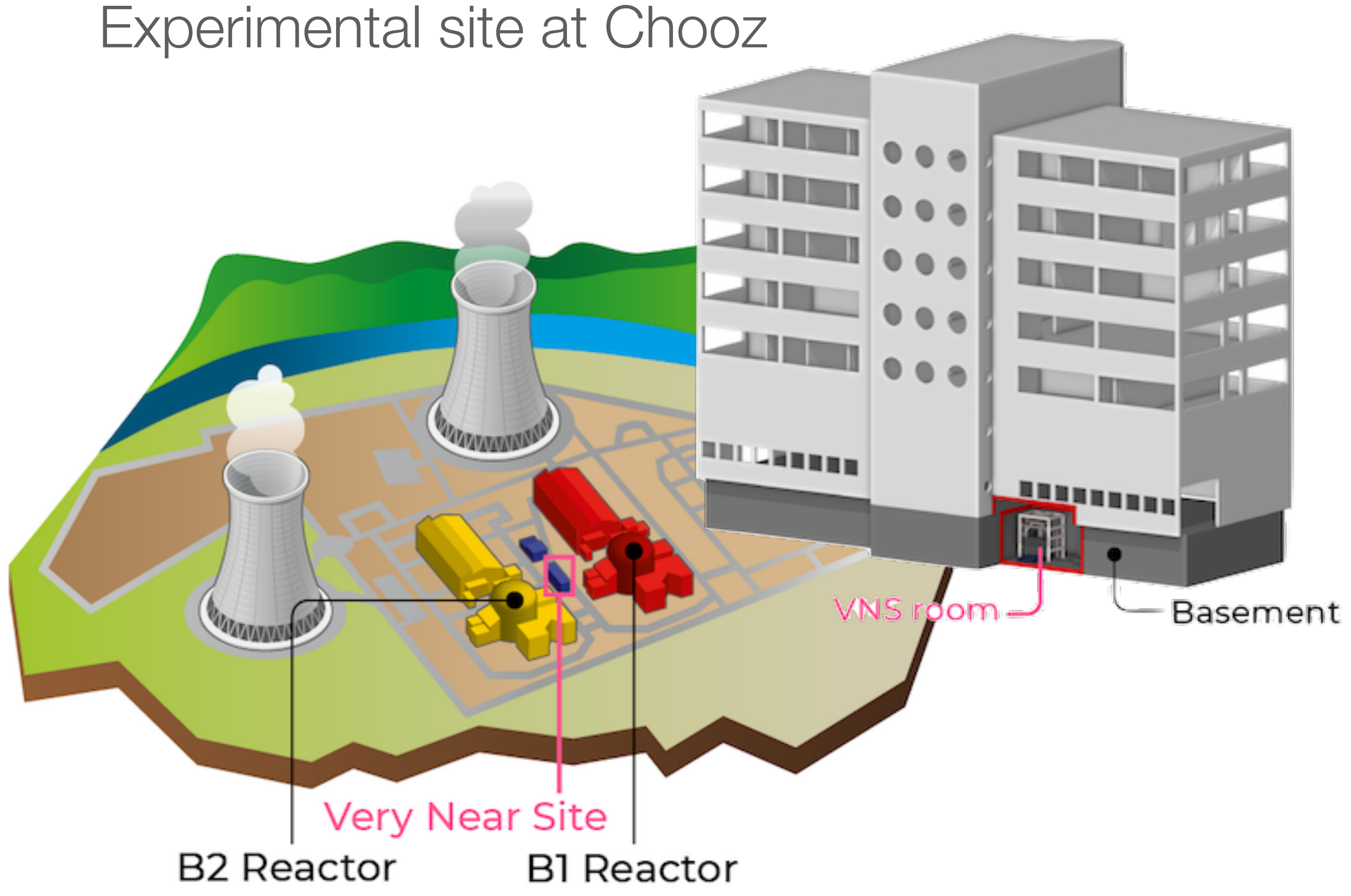
Funding agencies

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.

# Experimental concept

## Measure CEvNS with gram-scale cryogenic detectors at the Chooz nuclear power plant

Experimental site at Chooz




- Less than 100 m away from 2 x 4.25 $GW_{th}$ cores
- Neutrino flux ~1.7 $10^{12}$ $cm^{-2}$ $s^{-1}$
- Compact room, challenging integration constraints
- Almost no overburden (3 m.w.e)
- Full background characterization [paper to be released soon]

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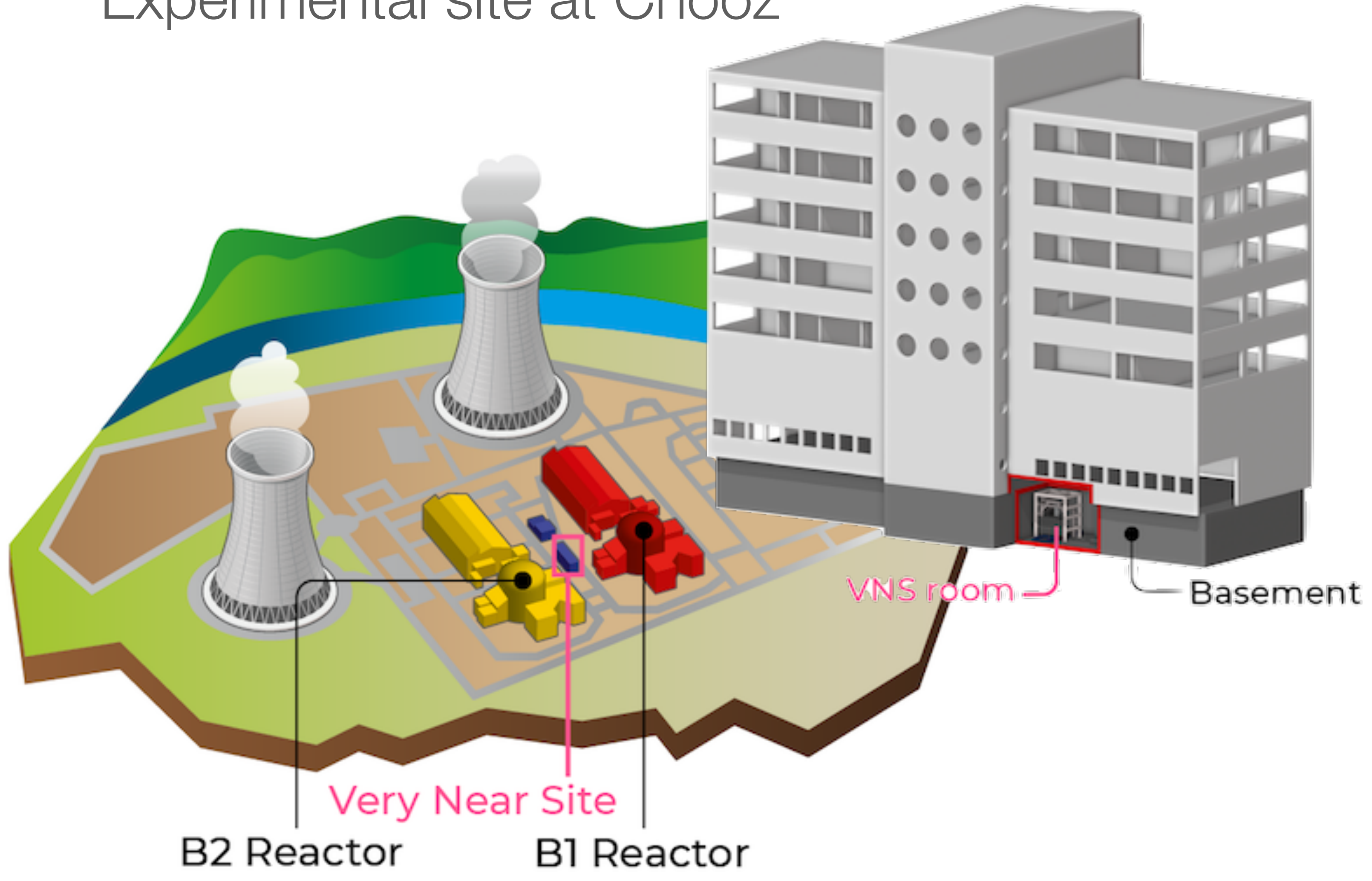


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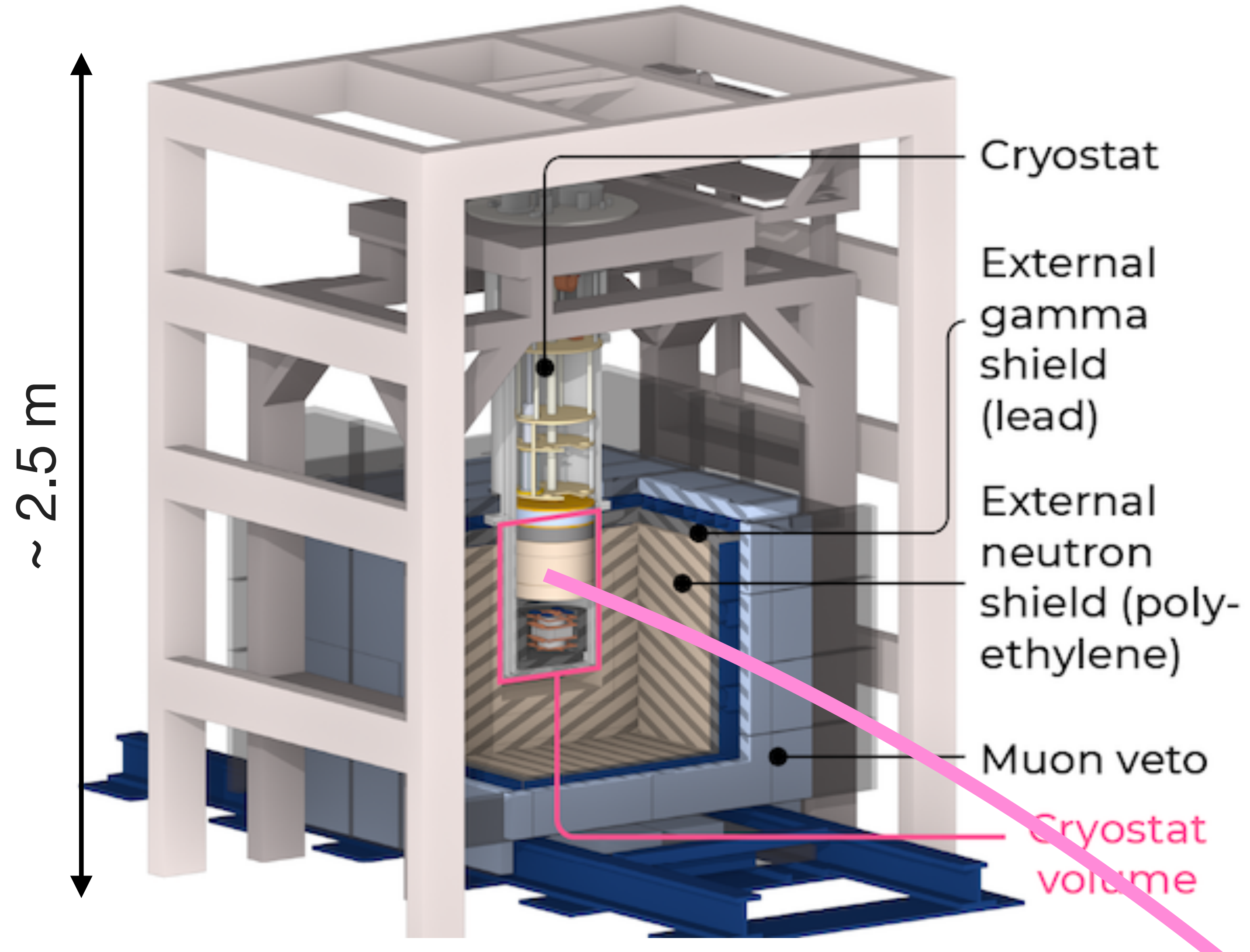
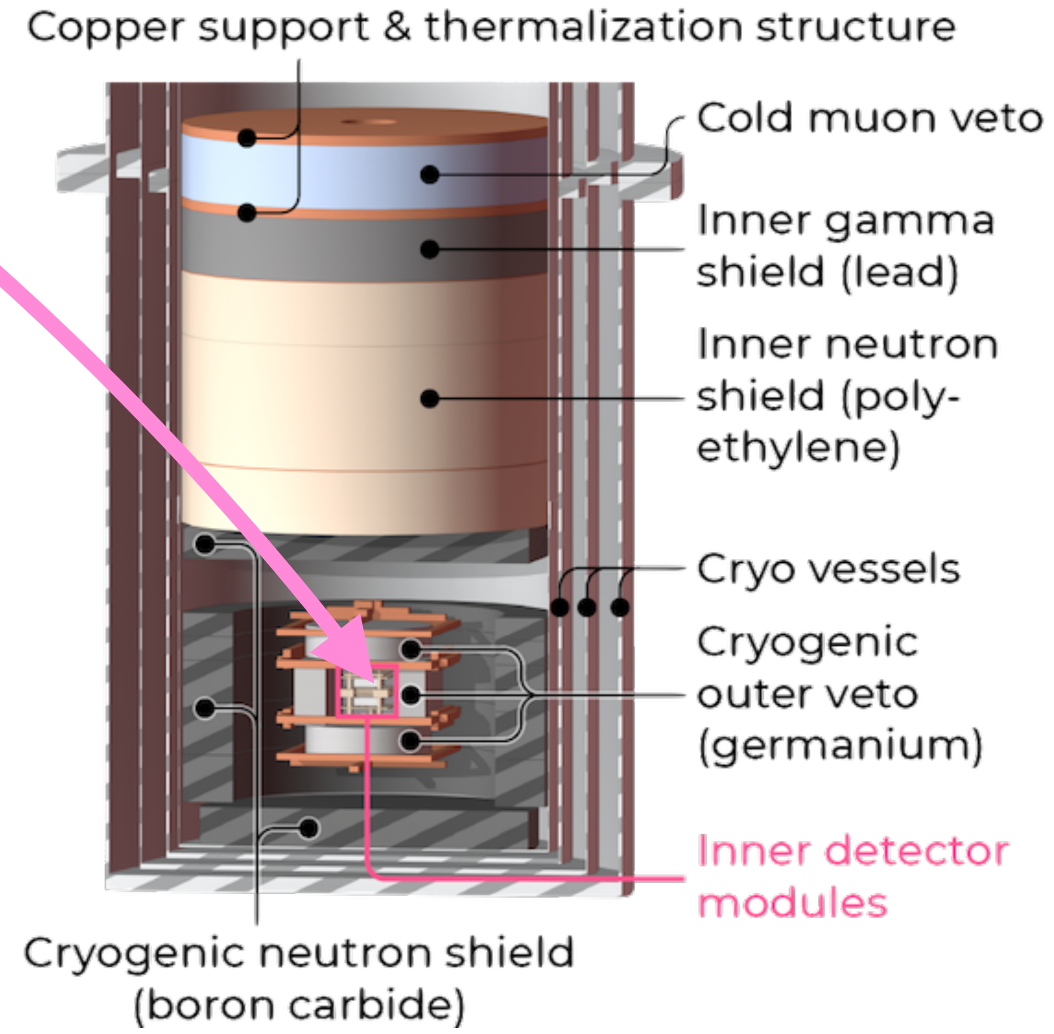
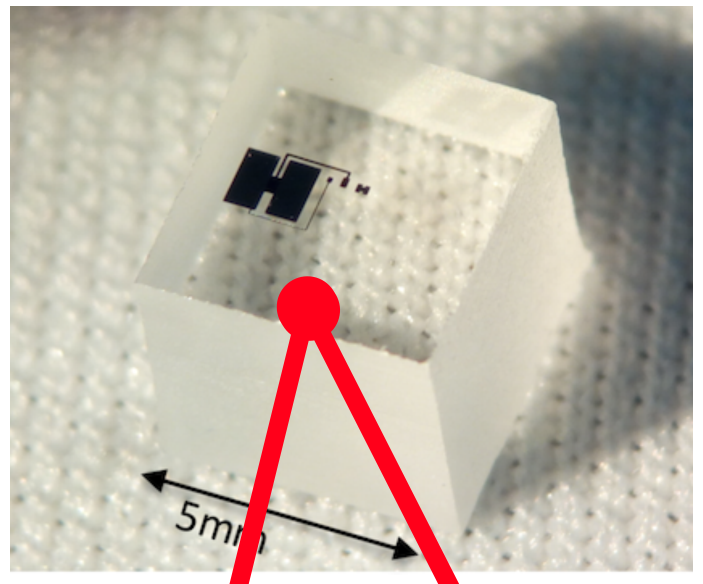
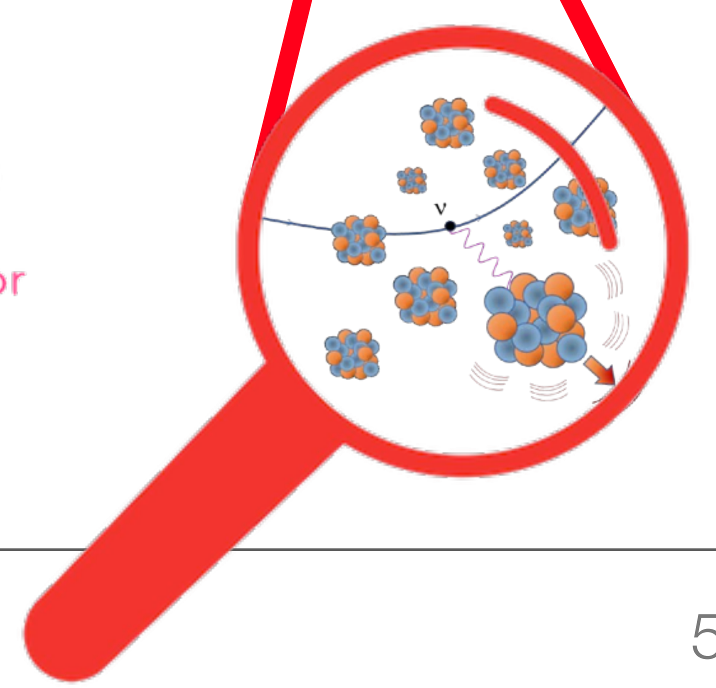
Experimental setup




- Cryogen-free dry dilution refrigerator
- Sophisticated shielding design (passive & active vetoes)
- TES-based cryogenic detectors:
  - Ultra low energy threshold (< 20 eV demonstrated)
  - $CaWO_4$/$Al_2O_3$ target materials (~ 10 g total mass, ~100 eV CEvNS-induced nuclear recoils)

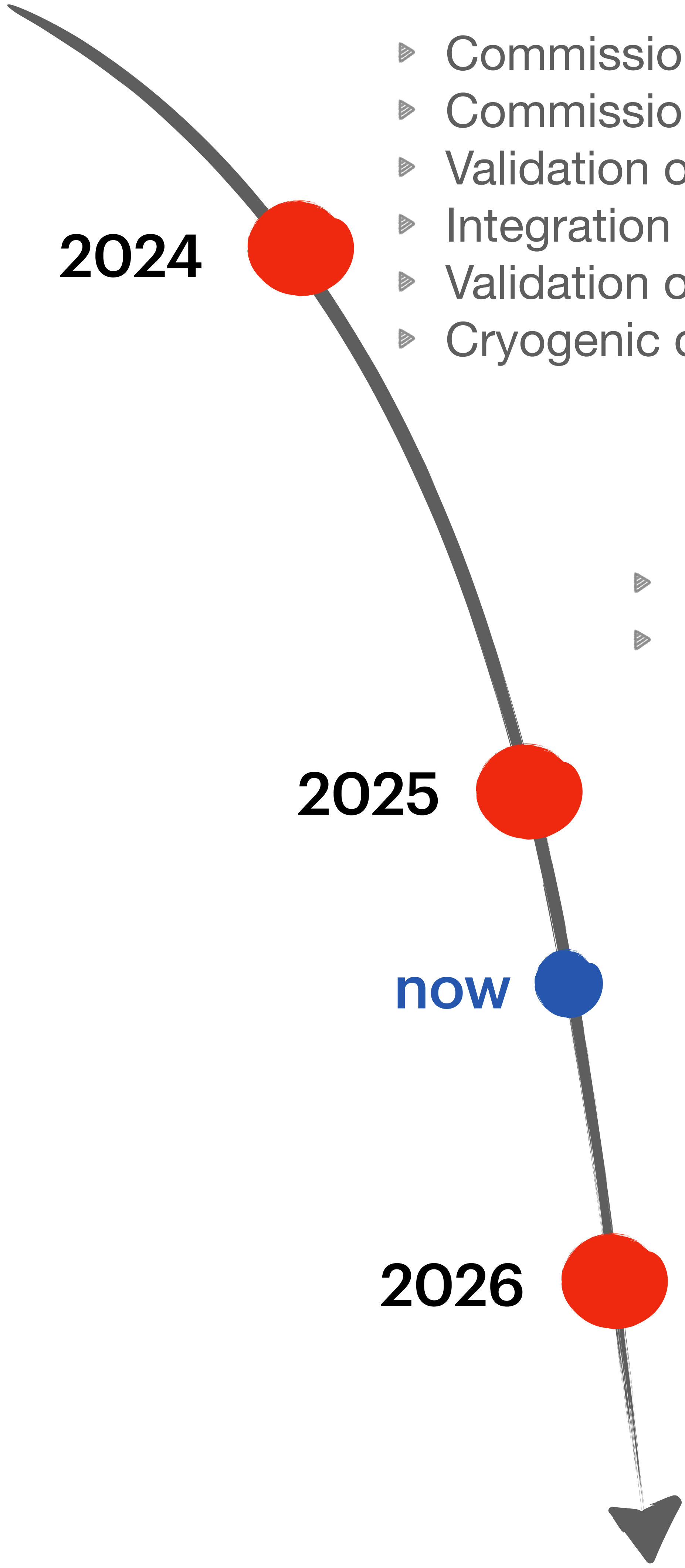


# Progress curve

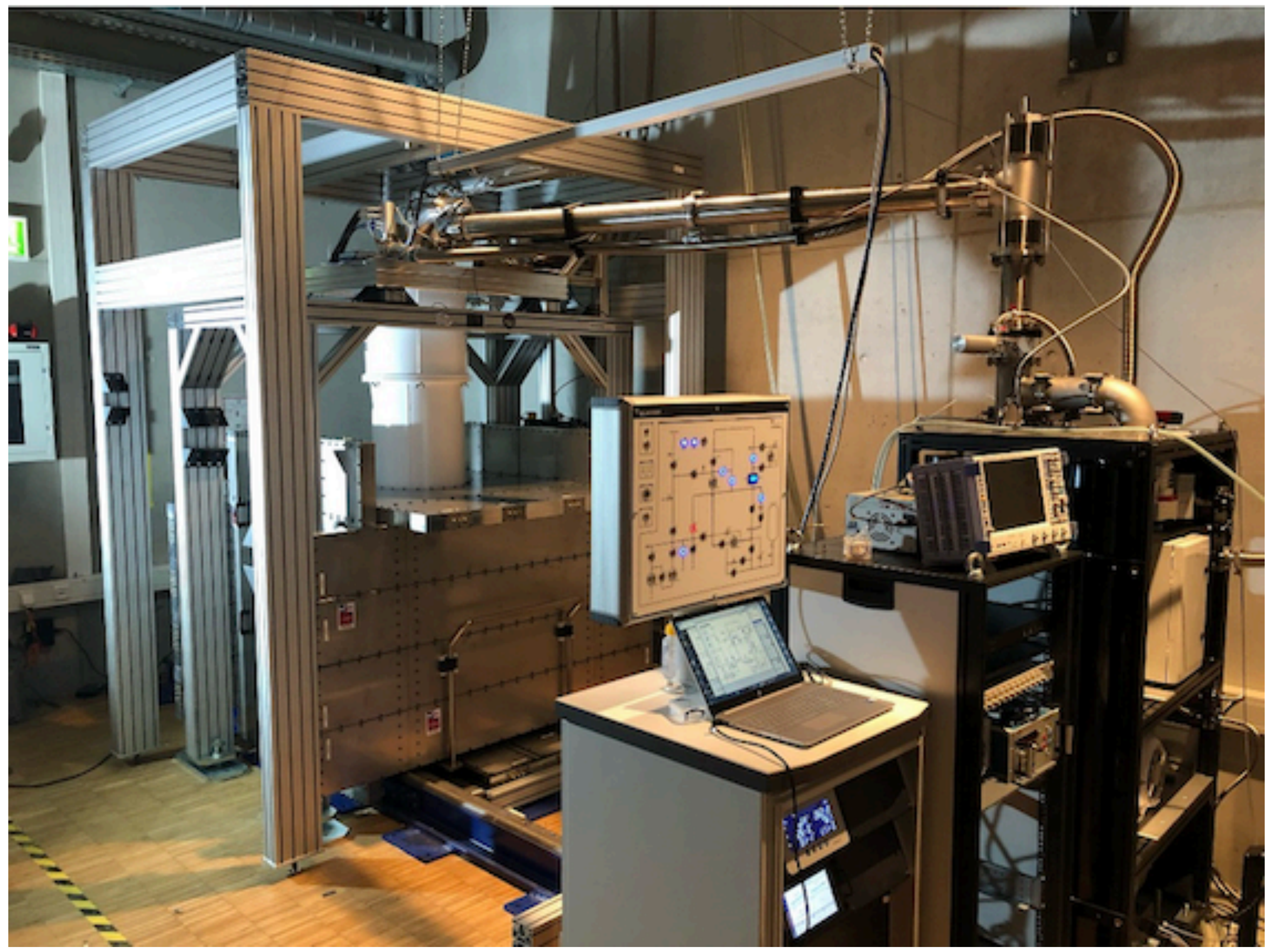
**End of R&D work and integration of the experiment at TU Munich**

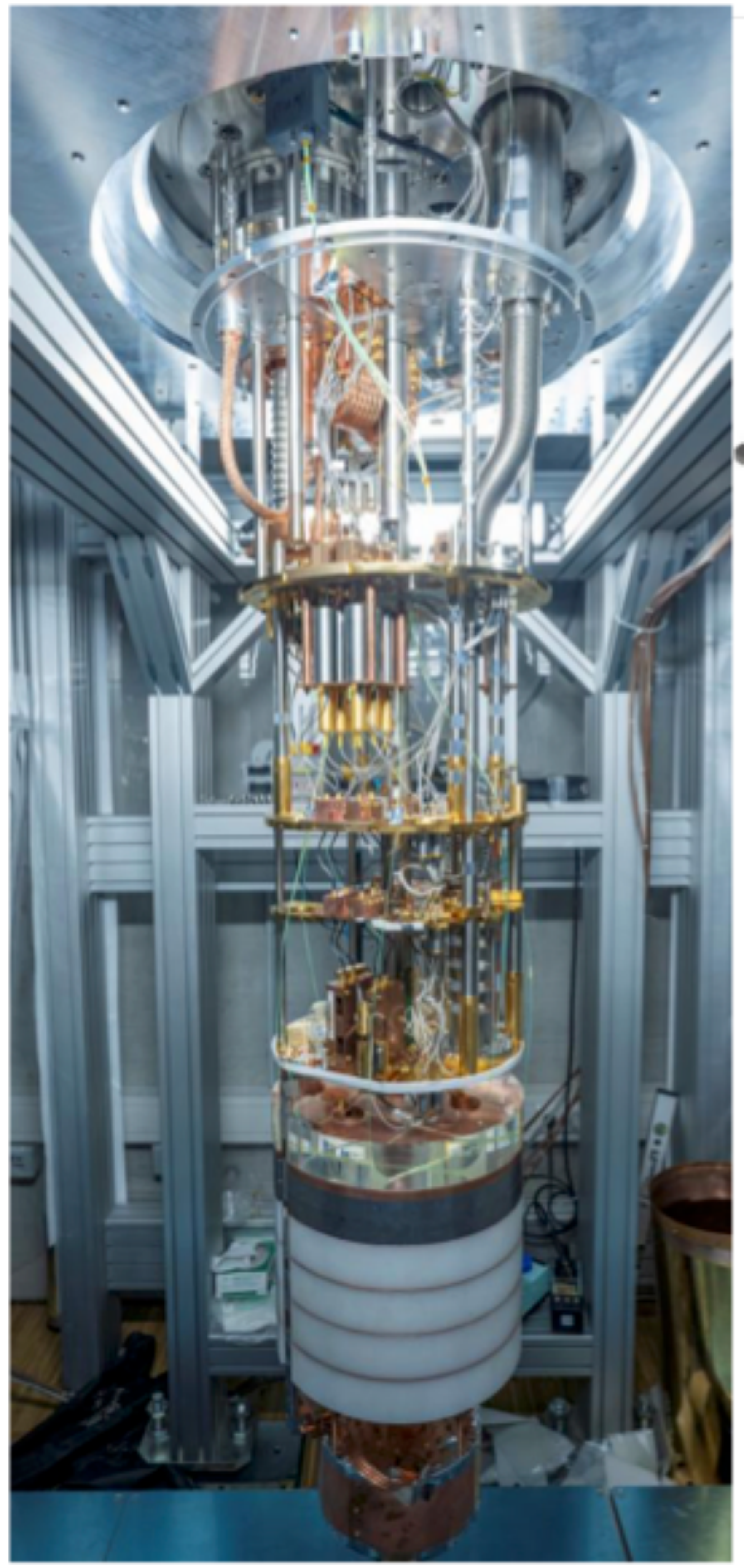



- Commissioning of cryostat ✔
- Commissioning of readout electronics ✔
- Validation of spring decoupling system ✔
- Integration of external and internal shields ✔
- Validation of thermalization ✔
- Cryogenic detector calibration ✔

**Commissioning run**

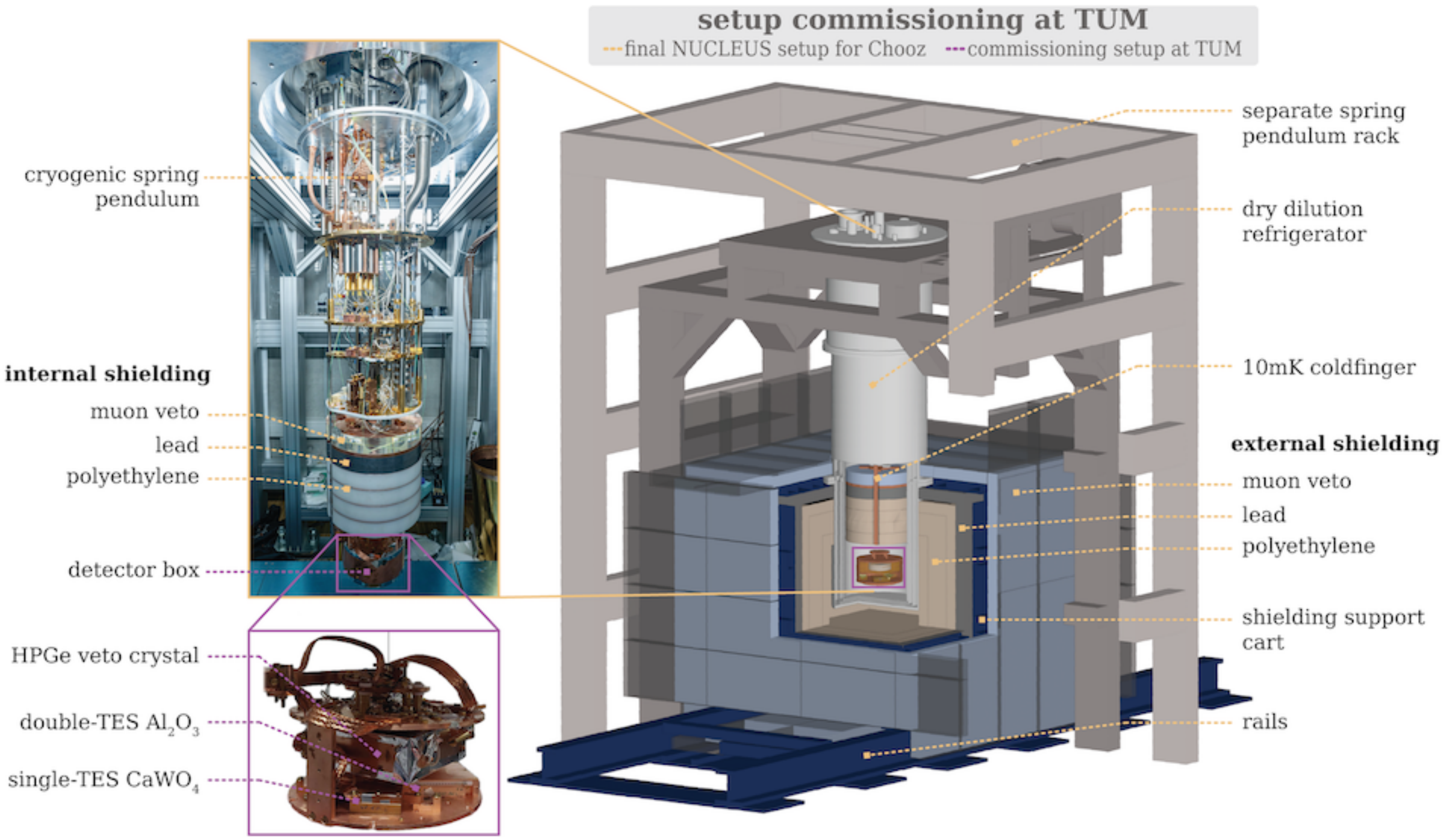
- Demonstration of experimental setup ✔
- First measurement of backgrounds ✔



# Commissioning run at TU Munich

**Simplified version of cryogenic setup operated at shallow underground lab (UGL) at TUM**

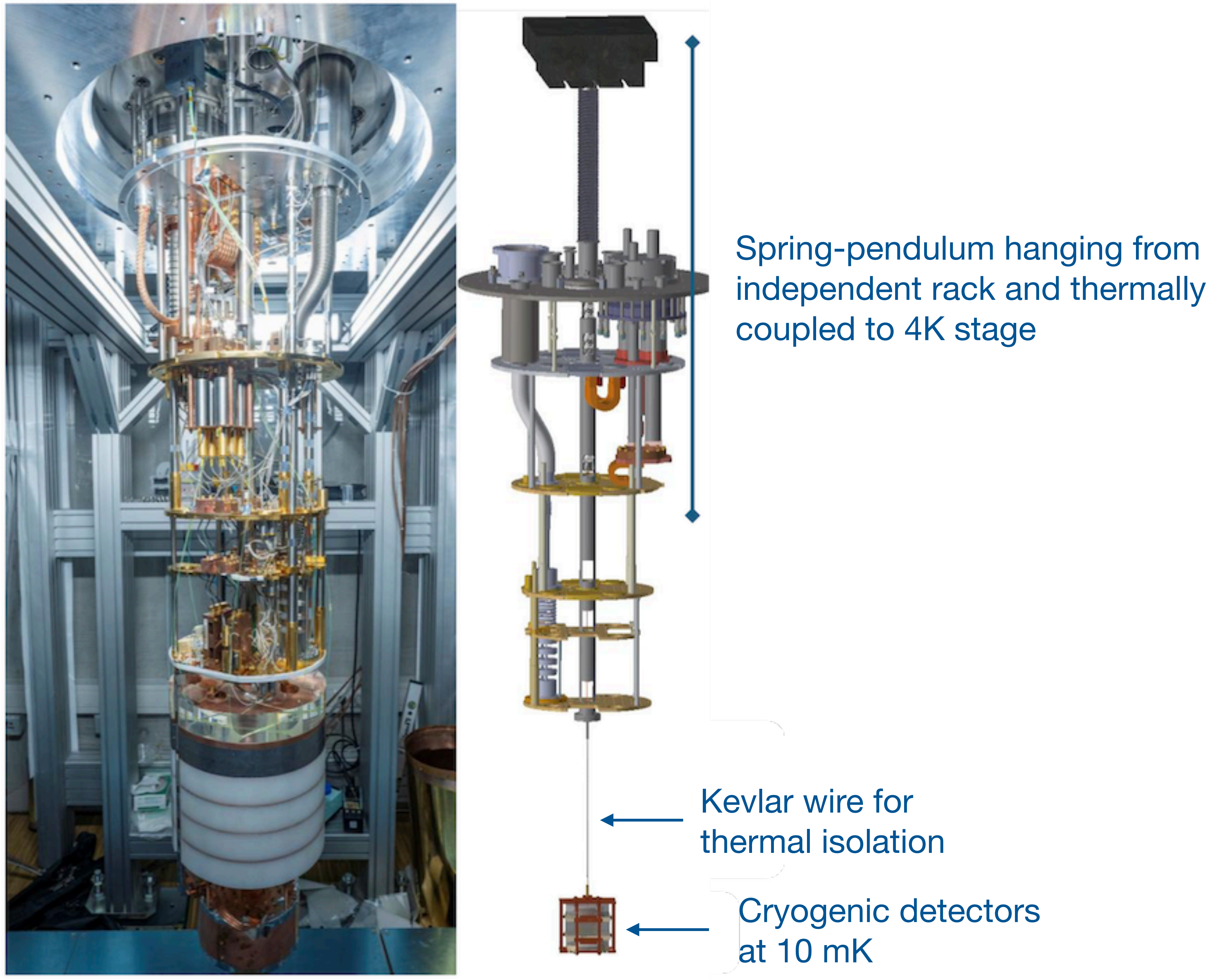



- Demonstrate simultaneous operation, specifications and stability of all detectors
- Prepare and test computing infrastructure
- Measure particle backgrounds & validate shielding strategy
- Investigate EXCESS background

**Article to be released soon !**

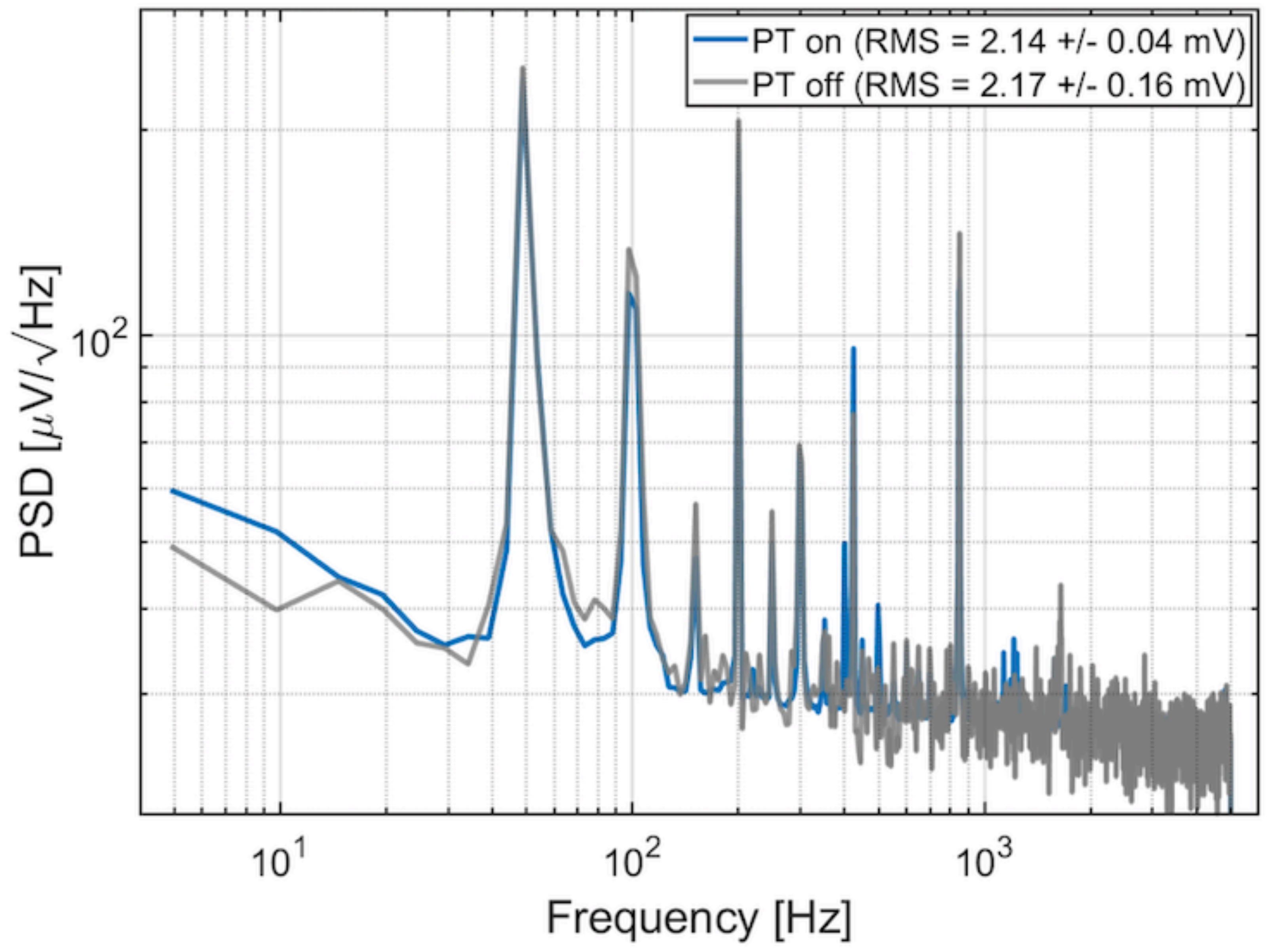
# Main results of the commissioning run

## Vibration decoupling system: continuous cryogenic detector operation in a dry cryostat




### Commissioning result:

More than 8 weeks of stable, continuous operation of cryogenic detectors independent of pulse tube vibrations



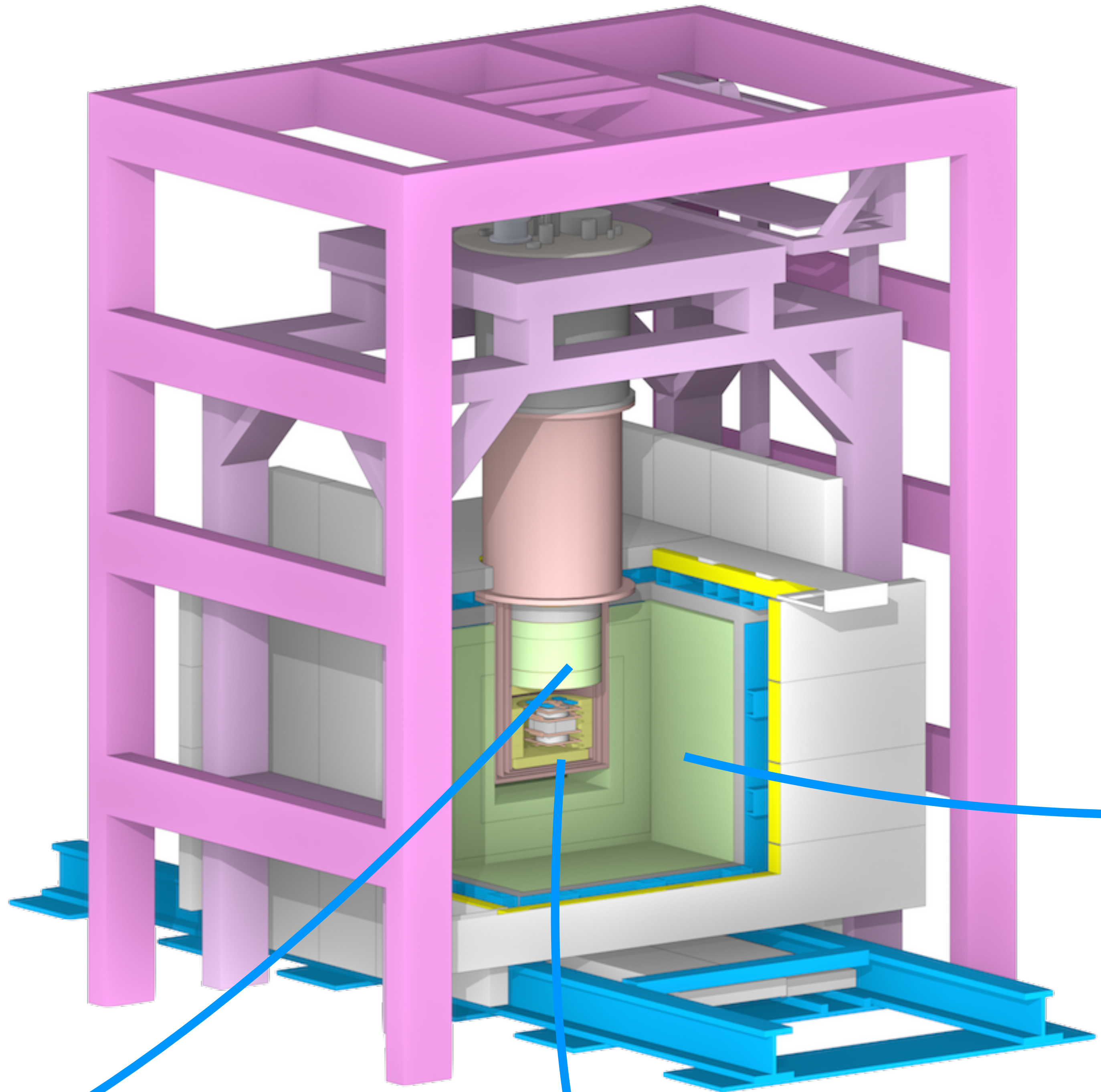

A. Wex et al. JINST 20 (2025) 05, P05022

# Main results of the commissioning run

## Shielding systems

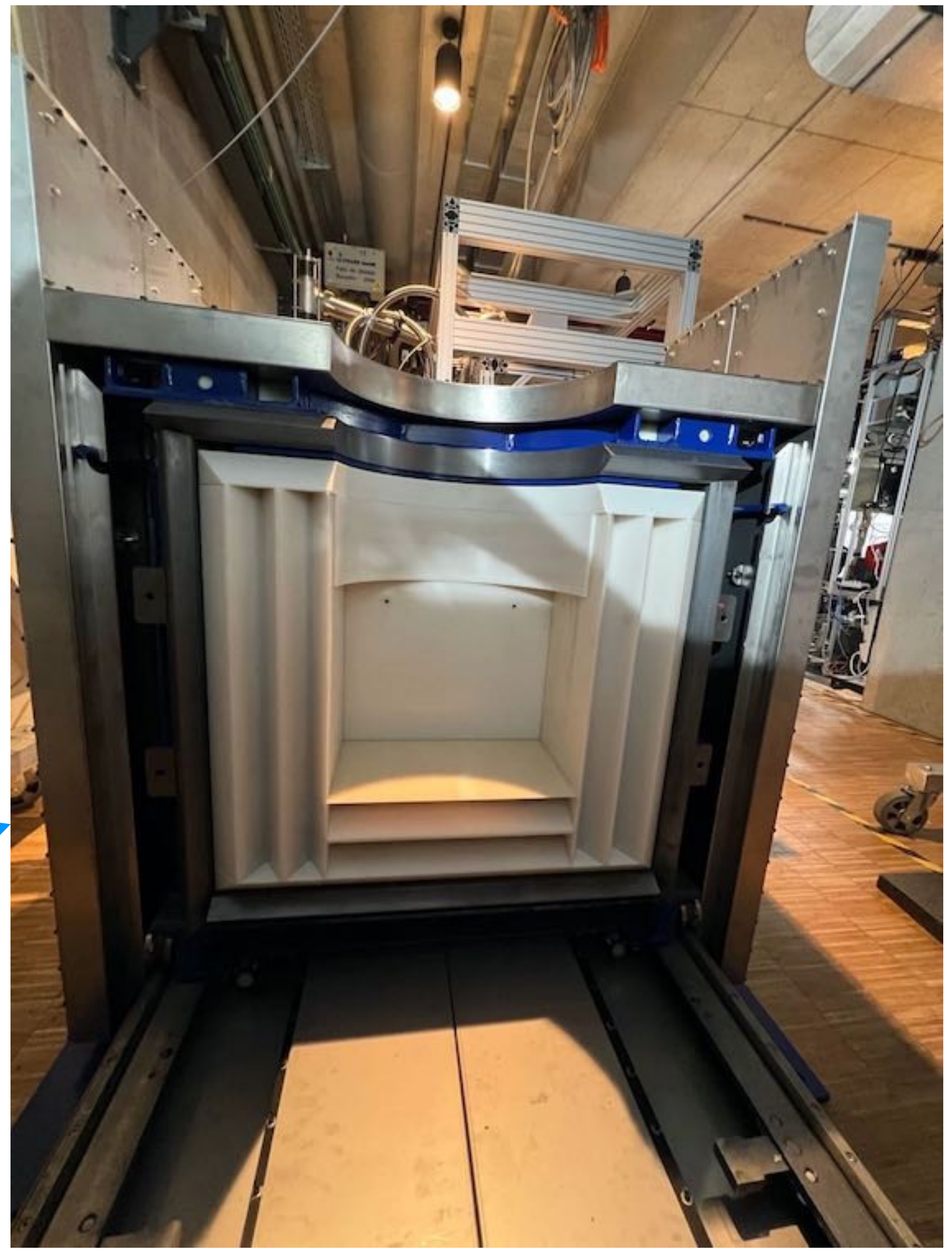
### Internal passive shields at cryogenic temperatures

- Extension of the external shield inside the cryostat (Pb, HDPE + muon veto)
- Thermalized by copper disks

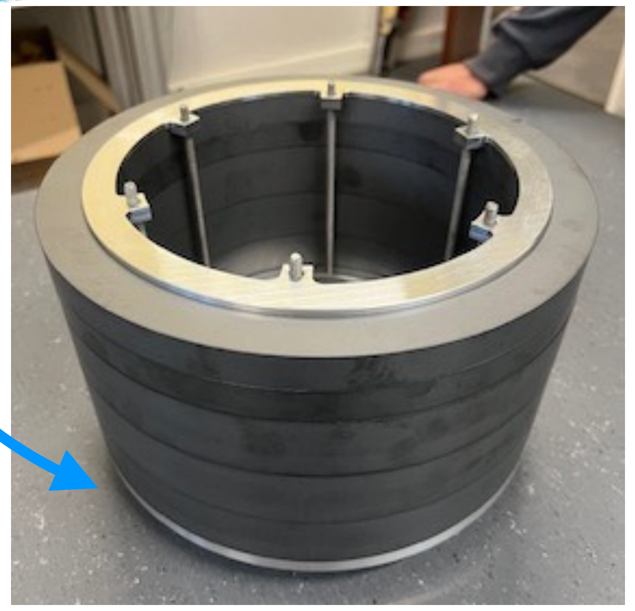


### External passive shields

- 5-cm Pb + 20-cm borated HDPE installed in mechanical structure



### $B_4C$ internal shield (not present)



- Additional neutron rejection
- Concept under validation, to be integrated at Chooz

### Commissioning results:

External shielding fully commissioned

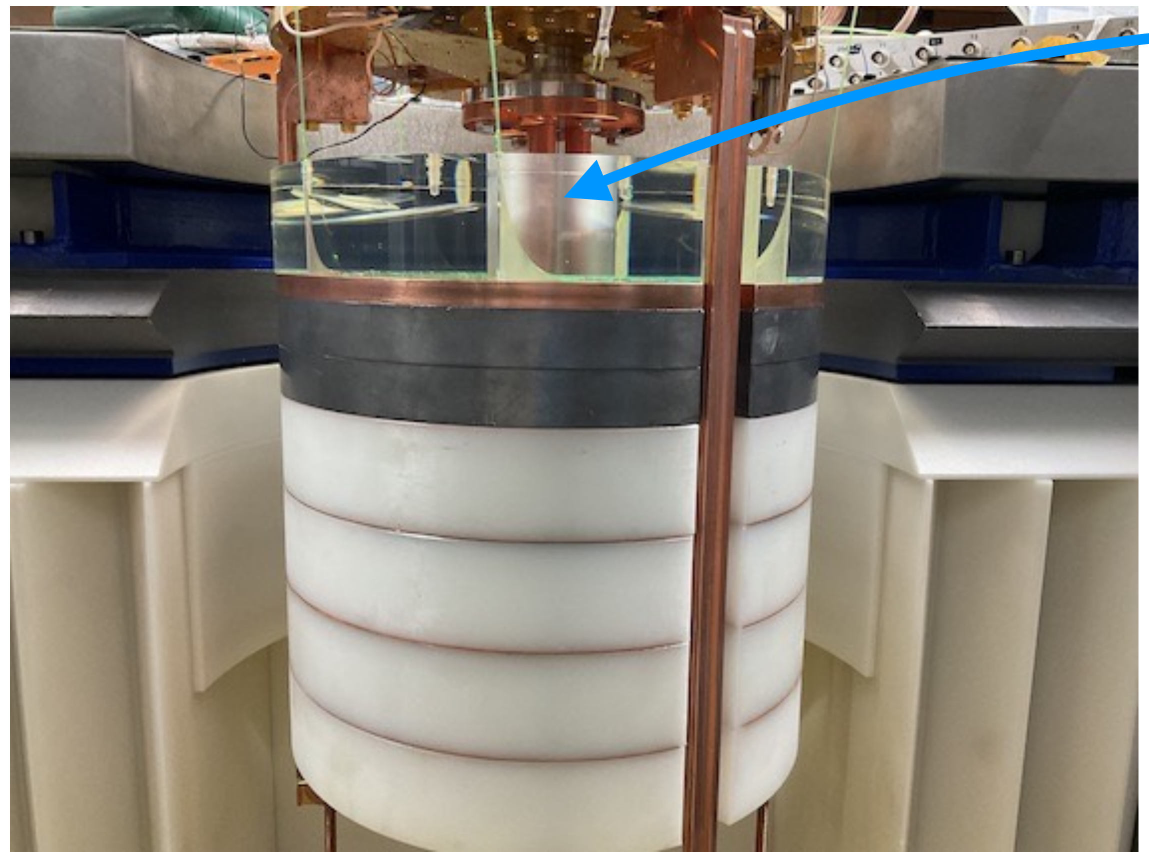
Thermalization of internal shielding (~ 50 kg of HDPE + Pb + Cu) achieved within 11 days

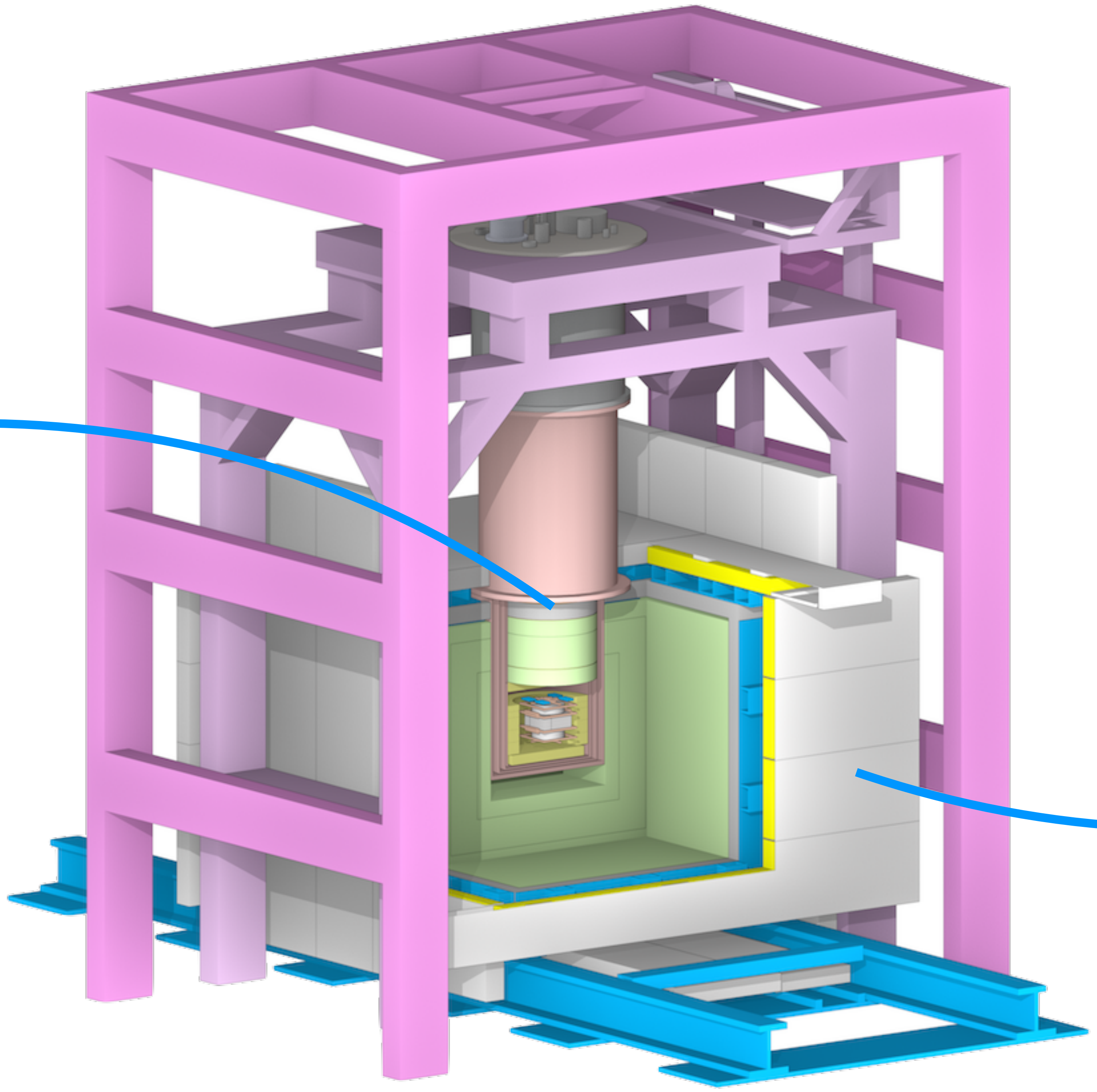
# Main results of the commissioning run

## External muon veto with cryogenic extension

### Cryogenic muon veto

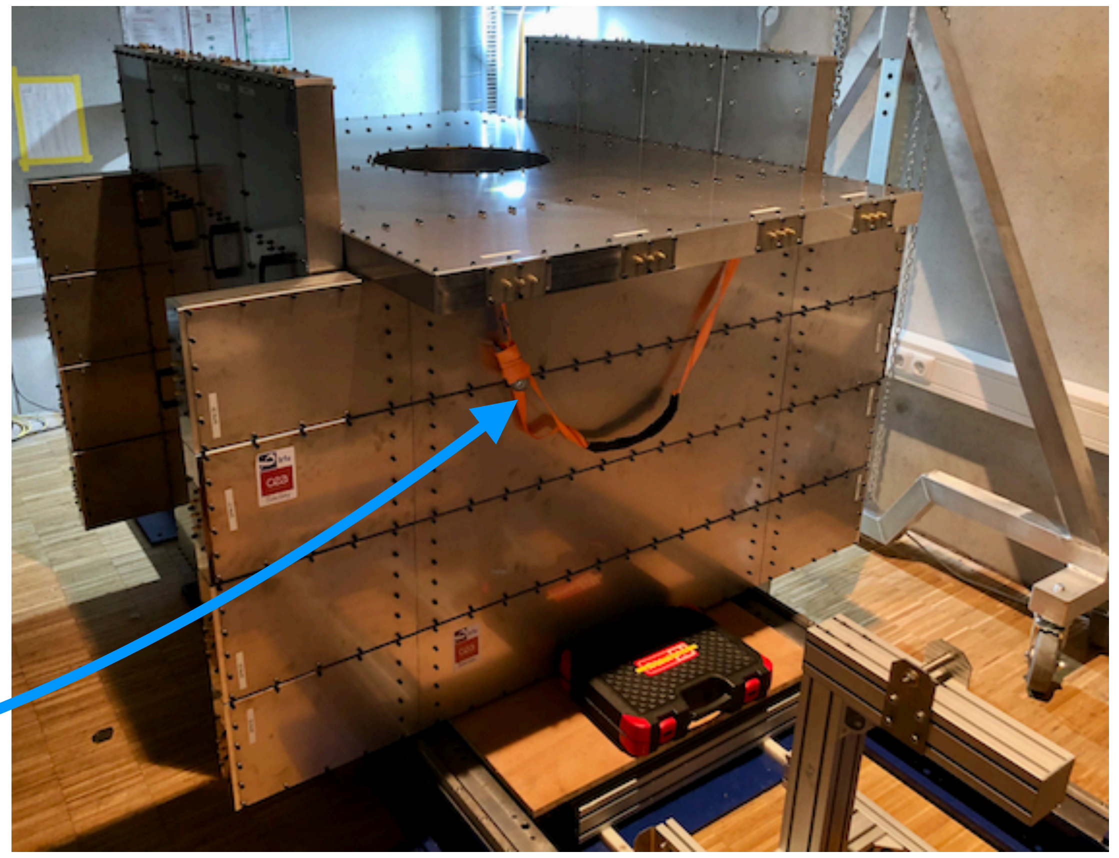
- Plastic scintillator thermalized at 800 mK
- WLS + Si-PM readout

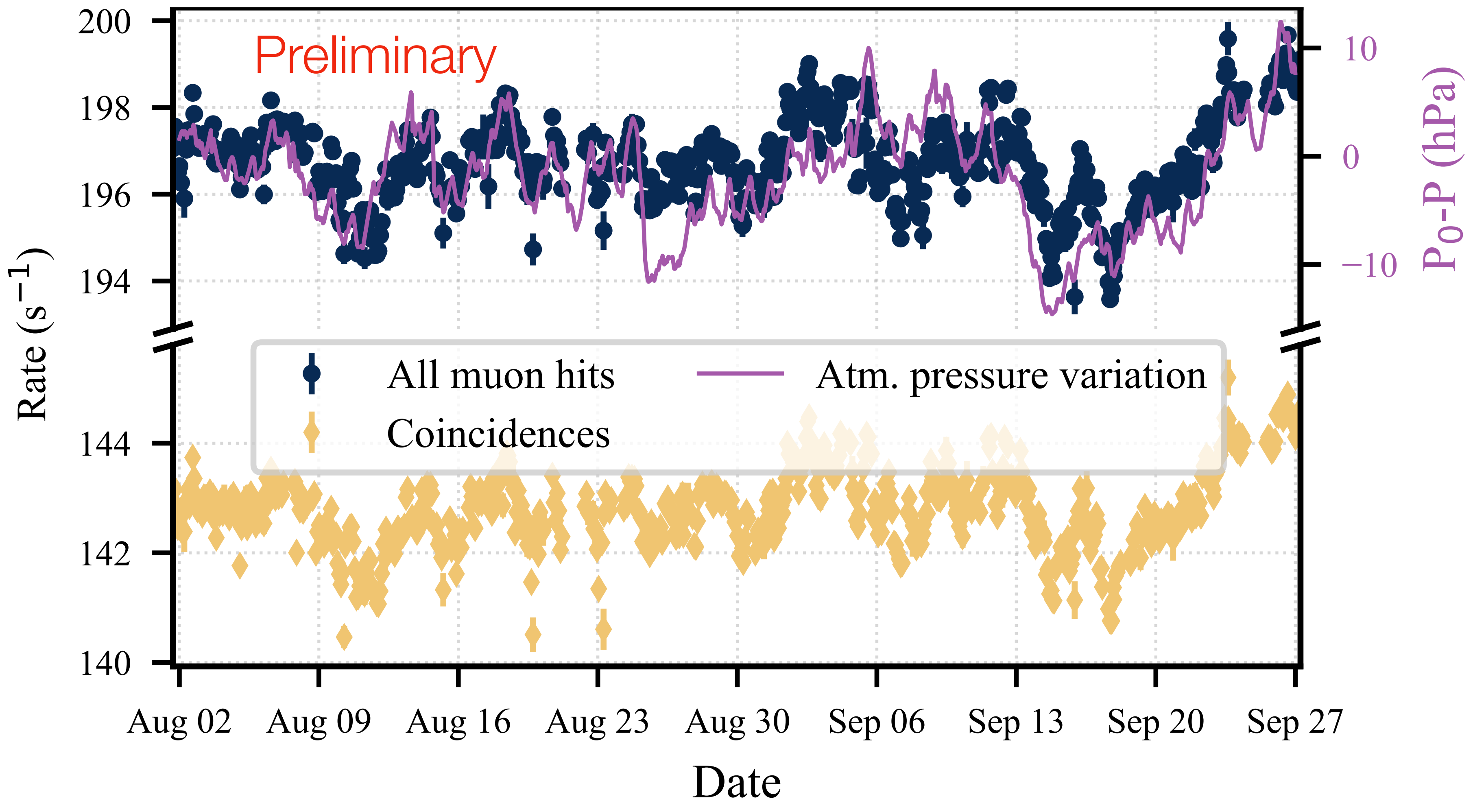




### External muon veto

- 28 x 5-cm thick plastic scintillator modules with WLS and Si-PM readout






### Commissioning results:

Full muon veto operated for a 2-month period

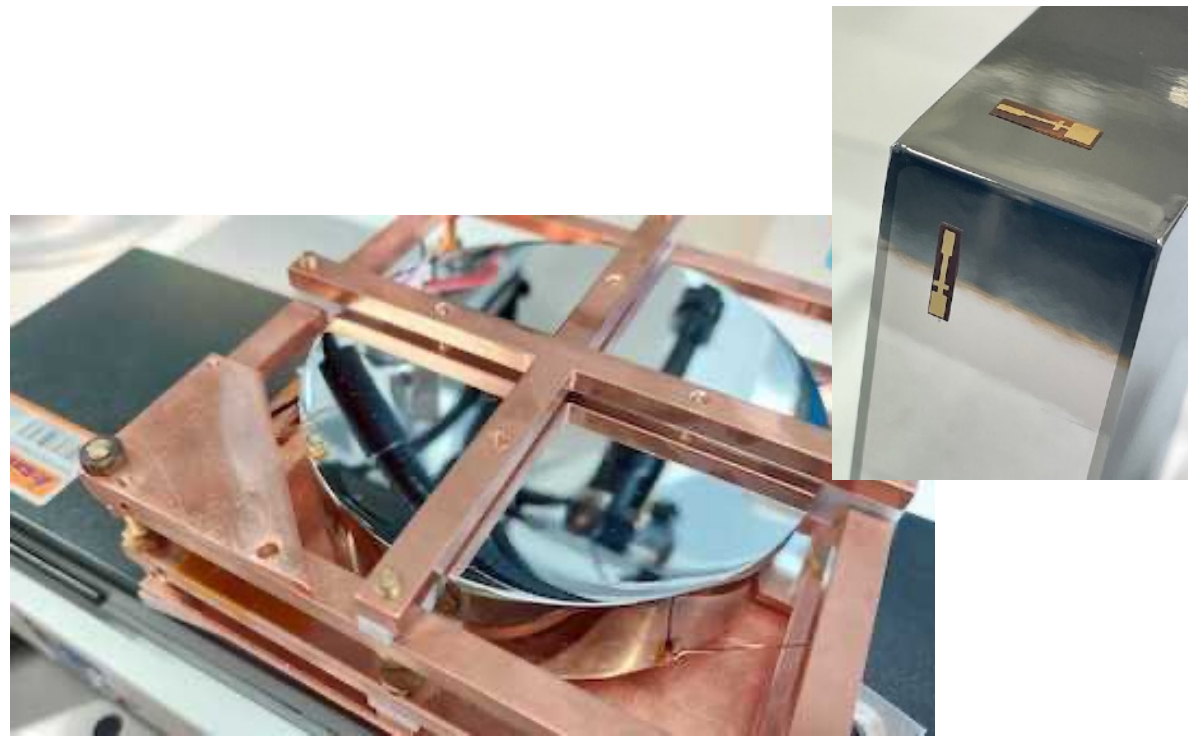
Simultaneous operation with cryogenic detectors demonstrated

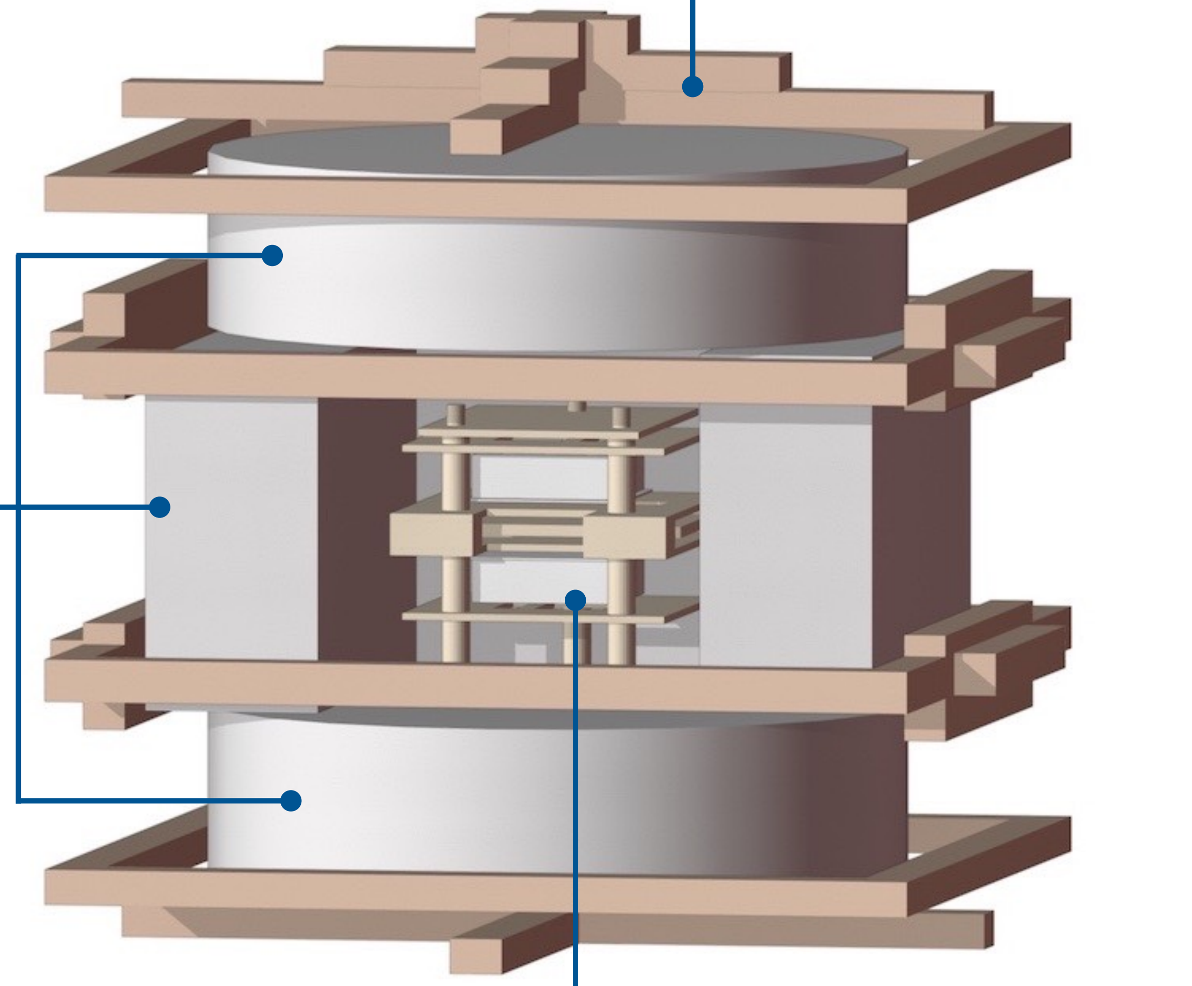
Rates, spectral shapes, efficiency and dead time understood

# Main results of the commissioning run

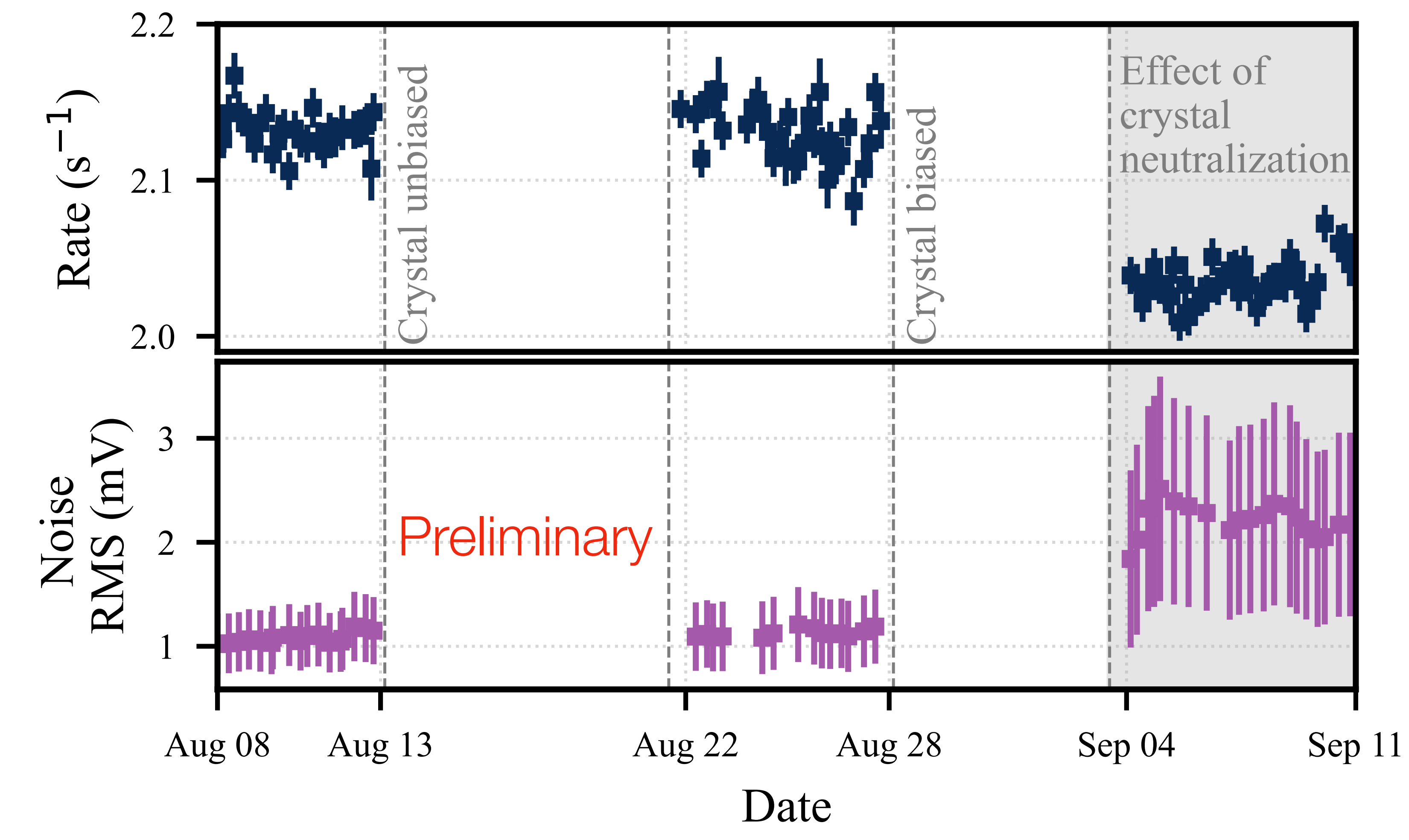
## Cryogenic high purity germanium outer veto (COV)

- 6 HPGe crystals with ~4$\pi$ coverage (4 kg)
- Suppression of external gamma rays (and neutrons)
- Fast ionization readout:
  - Planar electrodes
  - Two-stage charge amplification electronics
  - O(1-10 keV) energy thresholds

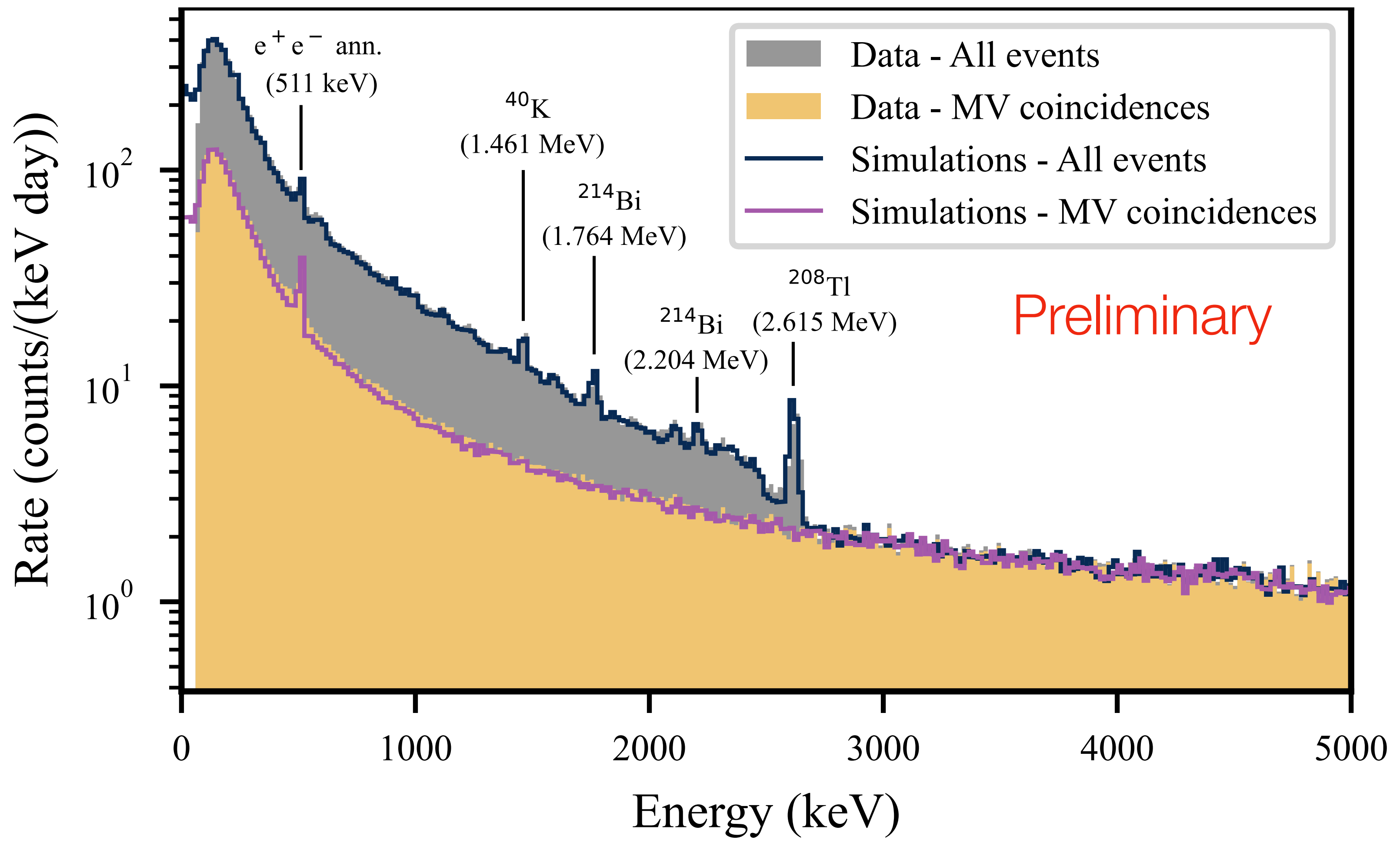





Stability




Energy spectrum




### Commissioning results:

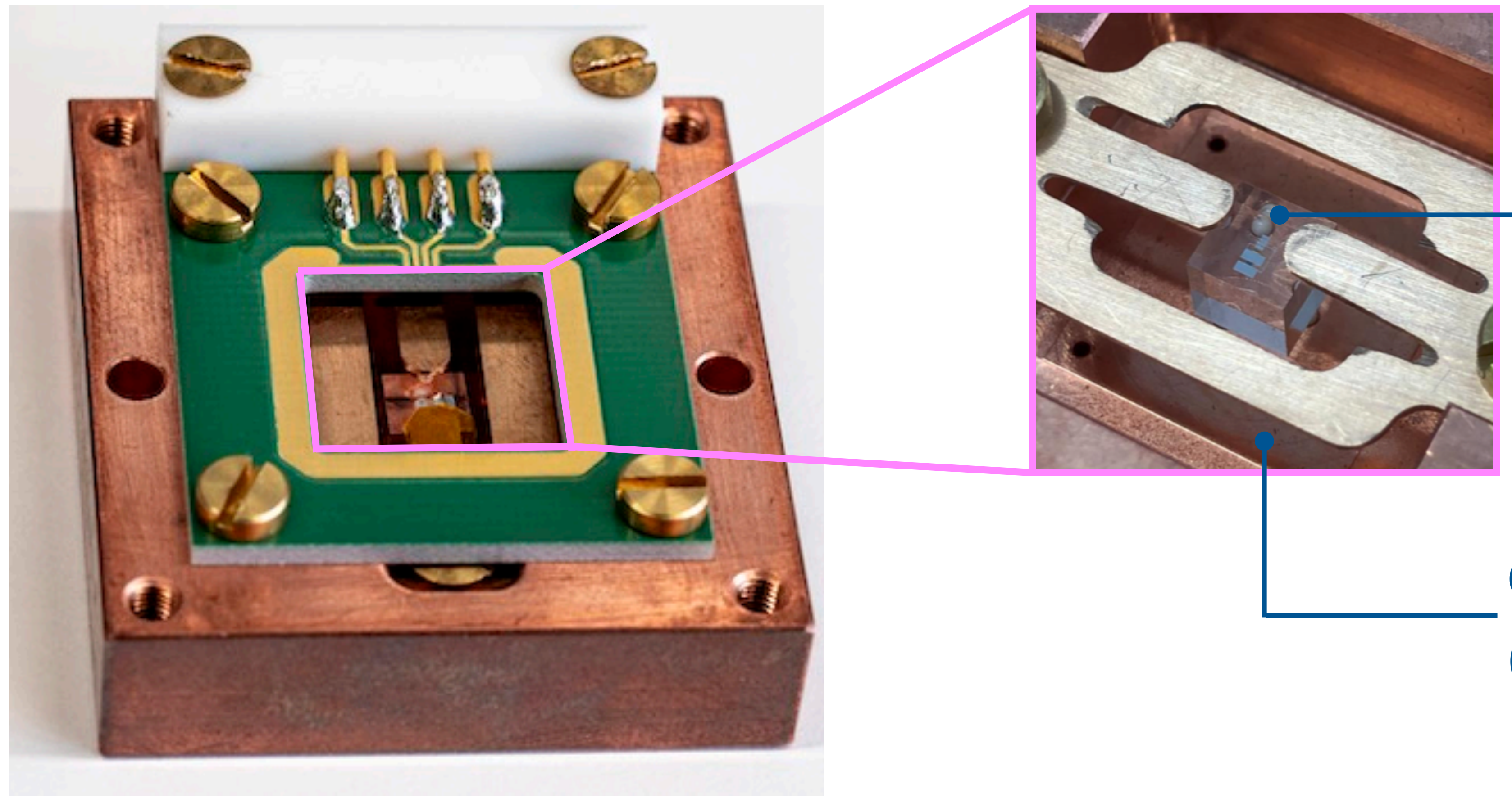
Stable operation of one cylindrical detector with ~6 keV$_{ee}$ energy threshold

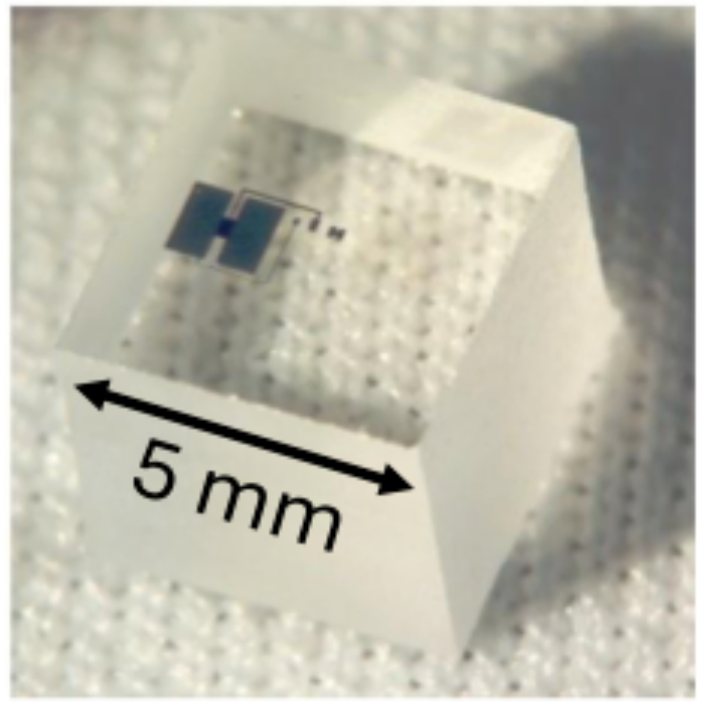
Simultaneous operation with cryogenic detectors demonstrated

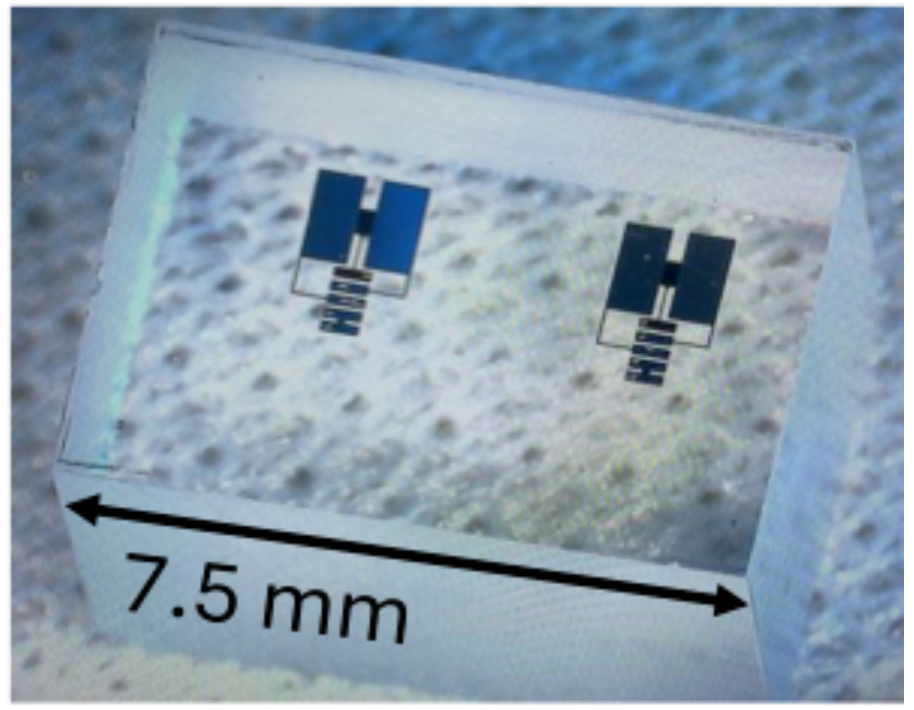
Rates, spectral shapes, efficiency and dead time understood

# Main results of the commissioning run

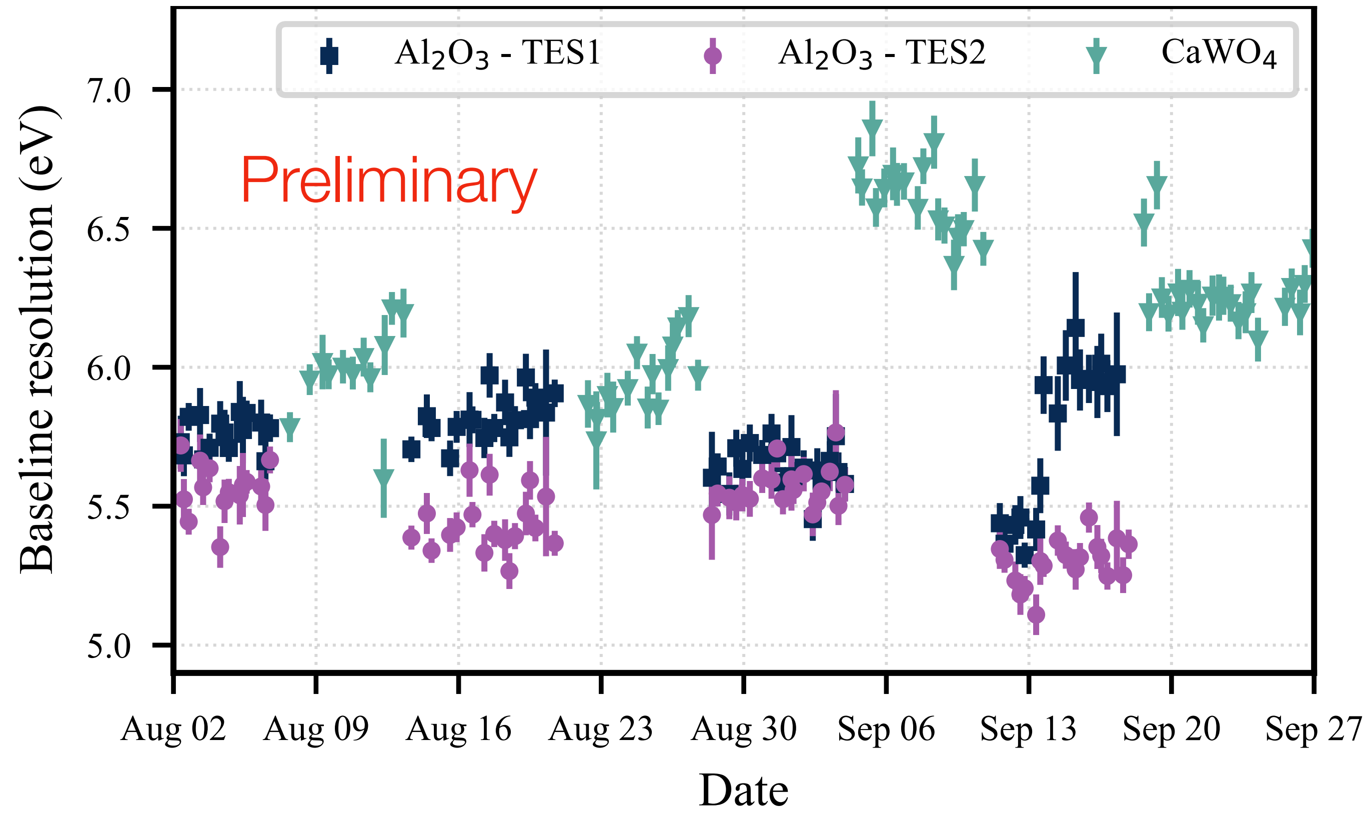
## Gram-scale cryogenic detectors with tungsten transition edge sensors



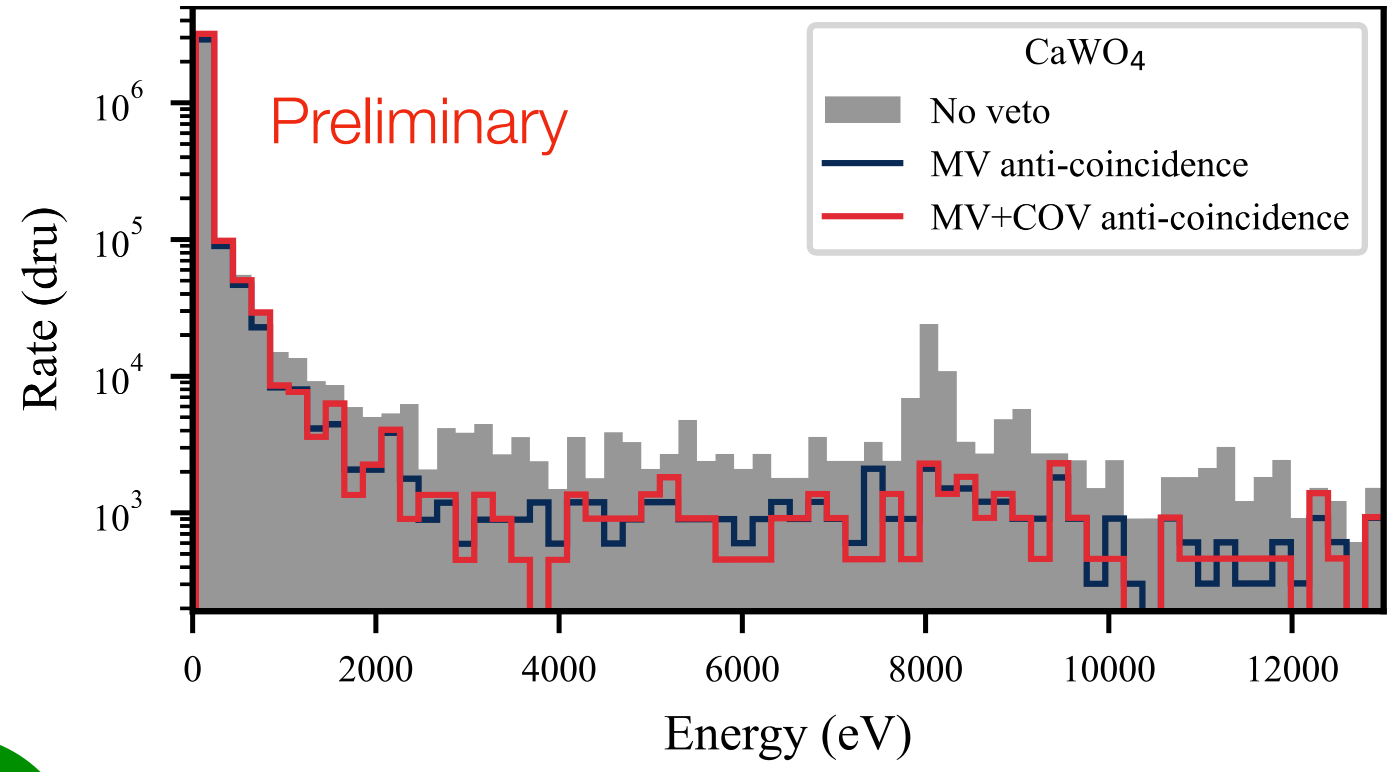




| Detector | $CaWO_4$, single TES | $Al_2O_3$, double TES |
|---|---|---|
| Baseline resolution | 6.2 ± 0.3 eV | 5.7 ± 0.2 eV, 5.5 ± 0.2 eV |




TES detector stability




$CaWO_4$ energy spectrum

**Commissioning results:**

Stable operation with energy threshold specifications

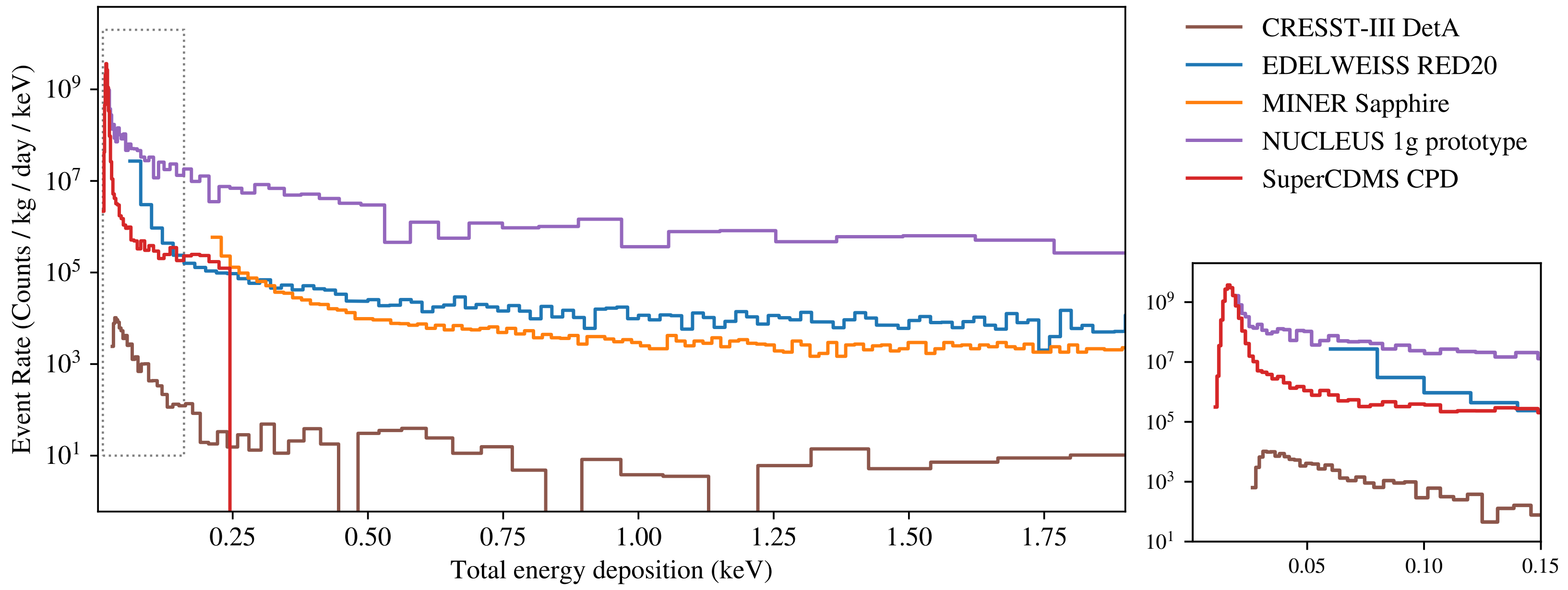
Simultaneous operation with veto detectors

# Main results of the commissioning run

## Investigation of the EXCESS background


- Many low threshold experiments observe rising event rates below a few hundred eV
- Much larger than expected particle backgrounds → large impact on sensitivity to CEvNS
- Tied to detector design rather than particle background environment

A. Fuss et al. SciPost Phys. Proc 9 (2022) 001



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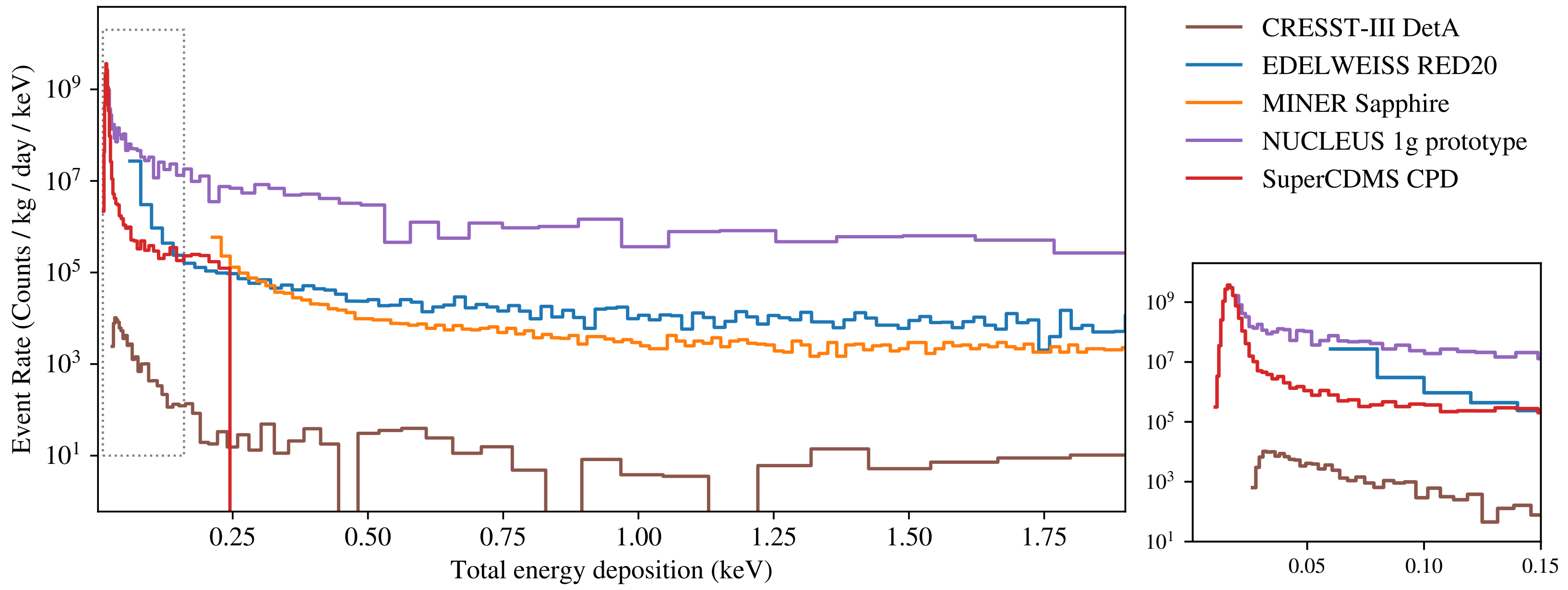
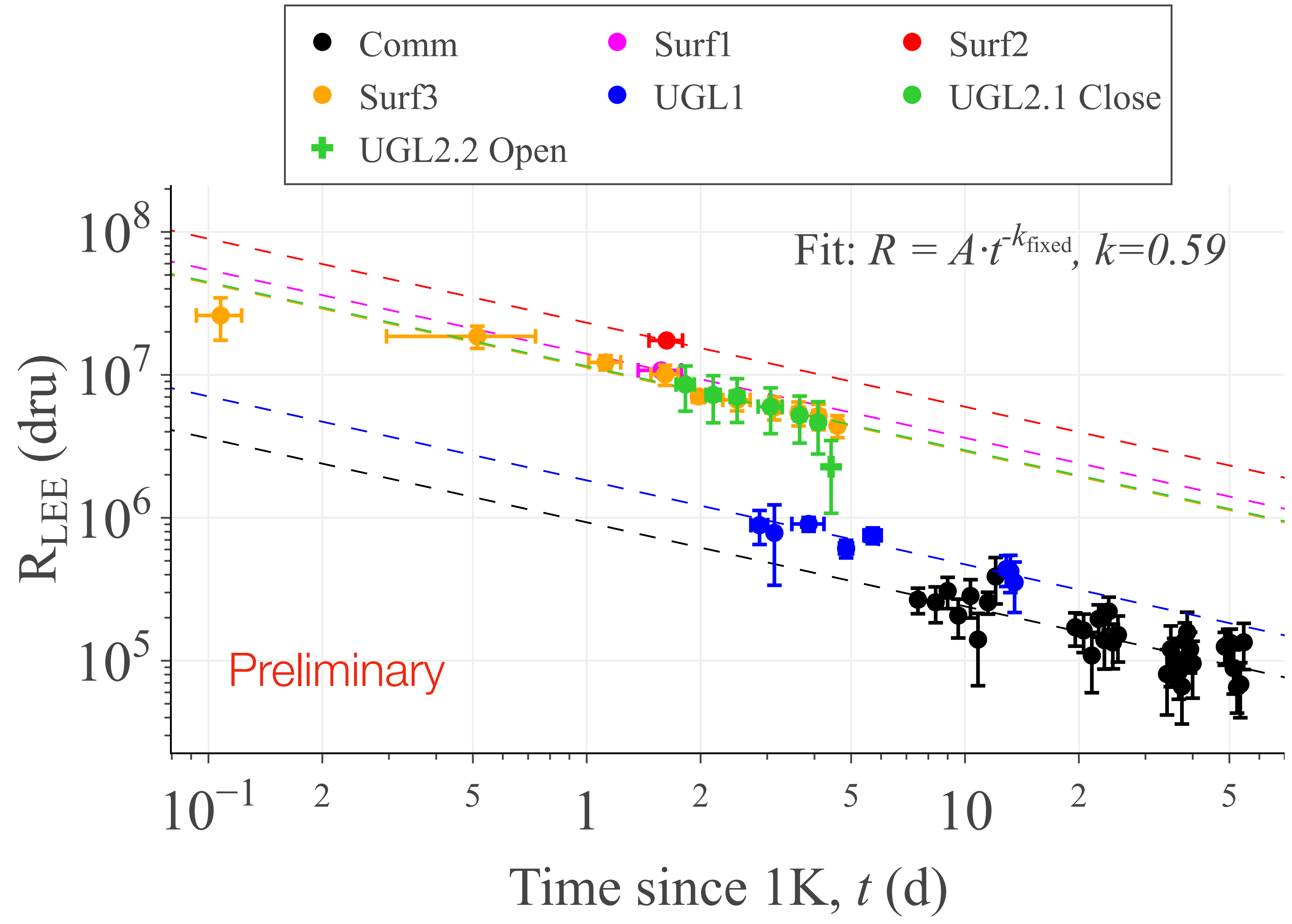



Time evolution of LEE rate in $Al_2O_3$ double-TES detector




### Commissioning results:

LEE rate not correlated with particle backgrounds

Correlation between LEE rate and cooldown duration identified

LEE decay rate well described by power law $R = A \cdot t^{-0.59}$

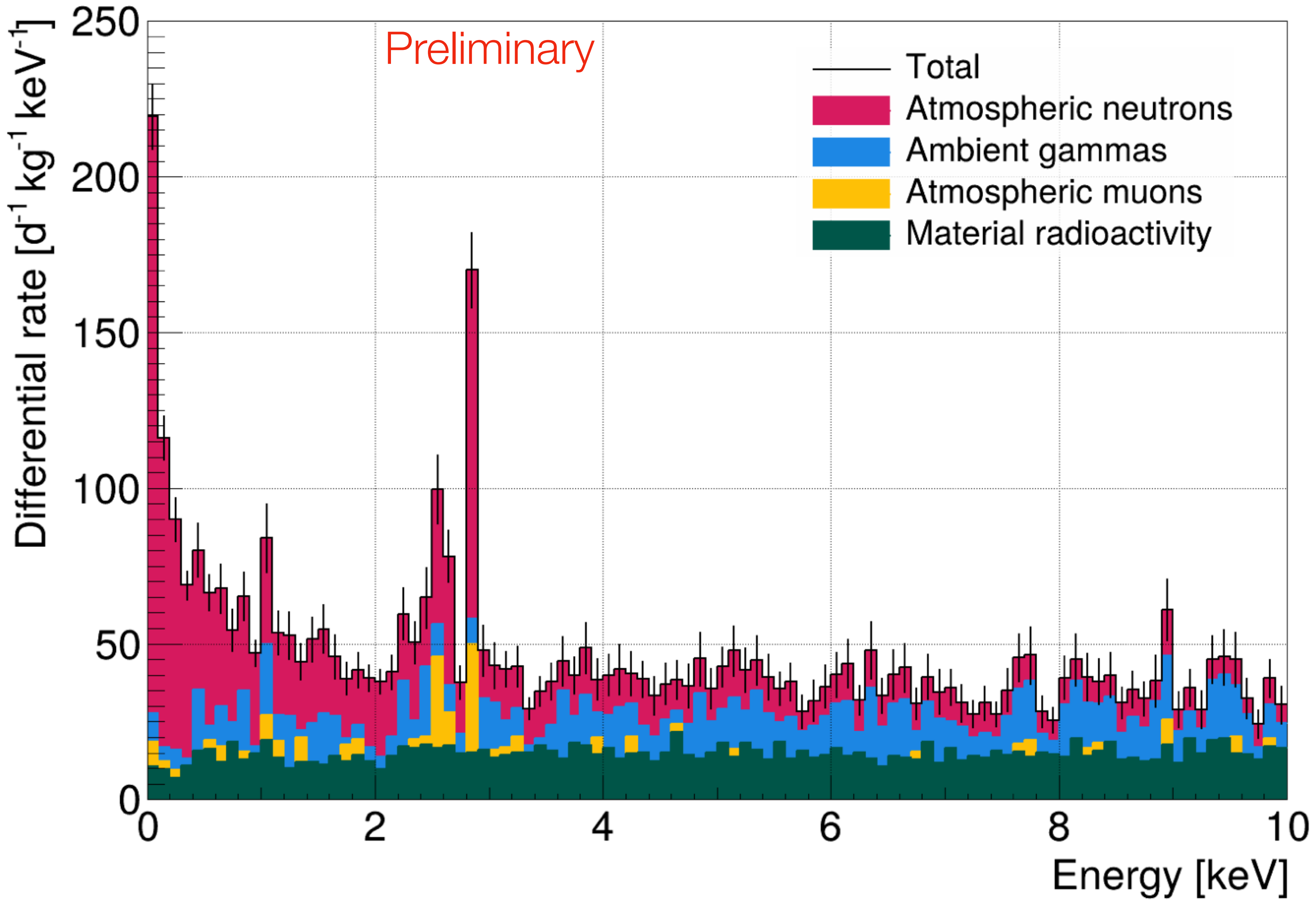
Initial LEE rate (A) smaller for slower cooldowns

**Dedicated article in preparation**

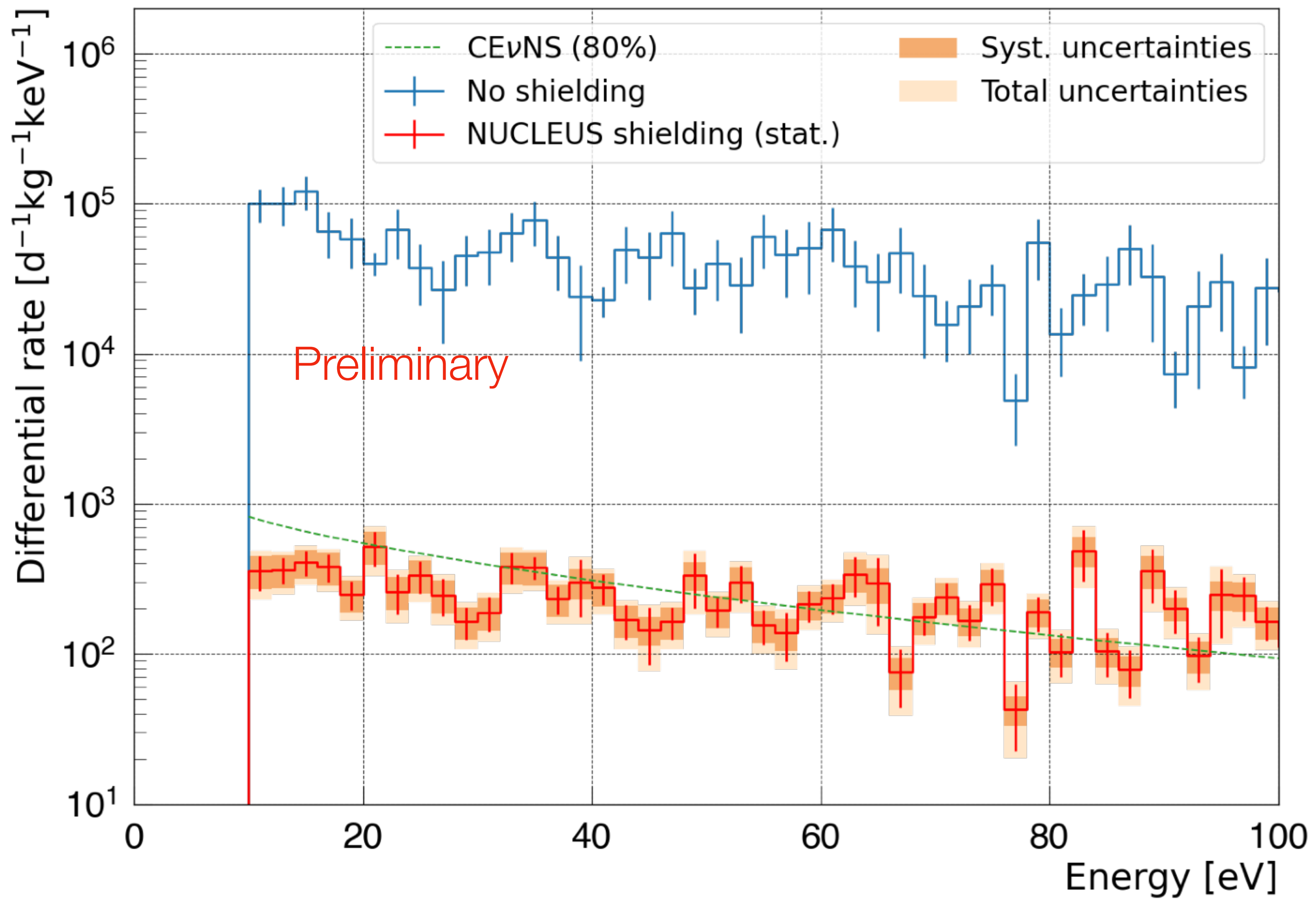
# Particle background modeling

- Thorough characterization of external background radiation environment at Chooz
- G4-based modeling ready and currently being fine-tuned against commissioning data
- CEvNS signal-over-particle background ratio ≥ 1 in the 10-100 eV region

Breakdown of particle background budget




Total rejection power expected in the 10-100 eV region

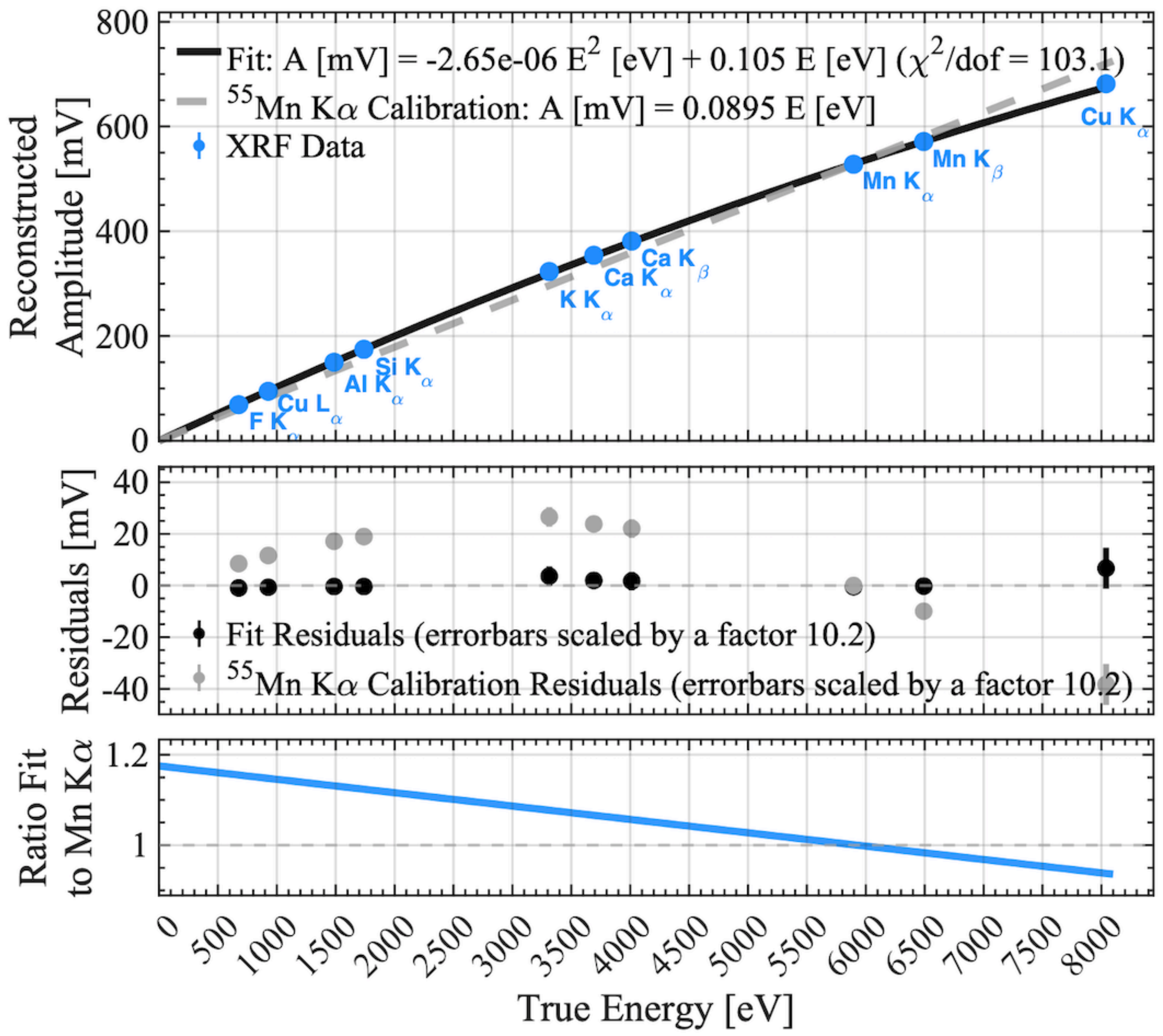



**Article to be released soon**

# Cryogenic detector calibration

## TES-detector response at sub-keV energies: non-linearities & possible ER/NR differences

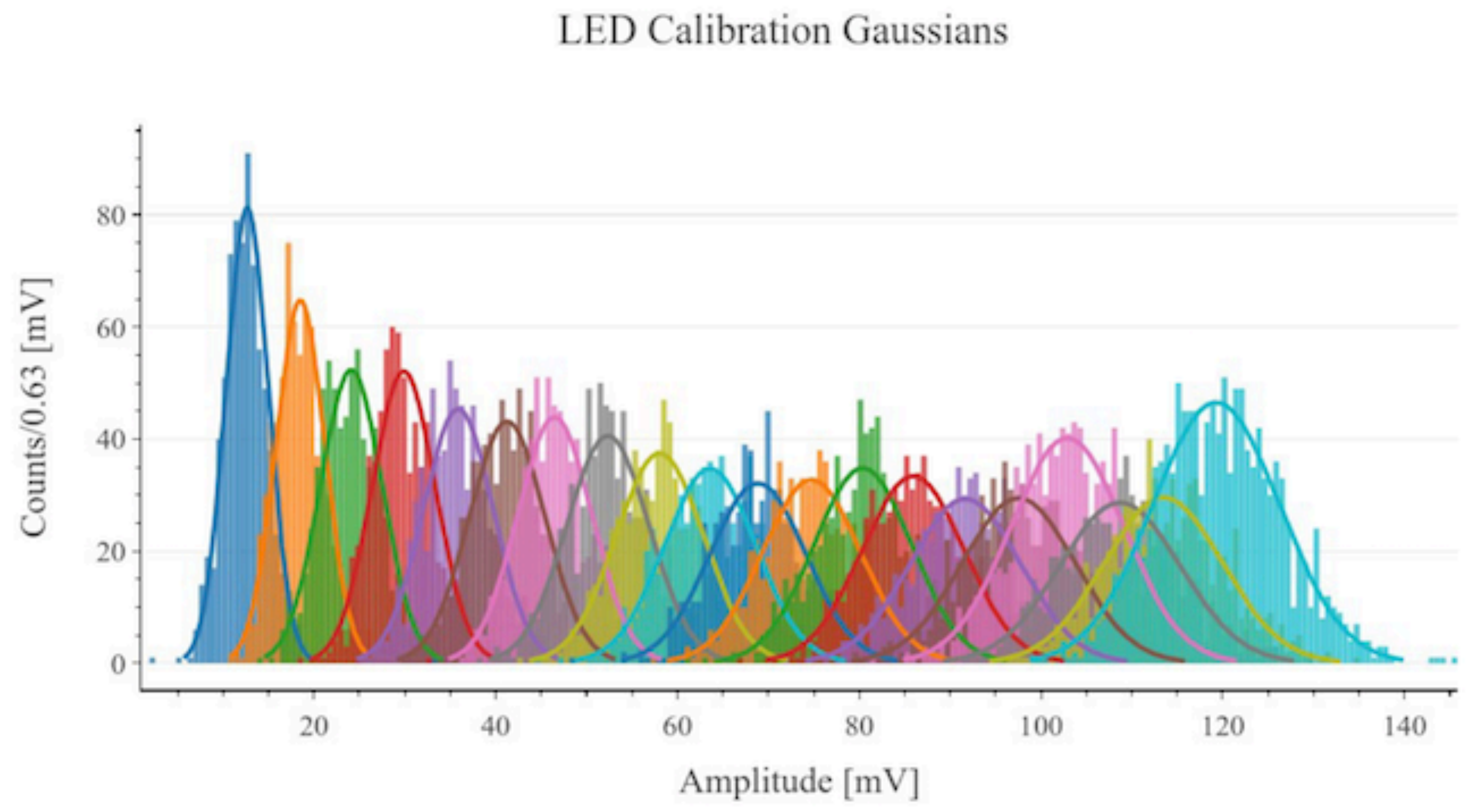
### Two-stage X-ray fluorescence source




H. Abele et al., arXiv:2505.17686

- Electron recoil calibration down to F Kα line at 677 eV in $CaWO_4$
- Non-linear energy response (quadratic) favored

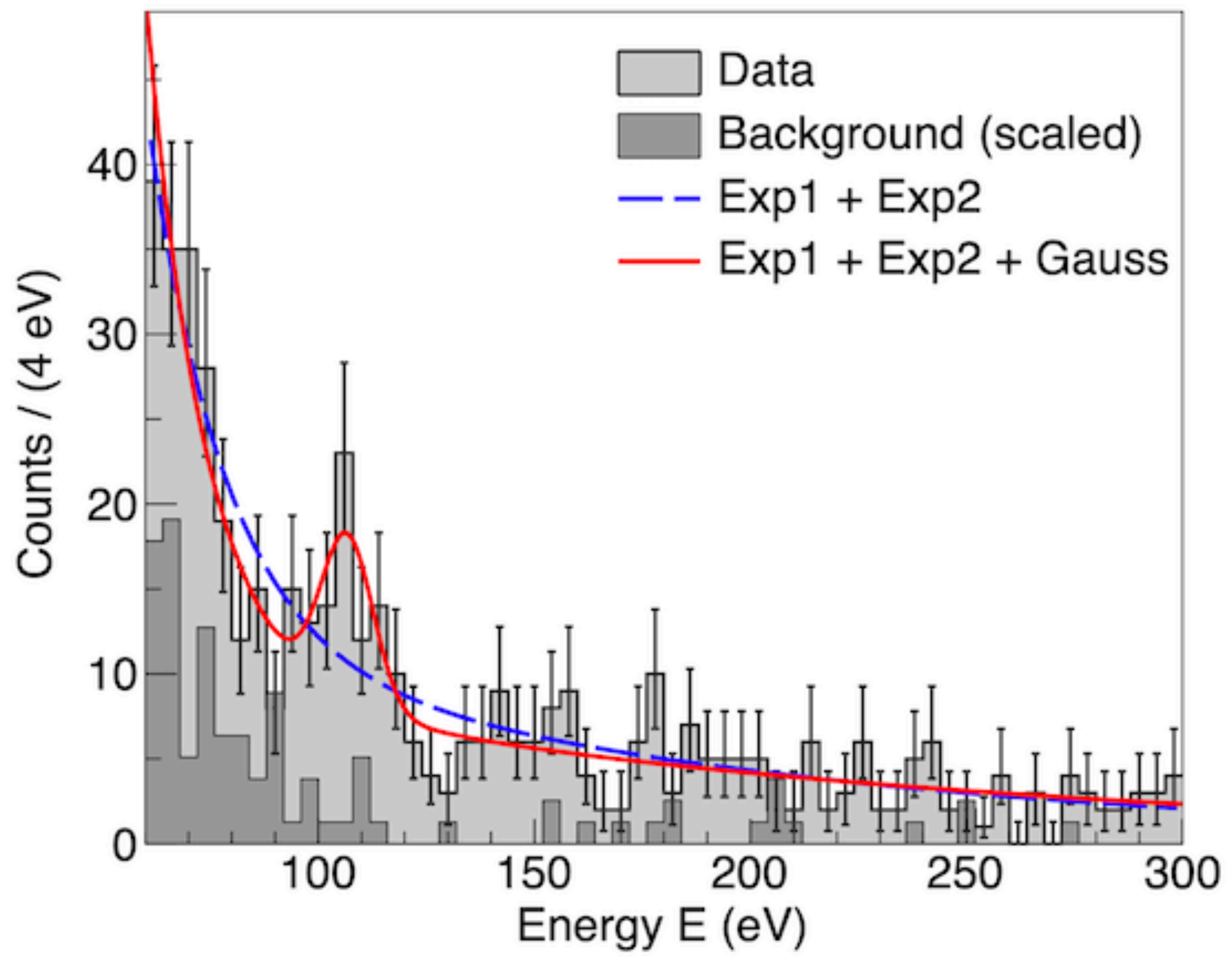
### LED shining system




- Monochromatic photon bursts to detectors
- Use phonon statistics to provide an absolute calibration of energy response
- In-situ and continuous monitoring of energy response at sub-keV energies w/o calibration sources

G. Del Castello NIM A 1068 (2024) 169728

### Nuclear recoil with neutron capture (CRAB)

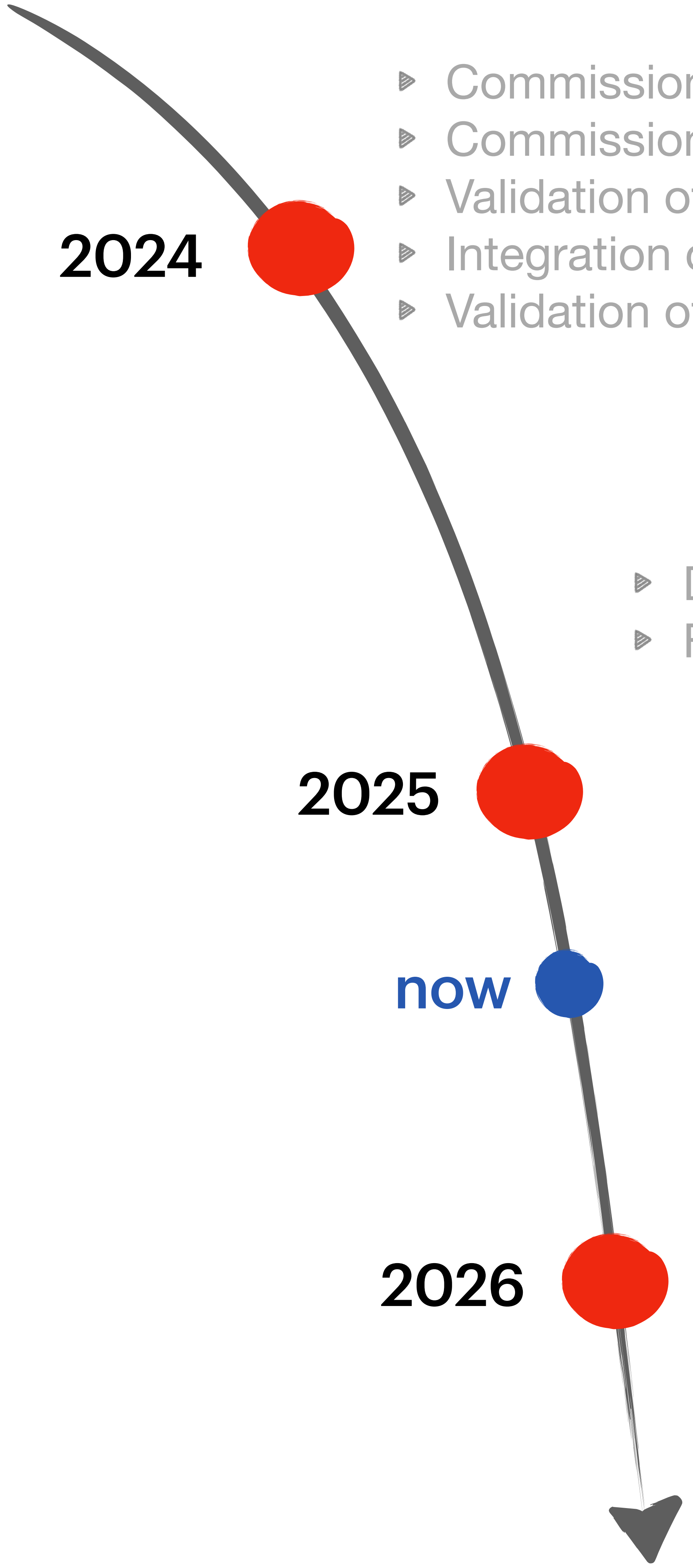



H. Abele et al., PRL 130 (2023) 21, 211802

- Ultimate method for NR calibration
- Proof-of-principle demonstrated
- Precision phase at TRIGA reactor (Vienna) on-going **[see talk from R. Martin]**

Cross-calibration remains to be studied

# Next steps




End of R&D work and integration of the experiment at TUM

- Commissioning of cryostat ✔
- Commissioning of readout electronics ✔
- Validation of spring decoupling system ✔
- Integration of external and internal shields ✔
- Validation of thermalization ✔

Commissioning run

- Demonstration of experimental setup ✔
- First measurement of backgrounds ✔

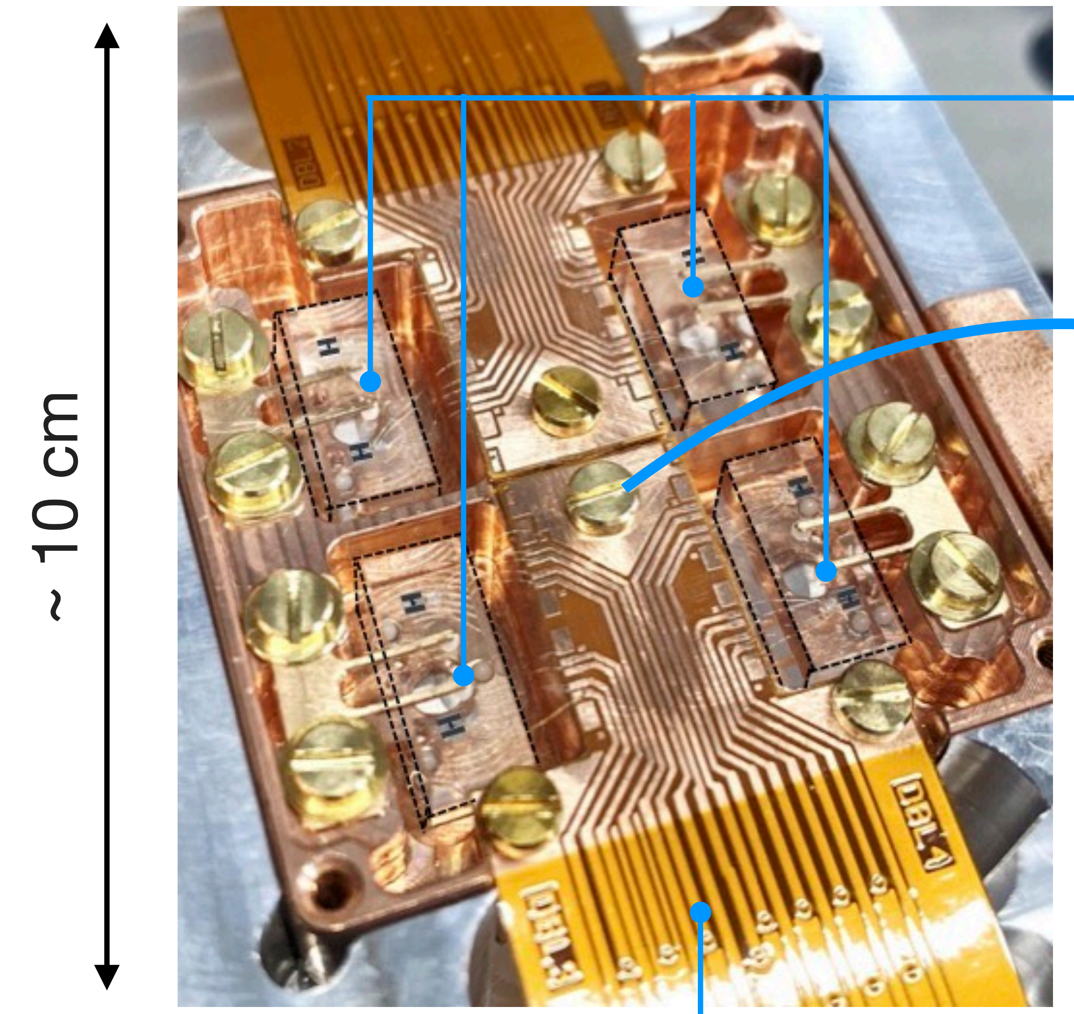
**Detector upgrades & relocation**

- COV upscaling ✔
- Integration of first cryogenic detector module
- Relocation of external shields ✔
- Relocation of cryostat (November 2025)

**Technical & physics runs at Chooz**

- Demonstration of particle backgrounds
- Validation of LEE mitigation strategy
- Neutrino detection with CEvNS

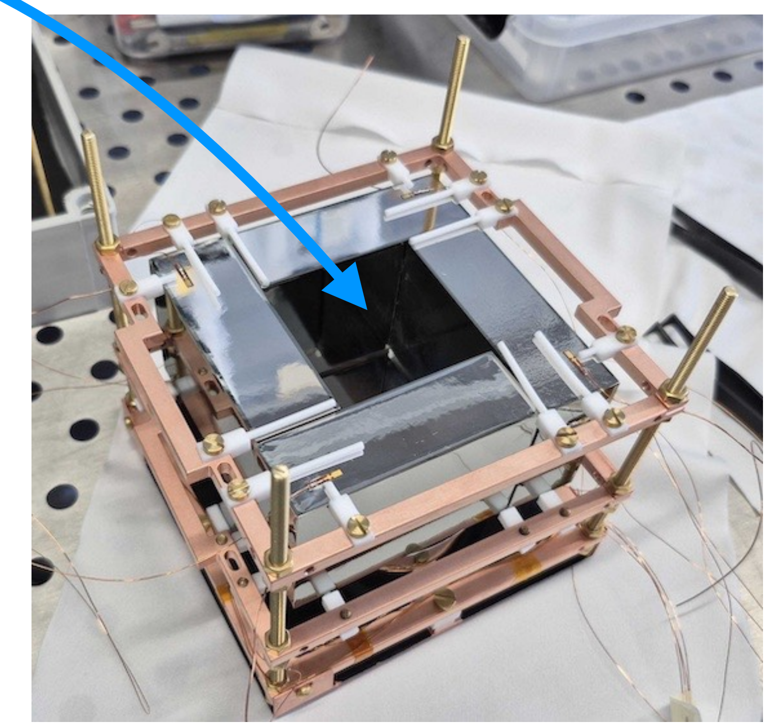
First cryogenic detector module for the technical run at Chooz



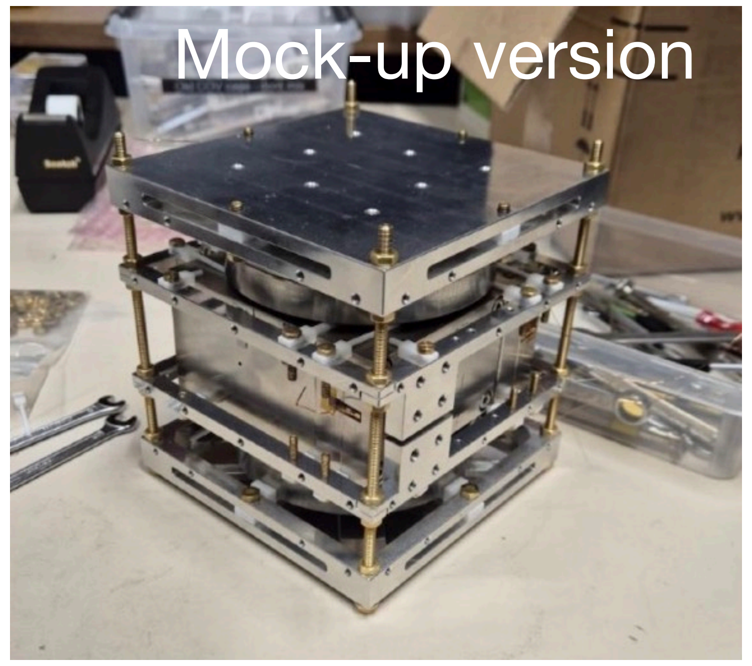

4 x double-TES $CaWO_4$ detector (6.1 g total mass)

Flat cable for detector thermalization and readout

Open COV



Full COV with upgraded mechanics



# Conclusions and outlook

### Success of NUCLEUS commissioning at TU Munich

- Practiced integration and operation of the full setup
- Test of computing infrastructure and data handling
- Demonstrated all sub-system performances and stability over a 2-month period
- First validation of shielding strategy
- Different strategies to mitigate the low energy excess are being completed

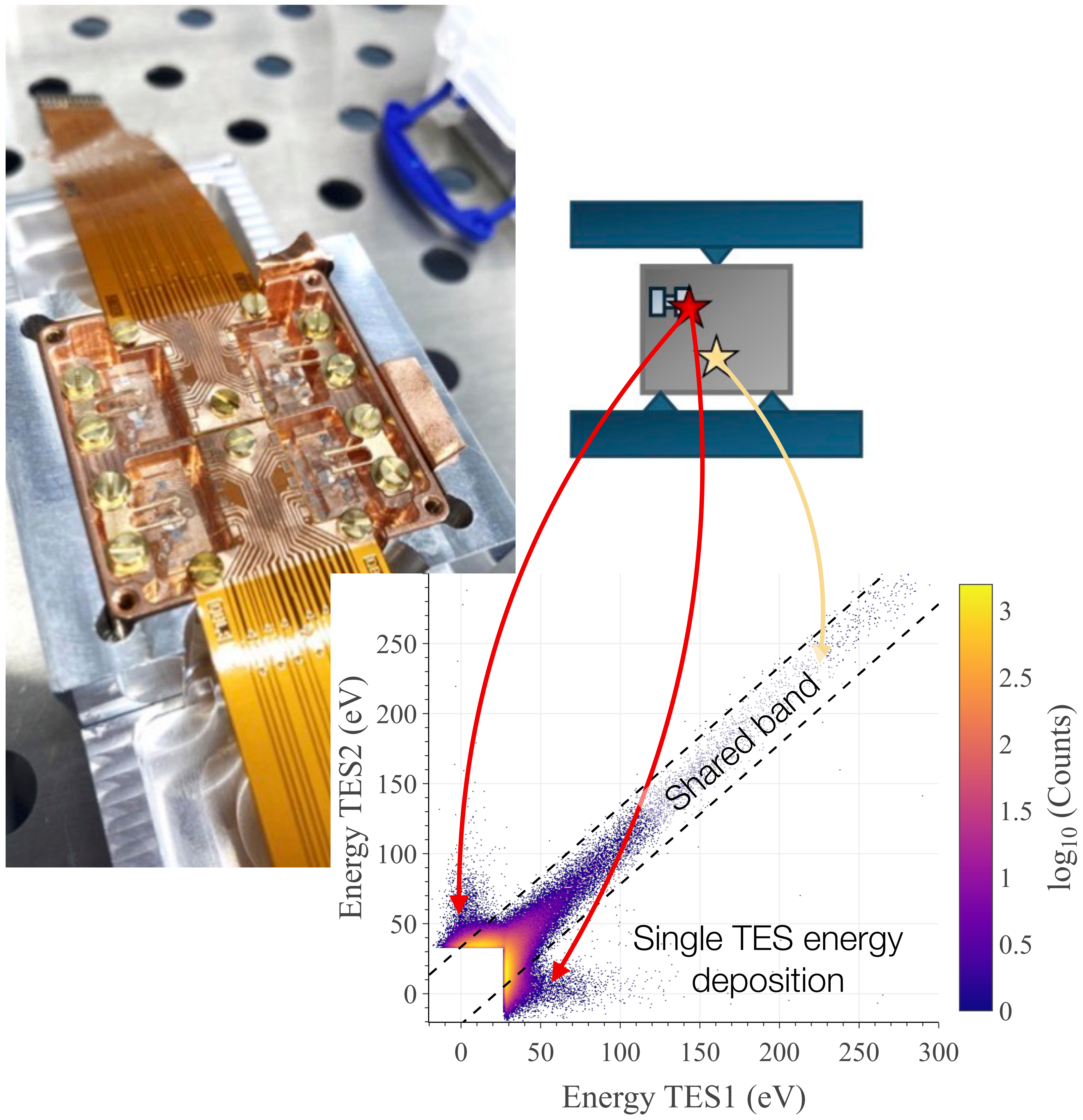

### Future of NUCLEUS

- Upgrade of cryogenic setup
  - 6-crystal COV
  - Integration of first detector module
- Relocation at Chooz (already started)
- Technical run with first data for the demonstration of backgrounds
- Neutrino physics run with final detector module

# Backup slides

# Strategy for LEE mitigation

Double-TES detectors to tag sensor-related LEE

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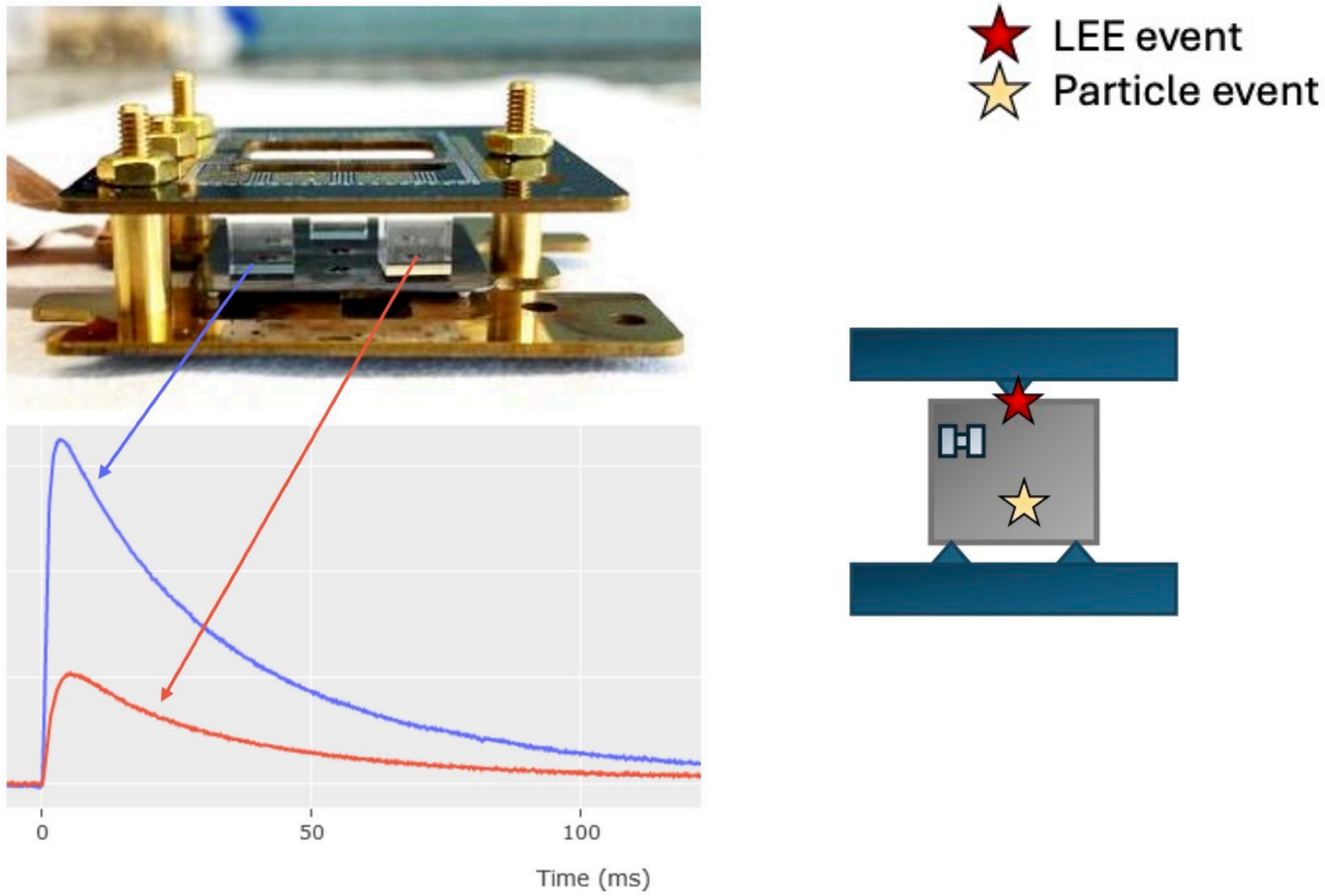
Instrumented holder to tag holder-related events




- Detectors operated in Si TES-instrumented holders with good performances and no cross-talk
- To be achieved:
  - Optimisation of inner veto TES
  - Demonstrate LEE discrimination power