New results from the commissioning of the NUCLEUS experiment at the Technical University of Munich

Elisabetta Bossio *on behalf of the NUCLEUS Collaboration*

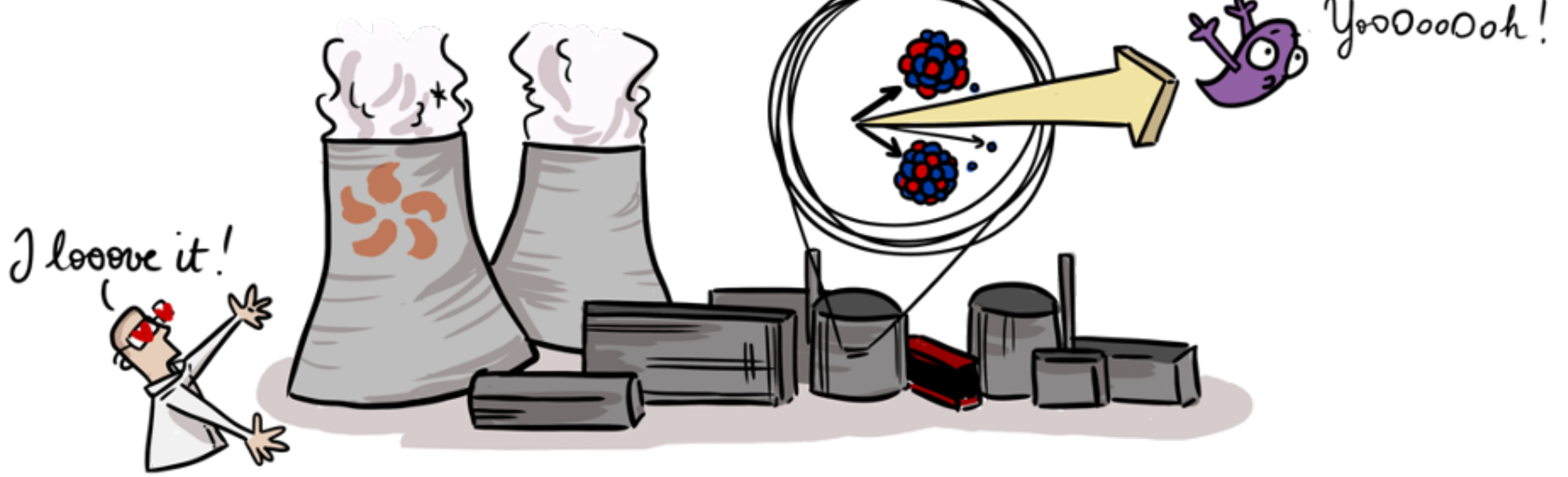
TAUP 2025, 24-30 Aug 2025, Xichang, China

The NUCLEUS collaboration

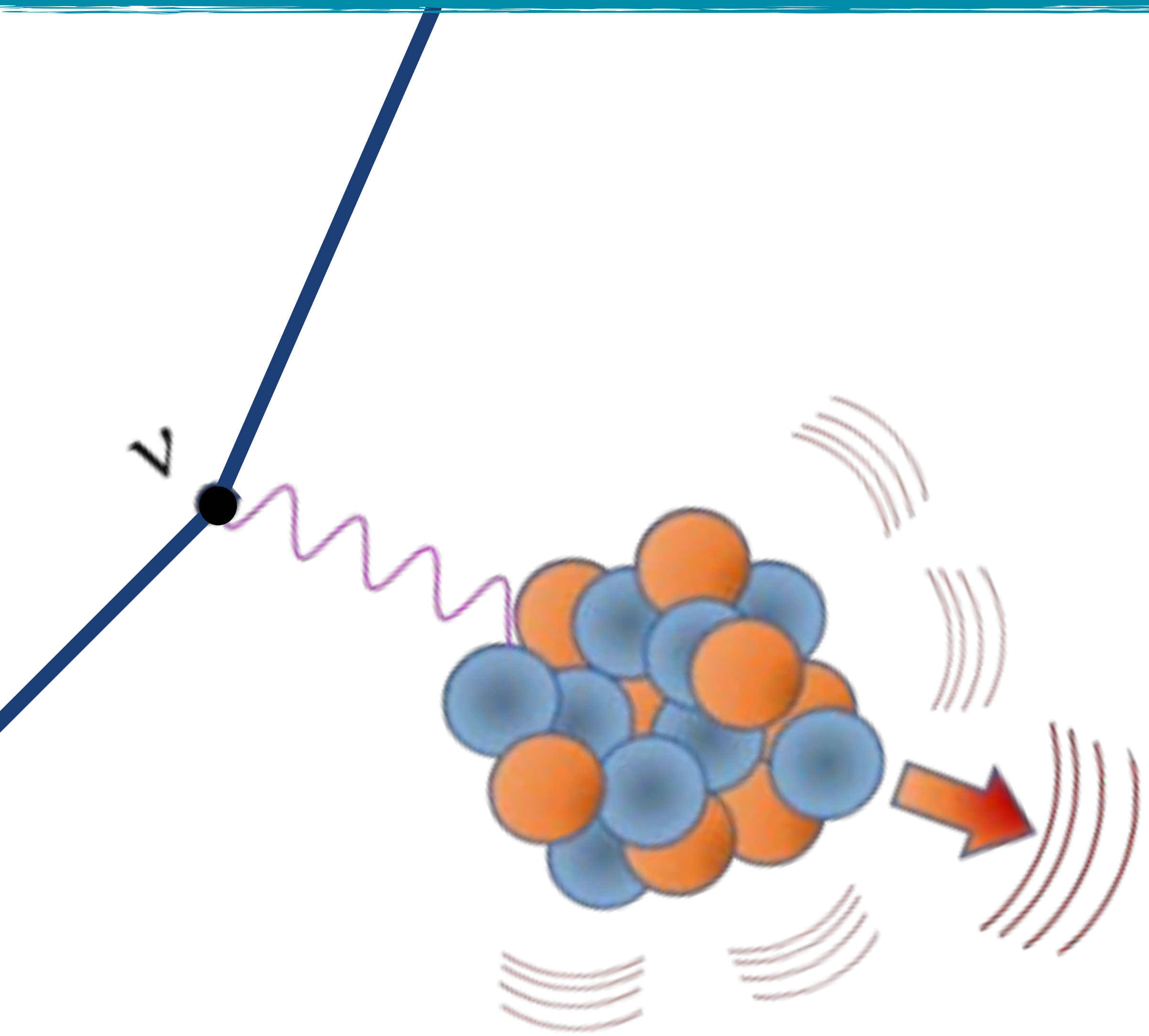
- *What?* Detection of reactor-antineutrinos via CEvNS
- *How?* $CaWO_4$ cryogenic detectors read out by Transition Edge Sensors
- *Where?* Chooz nuclear power plant in France

- 9 institutions, ~50 scientists

- Check out our website and comics
(credit: Chloé Goupy)



Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

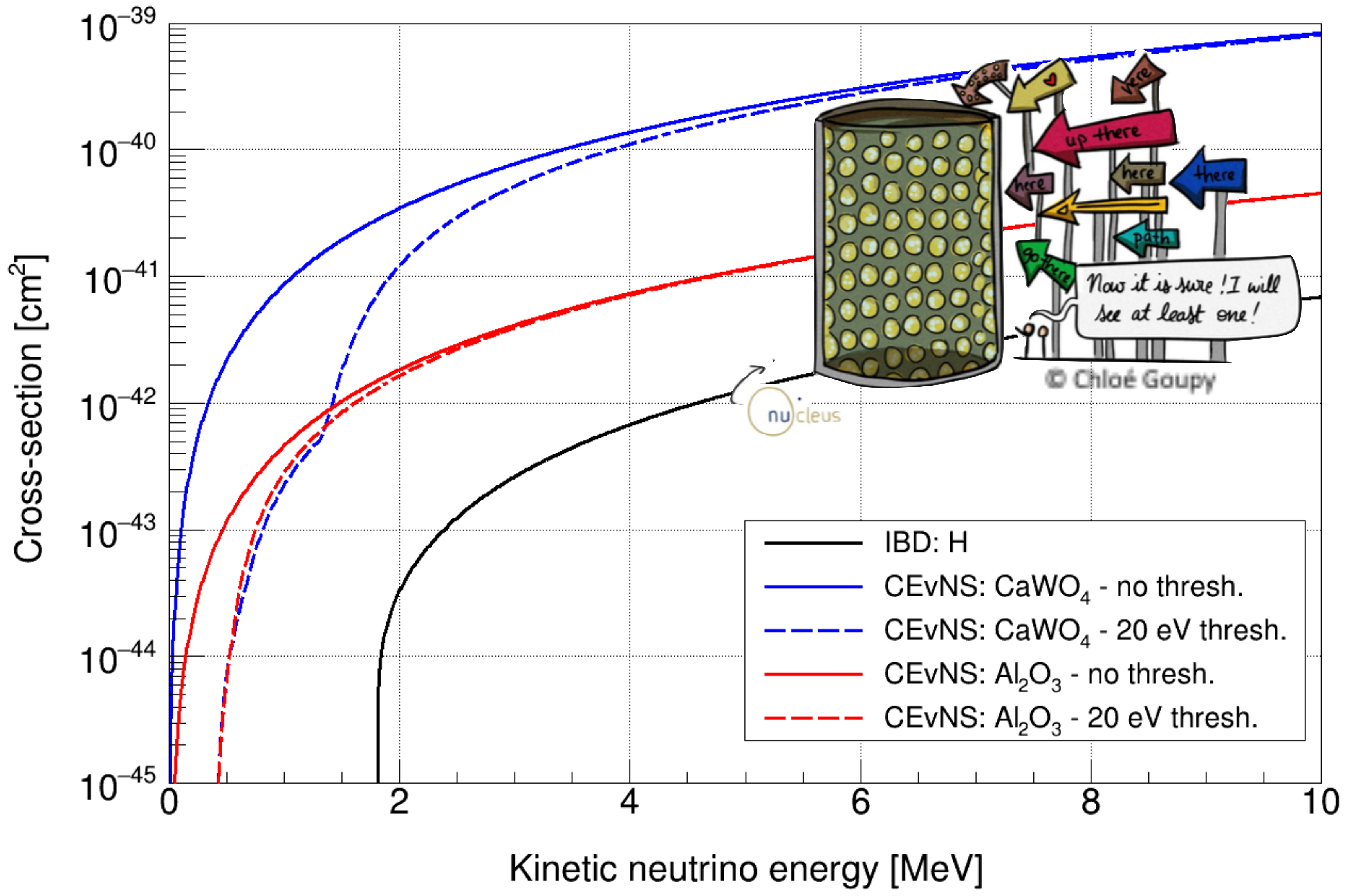


- Predicted by Freedman in 1974
- Dominant neutrino interaction for E_ν ~ 1-100 MeV
- Interesting: large cross-section with N² dependence

$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi}\left[Z(1-4\sin^2\theta_W)-N\right]^2 F^2(q^2)M\left(1-\frac{ME_R}{2E_\nu^2}\right)$$

- But experimentally very challenging: tiny nuclear recoils

$$E_{R,max} \sim \frac{2E_\nu^2}{M}$$

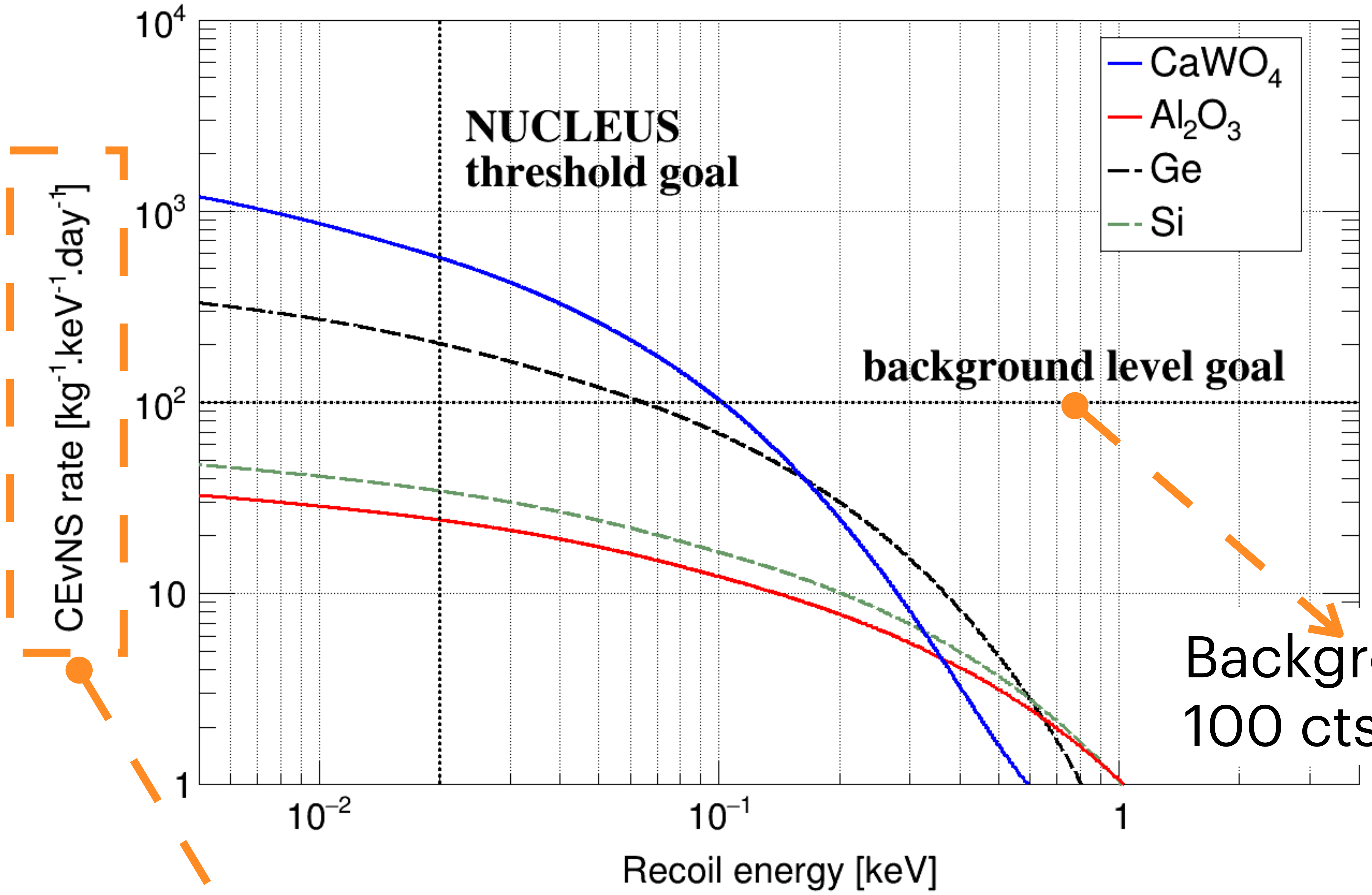


- First experimental observation only in 2017 by COHERENT experiment with neutrinos from Spallation Neutron Source
- First evidence with reactor neutrinos this year by CONUS+, more experiments to come
- Broad physics program: test of the Standard Model and beyond

See M. Lindner, "Coherent neutrino scattering, searches for sterile states"

Particle background challenge at Chooz

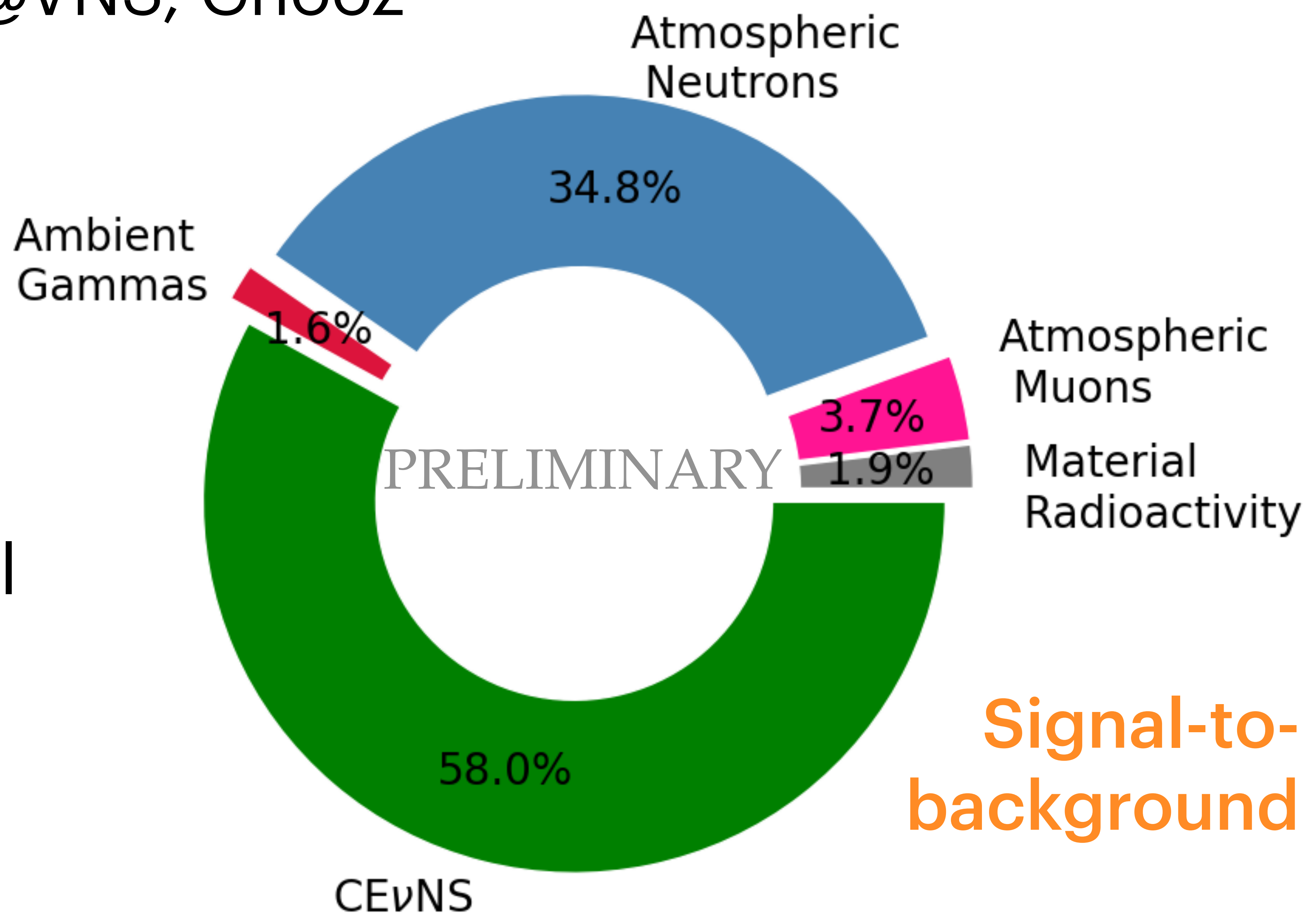
- NUCLEUS 10-g configuration:
  6.8 g of $CaWO_4$ + 4.4 g of Al_2O_3



Background level goal
100 cts/keV/kg/day

2 events per week expected above 20 eV

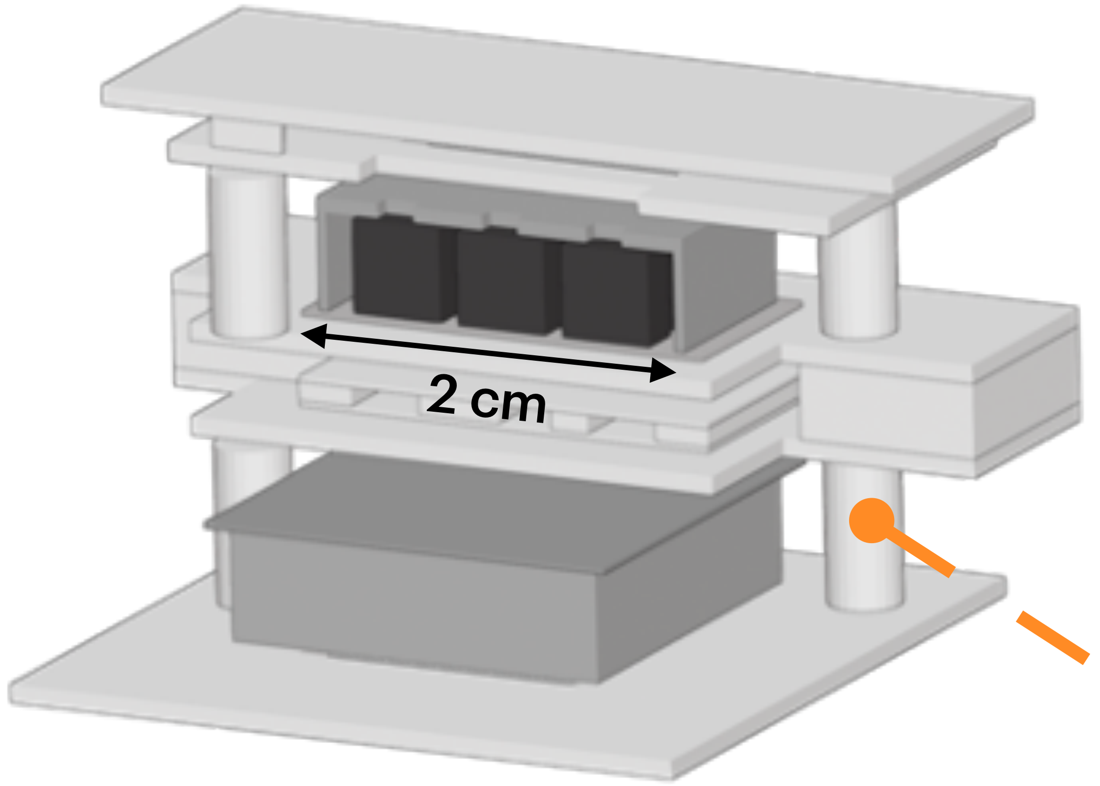
- Full characterisation of the environmental background at Chooz
- Extensive simulation work for the optimisation of the shielding strategy
- Particle background expectations for NUCLEUS 10-g @VNS, Chooz



Signal-to-background ~1

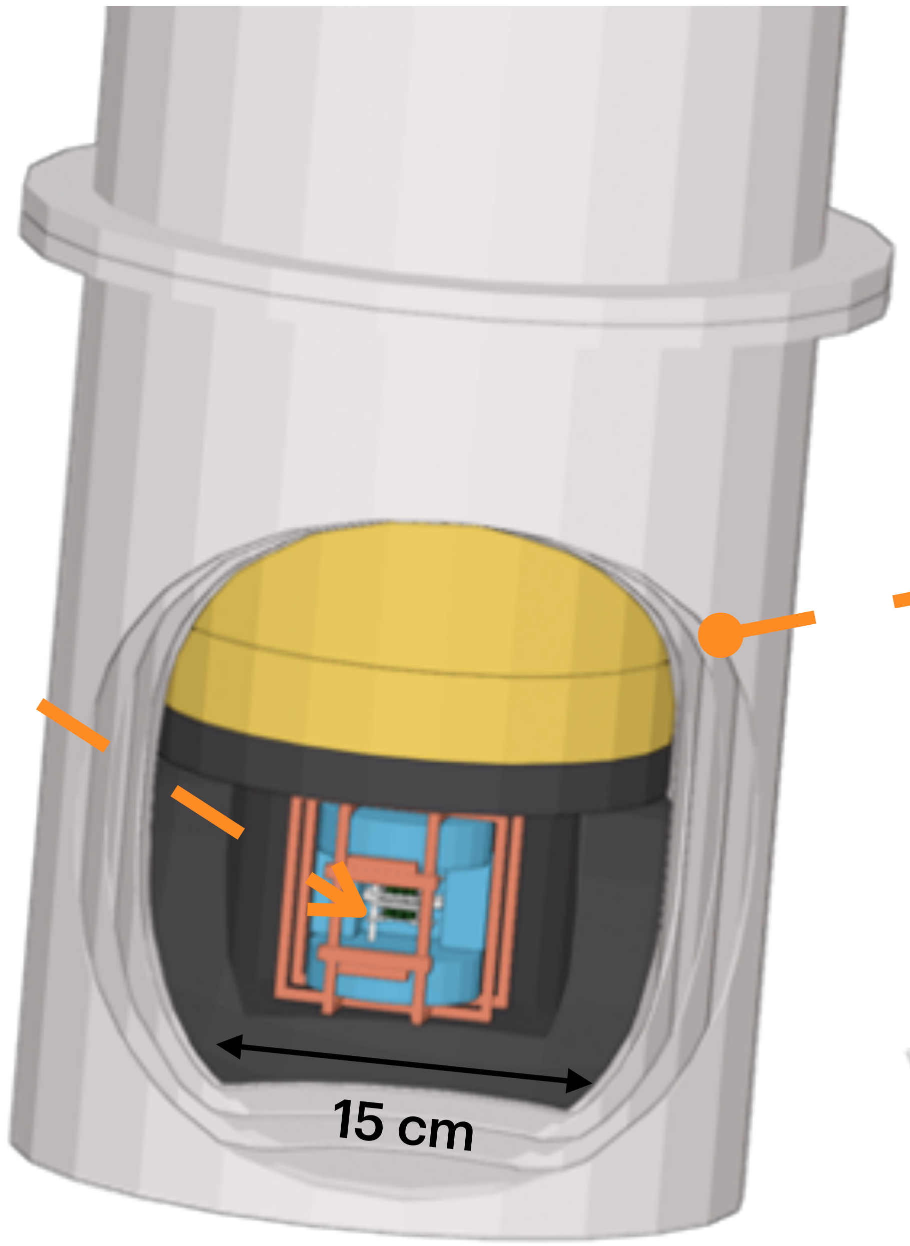
Chloé Goupy's PhD (2024), Publication in preparation

NUCLEUS setup

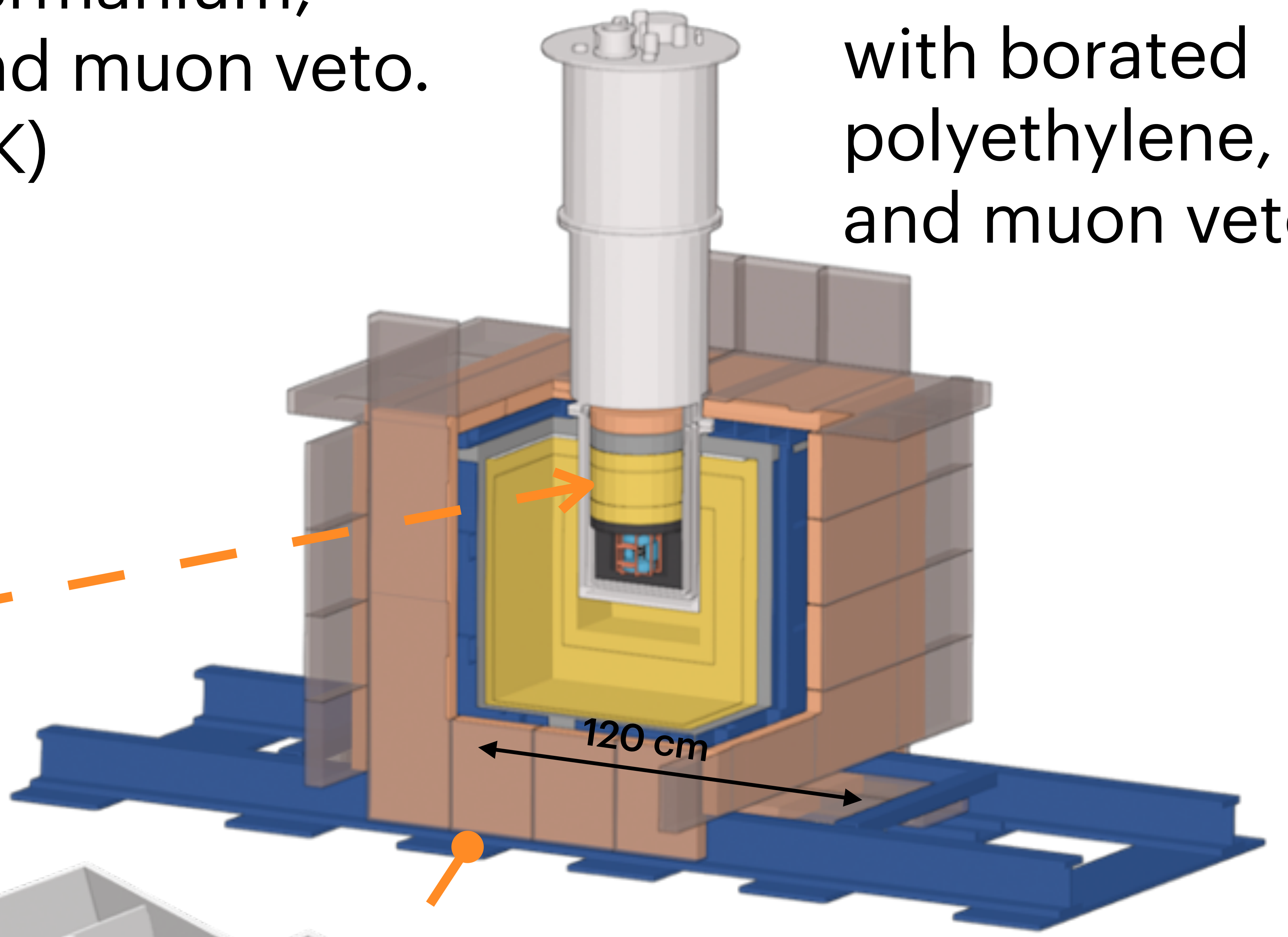


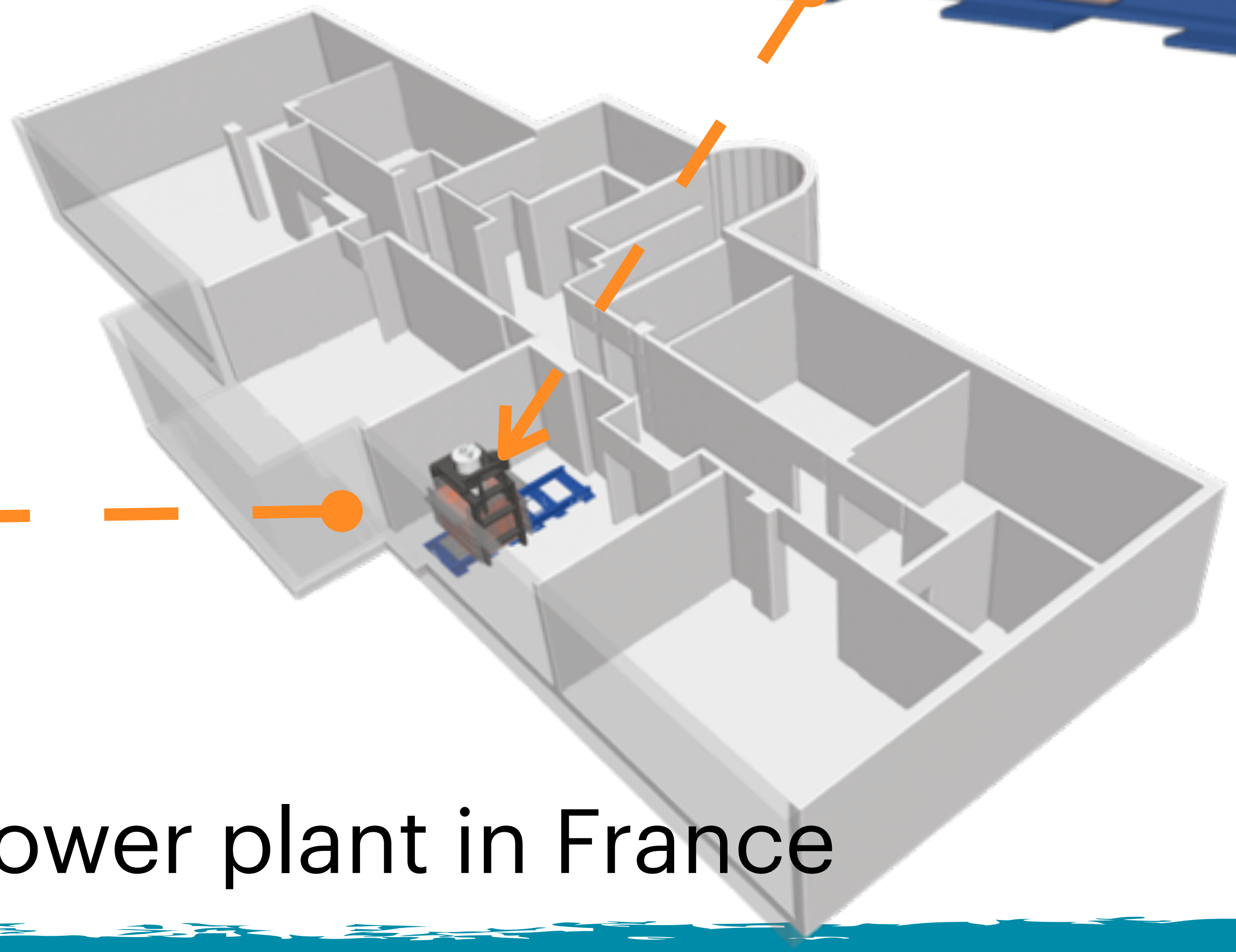
10 g cryogenic target detectors ($CaWO_4$ + Al_2O_3) with instrumented holder

Cryogenic shielding with active germanium, B_4C, borated polyethylene, lead and muon veto.
Dry dilution refrigerator at O(10 mK)

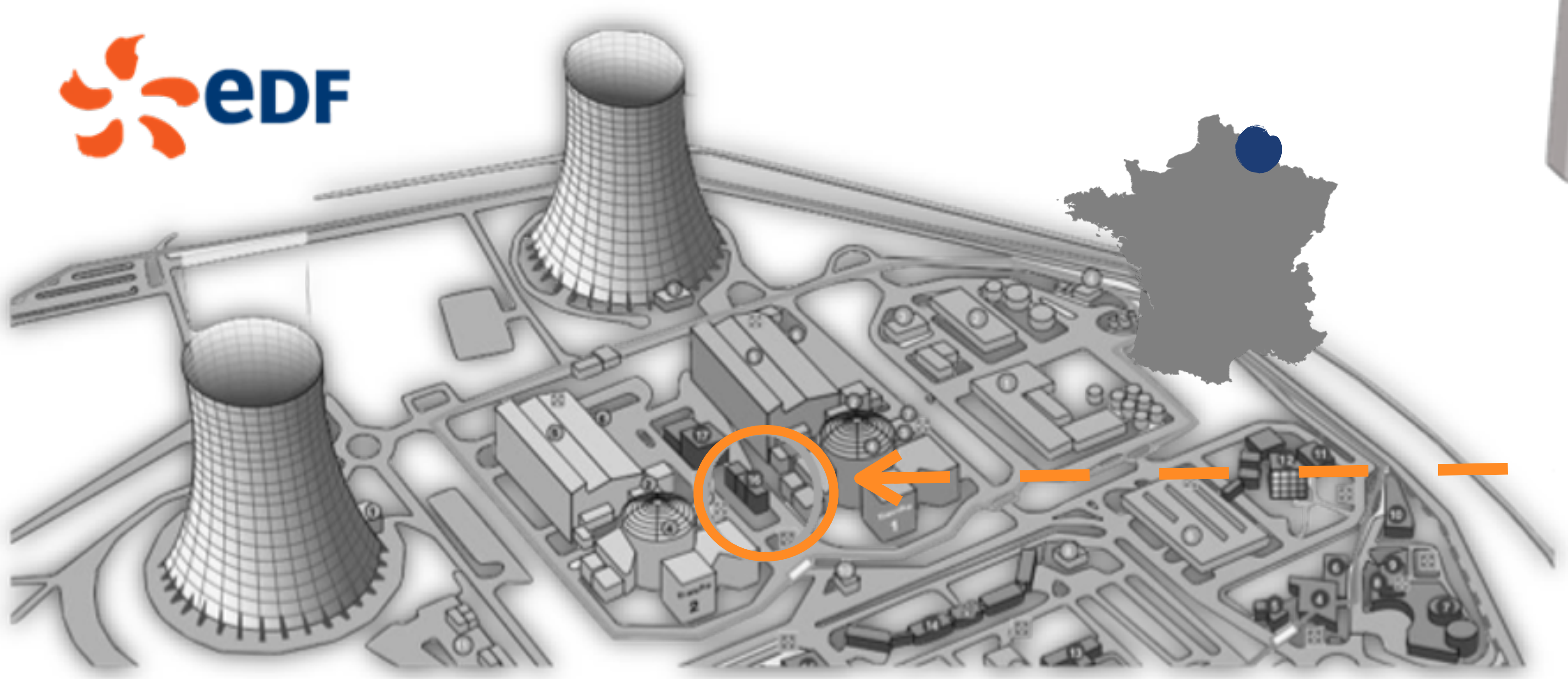


External shielding with borated polyethylene, lead and muon veto





Experiment located in the “very near site” basement room

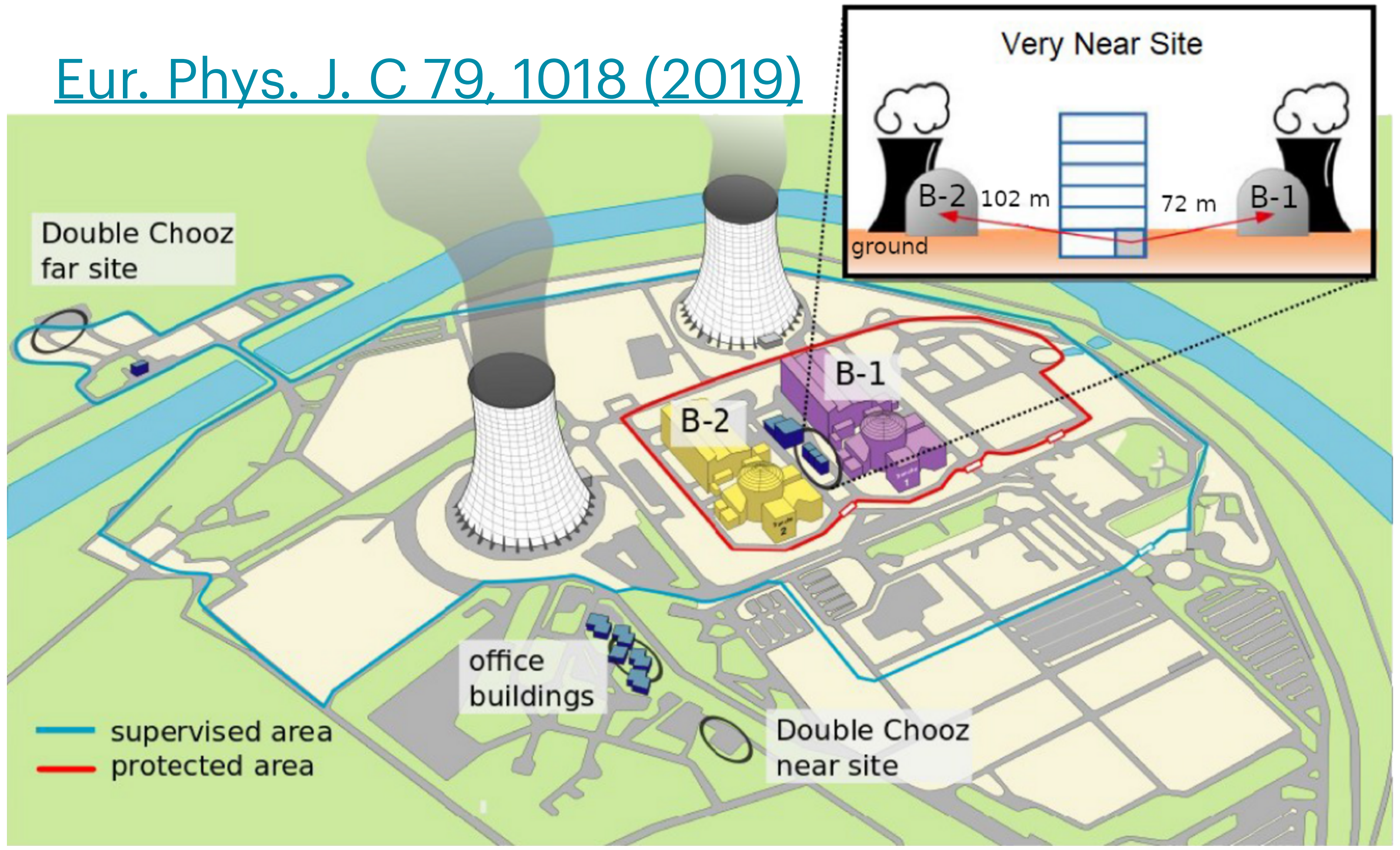


Antineutrinos from two reactor cores at the Chooz nuclear power plant in France

Experimental site

- Very Near Site (VNS): 24 m^2 basement room at 72 m and 102 m from two 4.25 GW$_{th}$ reactor cores
- Expected neutrino flux: 1.7 10^{12} ν/cm^2/s
- ~3 m w.e. shallow overburden, challenging background conditions
- Reactor correlated background negligible

Eur. Phys. J. C 79, 1018 (2019)

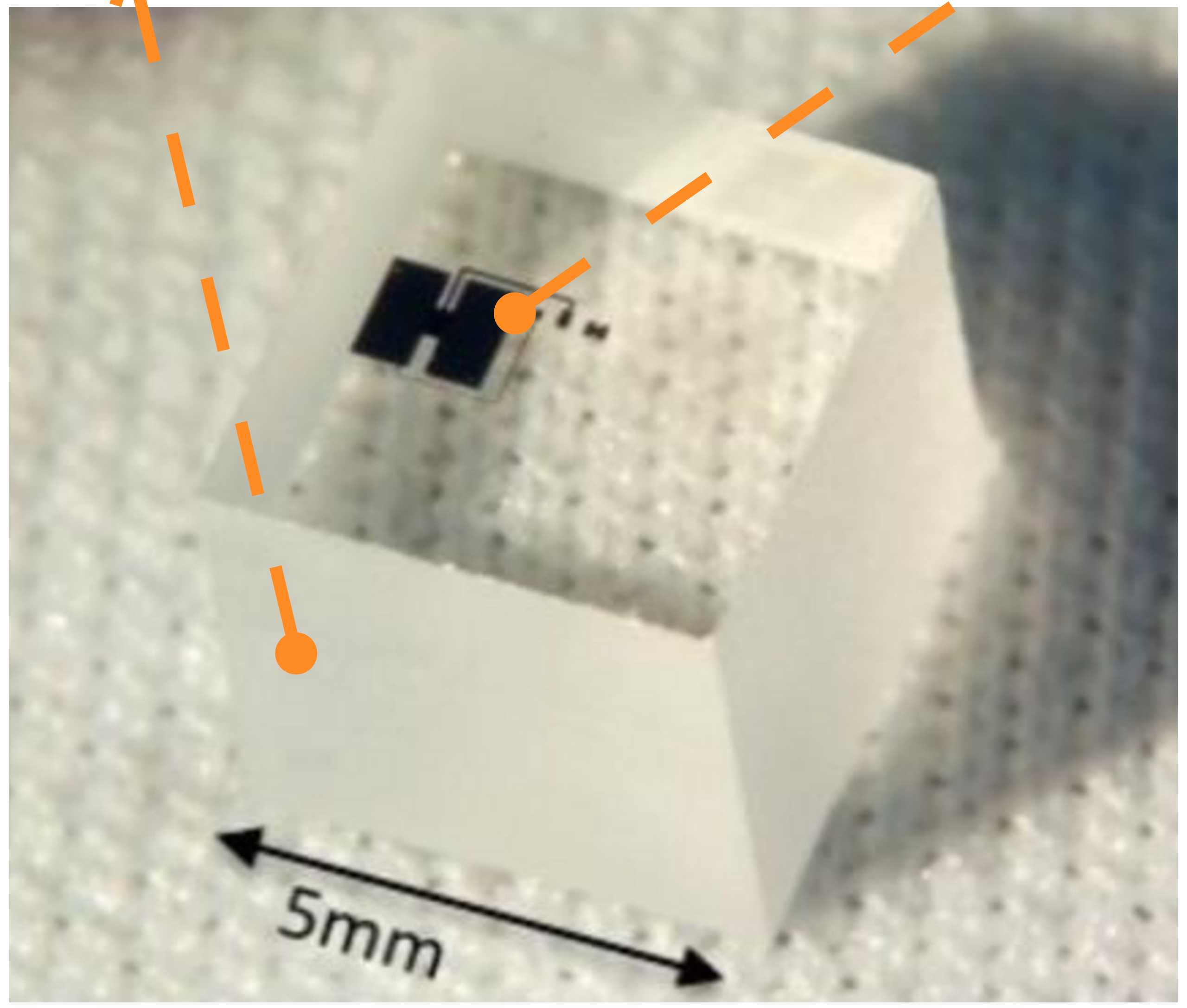


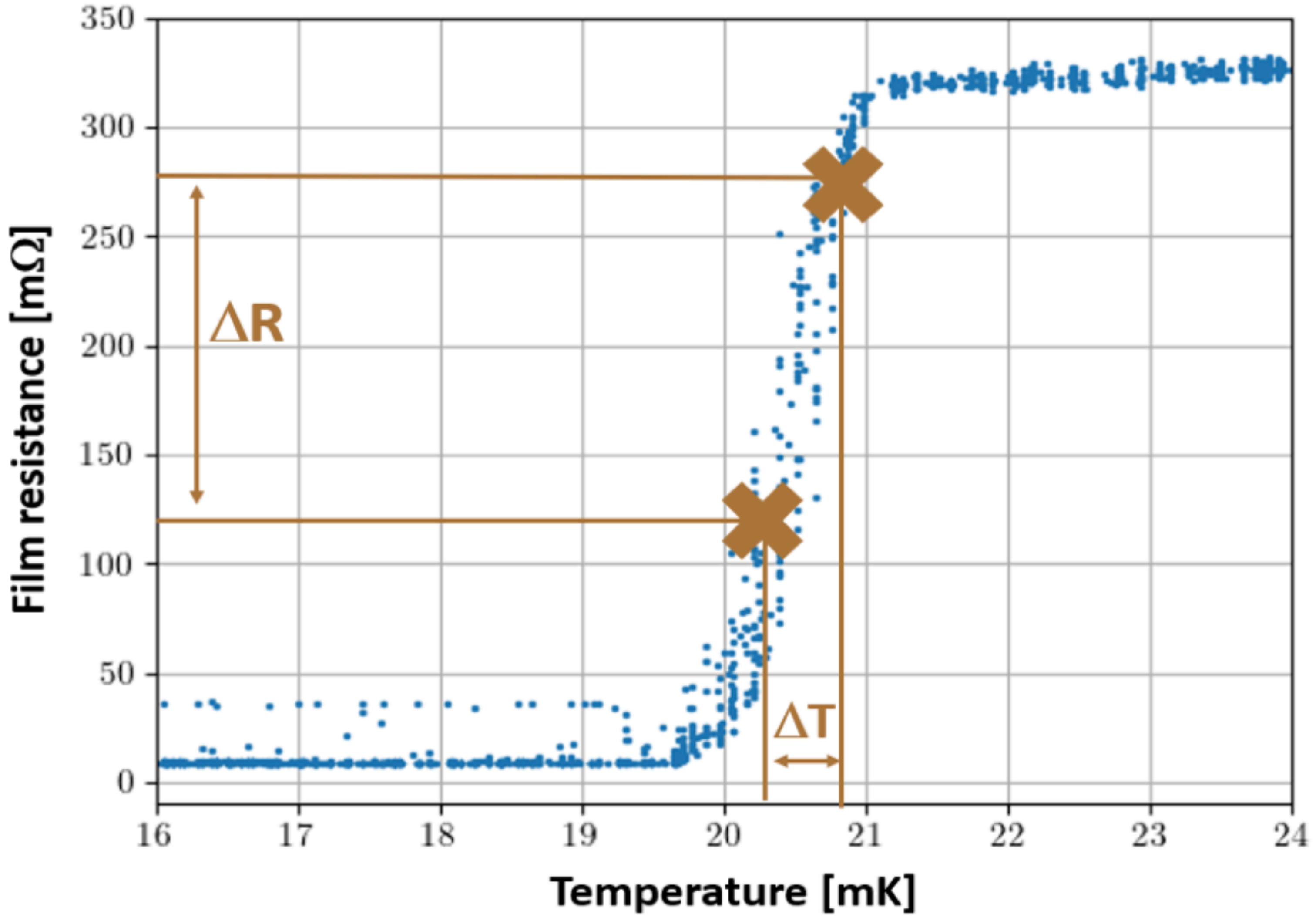
Preview of the VNS final setup

NUCLEUS cryogenic detectors

Absorber crystal: $CaWO_4$, Al_2O_3

Thermometer: Transition Edge Sensor (TES)





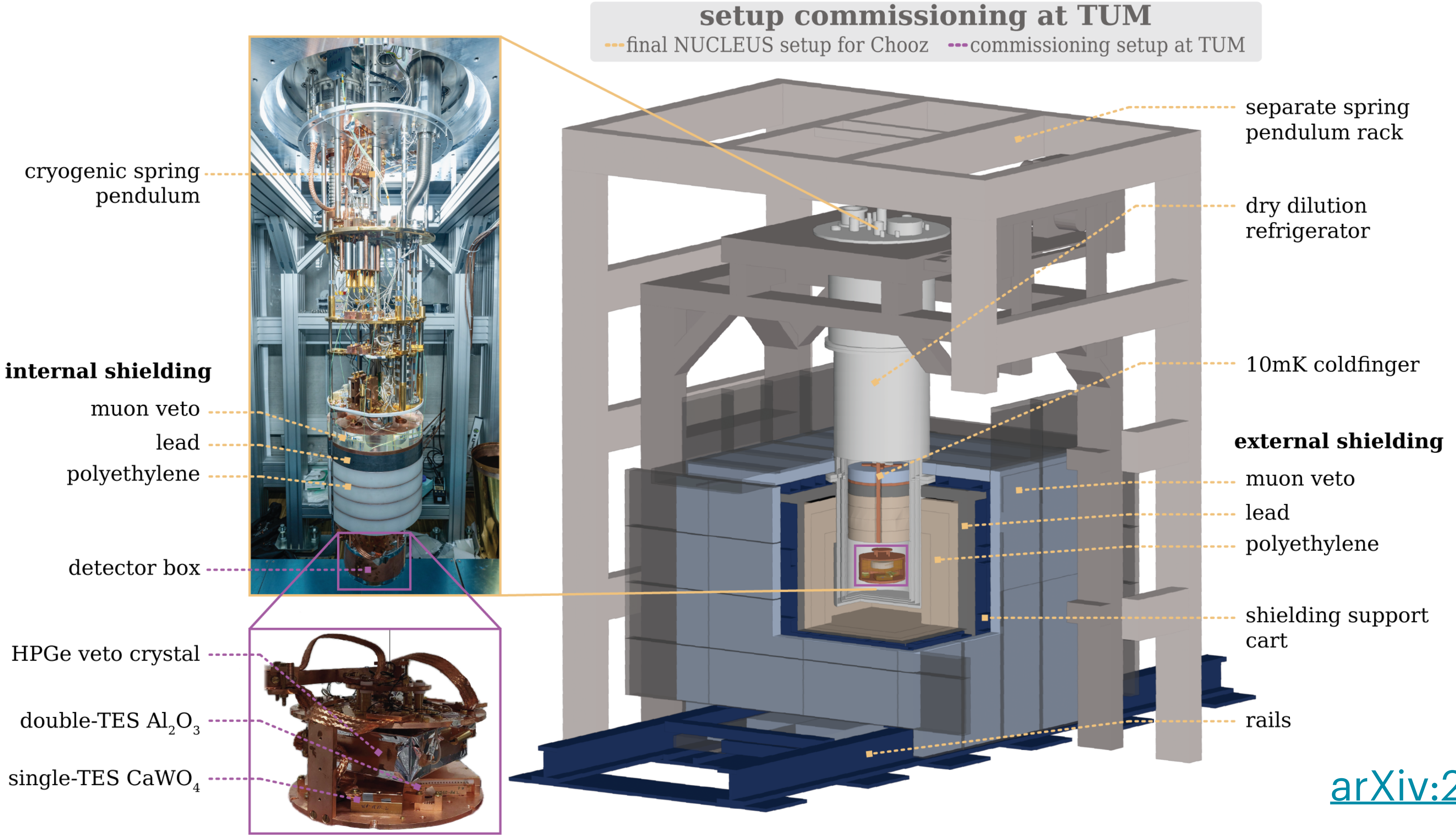
Phys. Rev. D 96, 022009 (2017)

- Excellent energy resolution and threshold O(20 eV)
  - NUCLEUS Al_2O_3 prototype (19.7 +/- 0.9) eV threshold
  - Similar performance achieved multiple times during development @TUM

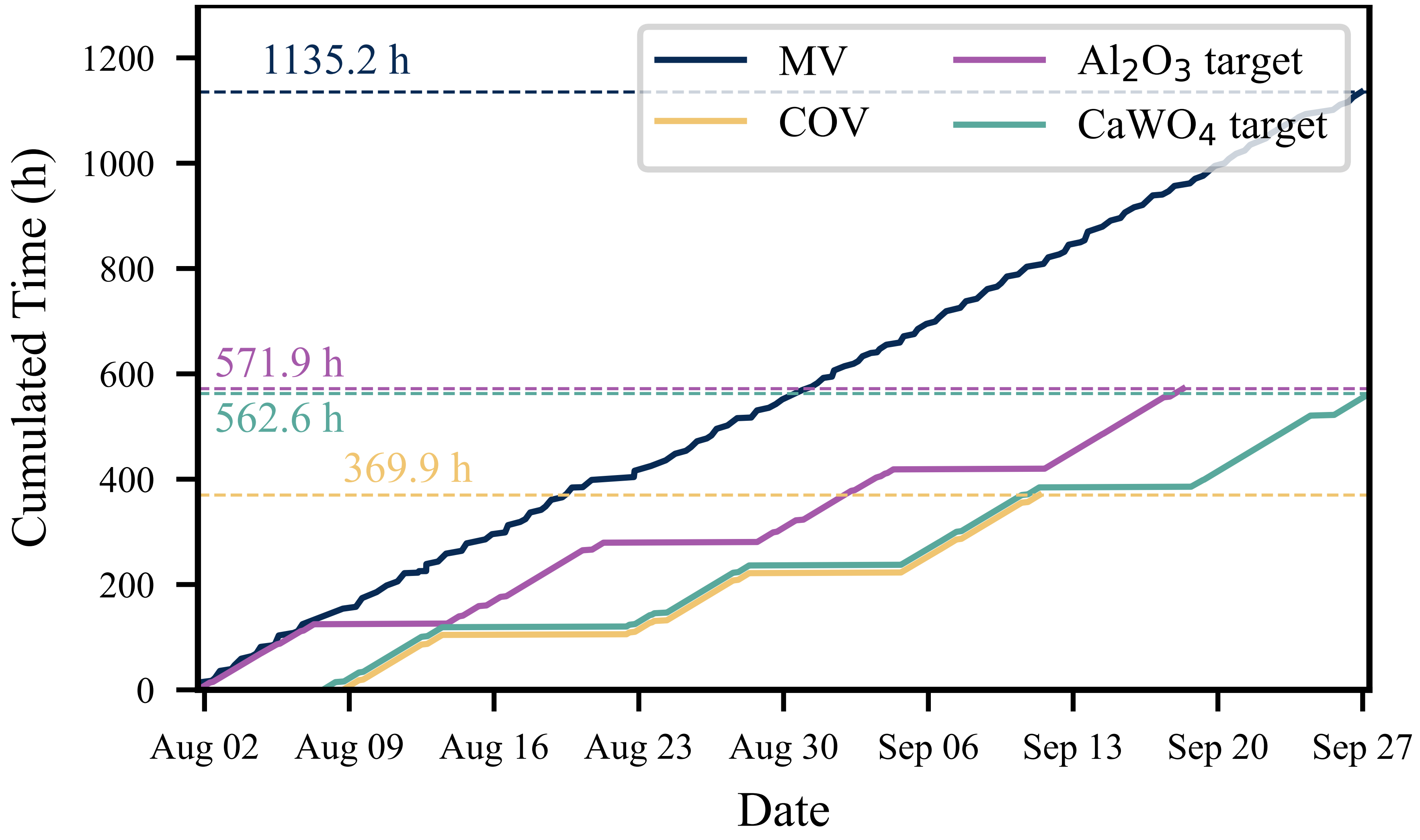
Neutrino scatters off a nucleus in the target crystal → Recoiling nucleus leads to temperature rise of the cryogenic target crystal → Temperature rise leads to resistance change of superconducting W-film of the TES

Result from the commissioning @TUM

- Commissioning of an essential version of the experiment @TUM completed in 2024
- Milestone: demonstrated experiment feasibility & two months stable operation of target detectors with active and passive shielding

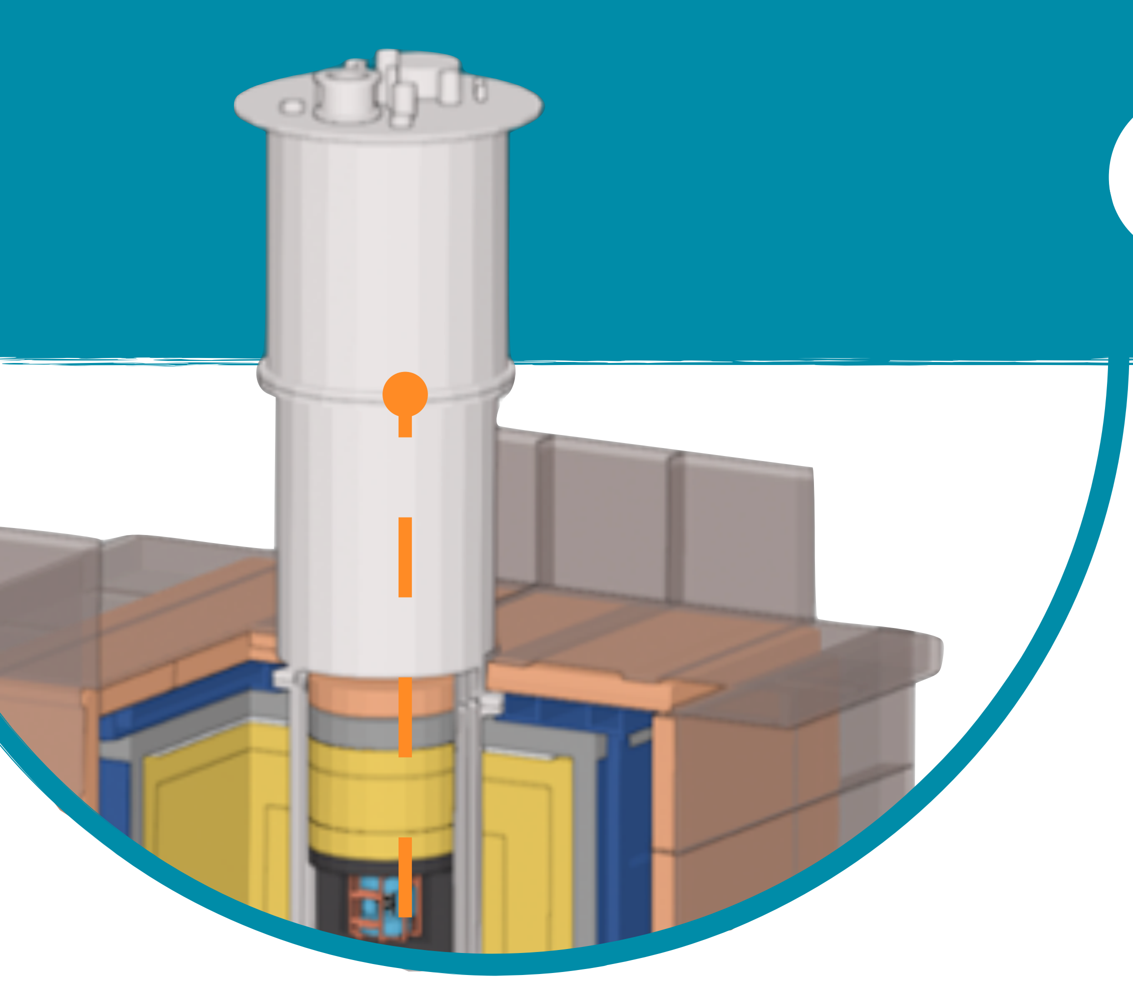


- One $CaWO_4$ crystal with TES, one Al_2O_3 crystal with two TESs
- One germanium outer veto crystal (COV)
- Full muon veto (MV)



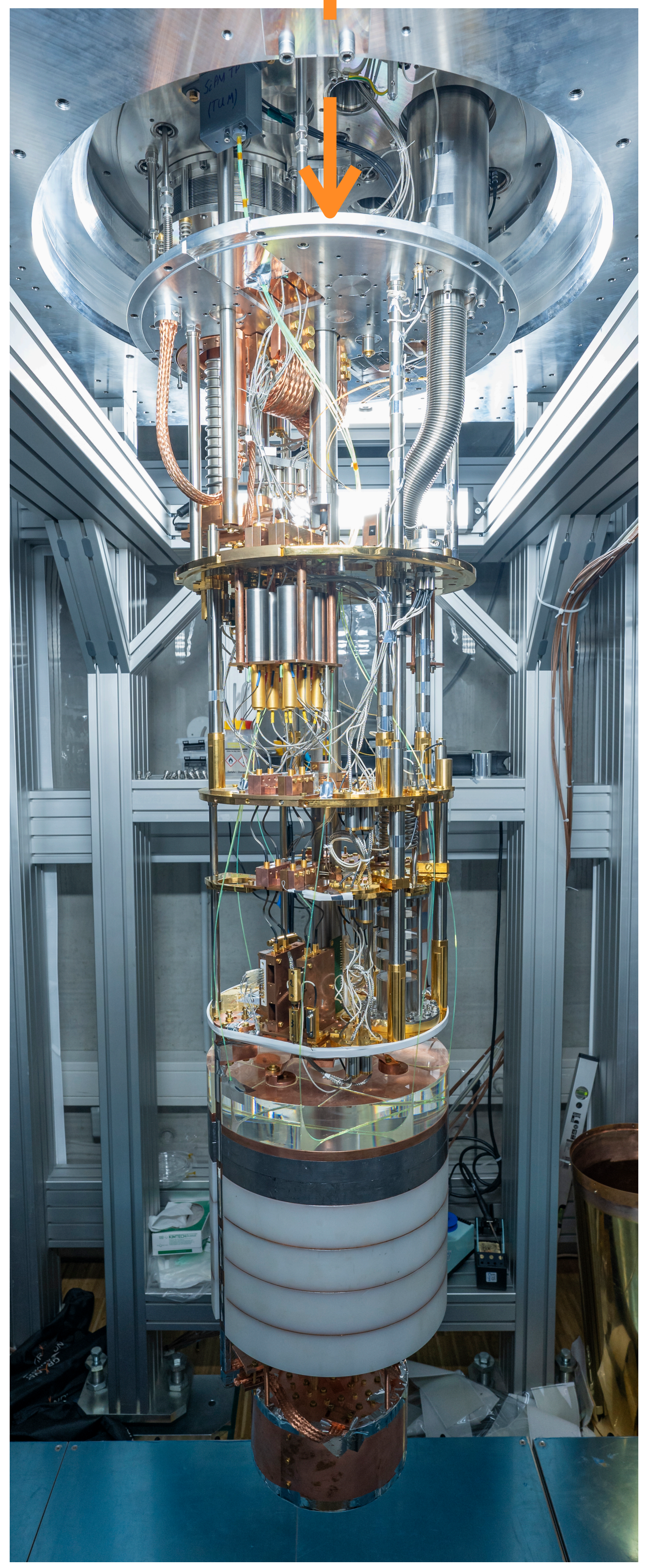
arXiv:2508.02488

Cryogenic detector operation



- Dry dilution refrigerator (BlueFors LD400) with 7 mK base temperature
- Pulsed tube cryocooler: challenging vibration environment
- Custom vibration decoupling system (patent protected)

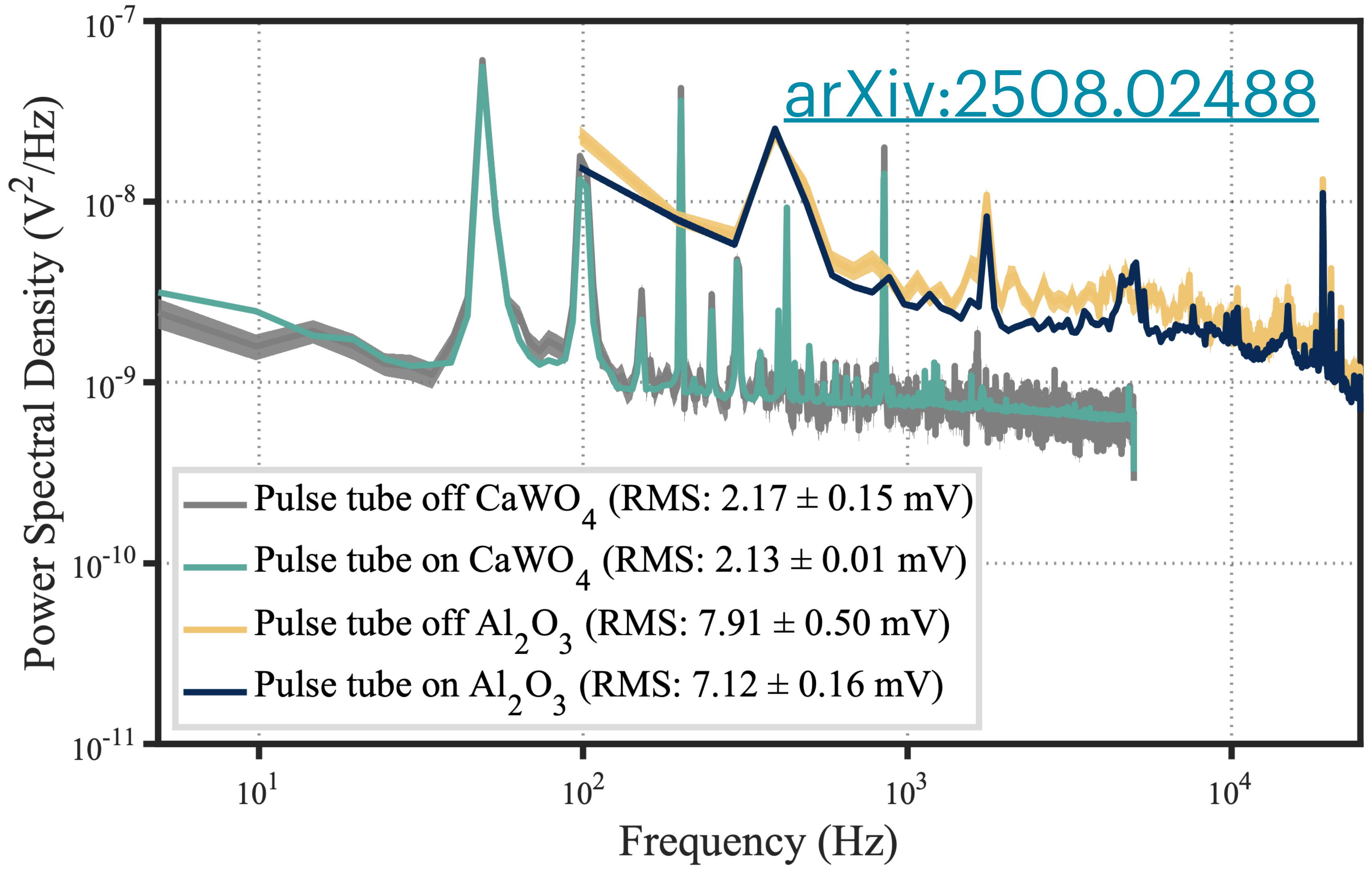
  [A. Wex et al 2025 JINST 20 P05022]



Spring hanging from independent rack, coupled to the 4K stage

Kevlar wire for thermal isolation

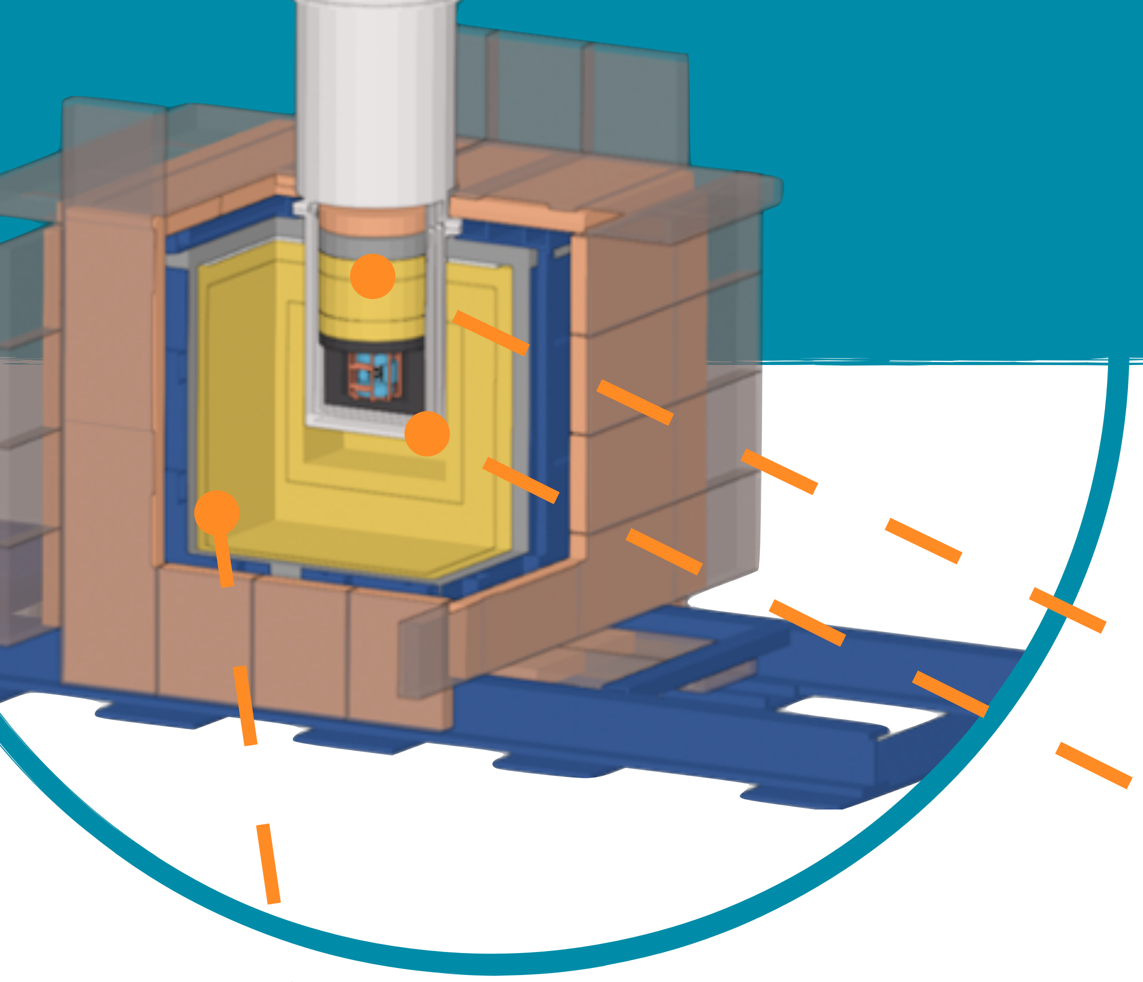
Detector box at < 10 mK

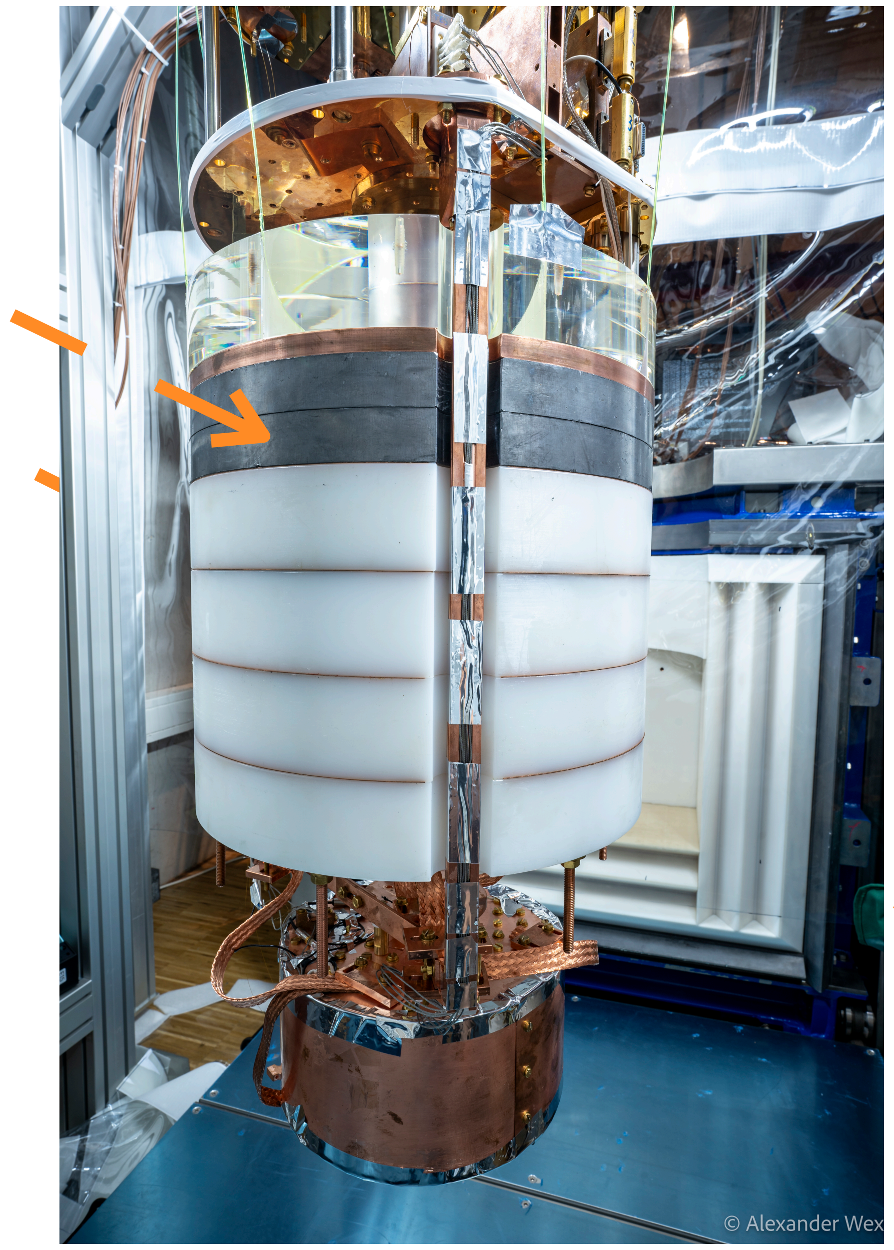


Commissioning results:

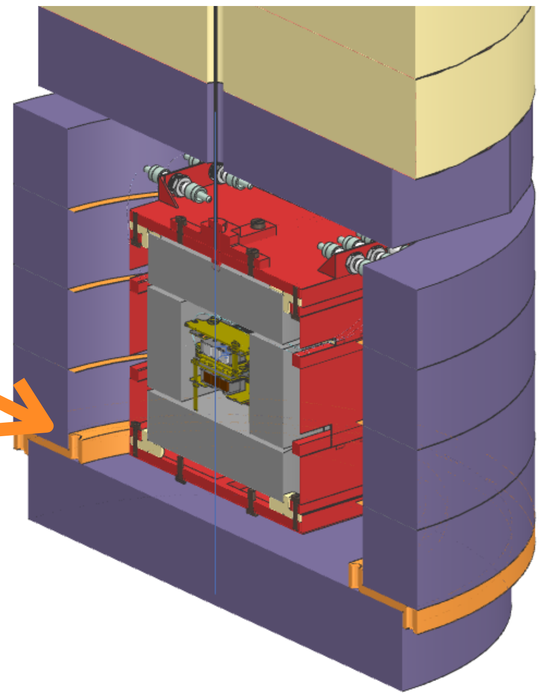
☑ More than 2 months stable and continuous operation of cryogenic detectors independent of pulse tube vibrations

Passive shielding



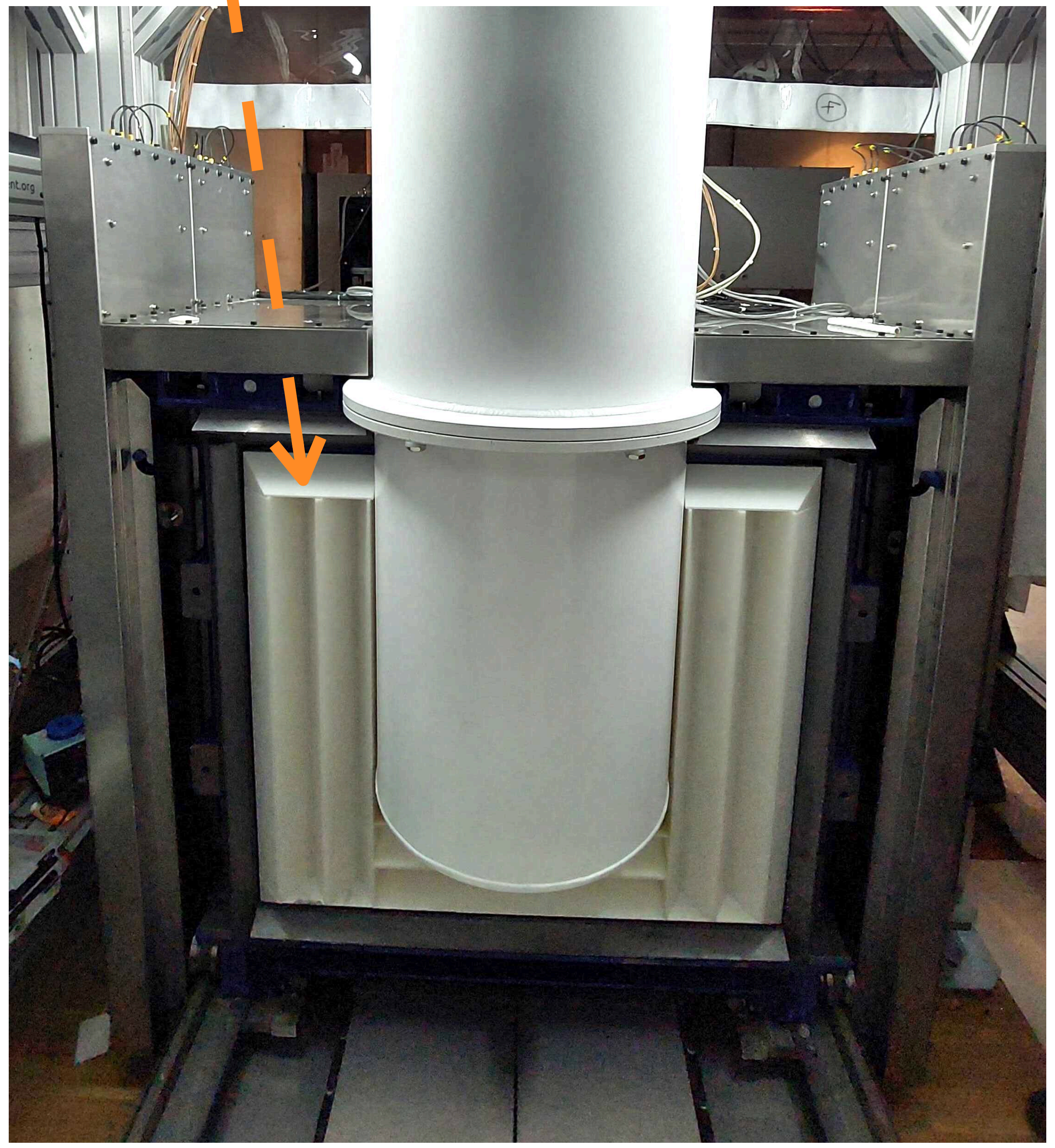


Cryogenic internal shielding:
extension of external shielding inside the cryostat with lead + borated polyethylene



Additional 4 cm **boron carbide (B_4C)** around the detectors:

- ☑ All pieces produced and delivered
- ☐ Integration to be done soon at VNS

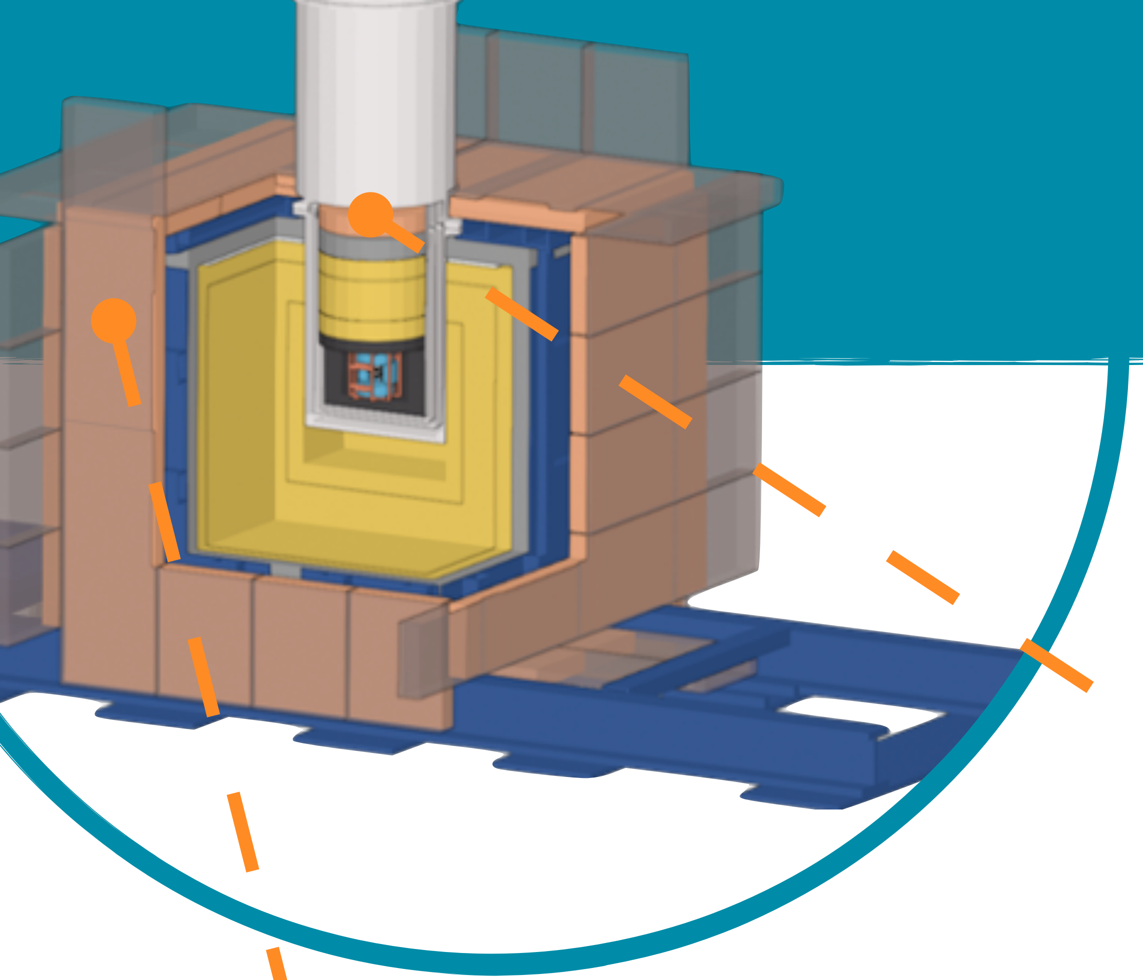


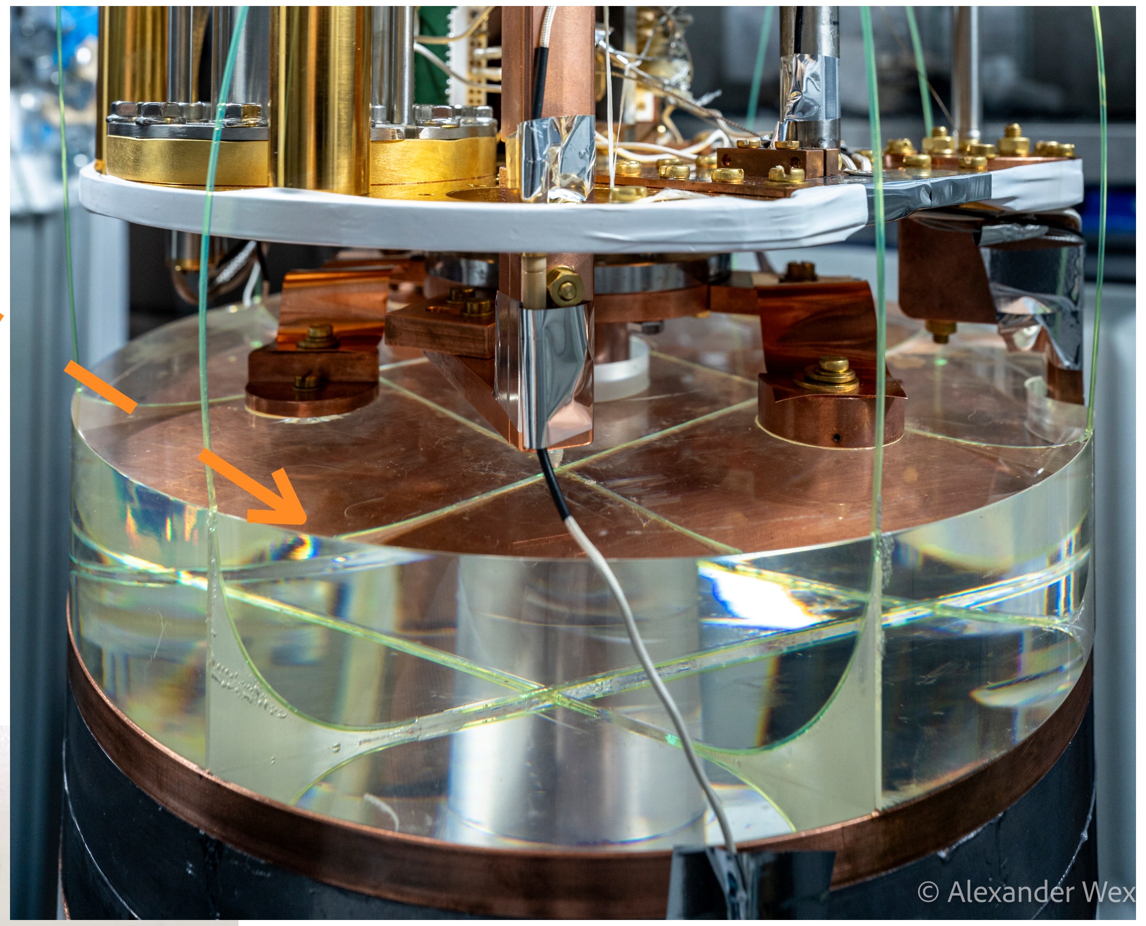
External shielding:
5cm lead + 20 cm borated polyethylene

Commissioning results:

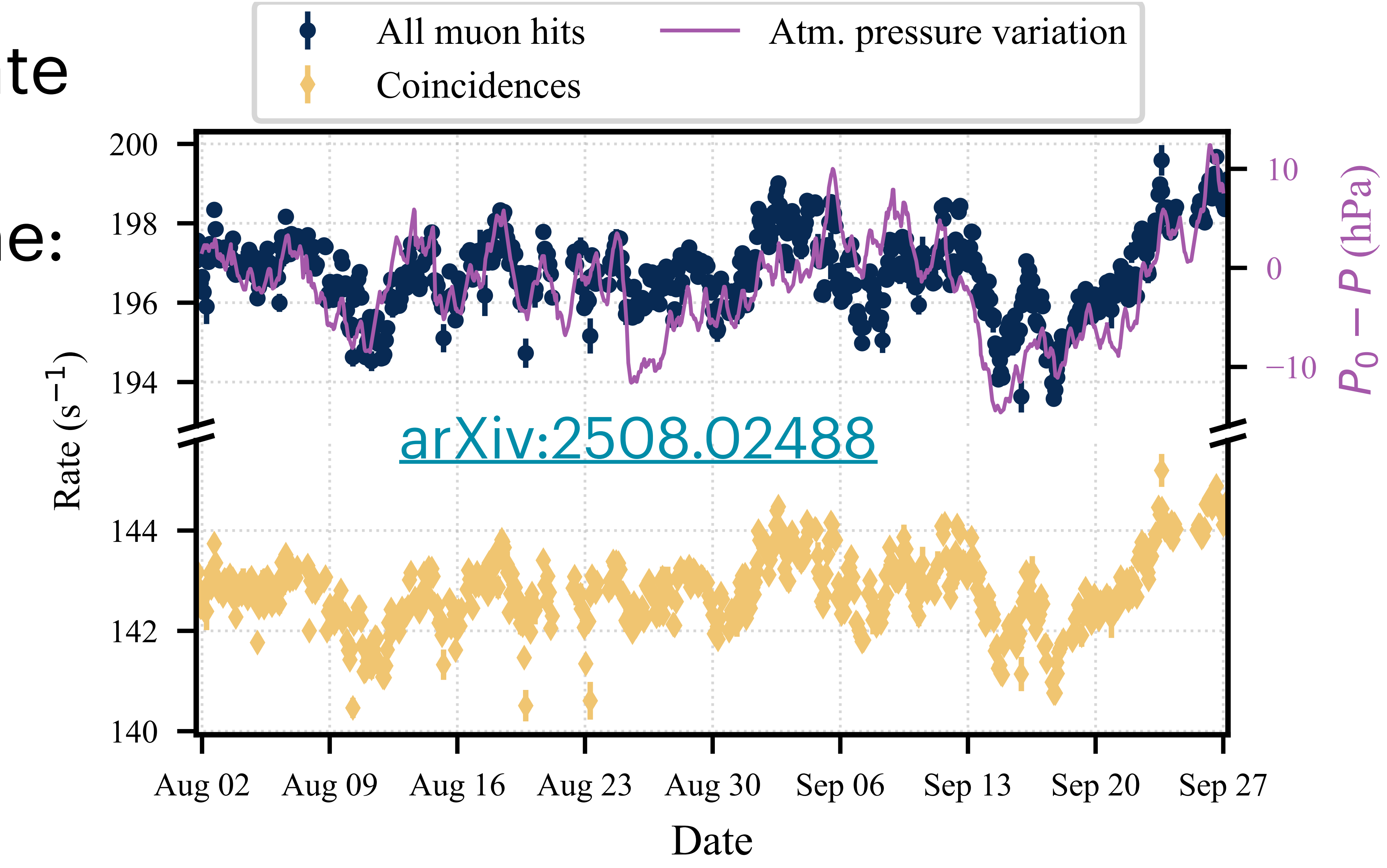
- ☑ External and internal shielding fully commissioned
- ☑ Full thermalisation of internal shielding (~50 kg) achieved in ~10 days
- ☑ Background suppression of ambient γs validated

Muon veto (MV)





Muon rate stability over time:



External Muon Veto:

28 plastic scintillator modules with WLS optical fibres and SiPM read out

V. Wagner et al 2022 JINST 17 T05020

Cryogenic extension:

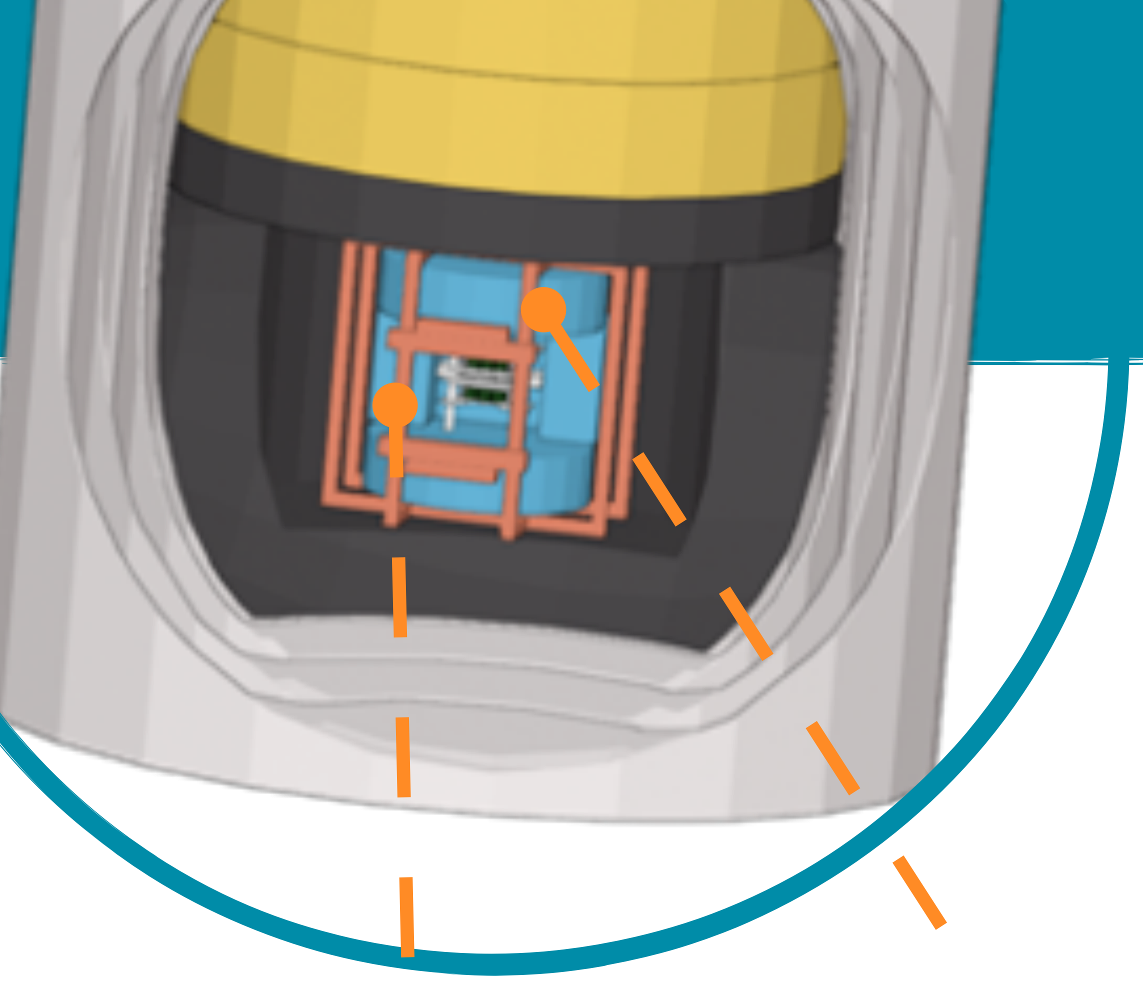
Disk-shaped cryogenic muon veto at ~800 mK for 4π coverage

A. Erhart et al J Low Temp Phys 209, 346–354 (2022)

Commissioning results:

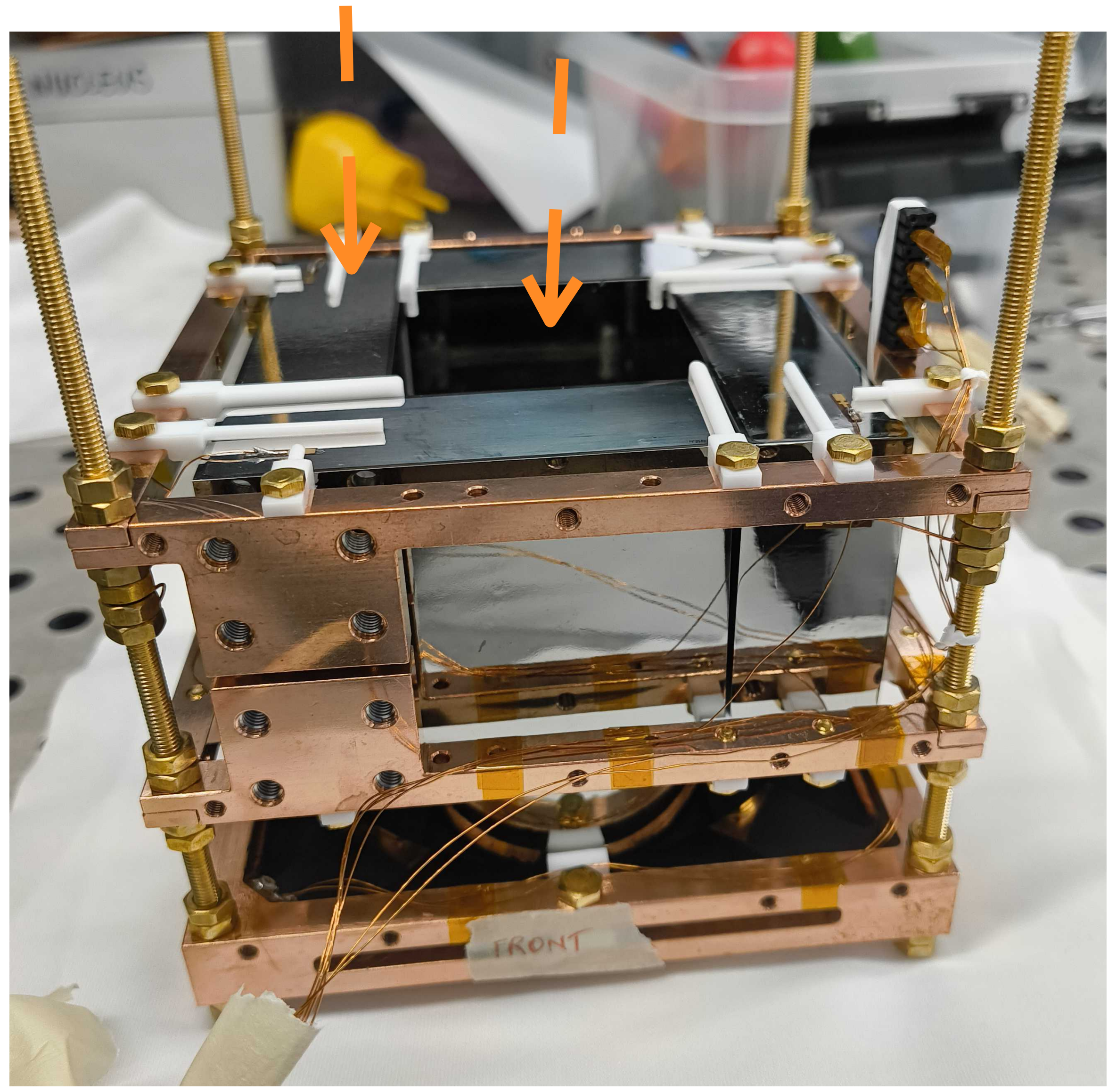
- ☑ Full muon veto continuously operated for 2 months
- ☑ Fully validated in terms of rate, efficiency and dead time

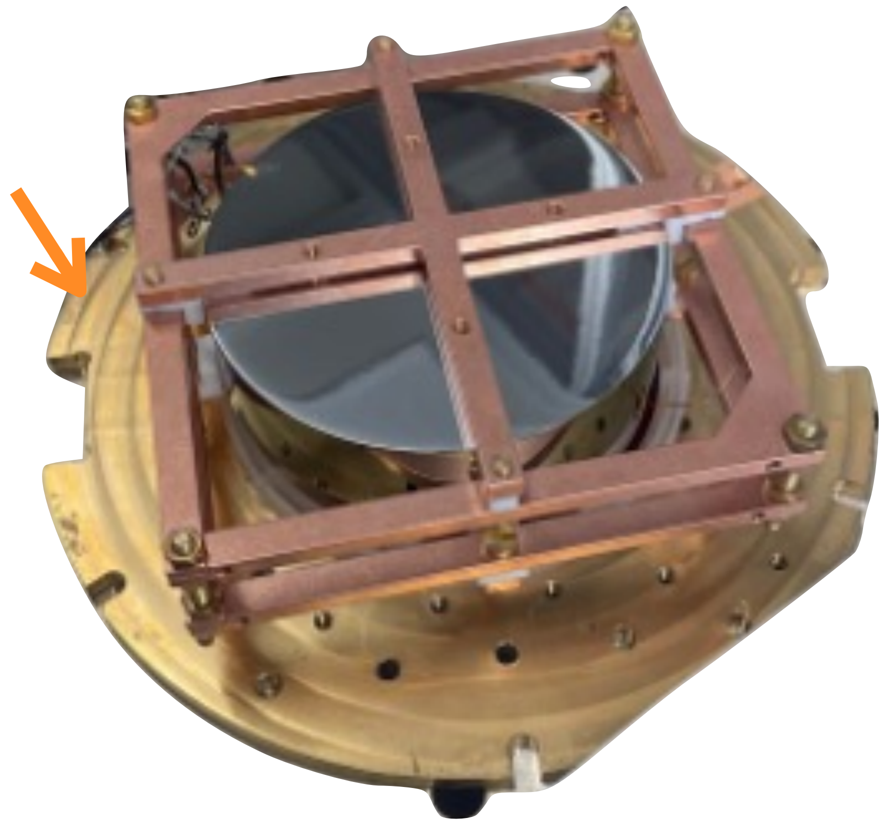
Cryogenic outer veto (COV)



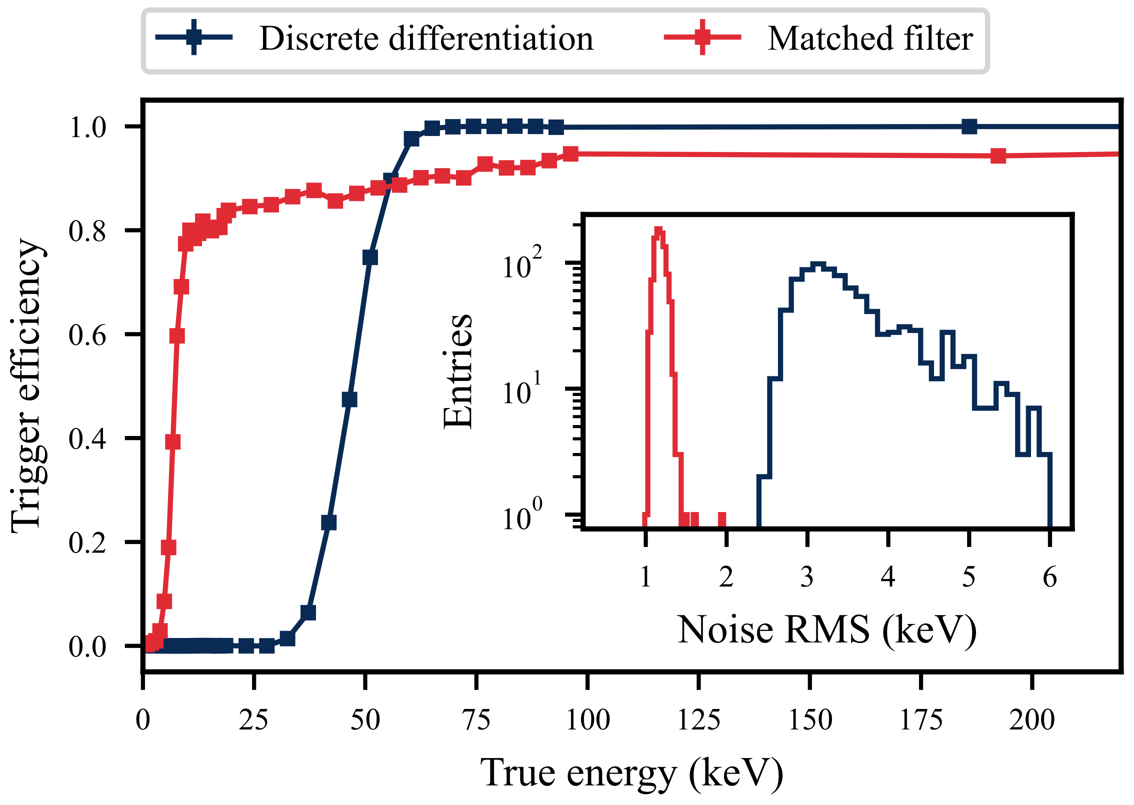
- 6 High purity germanium detectors (2 cylindrical and 4 rectangular)
- 4π coverage of target detectors
- Background suppression of external γs

Target detectors here!

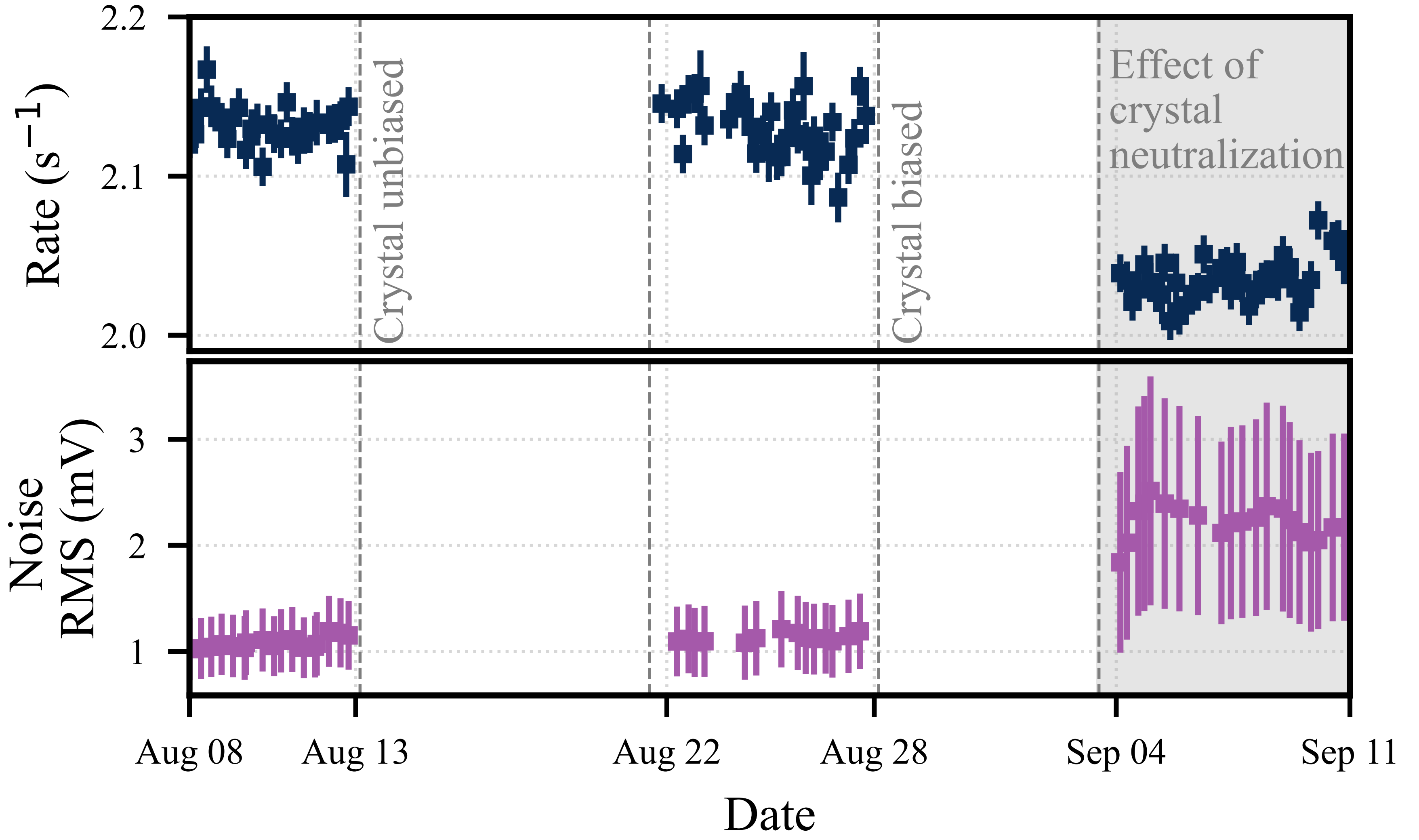




arXiv:2508.02488



Cryogenic outer veto stability over time:



Commissioning results:

- ☑ One cylindrical crystal with 6 keV energy threshold with one electrode read out
- ☑ Stable performances

Recent developments:

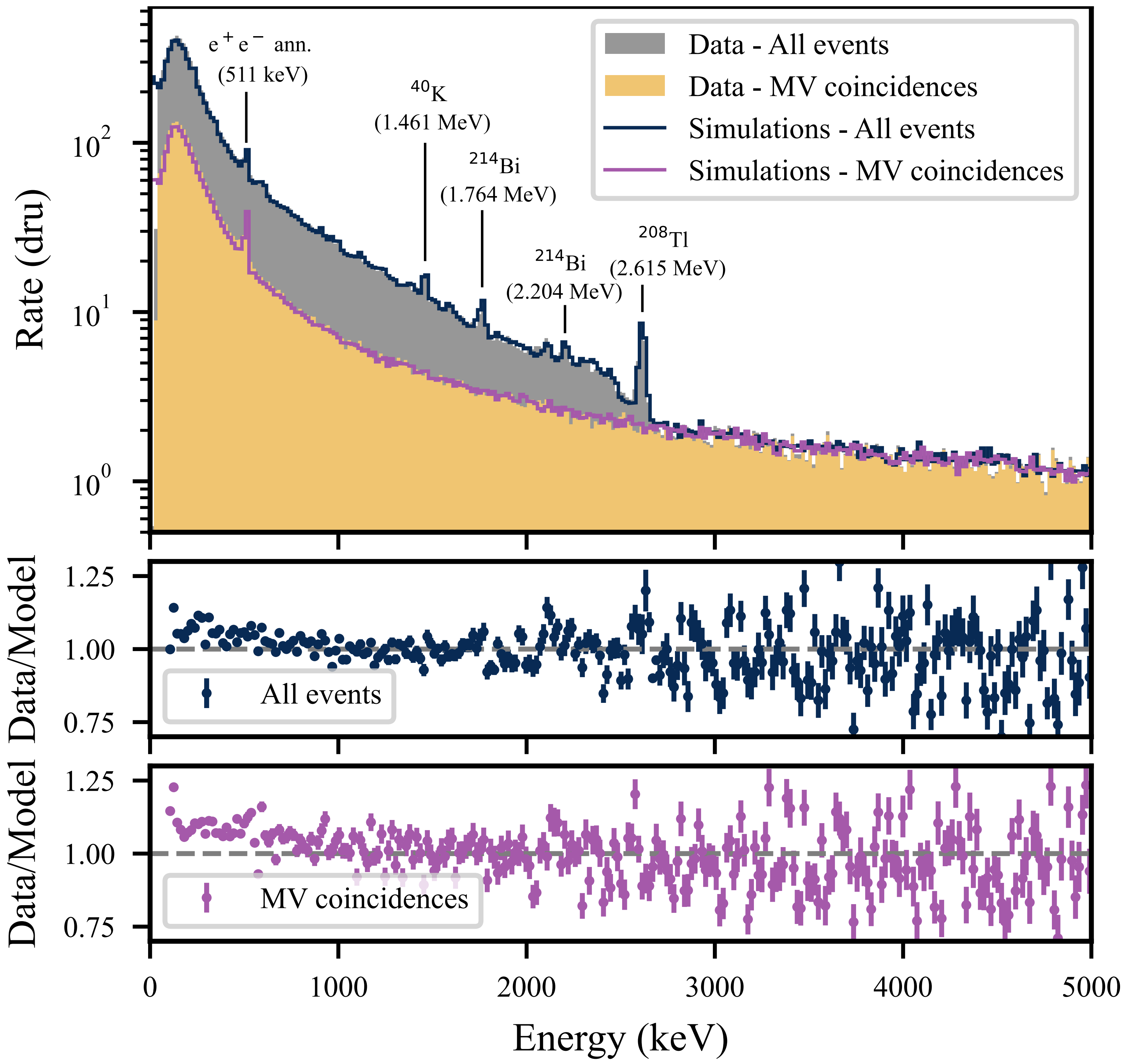
- ☑ Upscaling to 6 crystals with < 10 keV threshold demonstrated
- ☐ Cage optimisation, two electrodes read out, electronic improvements

Validation of simulation

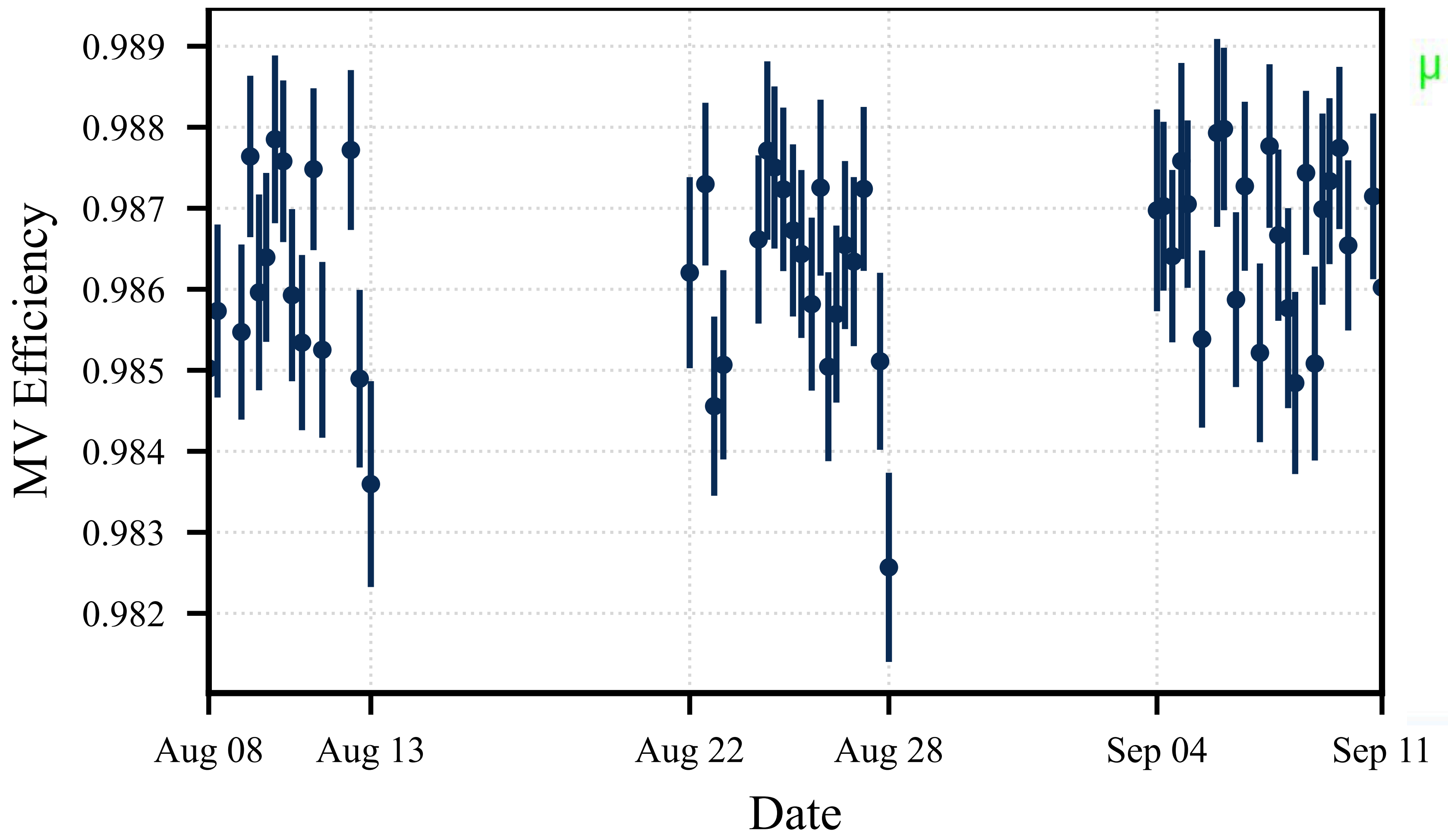
- COV allows a measurement of the background very close to the target detectors
- Coincidence analysis between COV and MV allows to identify γ/μ background contributions

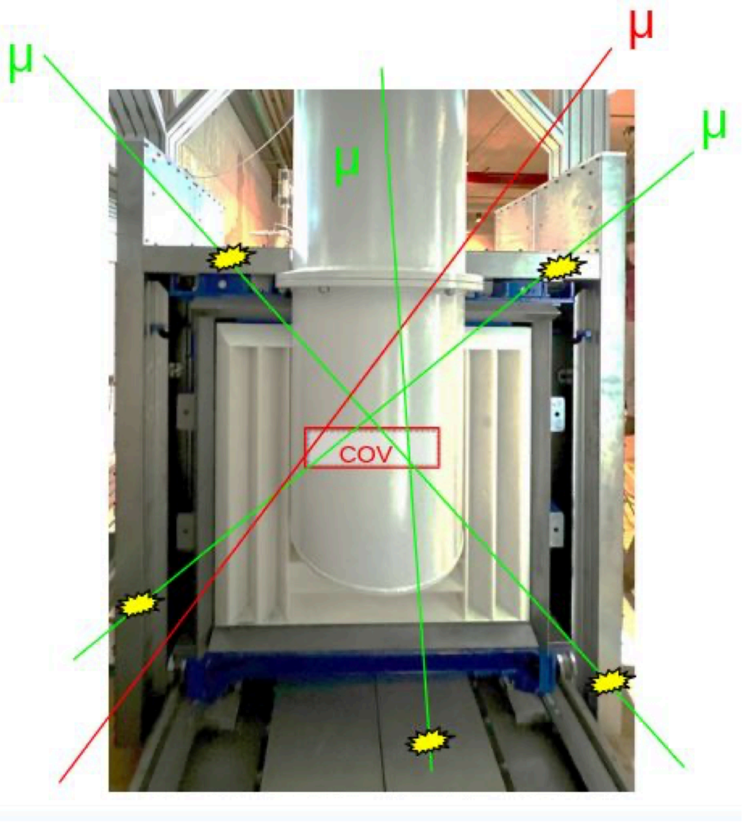
arXiv:2508.02488

Energy spectrum in the COV



Muon veto efficiency



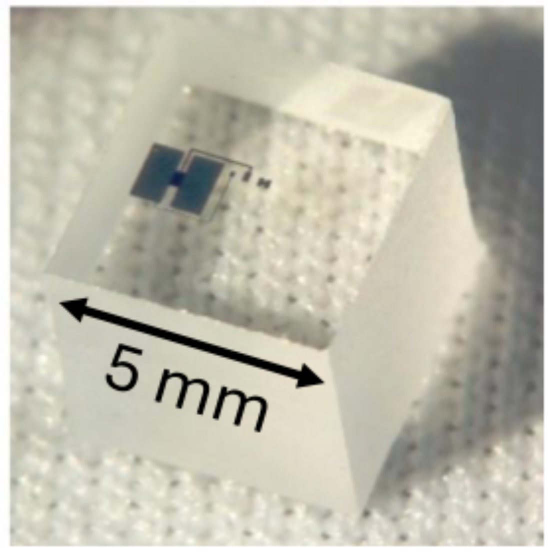


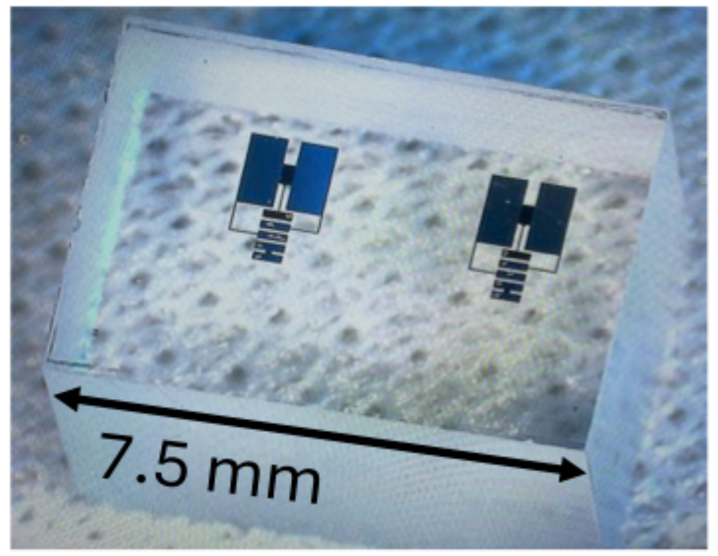
Commissioning results:

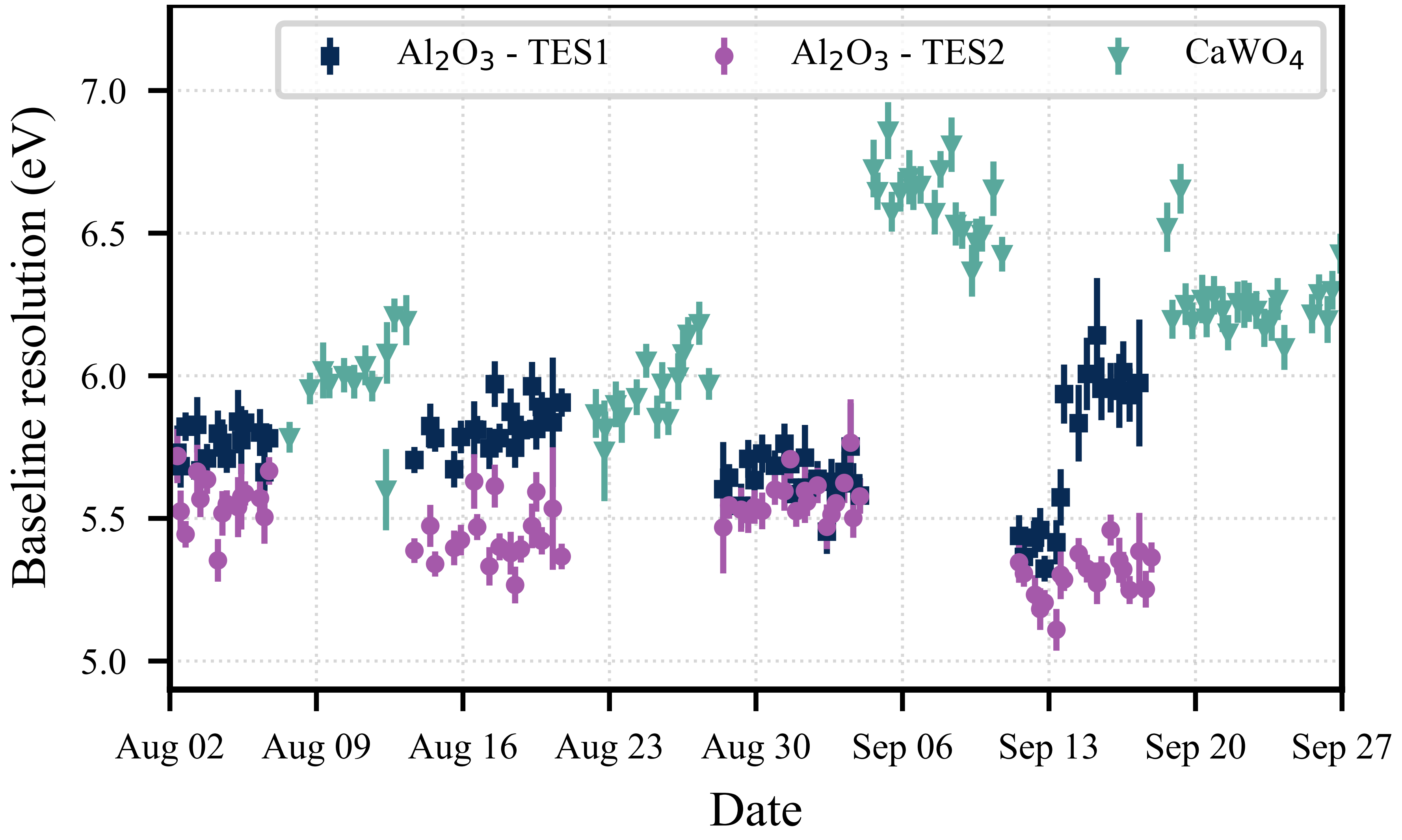
- ☑ Very good agreement between data and simulation for both COV and MV
- ☑ Validation of atmospheric muon simulations, ambient gamma model and implementation of shielding complex geometry

Cryogenic target detectors

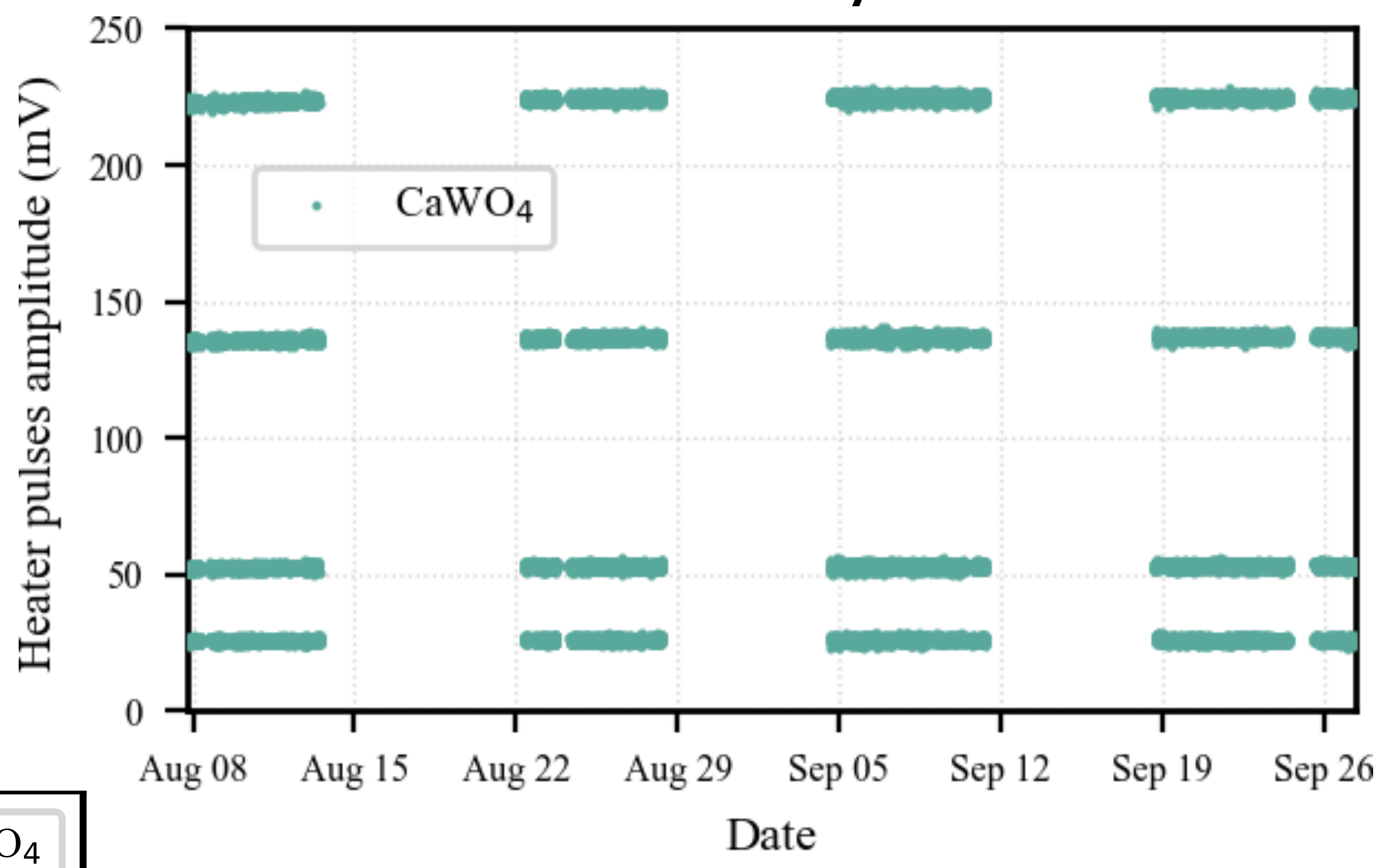
- Two cryogenic detectors: $CaWO_4$ with TES, Al_2O_3 with 2 TESs







Better than 1% stability over time:

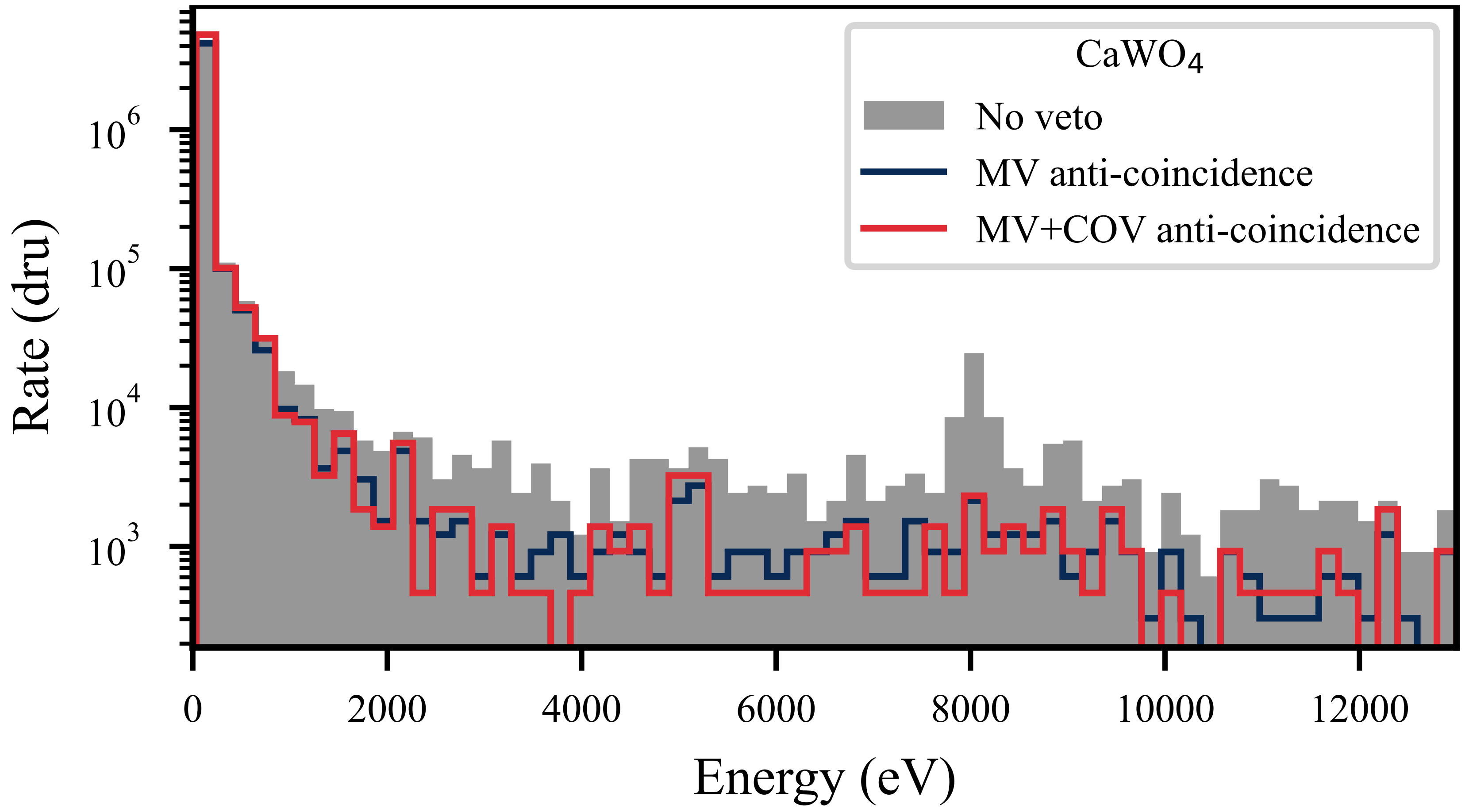


arXiv:2508.02488

Baseline resolution:

$CaWO_4$	Al_2O_3
6.2 +/- 0.3 eV	5.7 +/- 0.2 eV 5.5 +/- 0.2 eV

Background measurement with veto cuts:



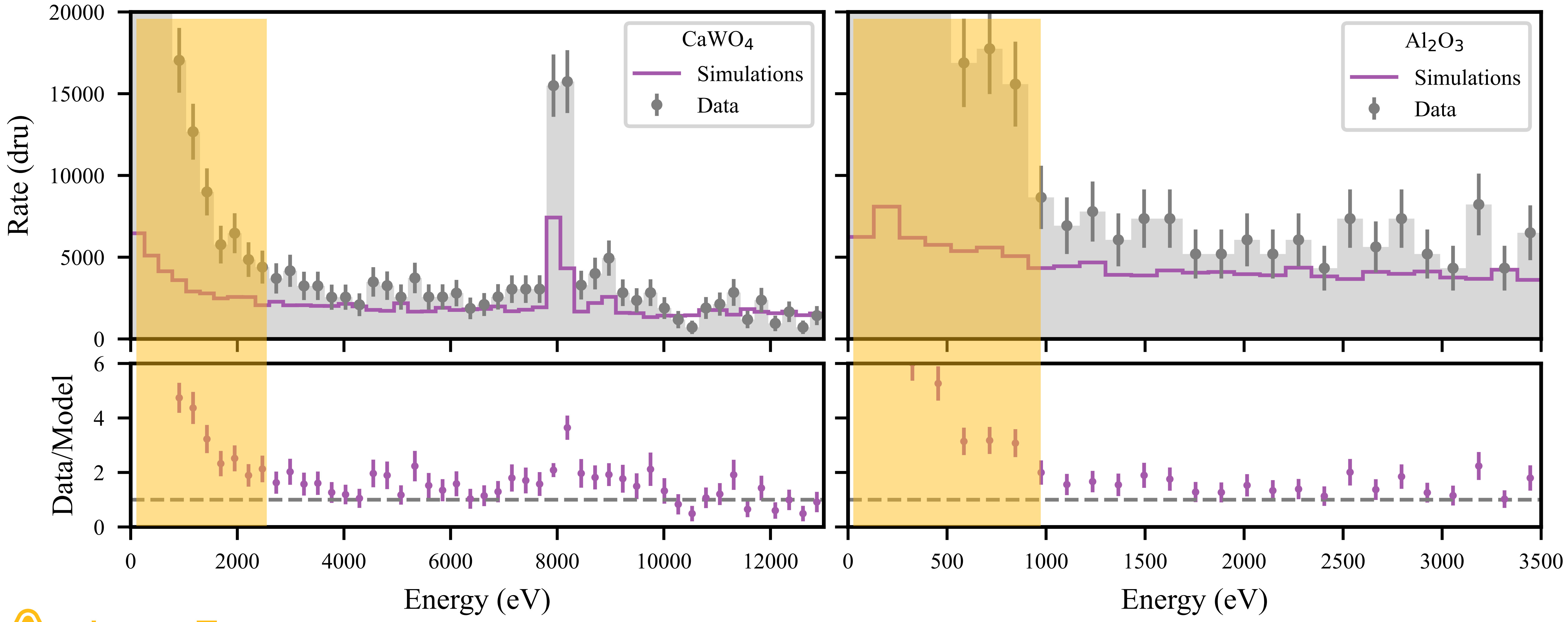
Commissioning results:

- ☑ Stable performance over the entire run
- ☑ Meeting threshold goal for technical run at Chooz

Simulation of low energy background

- GEANT4 simulation to estimate the particle background in the cryogenic target detectors
- Know challenge in low-energy rare-event searches: limitations of GEANT4 at low energies

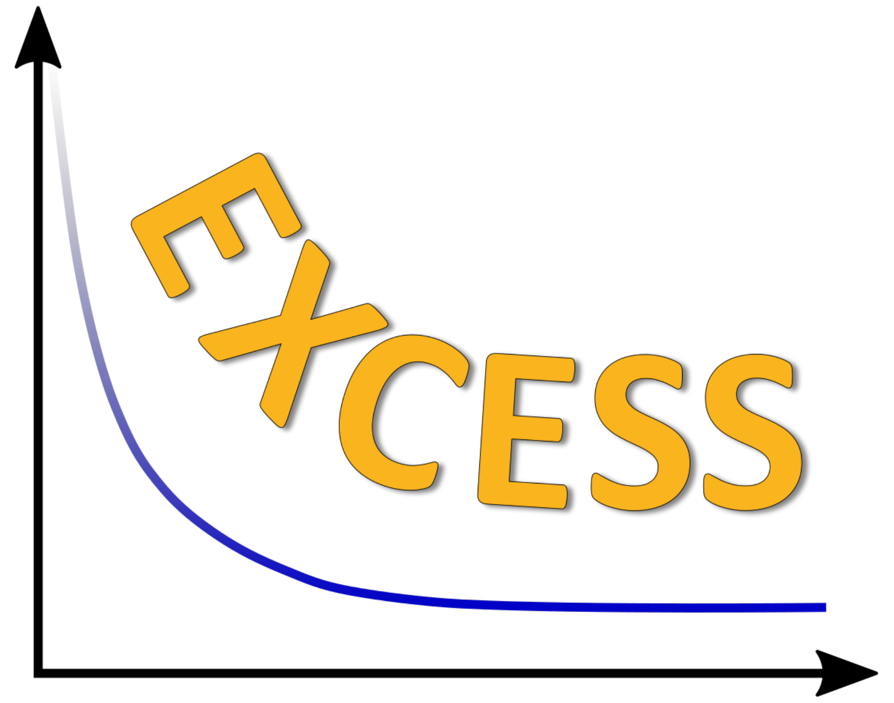
arXiv:2508.02488



Low Energy Excess!!!!!!!

- Data/simulation agreement up to a factor 1.5 in both detectors below the Copper X-ray lines
- Worse disagreement (~2.3) in the Copper X-ray line region
- Good agreement (~1) above
- Consistent picture after different veto cuts
- Further investigation ongoing

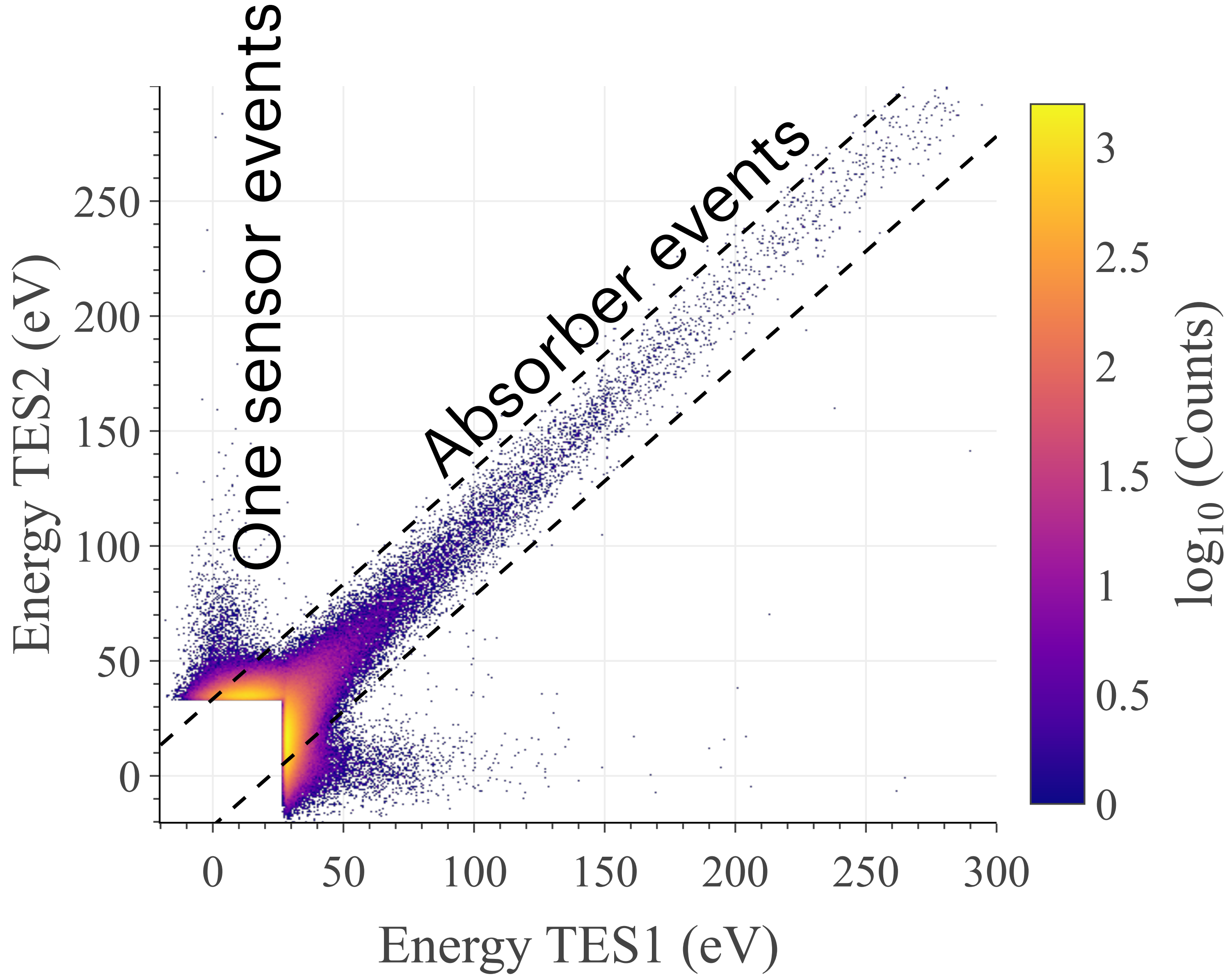
The Low Energy Excess (LEE)



[SciPost Phys.Proc. 9 (2022) 001]

- Many low-threshold experiments observe rising event rates of yet unknown origins below few hundreds eV and above the background expectation: **significant impact on CEvNS sensitivity**
- Two possible origins:

Credit: Nicole Schermer



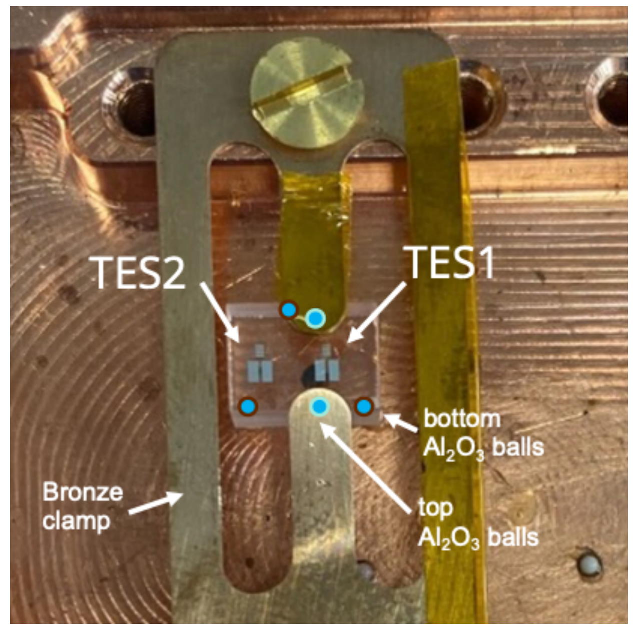
1. Sensor-related stress:
events at TES-detector interface

☑ Discrimination with double-TES detector (CRESST, TESSERACT)

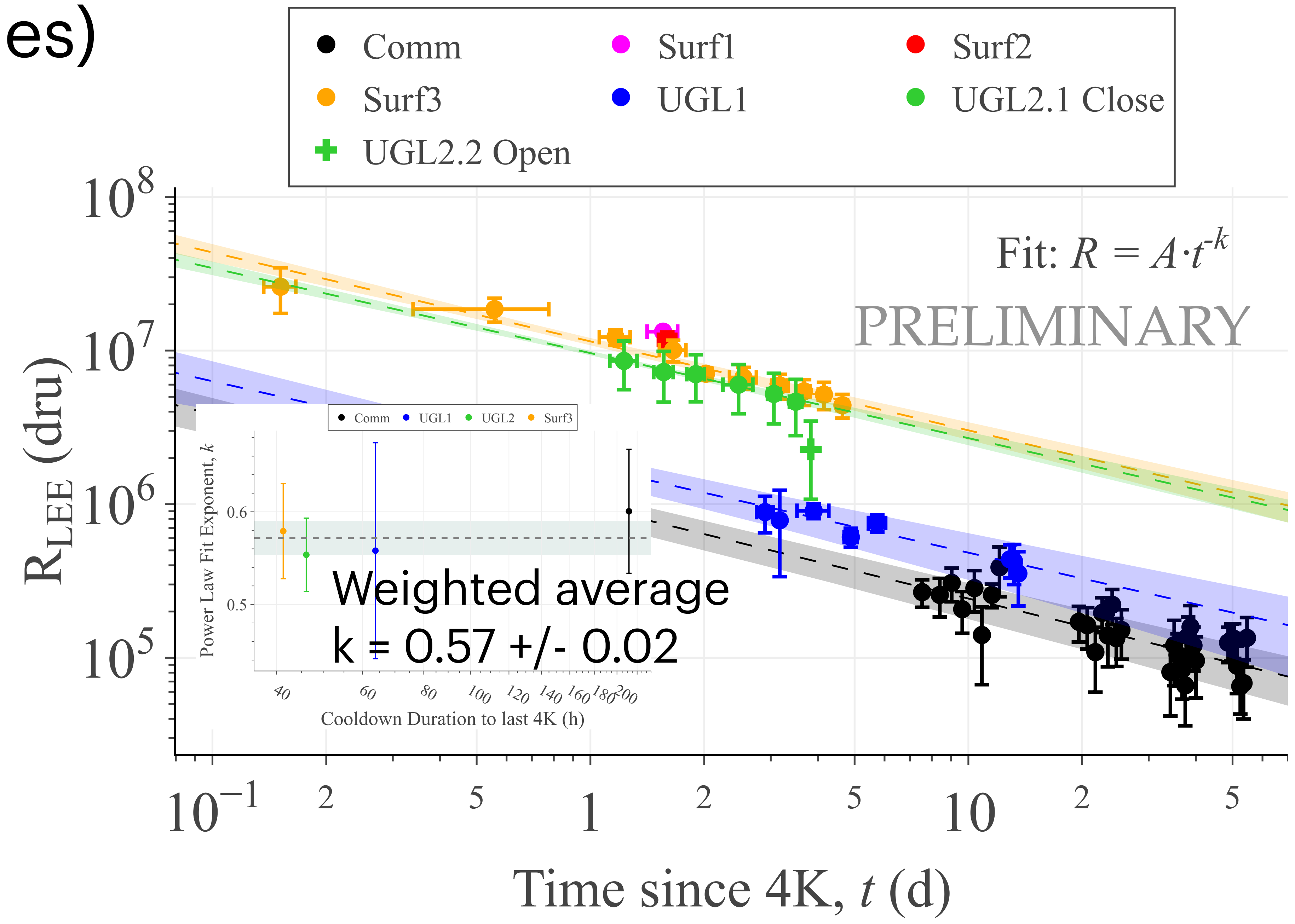
2. Holder-related stress:
events from stress relaxation in holder-detector interface

☐ R&D on instrumented holder: discrimination power to be demonstrated

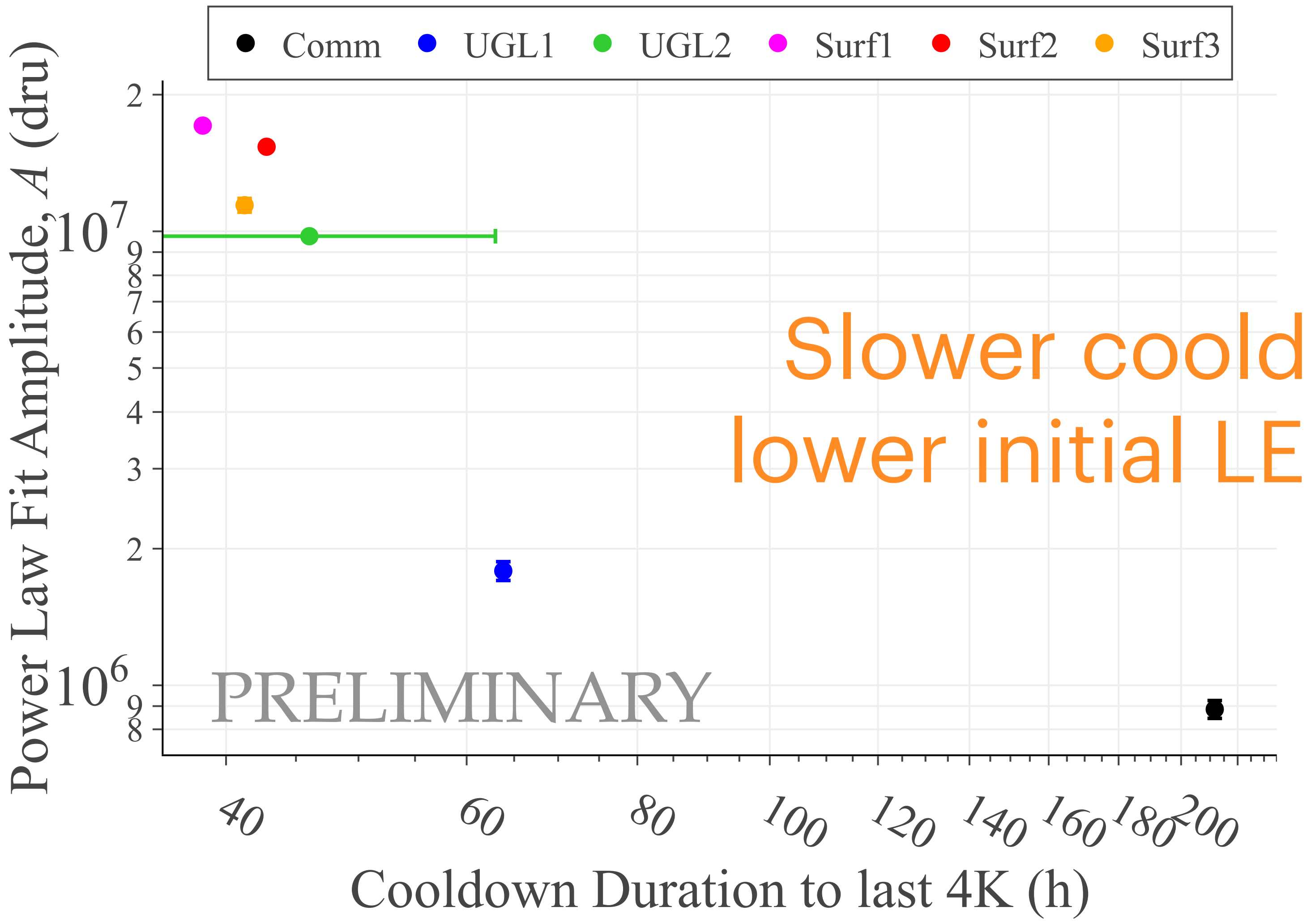
Results on LEE with a double-TES Al_2O_3 detector



- Several measurements with Al_2O_3 detector instrumented with 2 TESs between 2023-2024
- Main results:
  - **No correlation** with particle background
  - **No correlation** with muons
  - **Correlation** with cooldown duration (room temperature to last time at 4K)
  - **No correlation** with other thermal history parameters (condensation time, cumulative time at 10 mK, thermal cycles)



EXCESS Workshop 2025, Publication in preparation

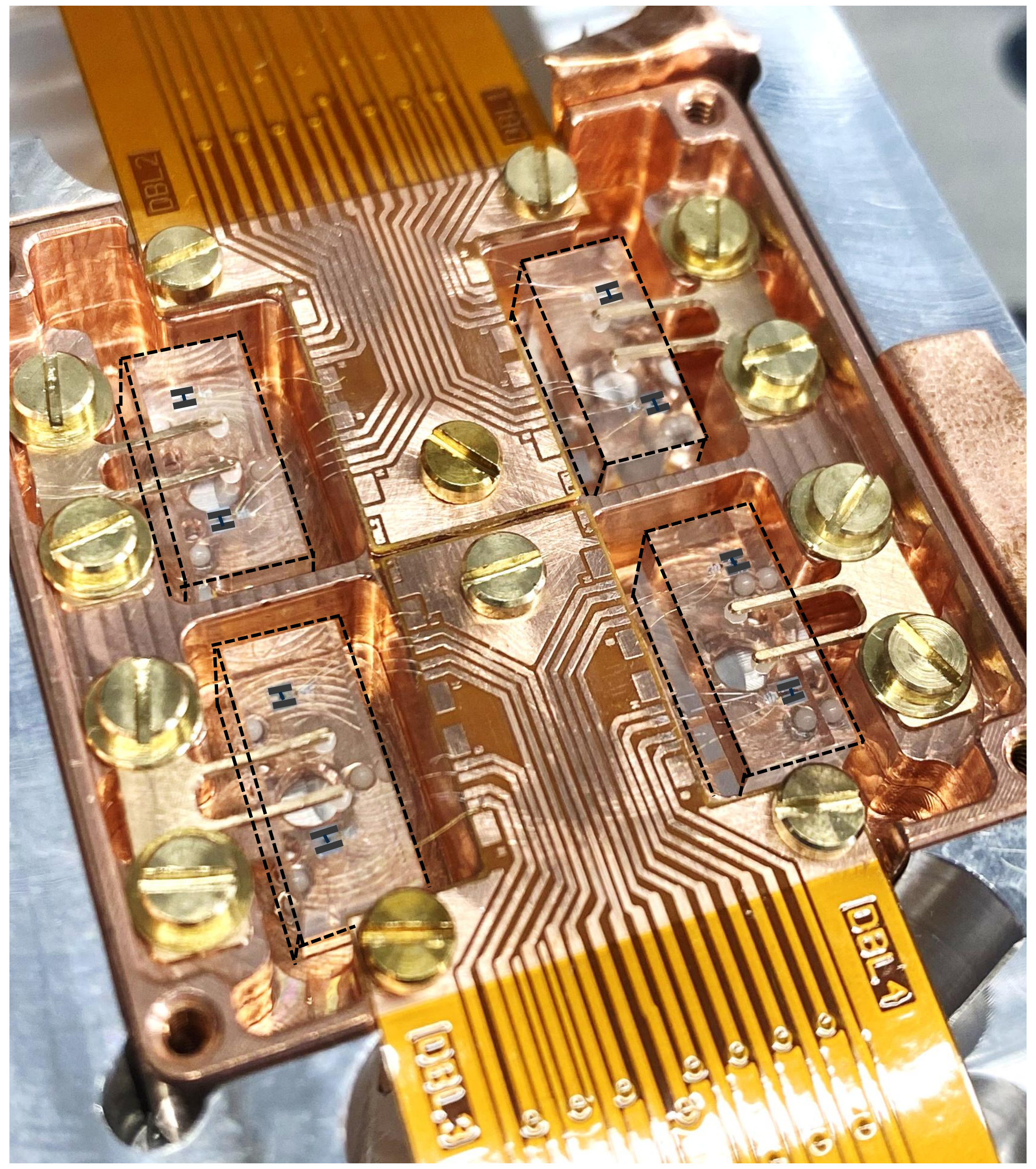


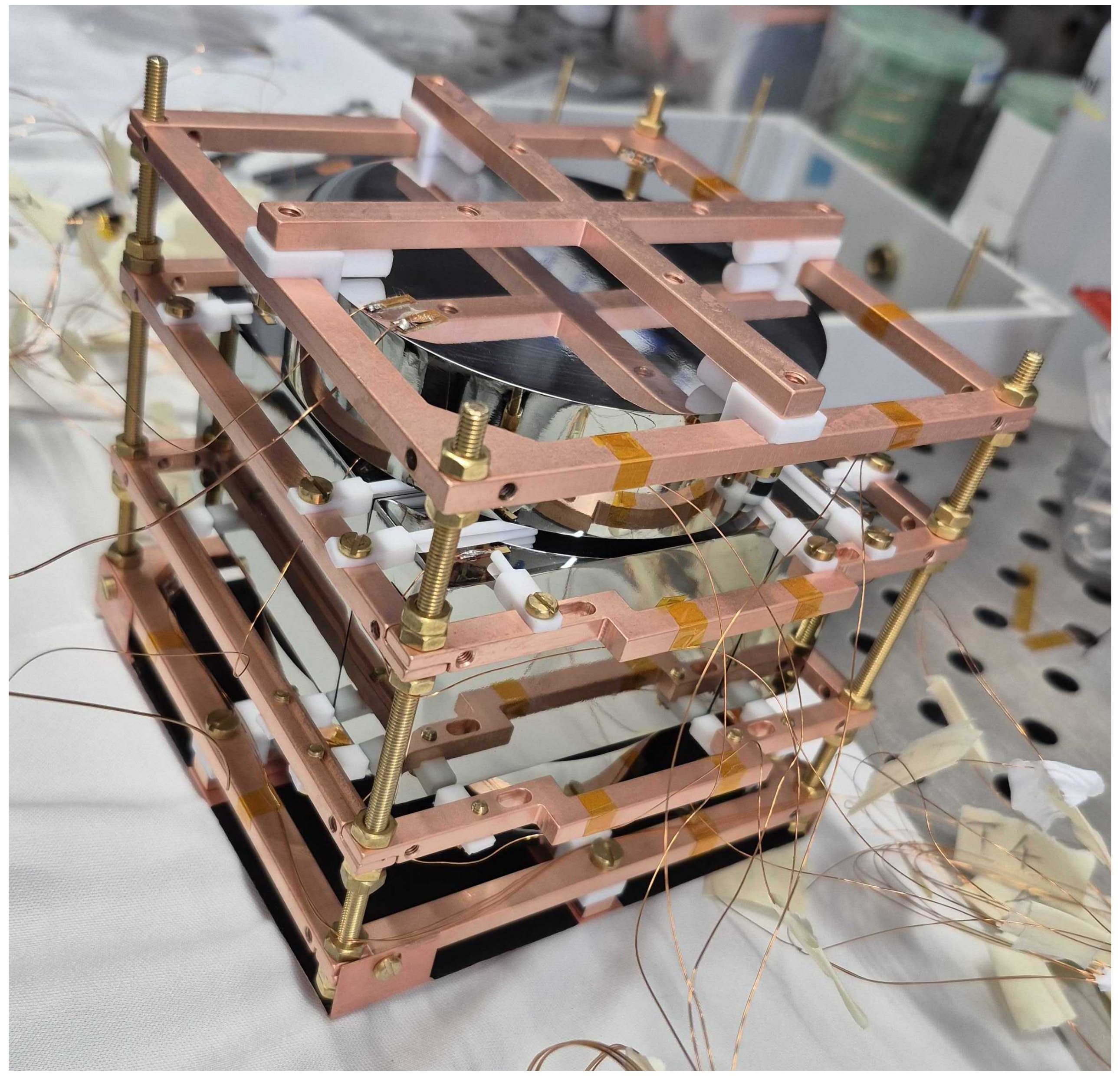
Slower cooldown, lower initial LEE rate!

Next milestone: technical run at Chooz

- Detector upgrades @TUM

- Relocation @Chooz started





- Cryogenic detector module and full scale cryogenic outer veto validated: performances on specs
- Integration of both together ongoing

- Passive shielding and Muon Veto integrated and commissioned
- Cryostat relocation at the end of the year

Conclusions and Outlook

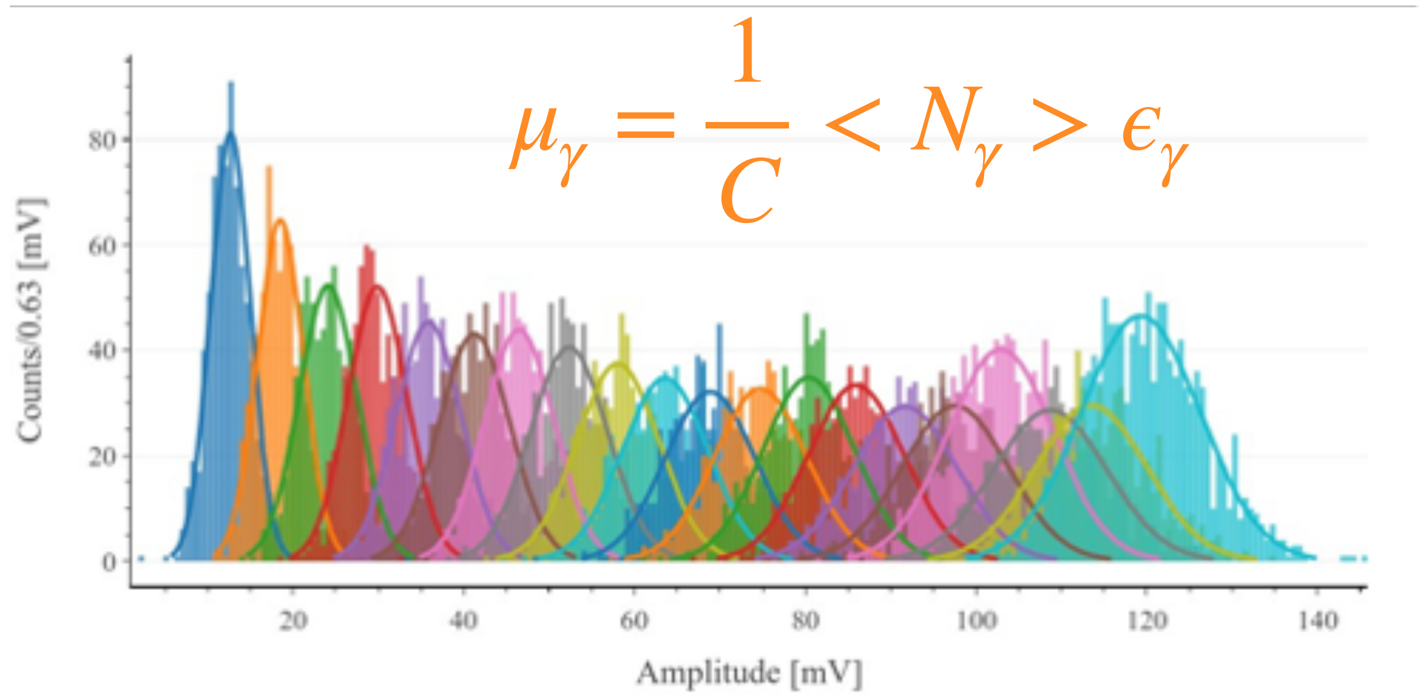
- NUCLEUS will exploit sensitive cryogenic calorimeters and extensive shielding techniques to measure CEvNS at reactors
- **New Milestone: Commissioning Run @TUM** proved the feasibility of the experiment and demonstrated stable operation over longer timescales
- **New results** on low energy excess and validation of simulations from the Commissioning Run
- Detector upgrade and **relocation @Chooz** happening now!
- **Technical Run @Chooz** next year!

2024	2025	2026	
Commissioning Run @TUM	Relocation @Chooz	Technical Run @Chooz	Stay tuned for physics run!

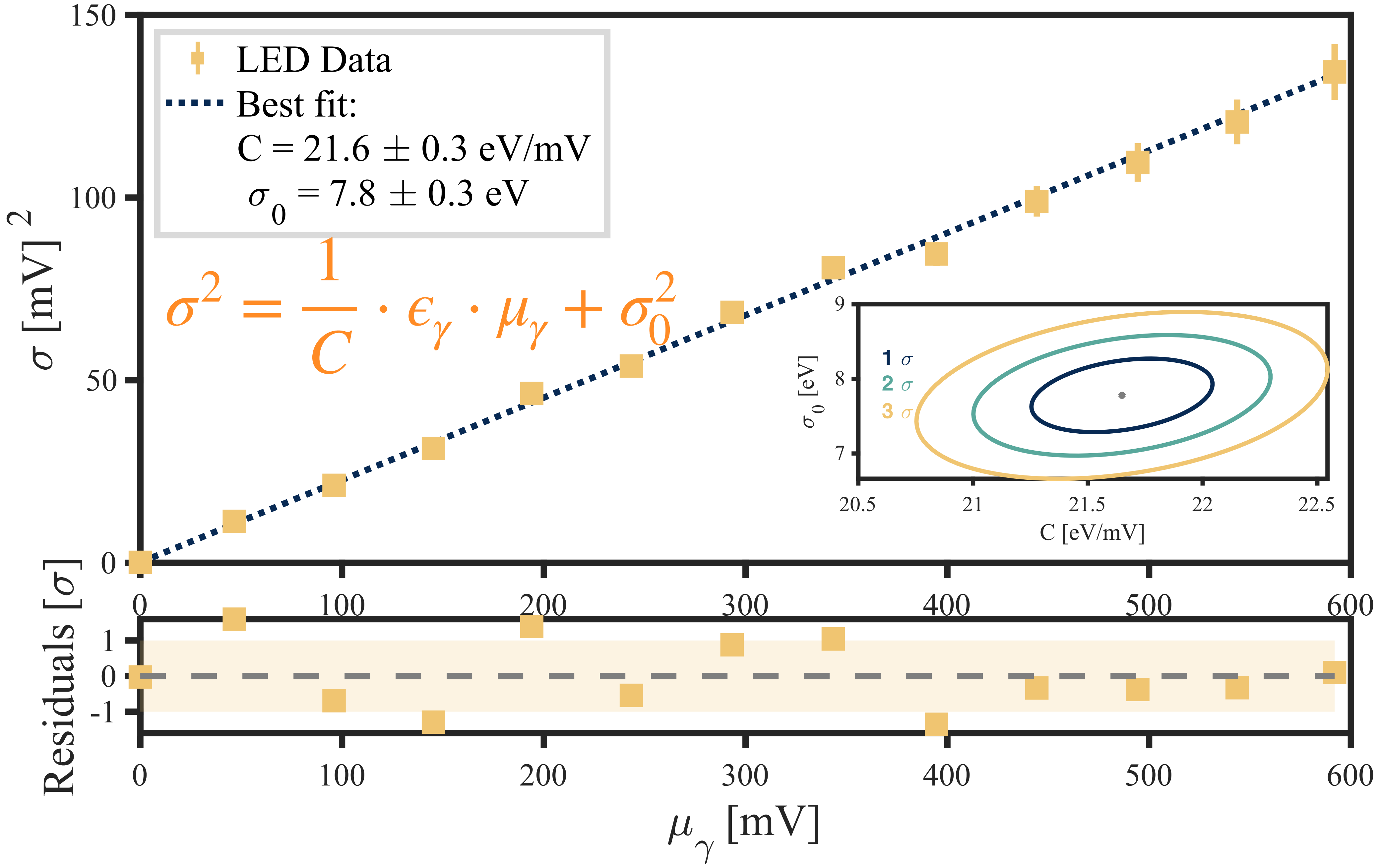
Backup

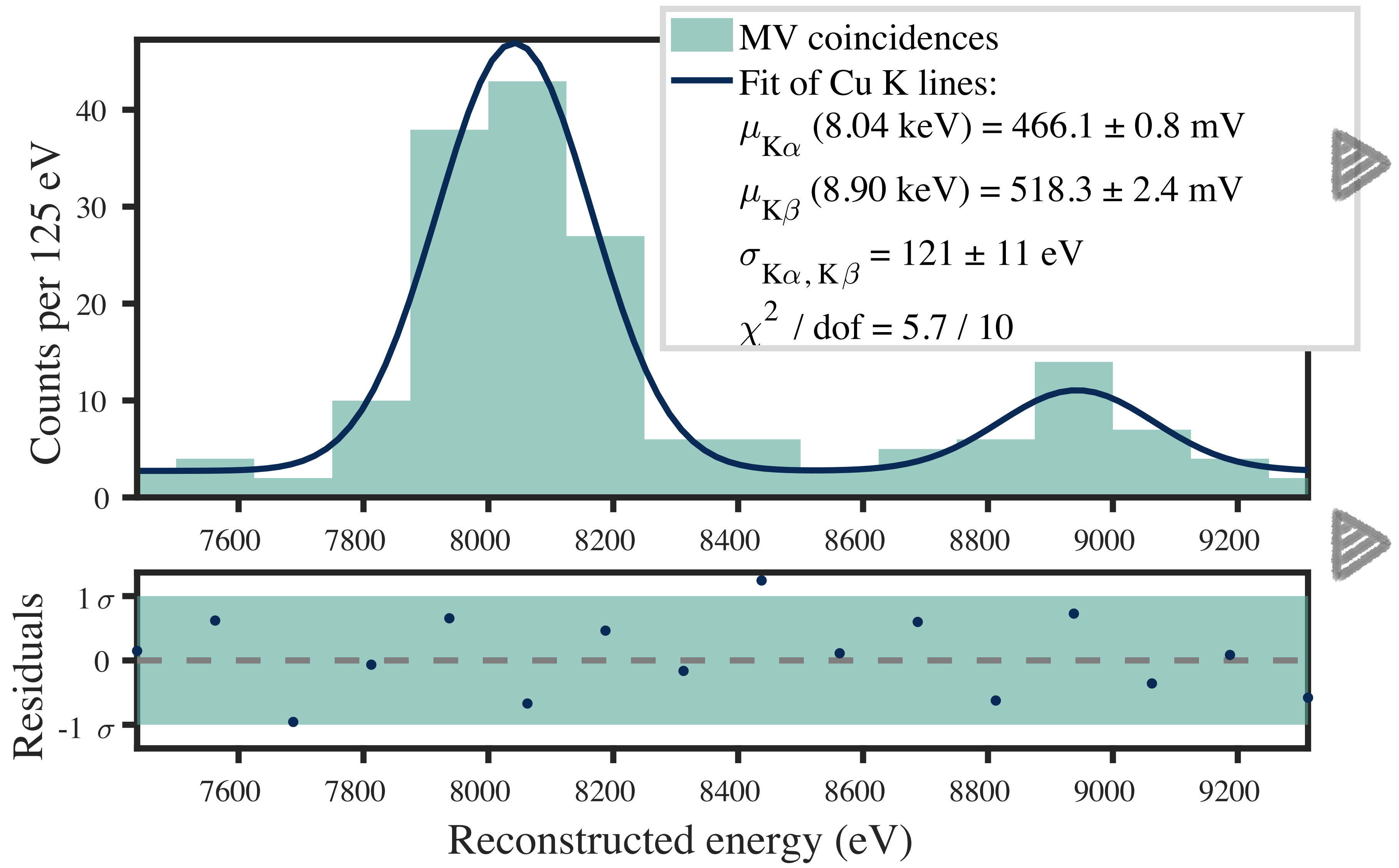
Low energy calibration

- **LED calibration**: shine monochromatic LED to the detector, use phonon statistics to measure the calibration constant
- In-situ, continuously available, sub-keV calibration (no radioactive source needed)



Example from $CaWO_4$ detector in commissioning run



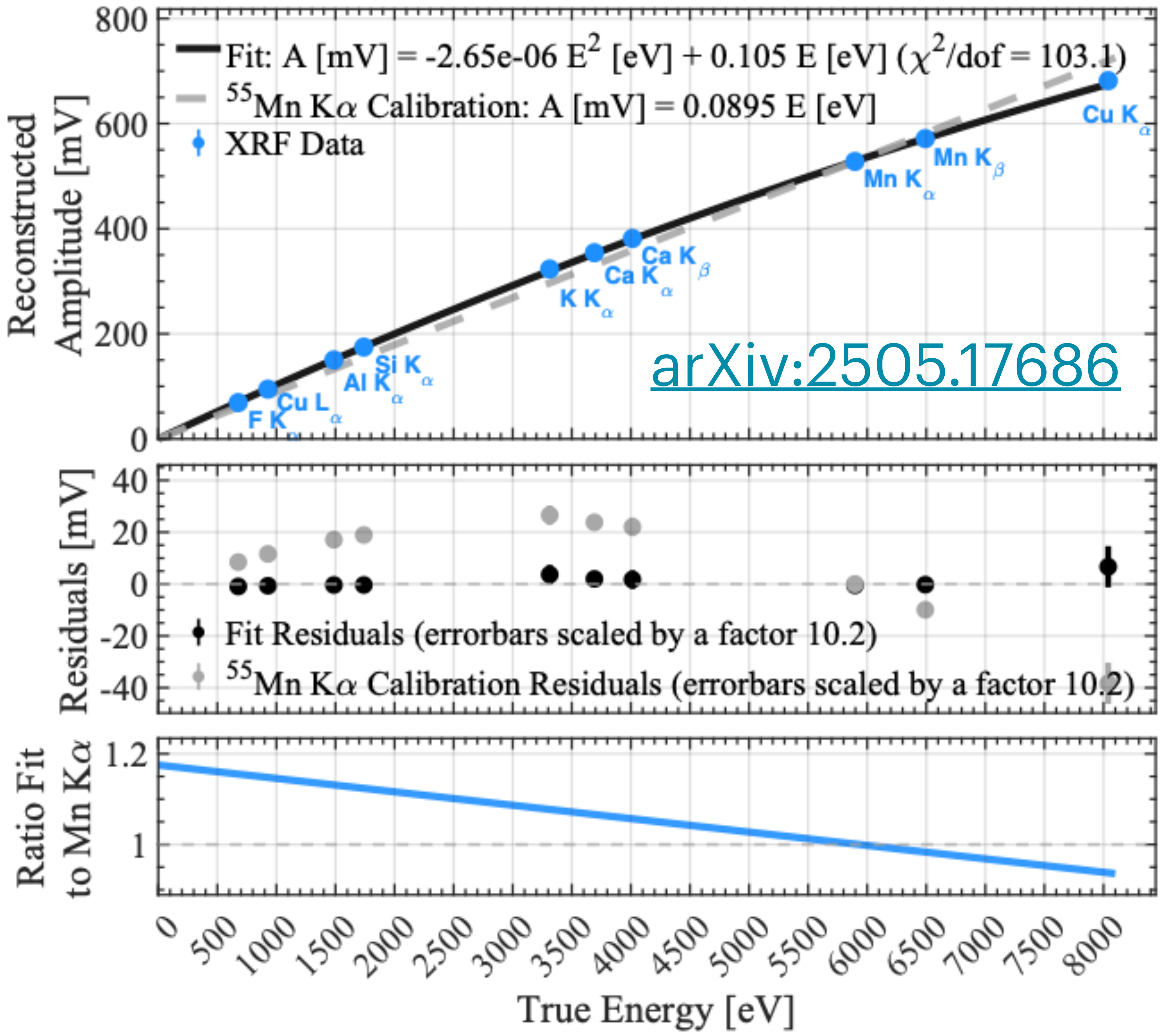


- 25% disagreement with Copper X-ray position not yet understood
- Bulk vs surface recoil difference?

arXiv:2508.02488

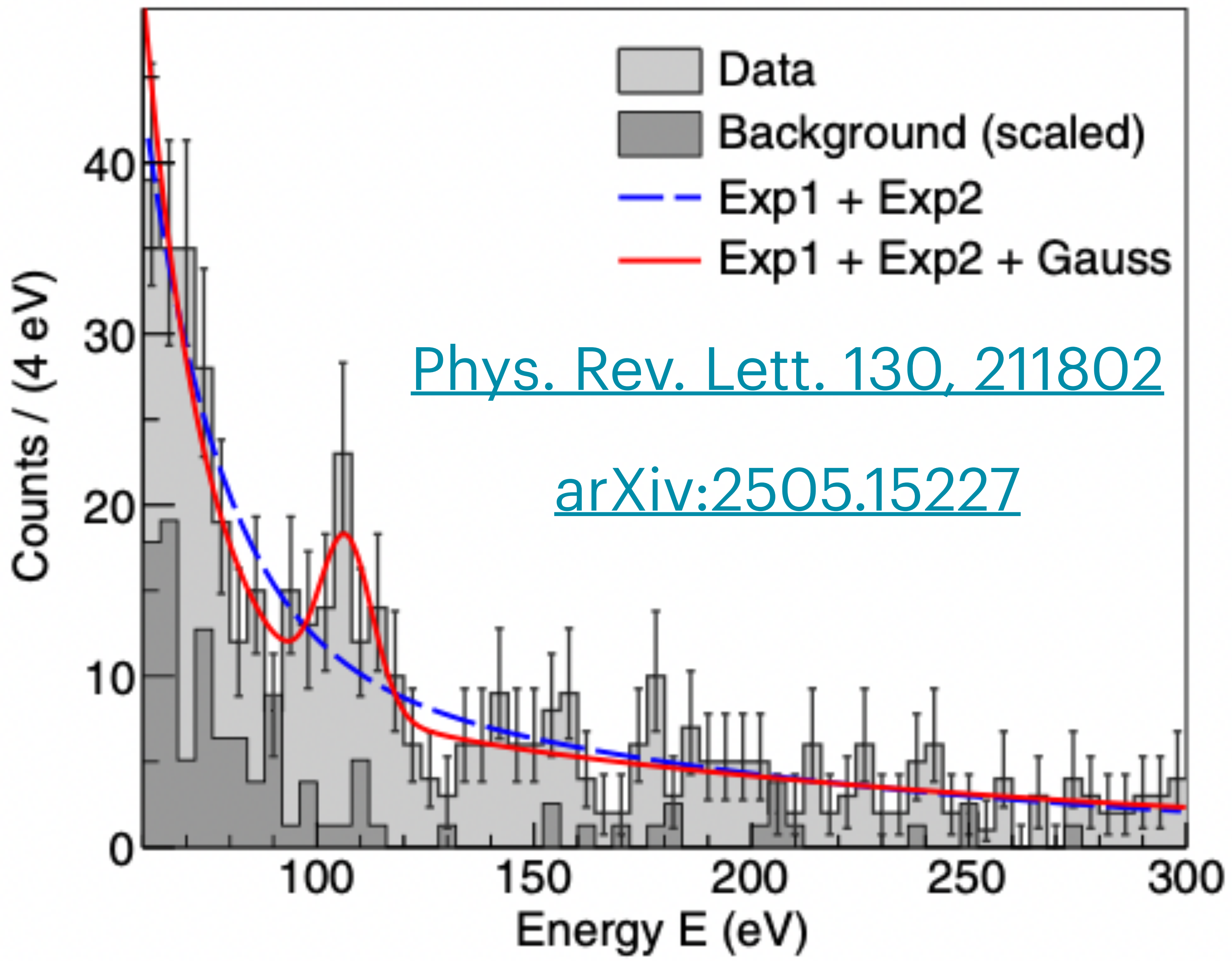
Low energy calibration

Low energy X-ray source



arXiv:2505.17686

Nuclear recoil calibration with CRAB



Phys. Rev. Lett. 130, 211802

arXiv:2505.15227

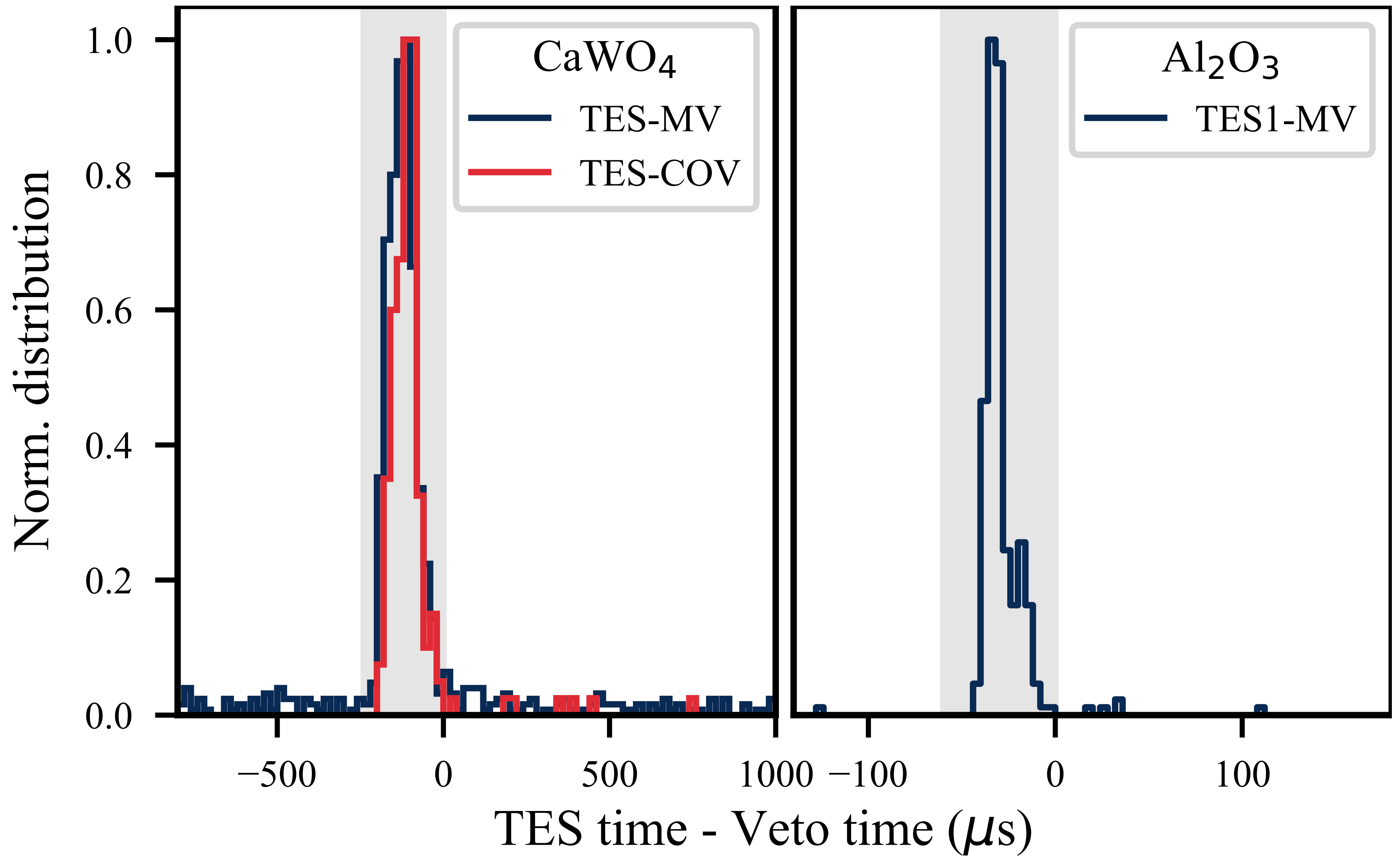
Talk later today: E. Bossio, “First results from the CRAB experiment at the TRIGA Mark-II reactor”

- Combine different methods to investigate systematics: detector non linearities? Nuclear vs electron recoil? Bulk vs surface recoil?

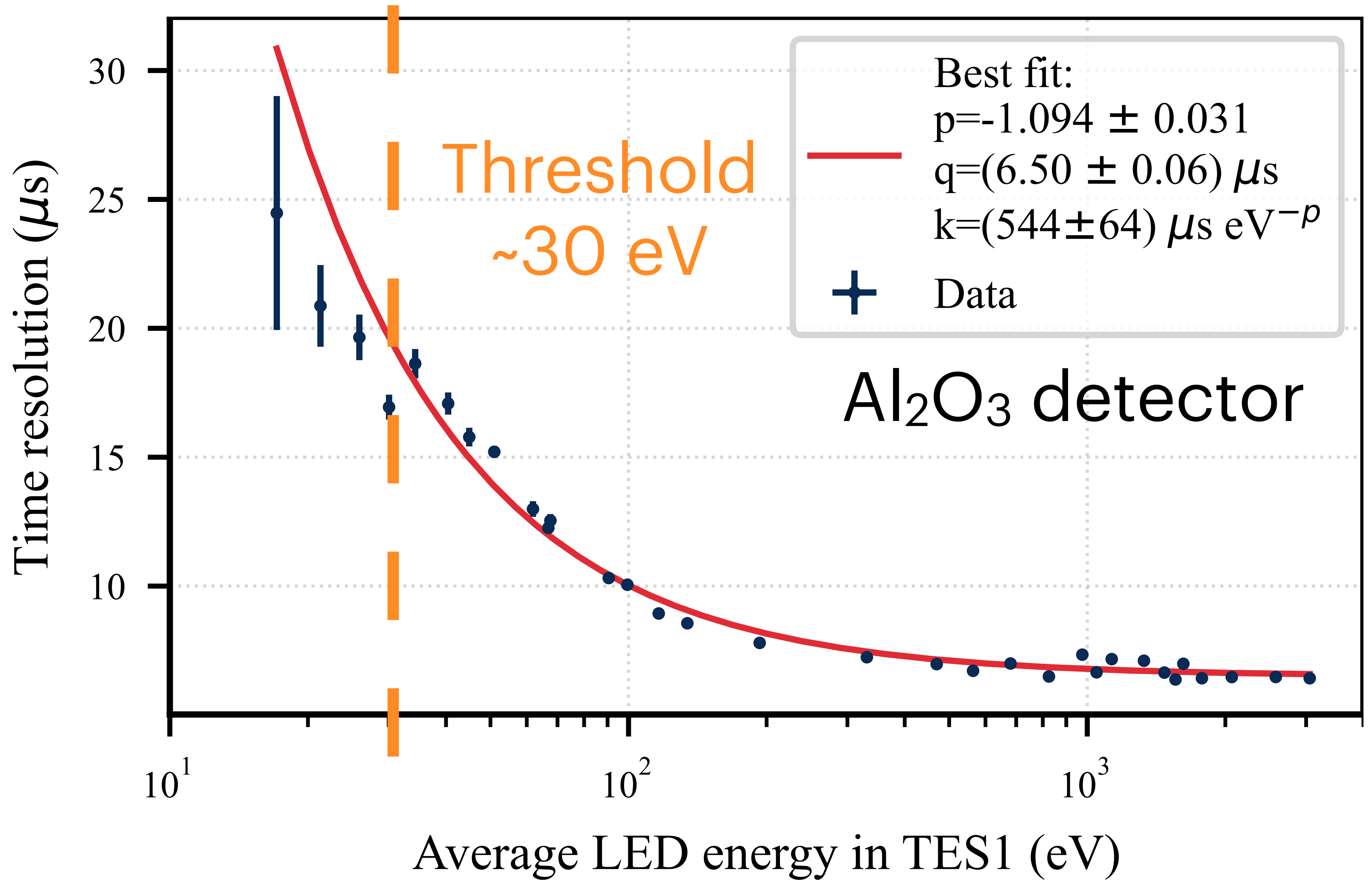
Time resolution

- Time difference between TES event and nearest in time event in the veto detector (MV, COV)

arXiv:2508.02488



- Width of the distribution due to limited resolution of time reconstruction in TES events (about 40 μs in $CaWO_4$, 7 μs in Al_2O_3)
- With 325 Hz muon rate at Chooz, dead time < 10%

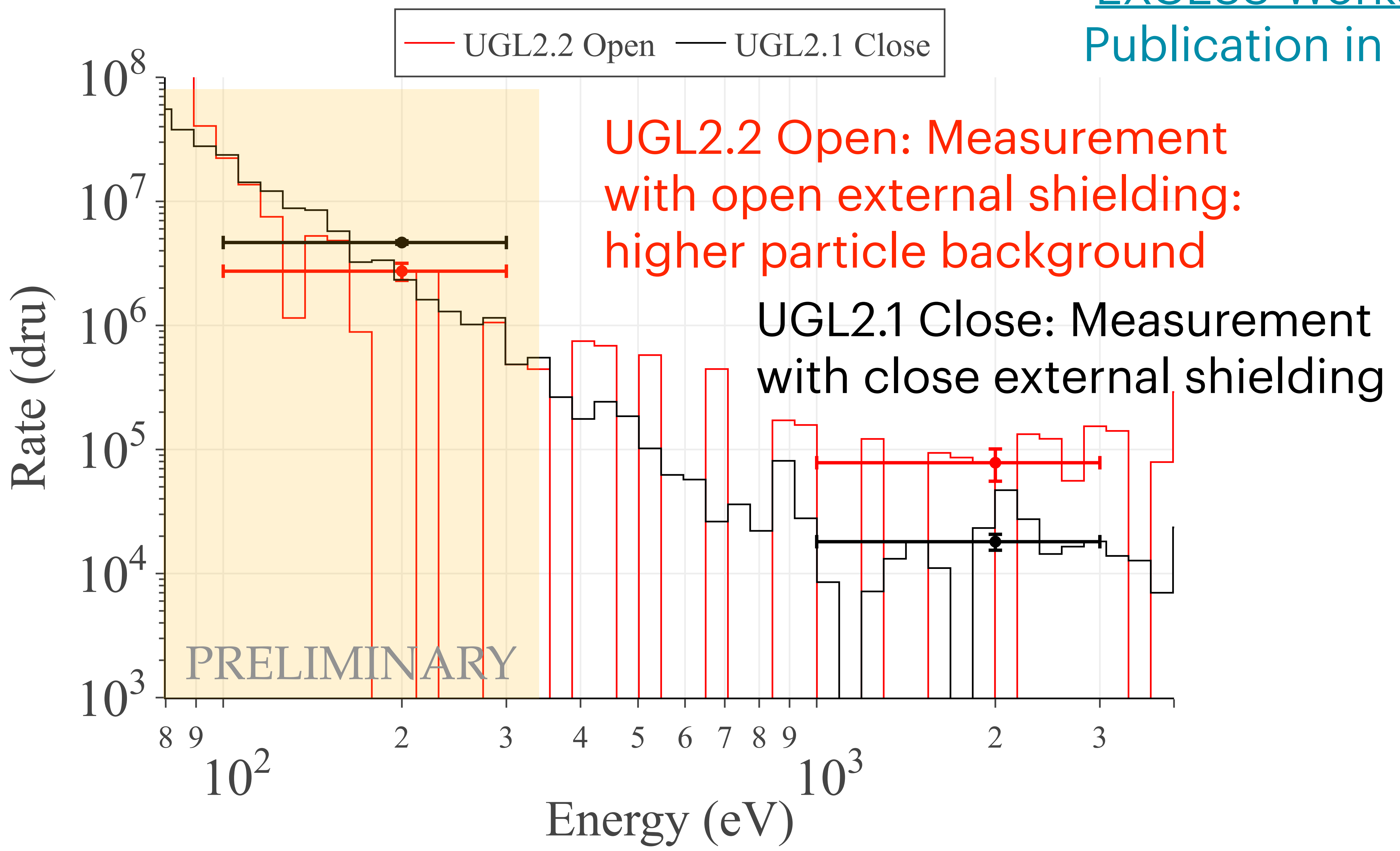


- Time resolution under control also at threshold

More LEE results

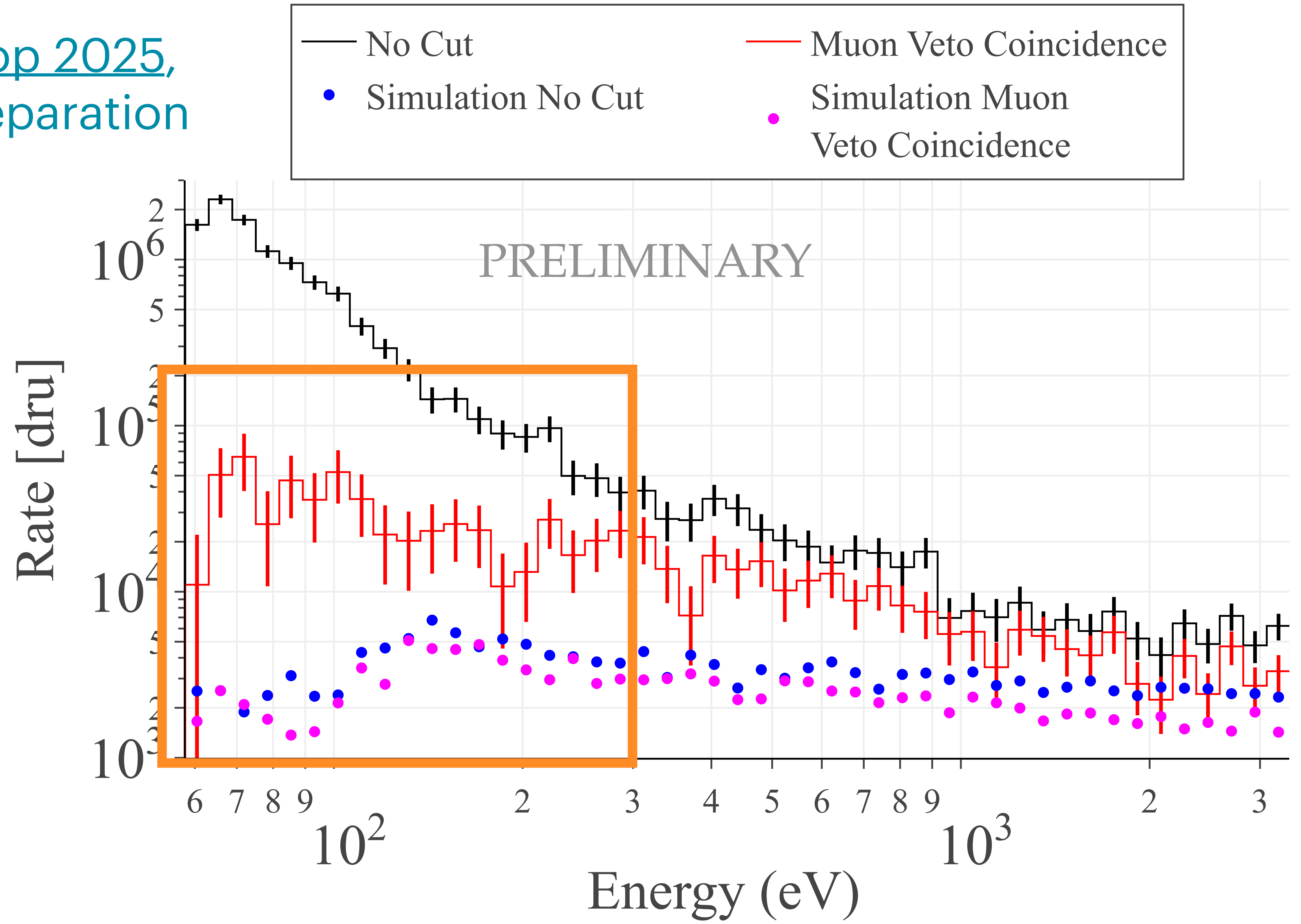
- Test correlation of LEE with particle background and muons

Short UGL run (same cooldown):



EXCESS Workshop 2025,
Publication in preparation

Commissioning run, Al_2O_3 detector:



- Different particle background rate but similar LEE rate, no correlation!
- No LEE coincidence with muons above random coincidences

Inner Veto

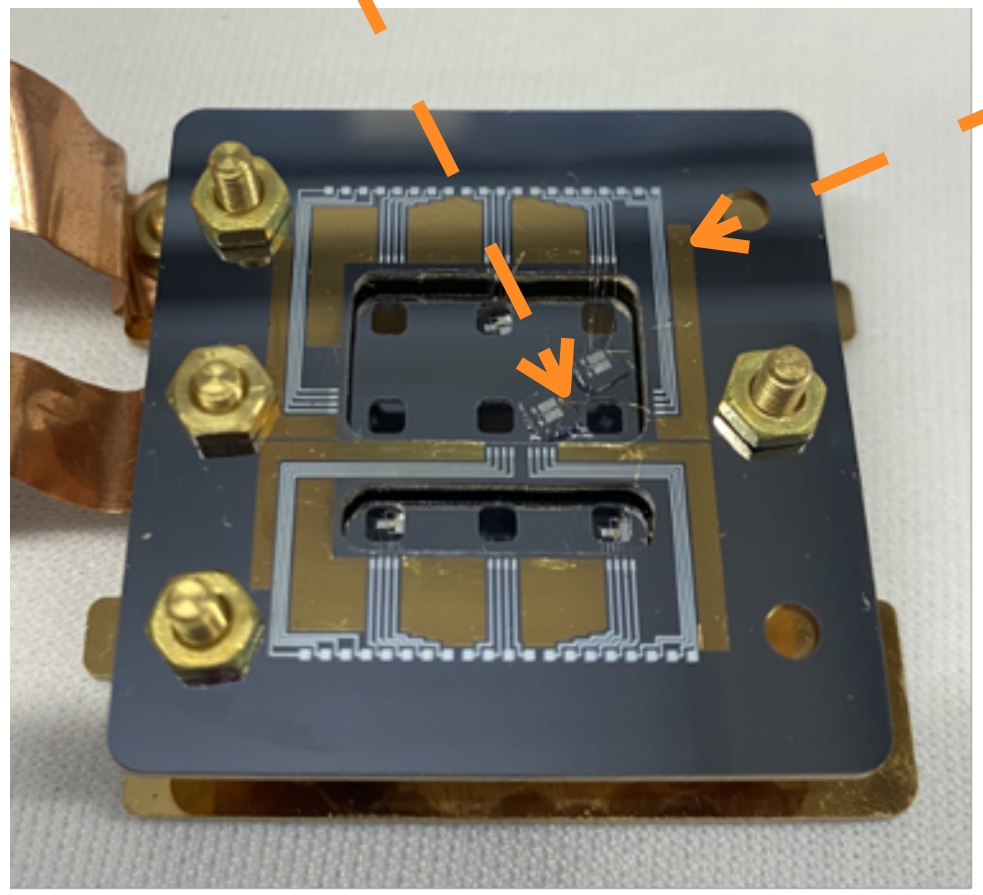
- Instrumented holder for target detectors: Silicon wafers with TES read out
- Veto of surface events and mechanical stress relaxation-induced events (LEE)

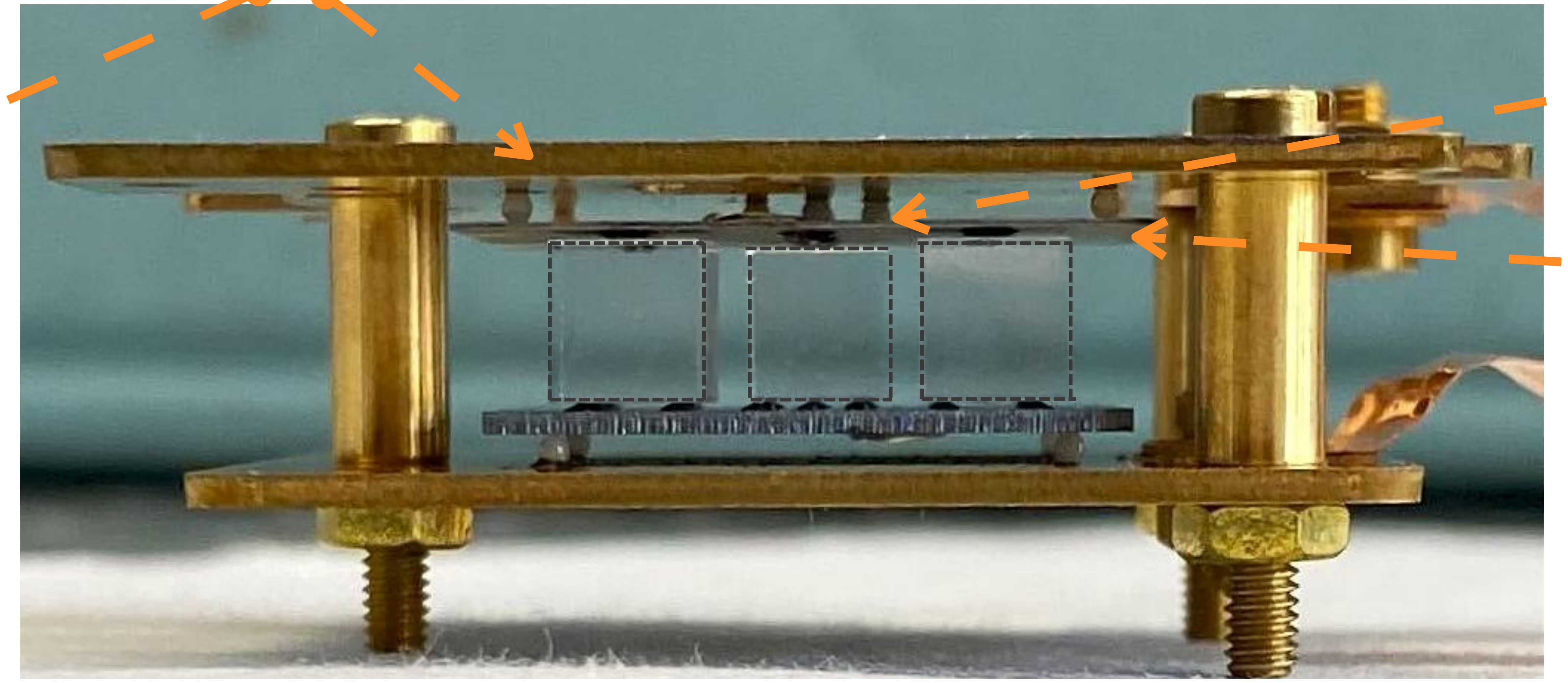
Inner veto TESs

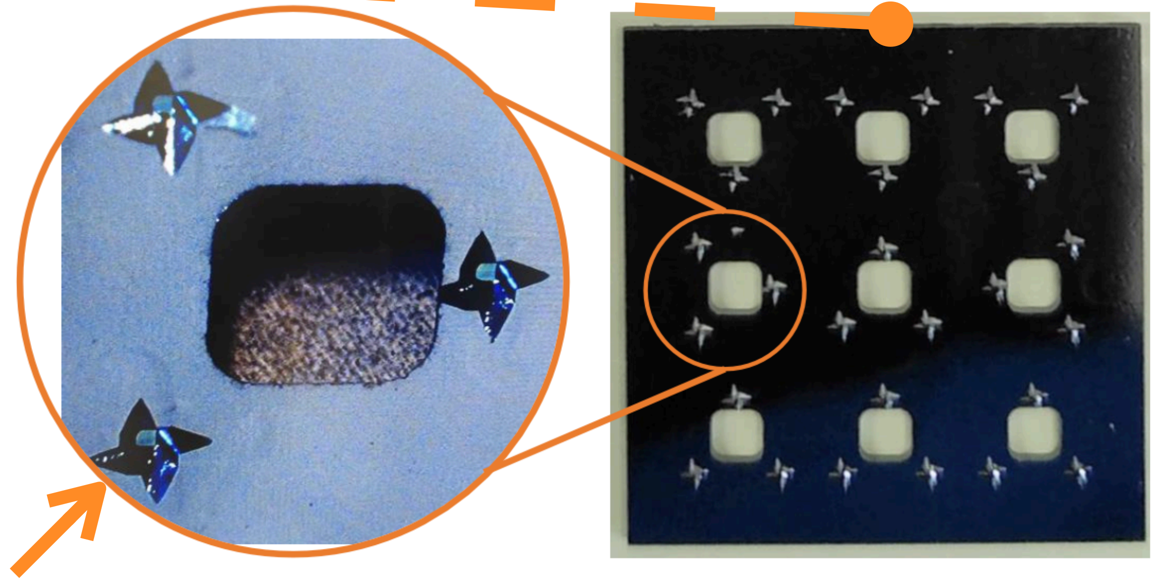
Holding plates with electrical & thermal contacts

Support spheres

Inner veto wafer







- ☑ Detectors operated in inner veto module with good performances and no cross-talk
- ☐ R&D ongoing: optimisation of inner veto TES design

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