Status of the NUCLEUS experiment: first light from the commissioning run

On behalf of the NUCLEUS Collaboration:
Elisabetta Bossio (CEA)
elisabetta.bossio@cea.fr

IRN Neutrino Meeting, October 9-10 2024, Paris

NUCLEUS in a nutshell

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The neutrino source

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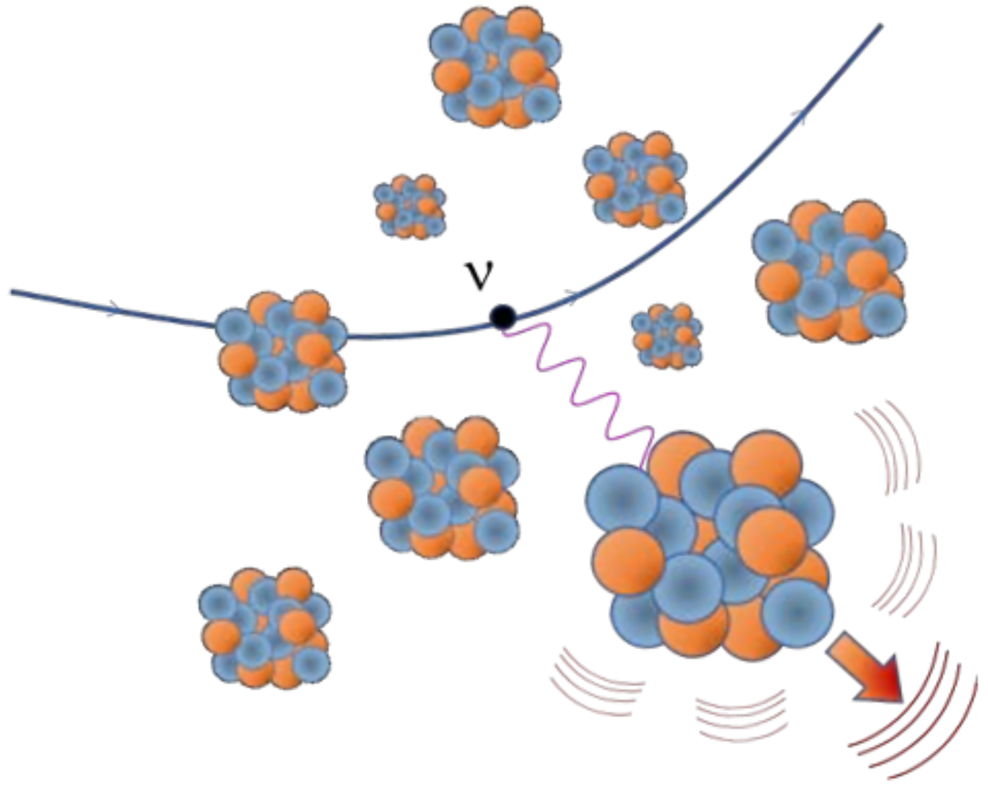
The interaction: CEvNS



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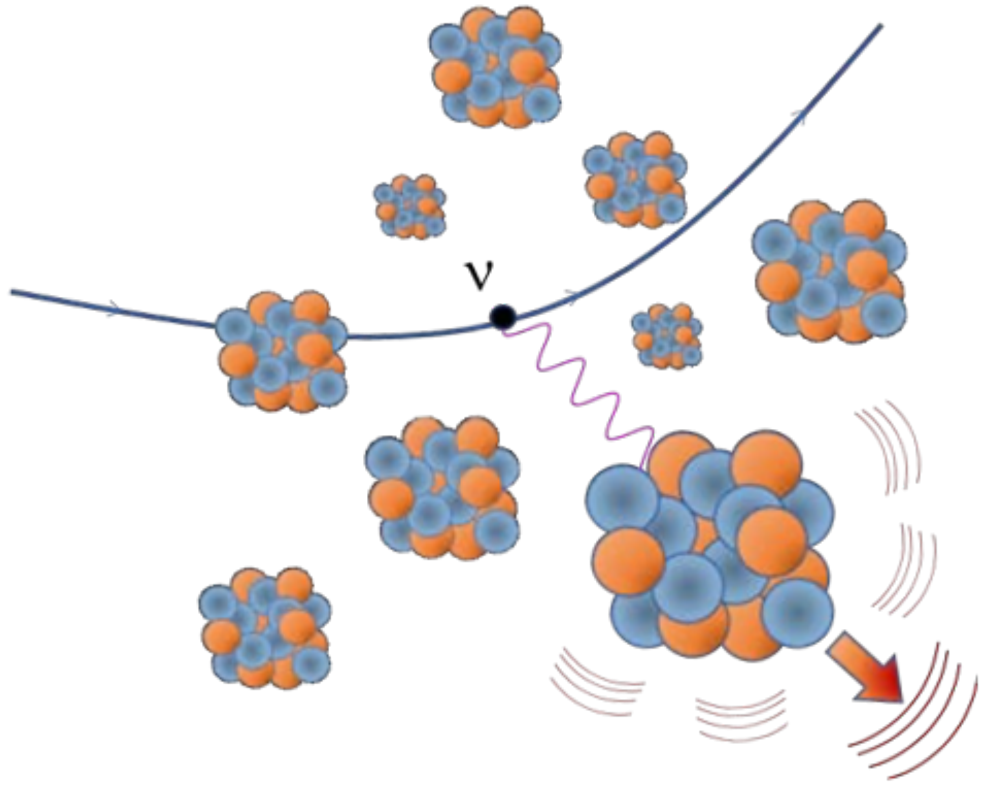

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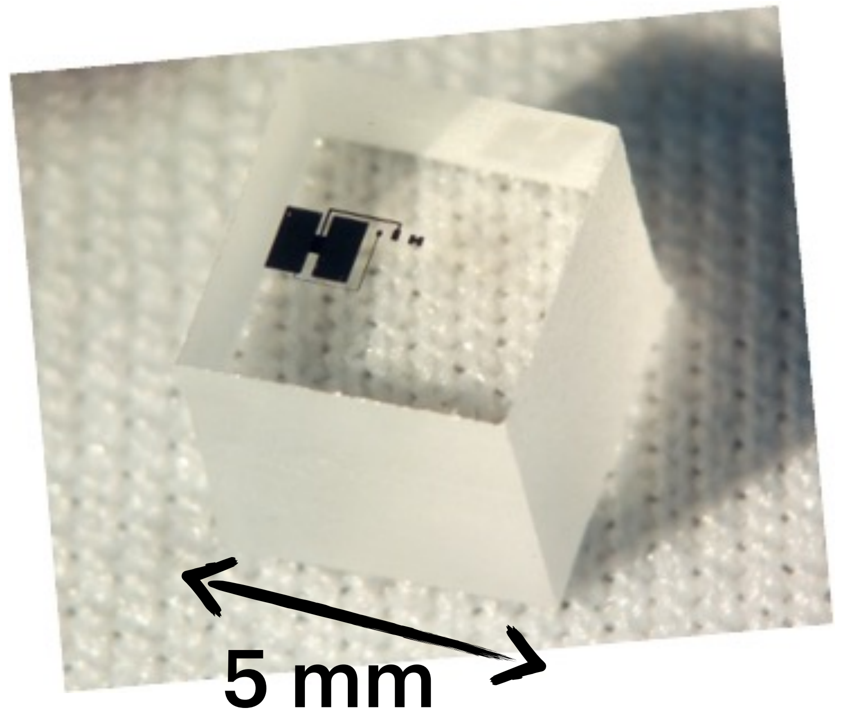

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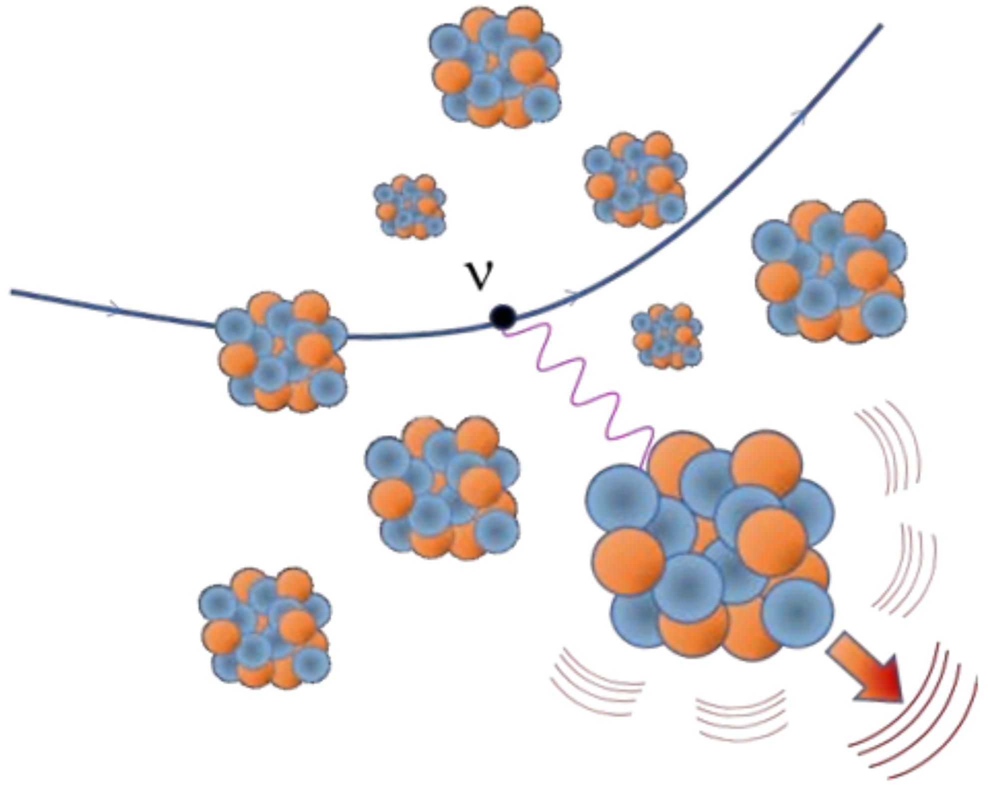

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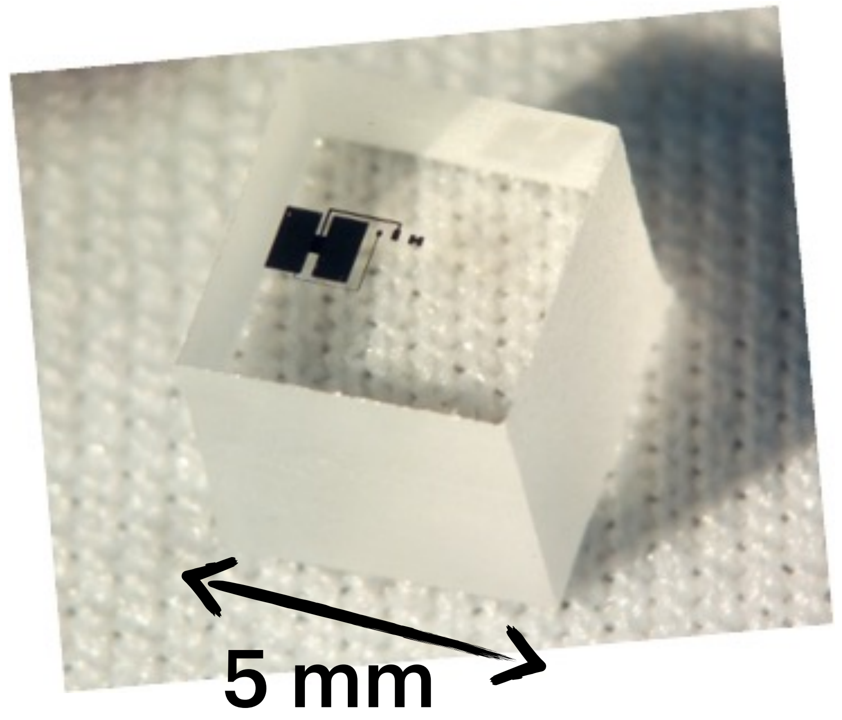

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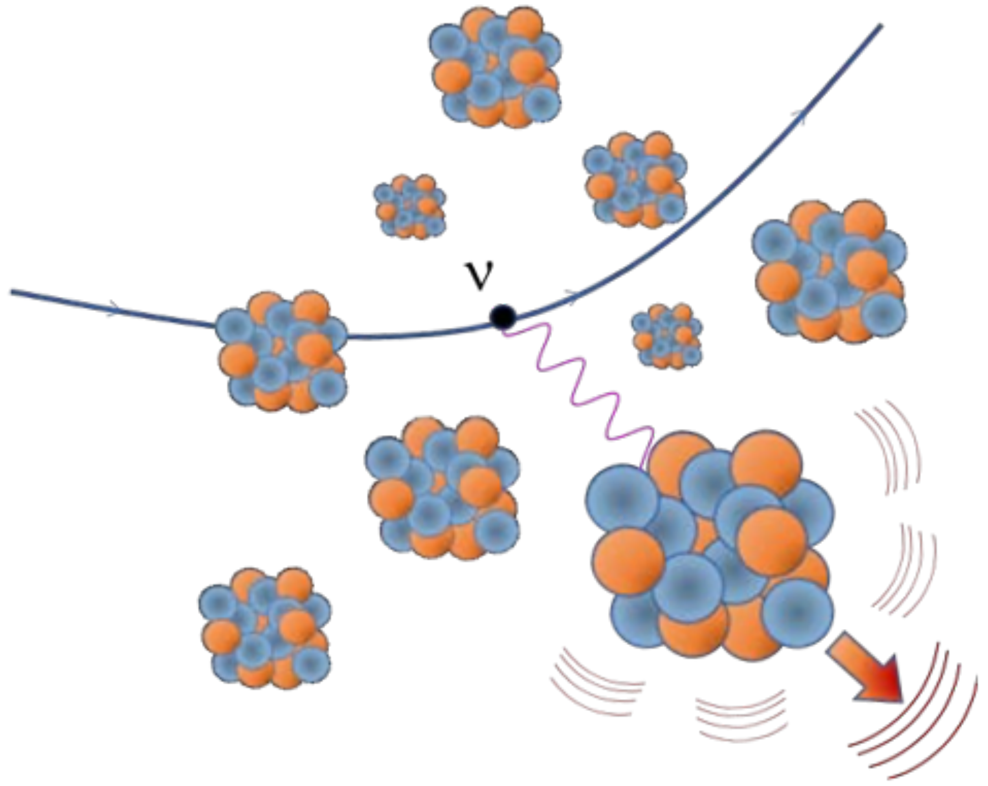

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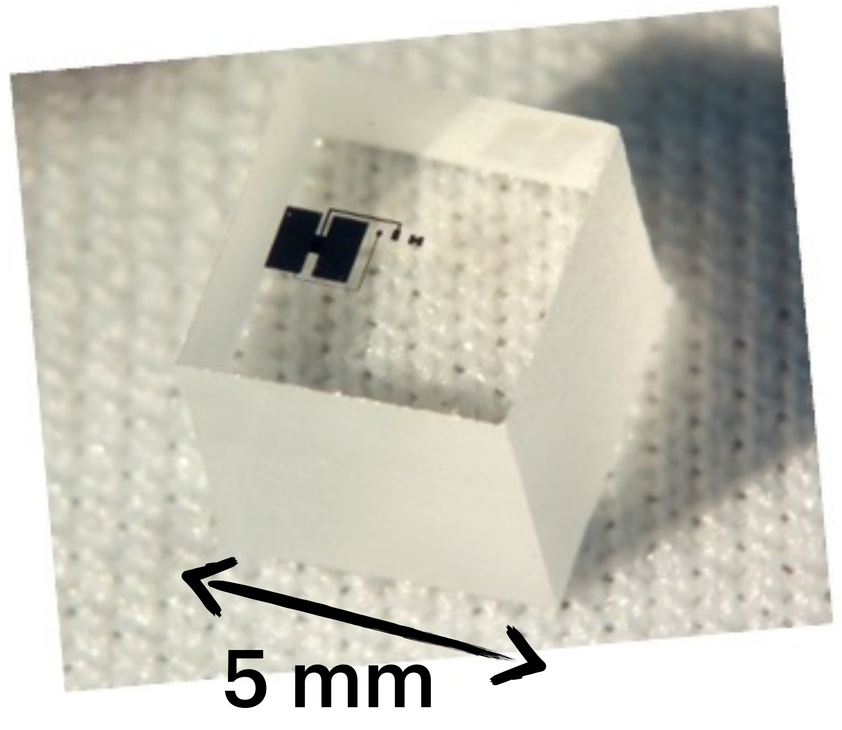

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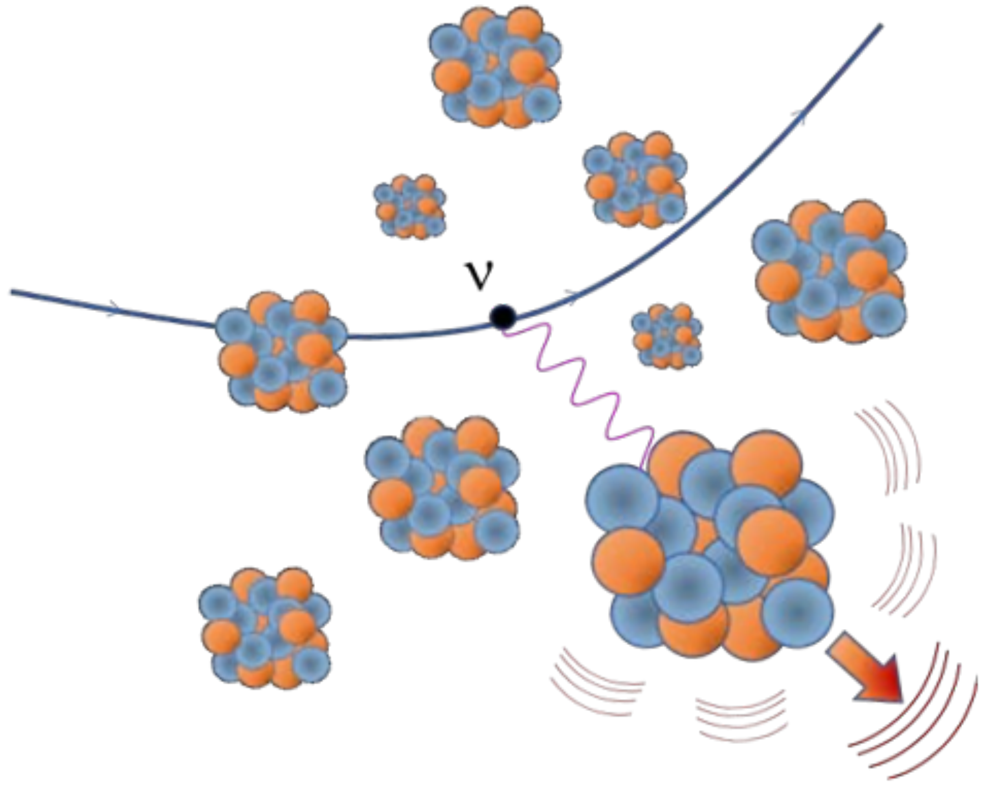

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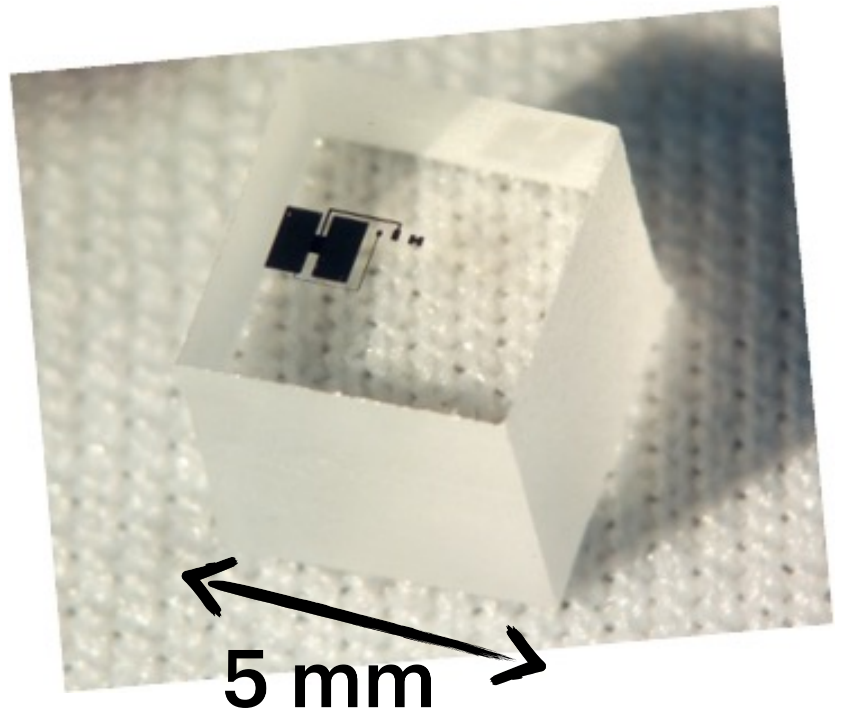

- Gram-scale cryogenic calorimeters
- Read-out by Transition-edge-sensors (TES) operated at 10 mK
- Energy threshold of O(10) eV
- Technology developed within CRESST dark matter experiment

Expected CEvNS signal and background @Chooz

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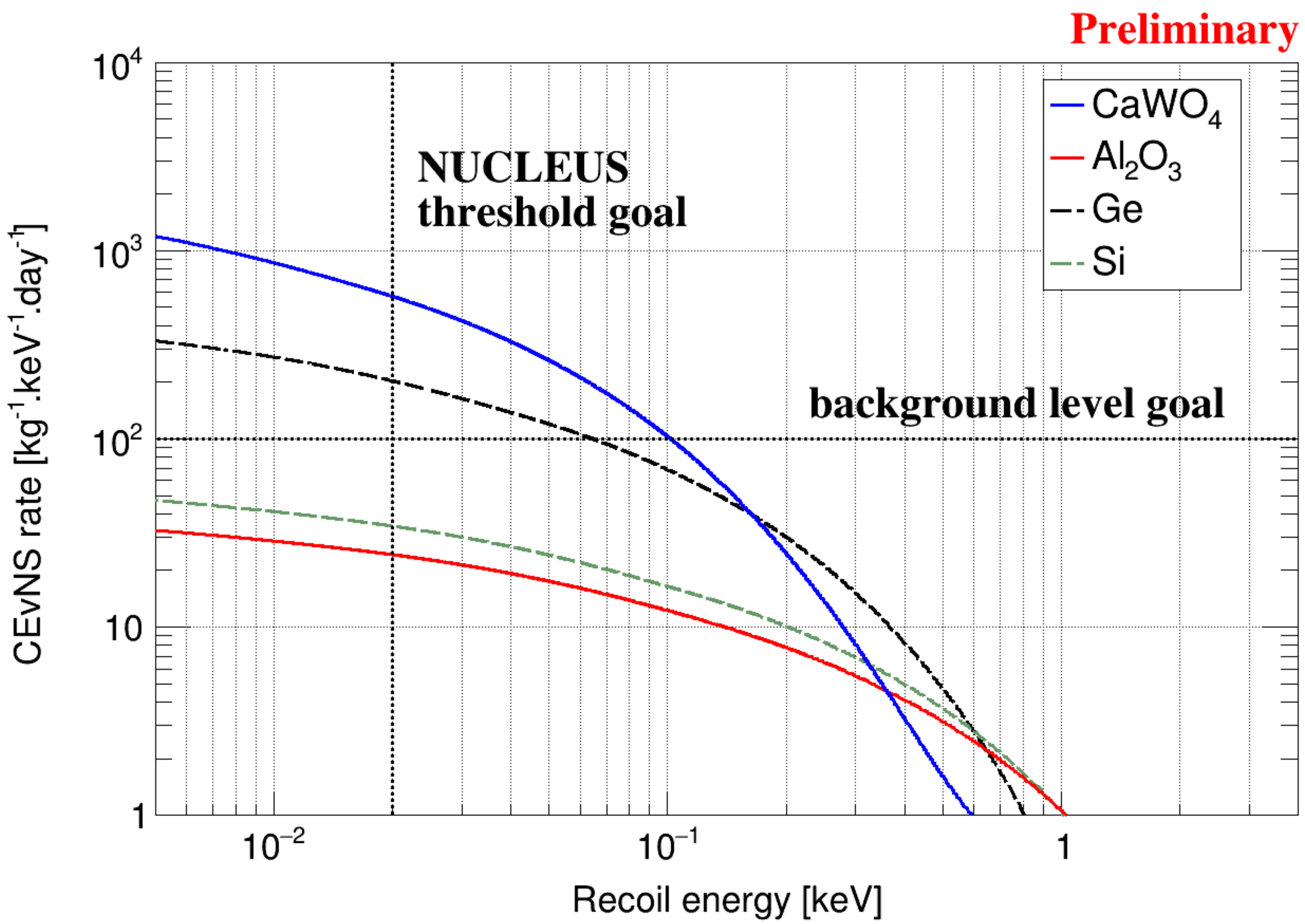
- NUCLEUS 10-g configuration: 6.8 g of $CaWO_4$ + 4.4 g of Al_2O_3



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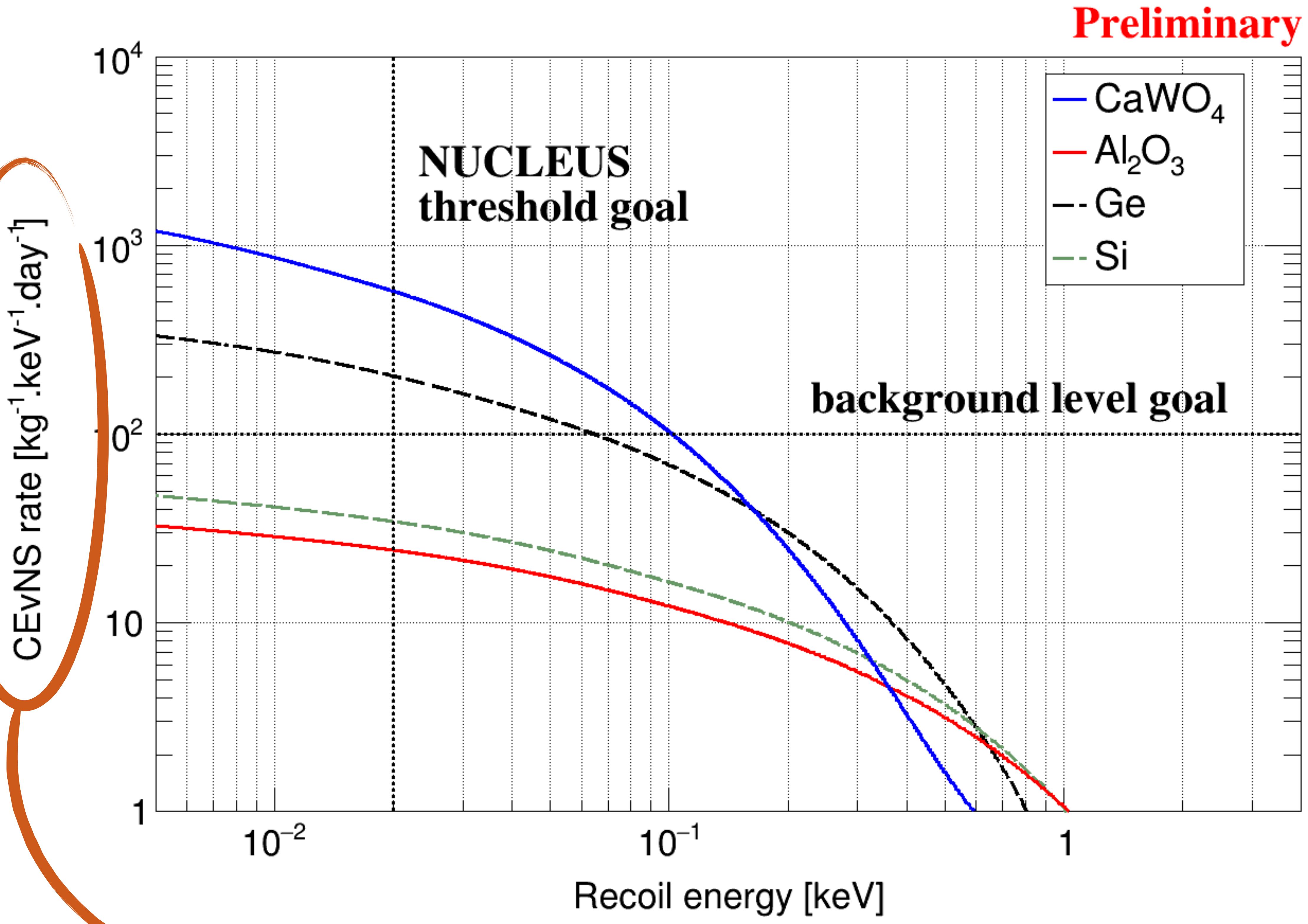

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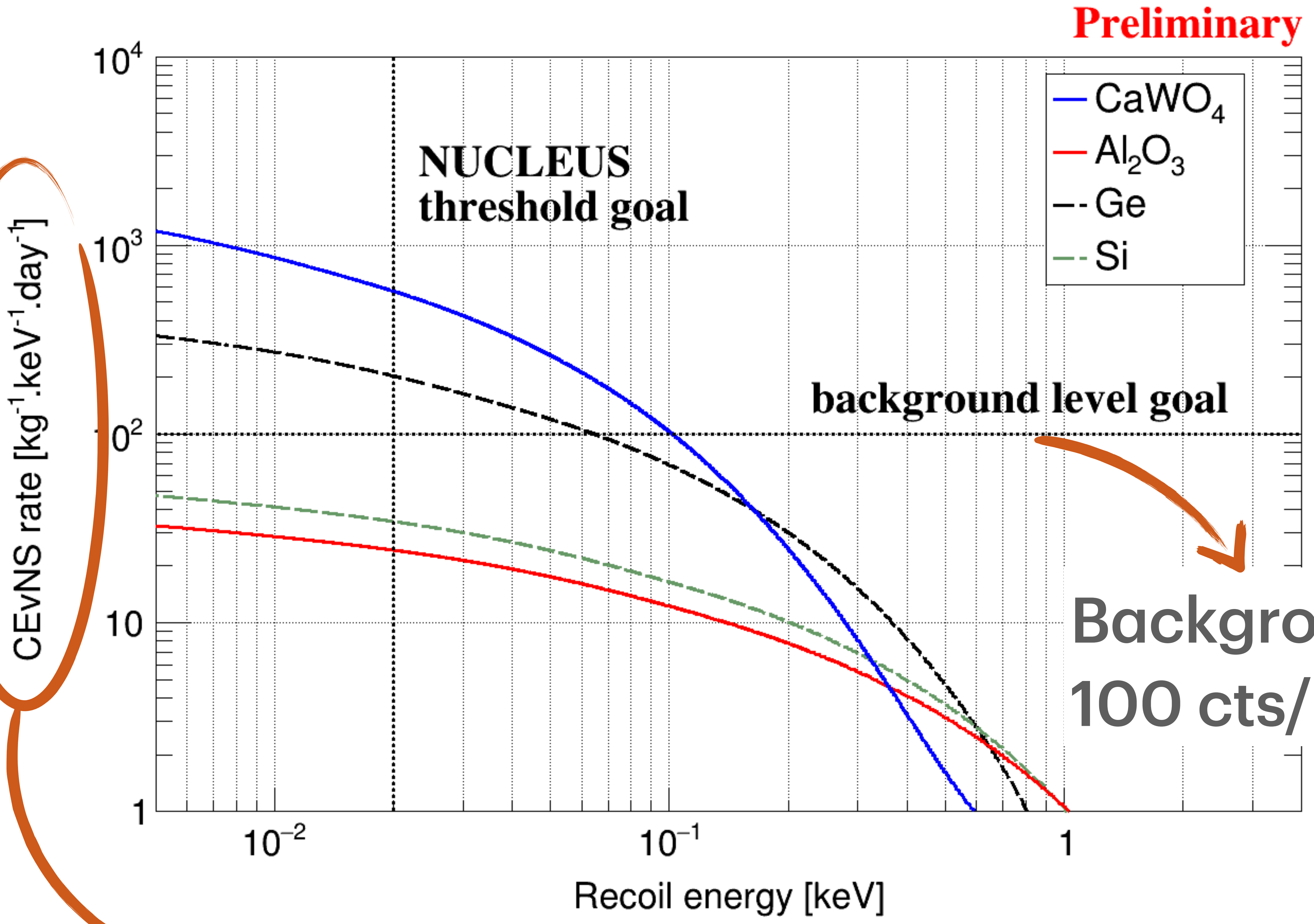

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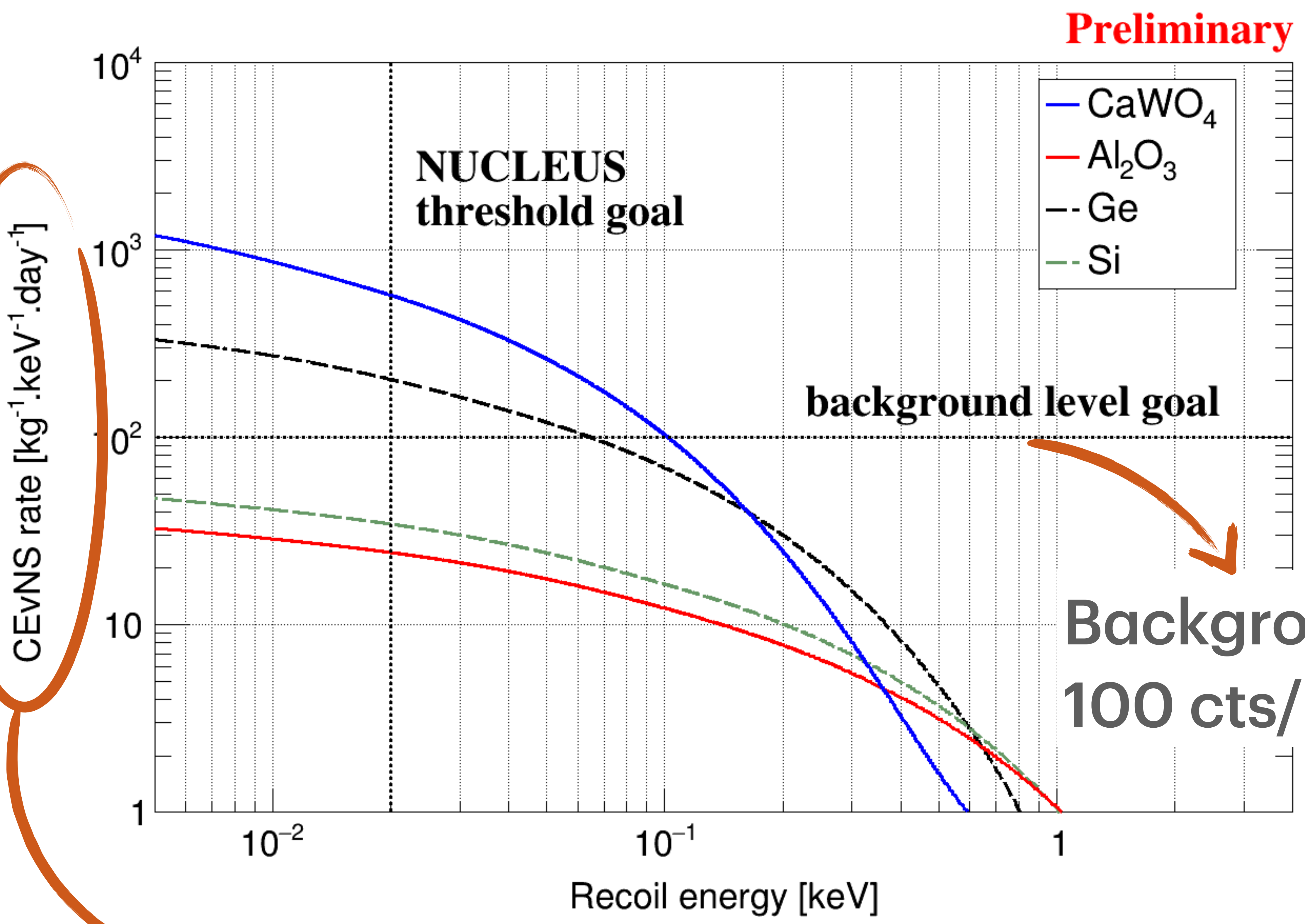

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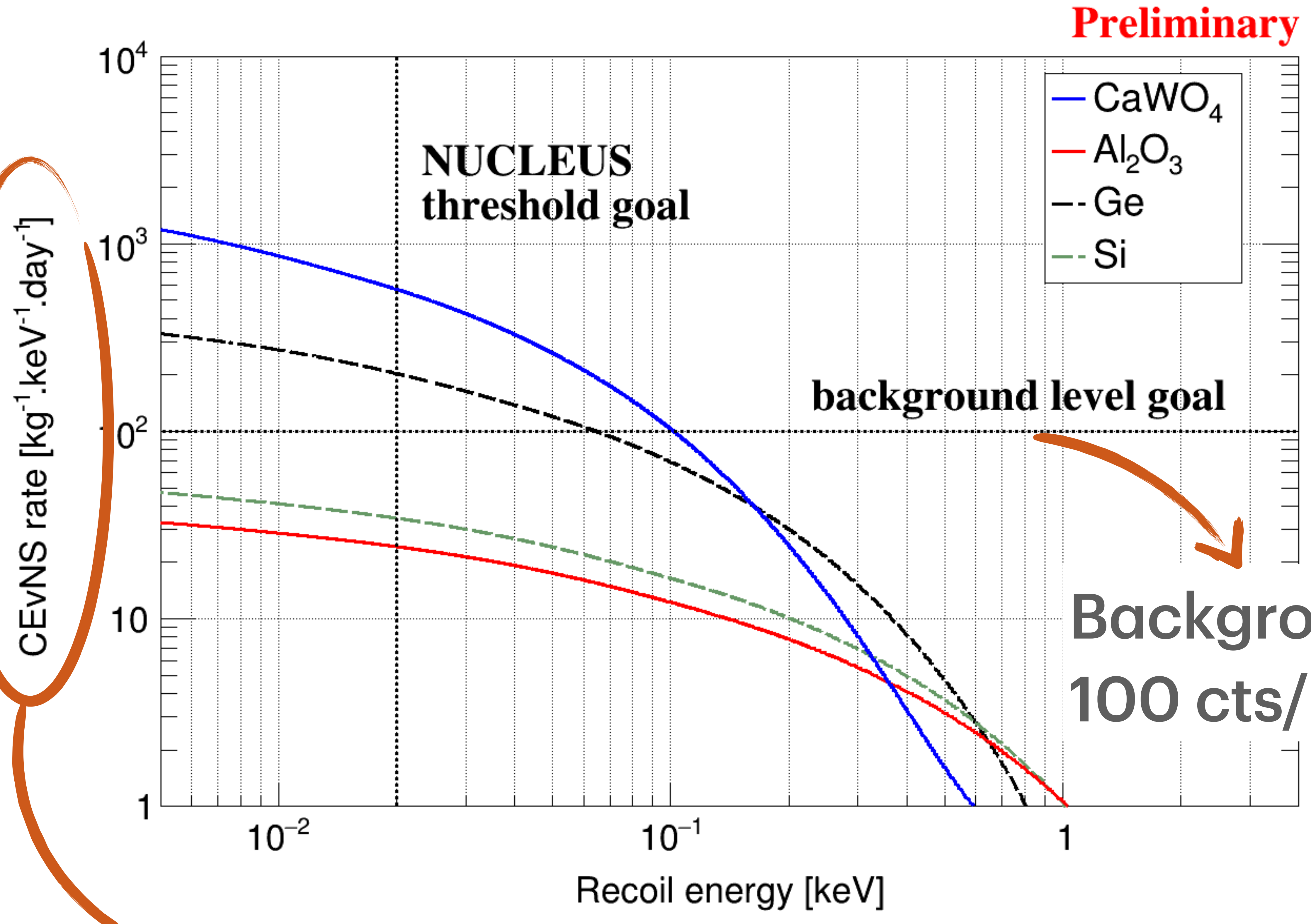

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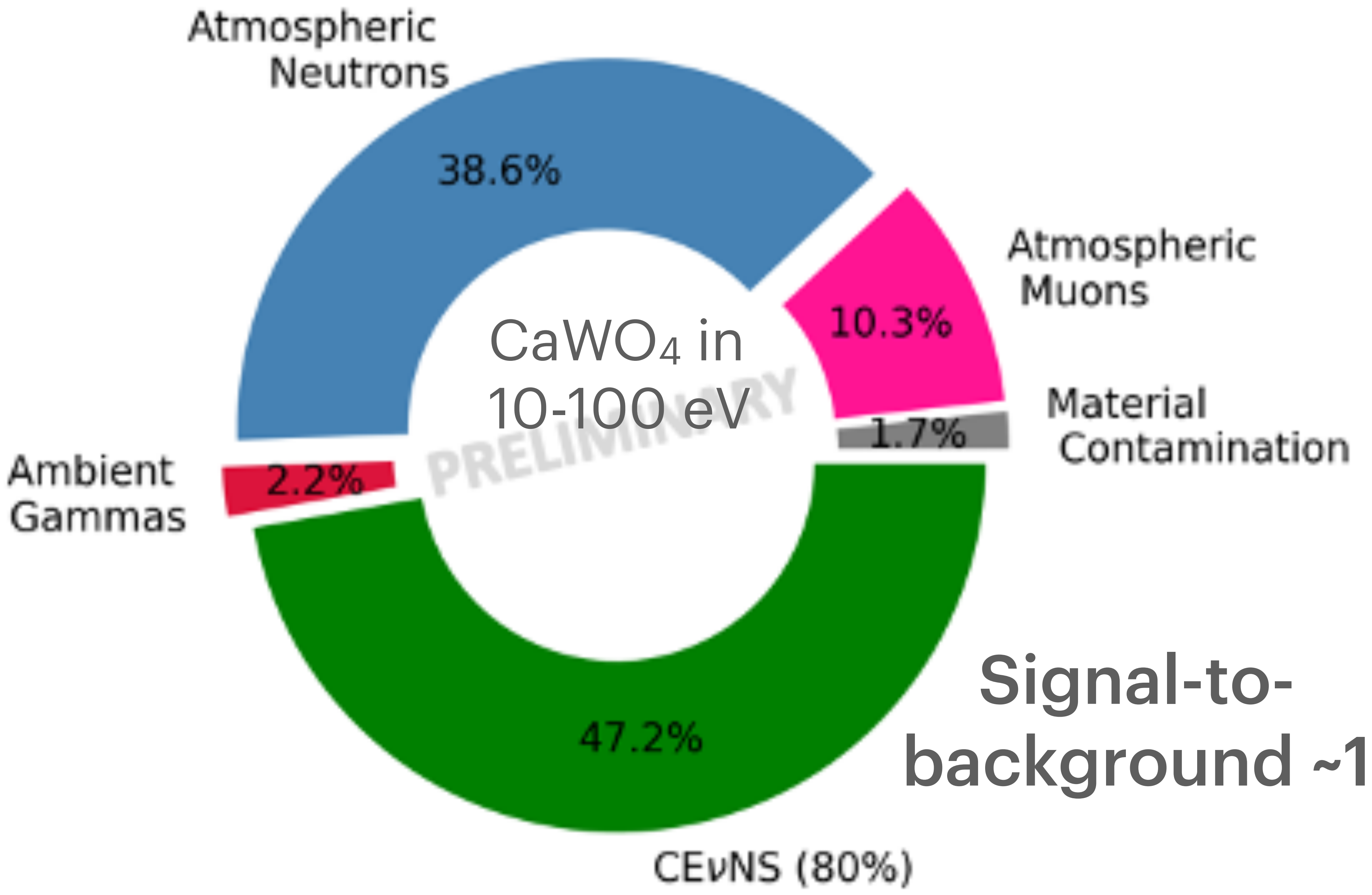

Signal-to-background ~1

Chloé Goupy's PhD, CEA, 2024

The NUCLEUS Experiment

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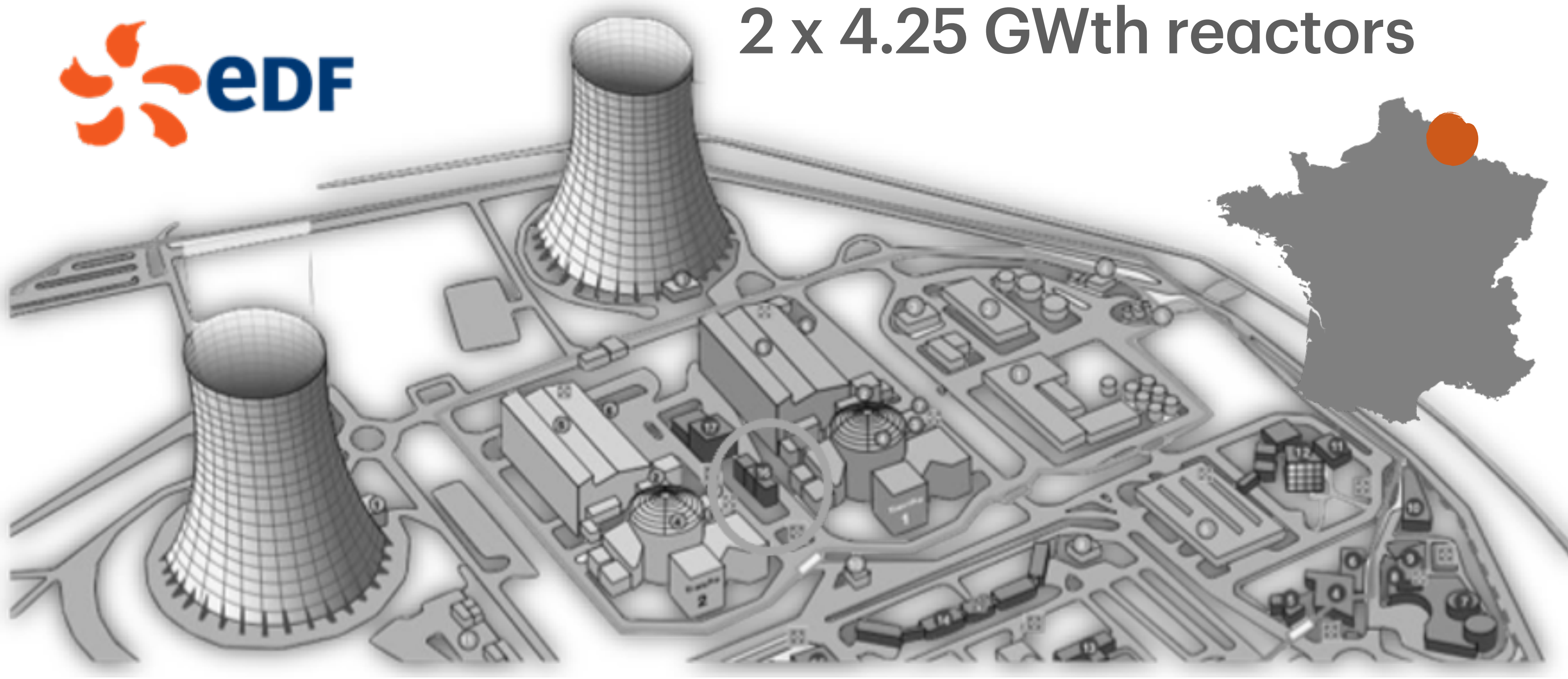
Chooz B nuclear power plant:
2 x 4.25 GWth reactors



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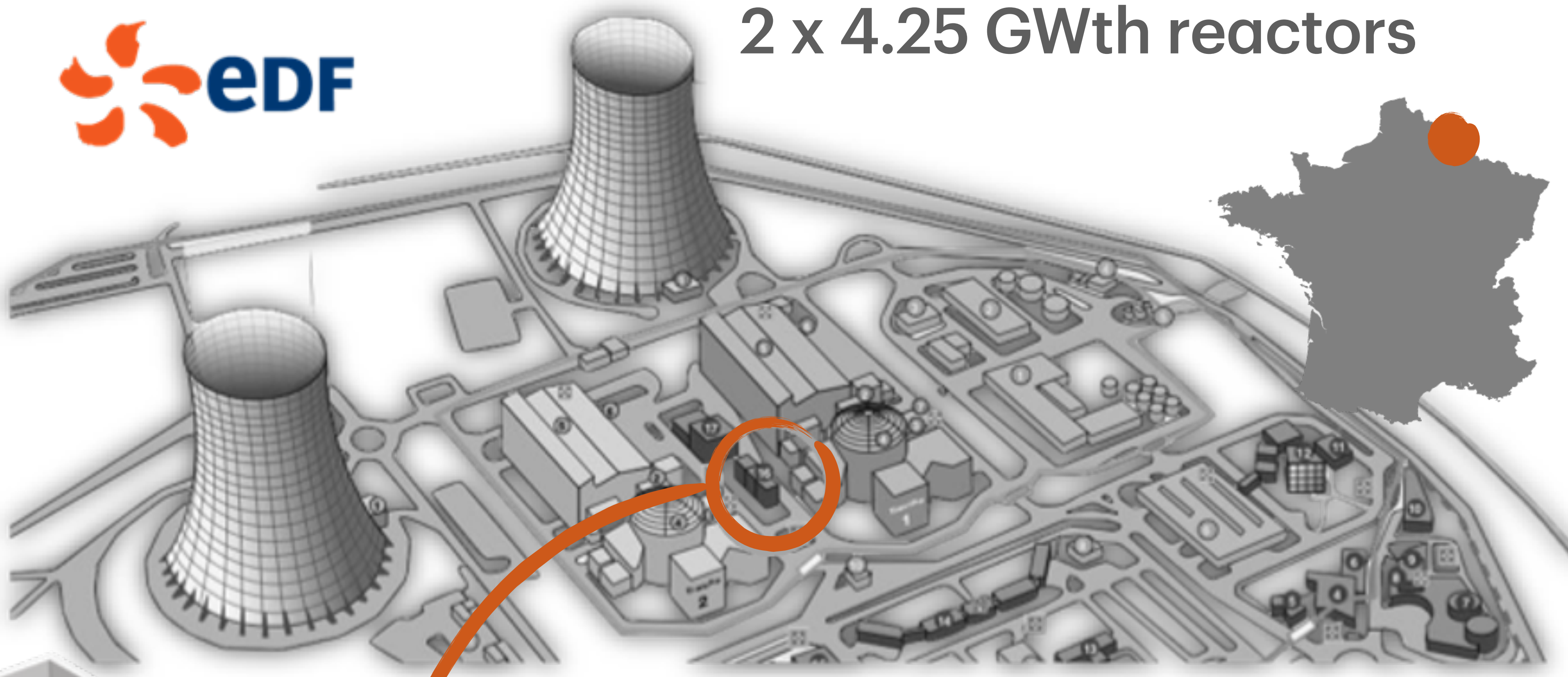

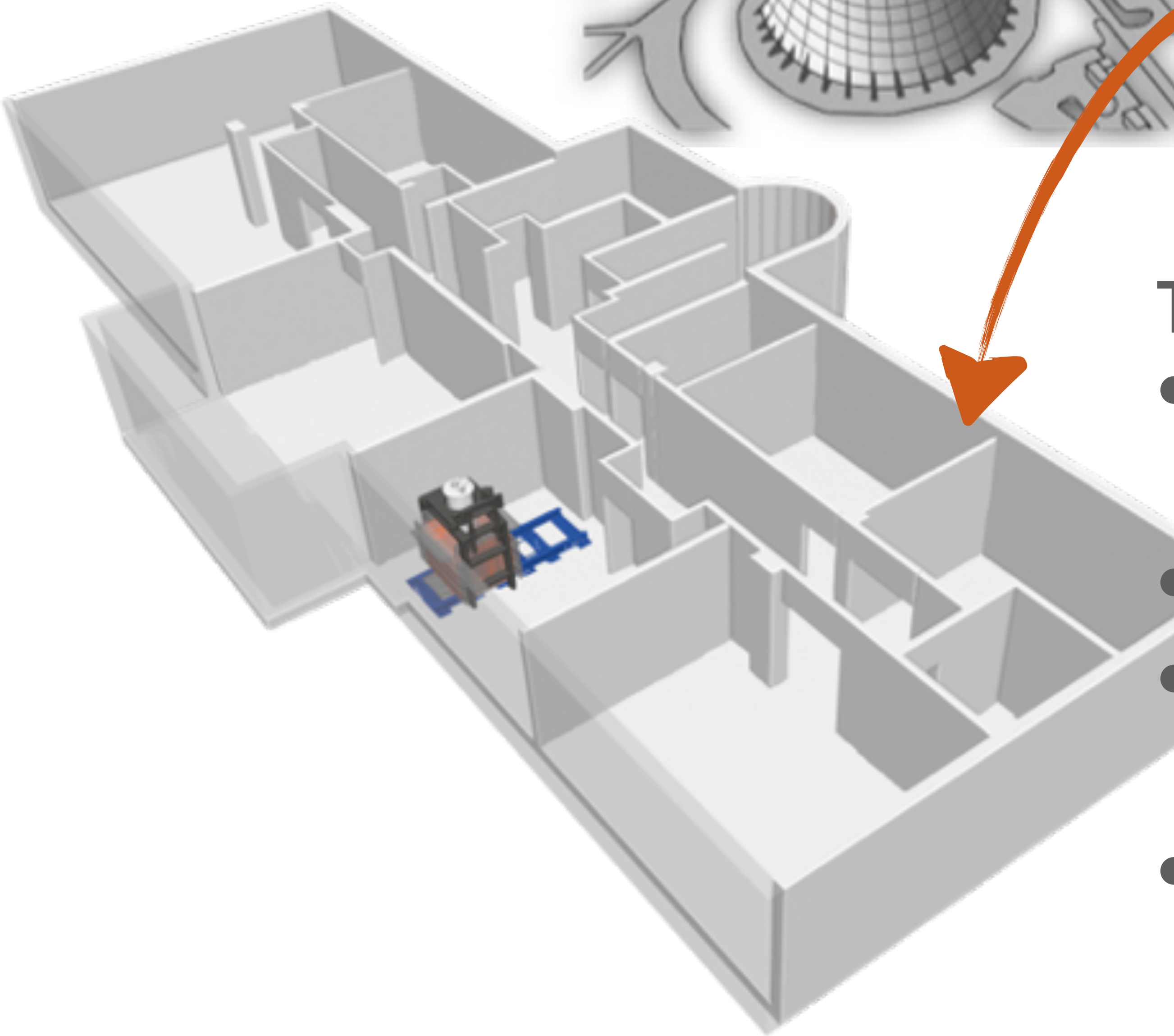

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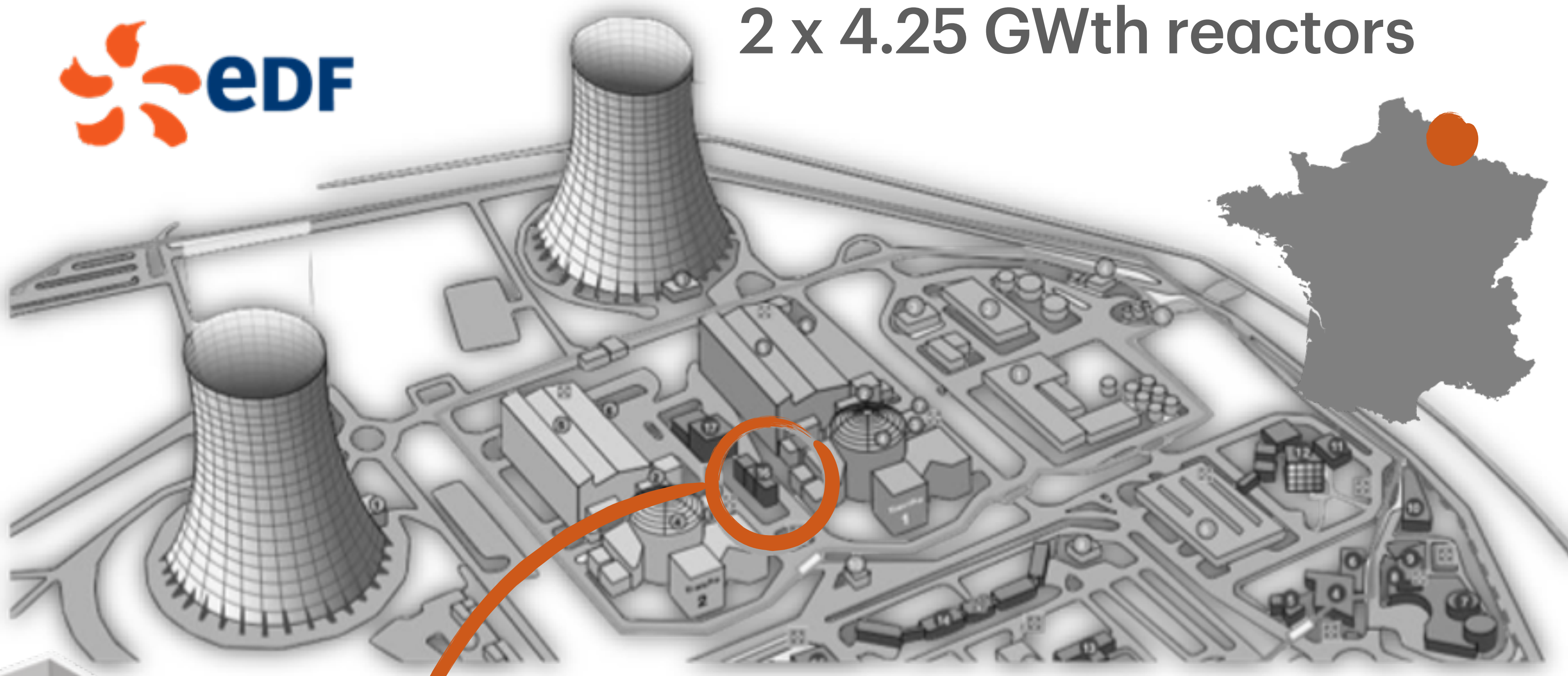

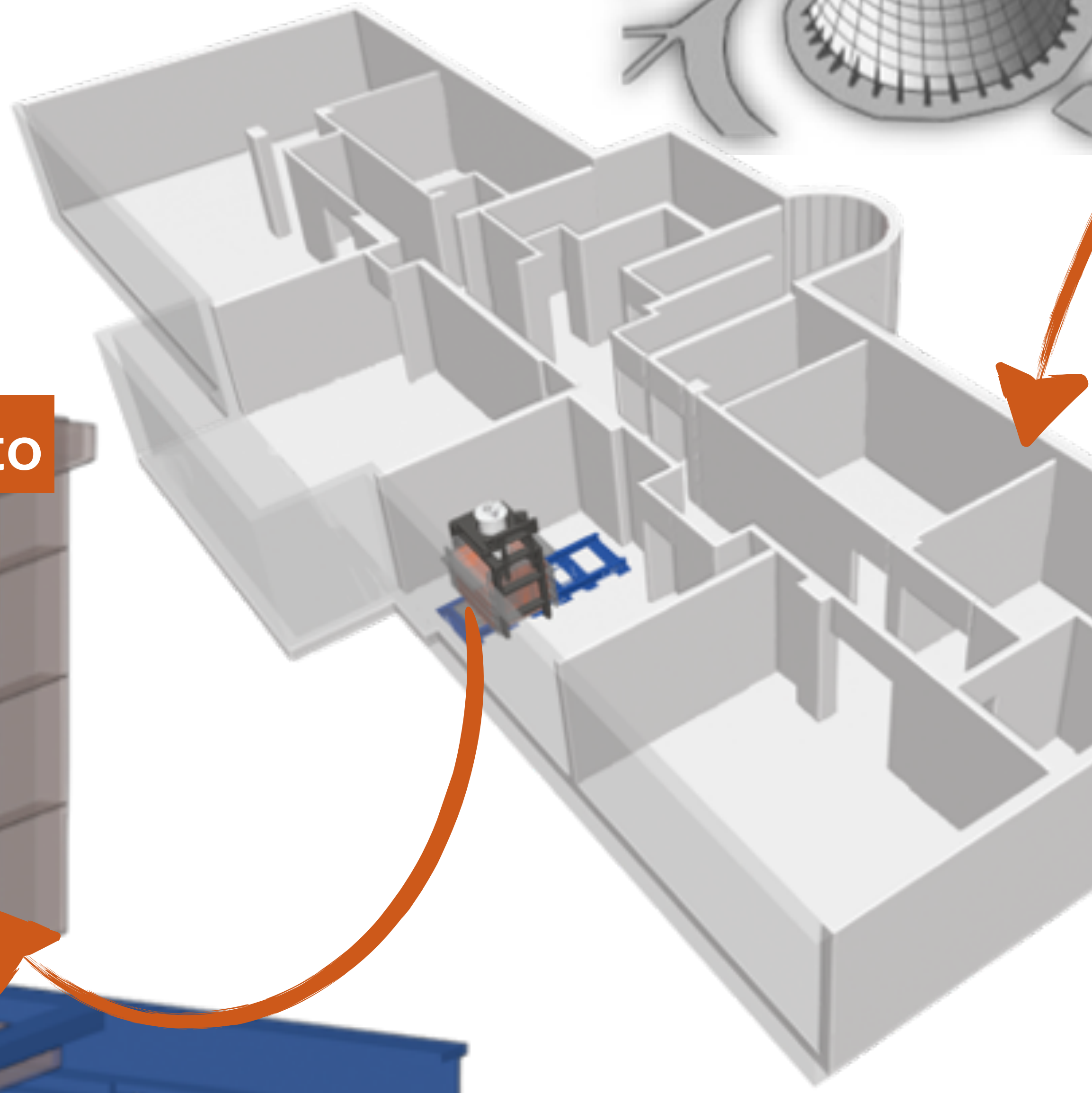

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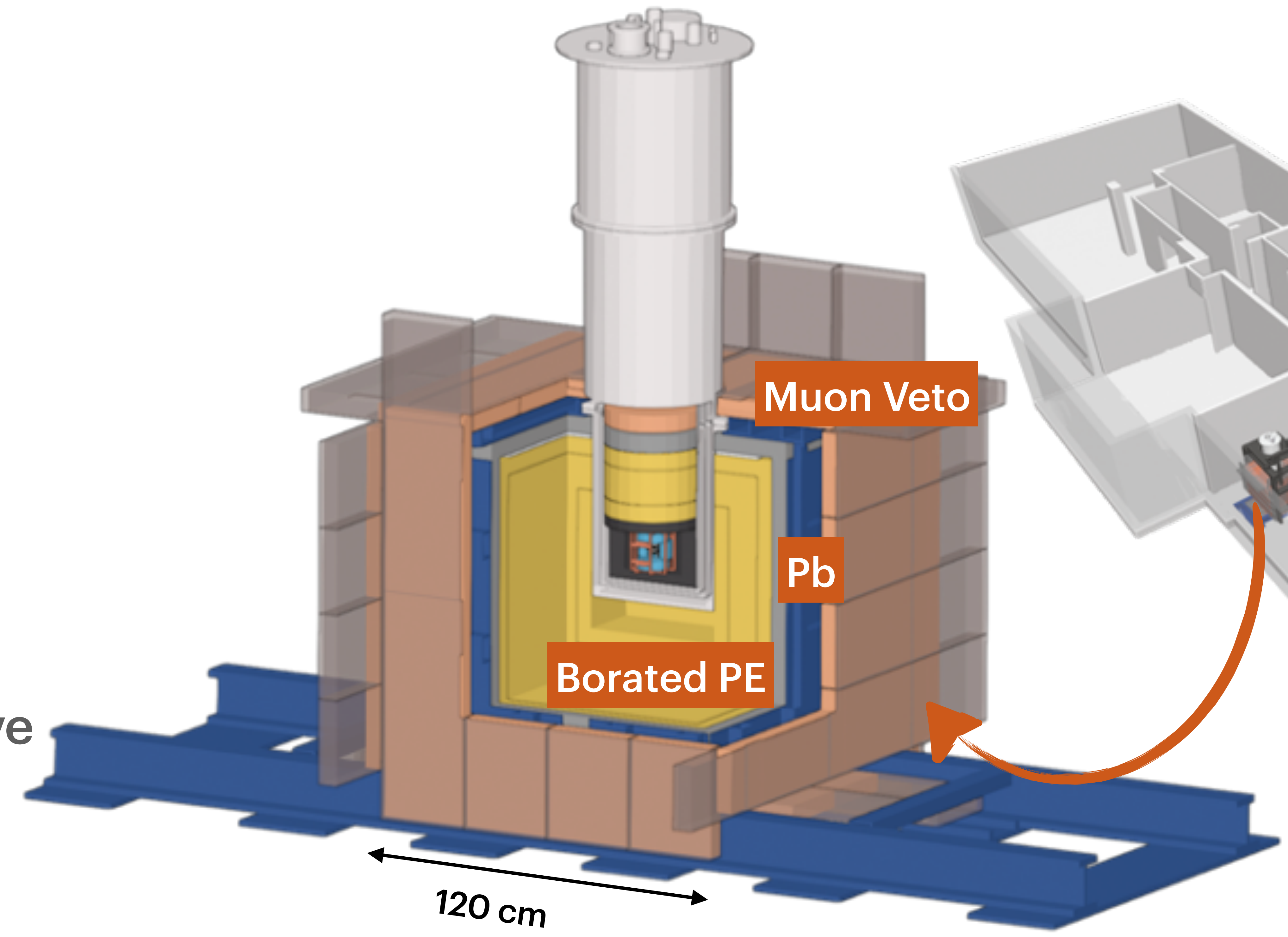
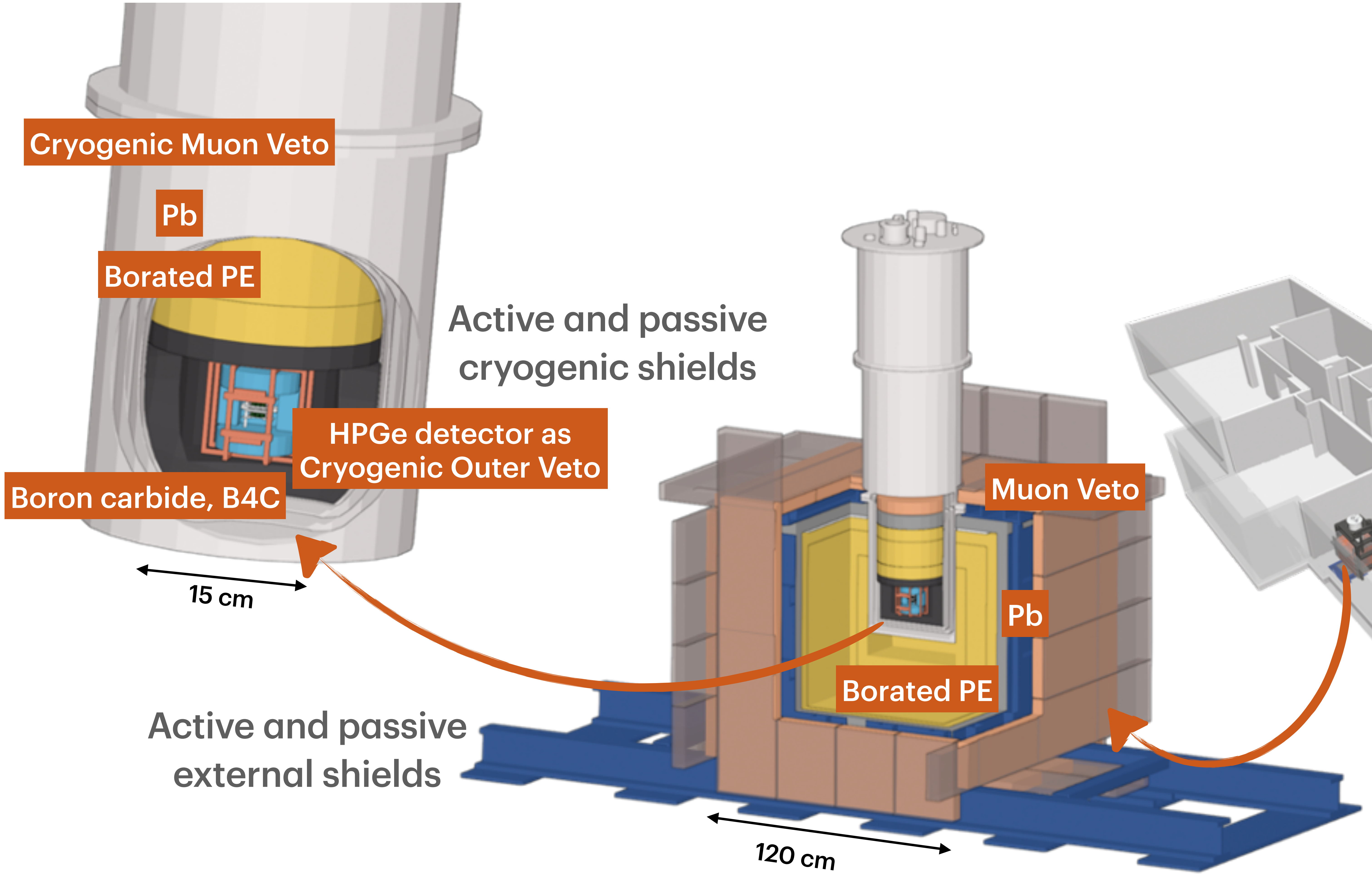
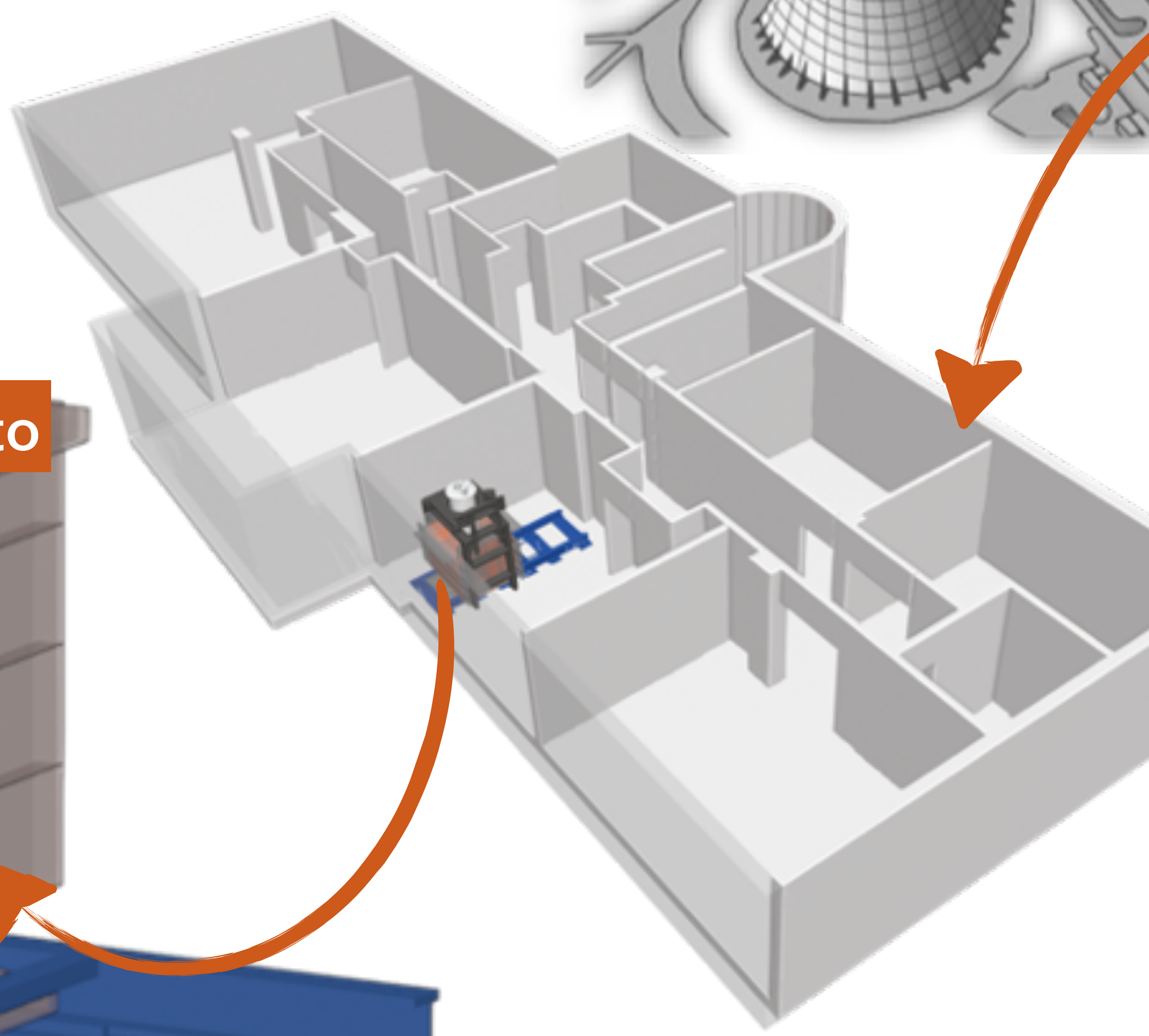


Active and passive external shields

The NUCLEUS Experiment





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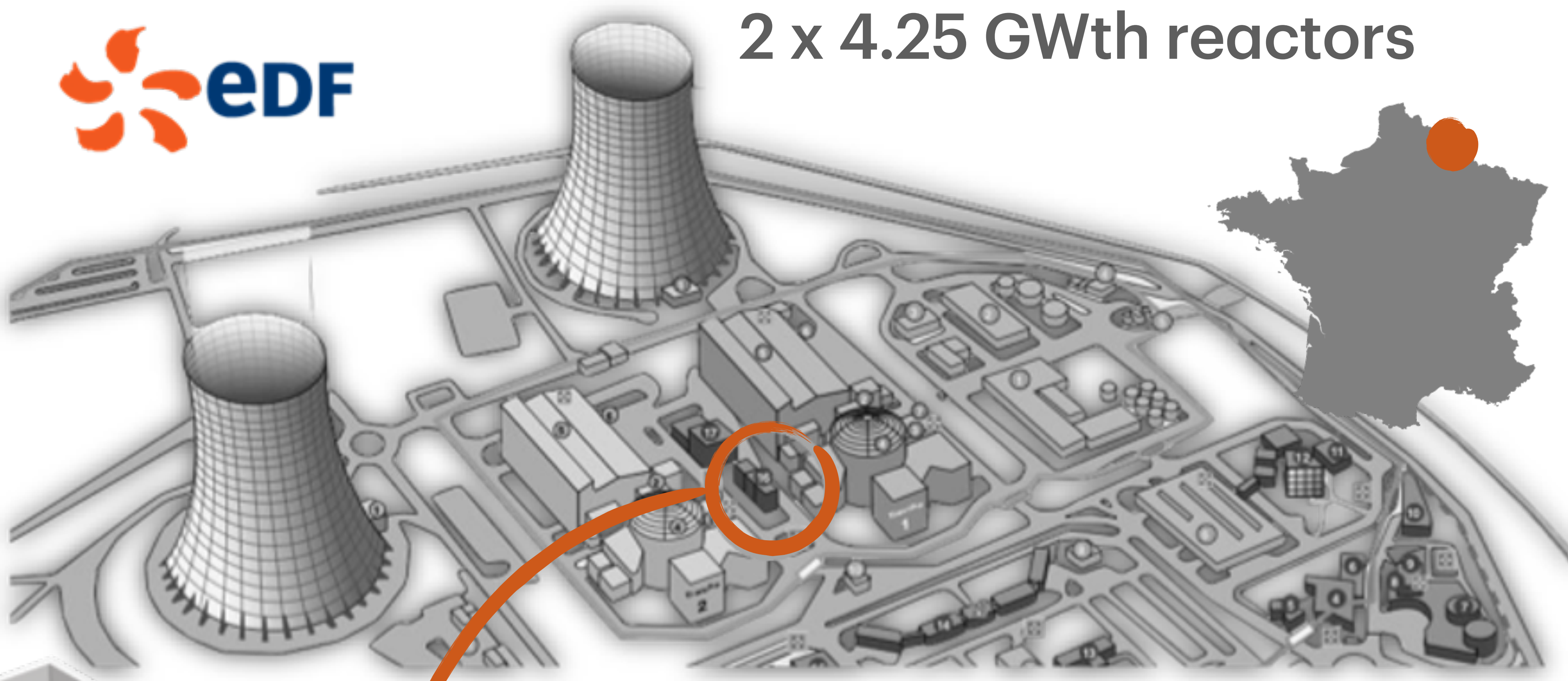

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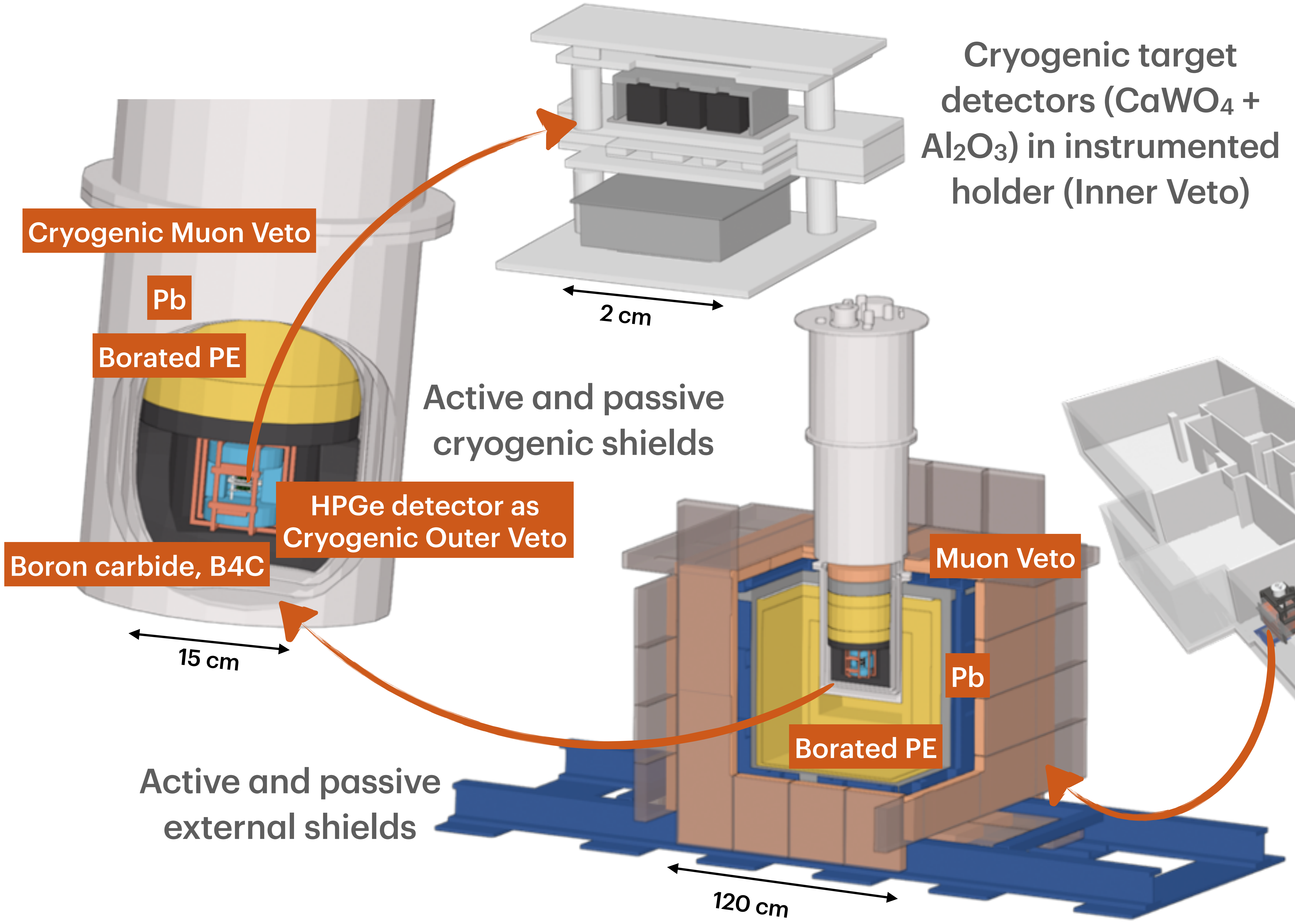

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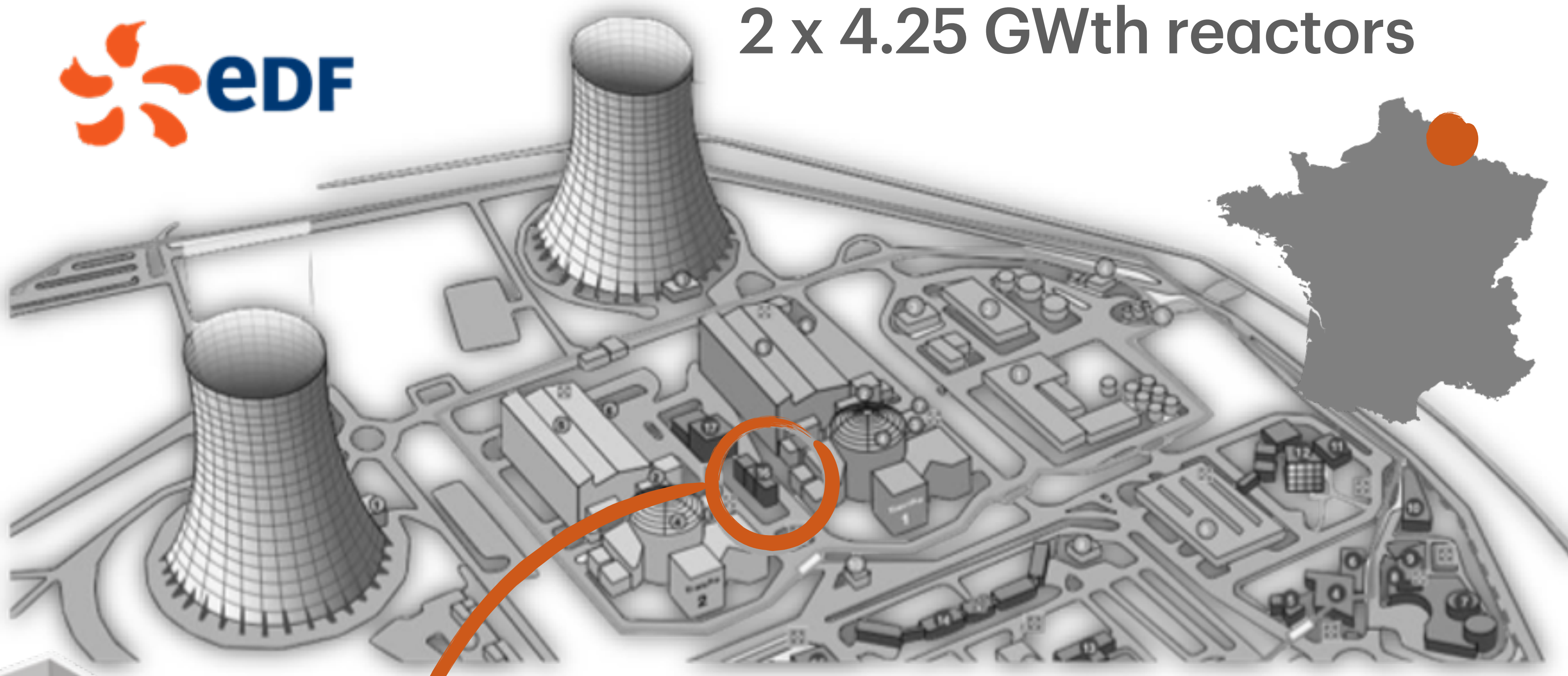

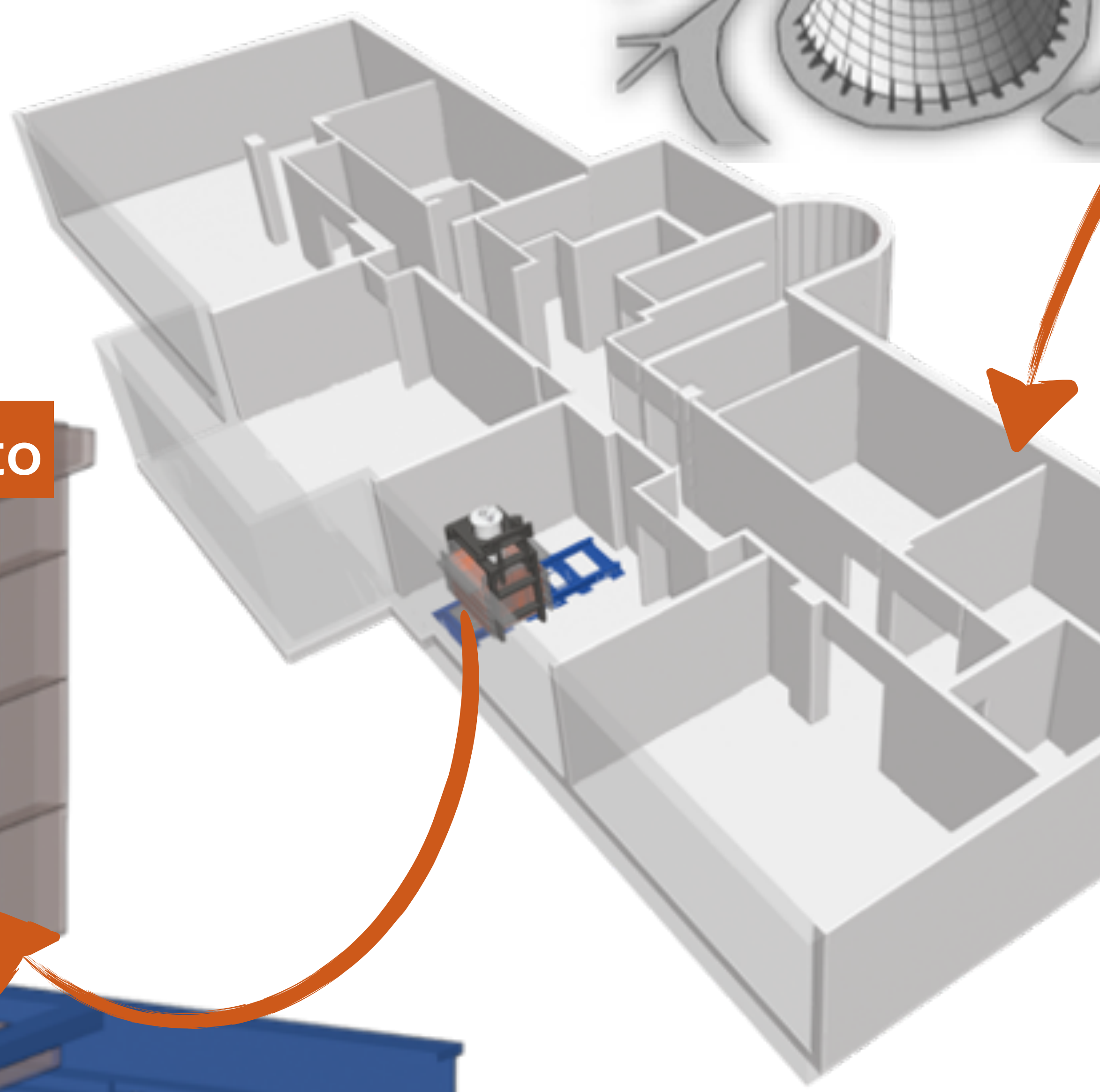

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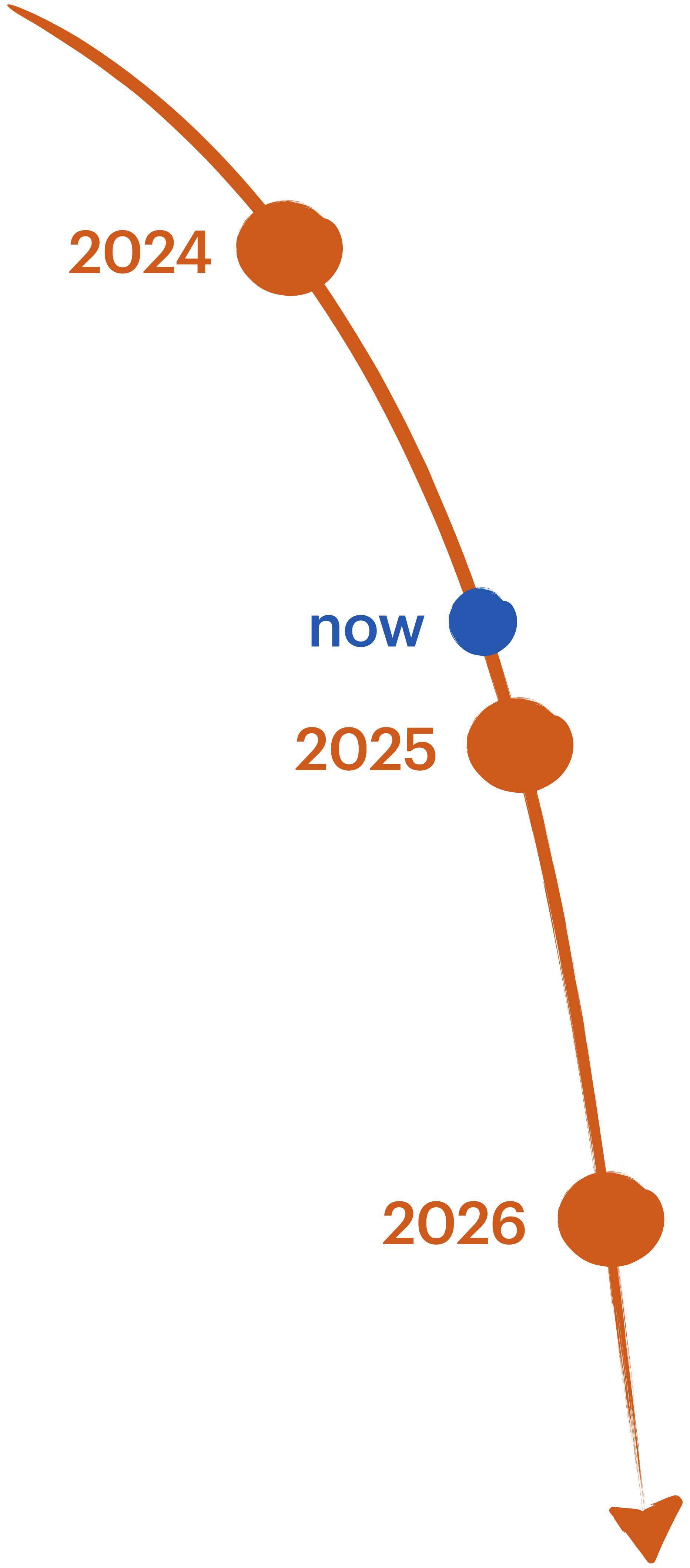

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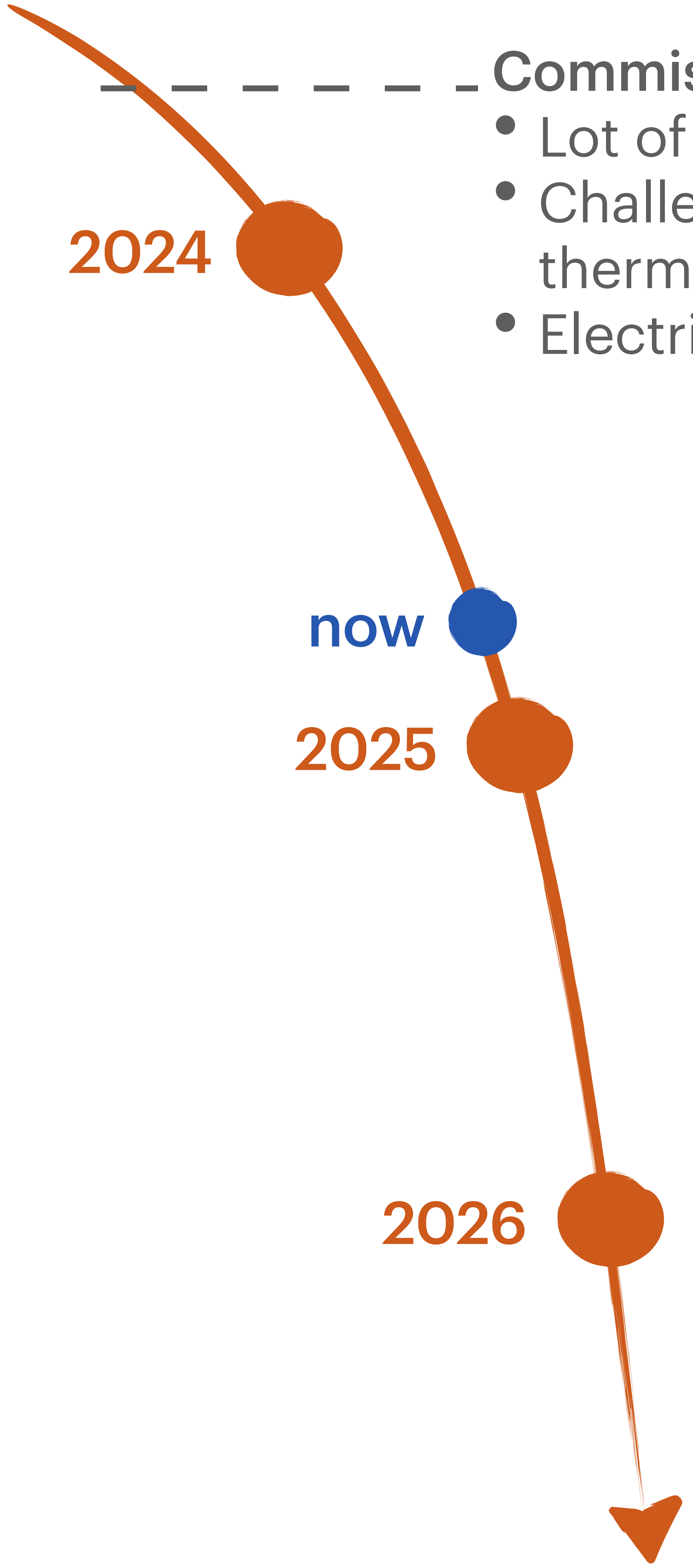

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- Challenges within the cryostat: thermal couplings and vibrations
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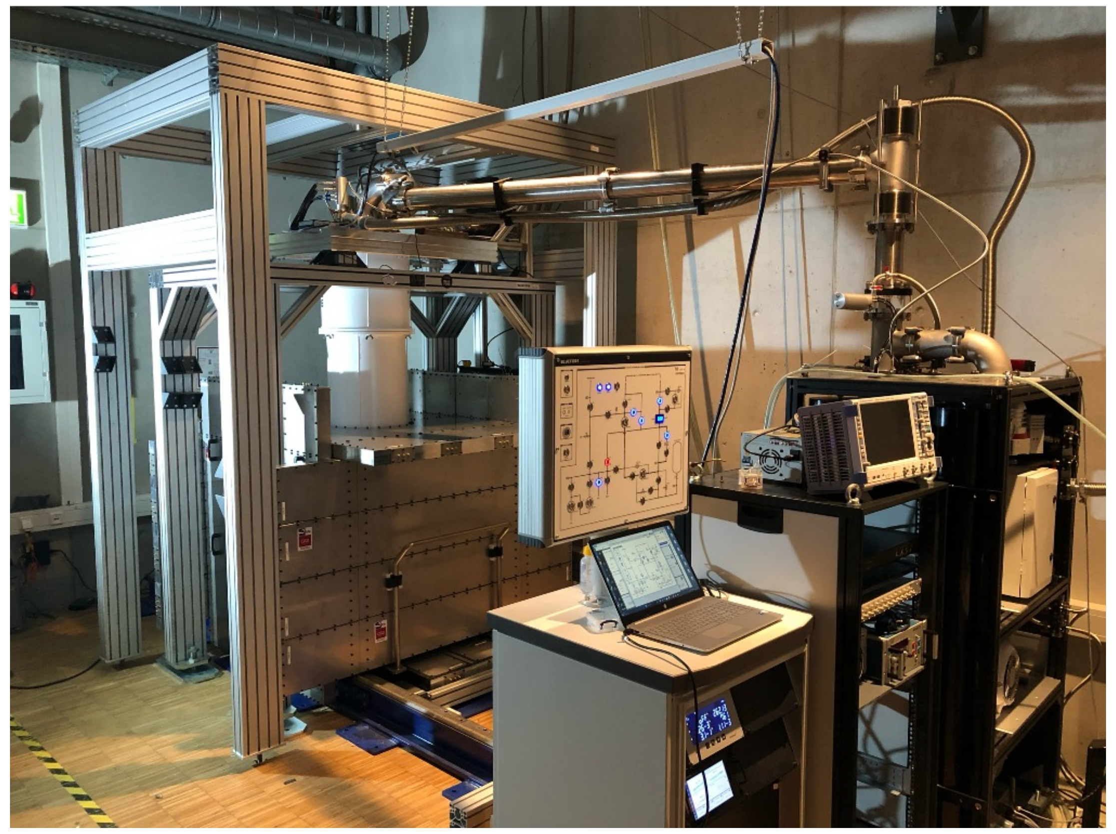

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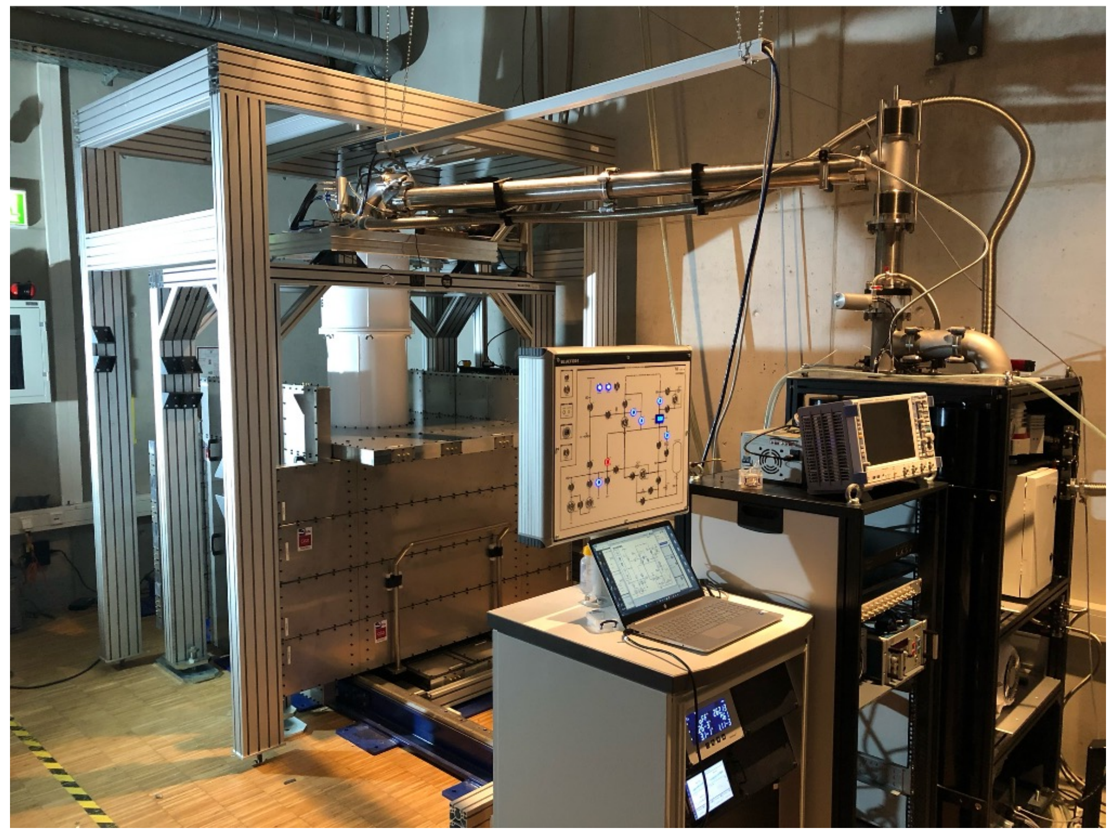
Long Background Run @TUM
- Demonstration of experimental setup
- First background measurement

now

2025

2026


Shallow underground lab @TUM



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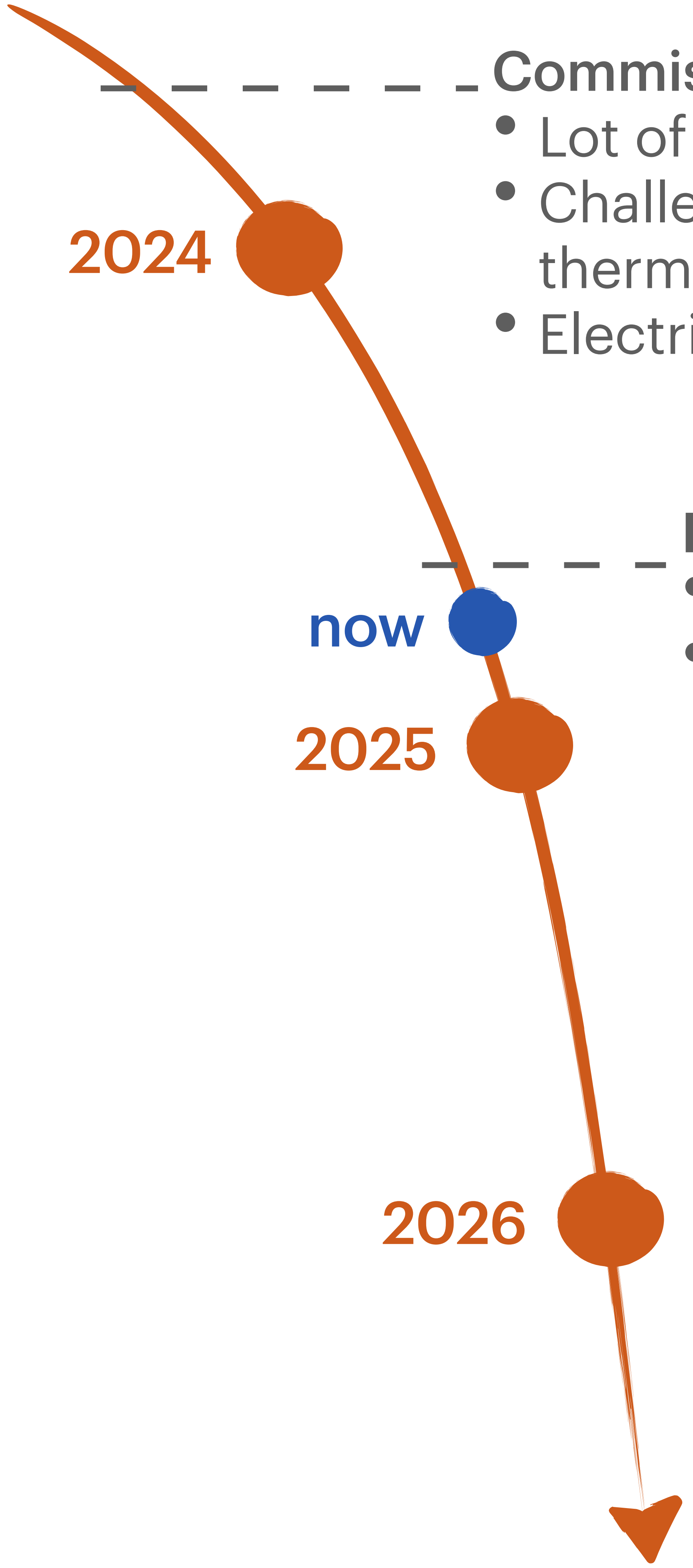

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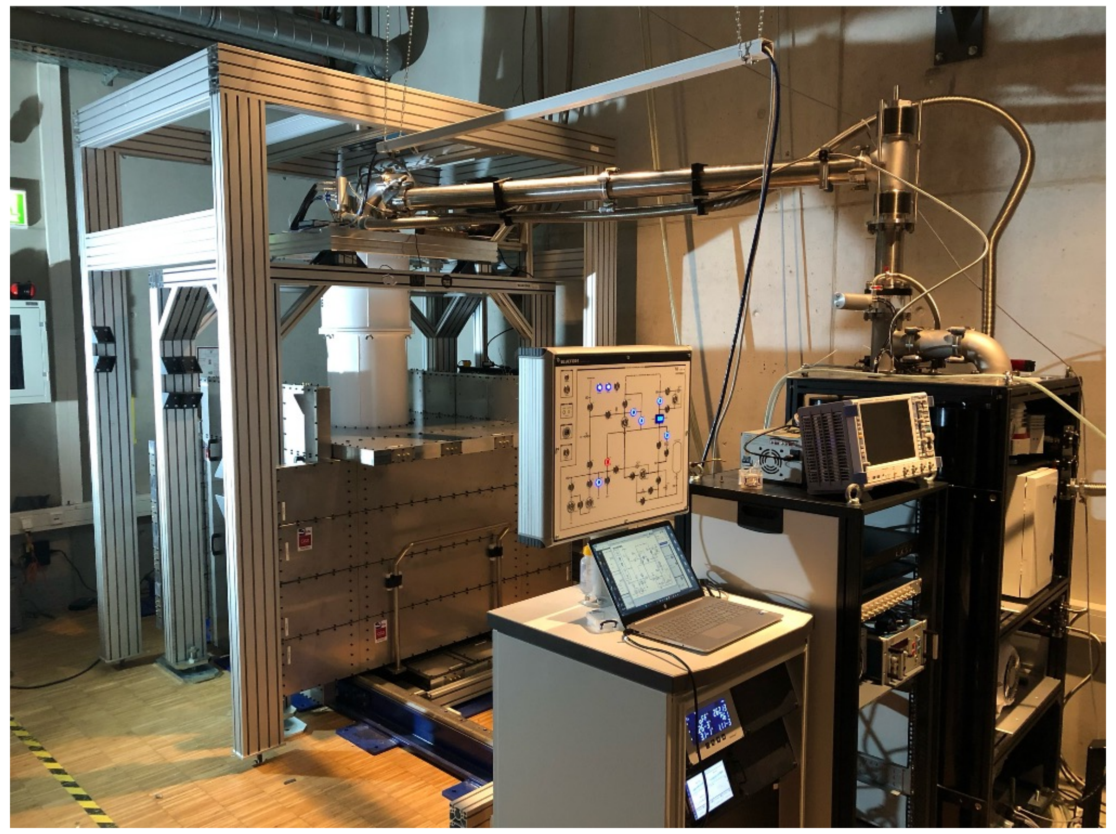

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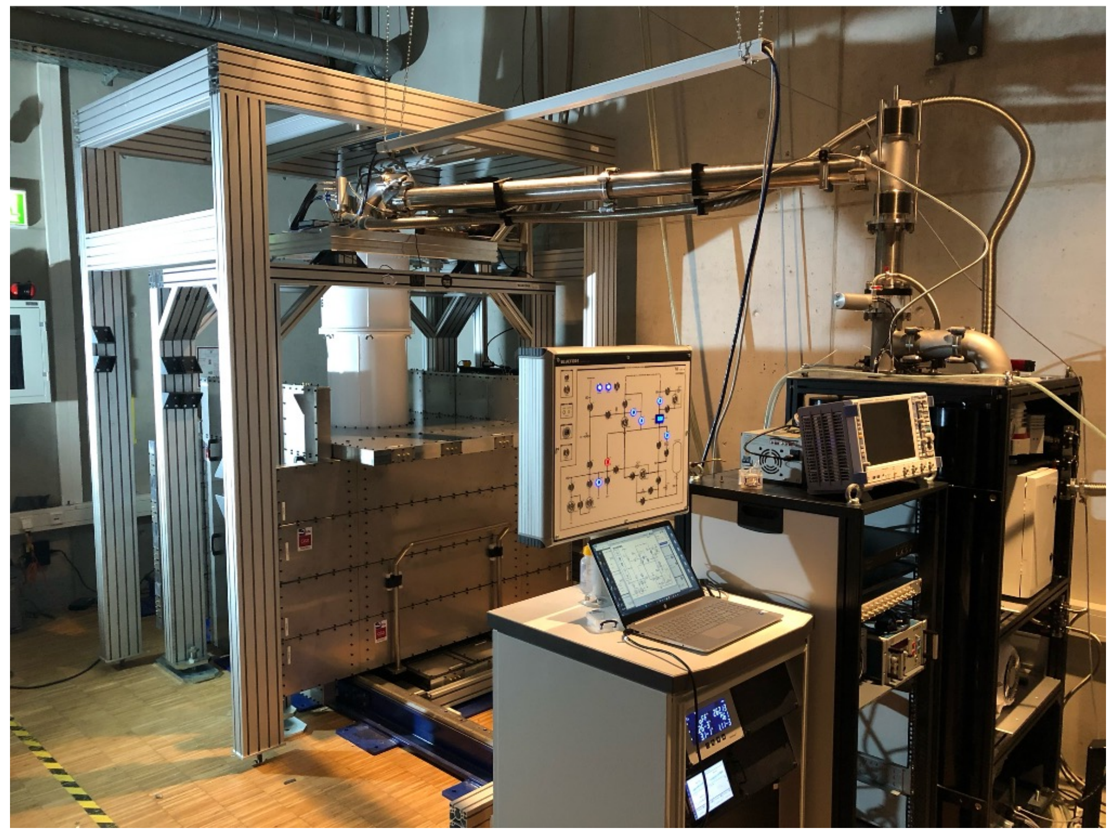

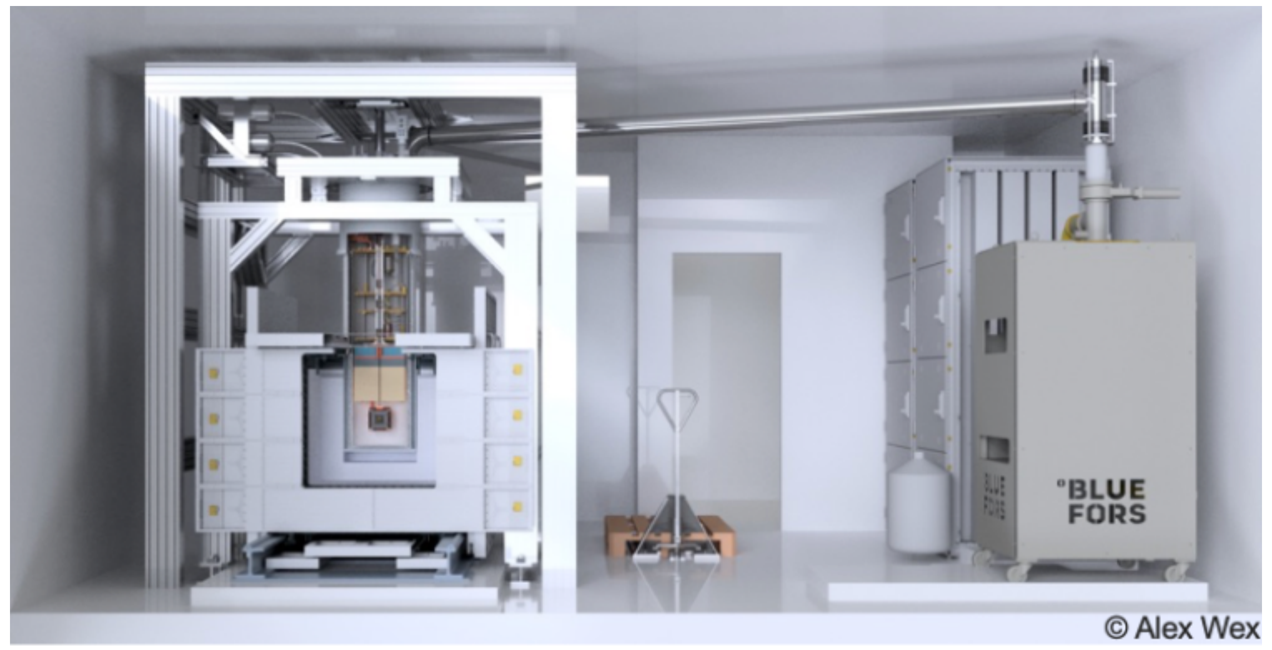

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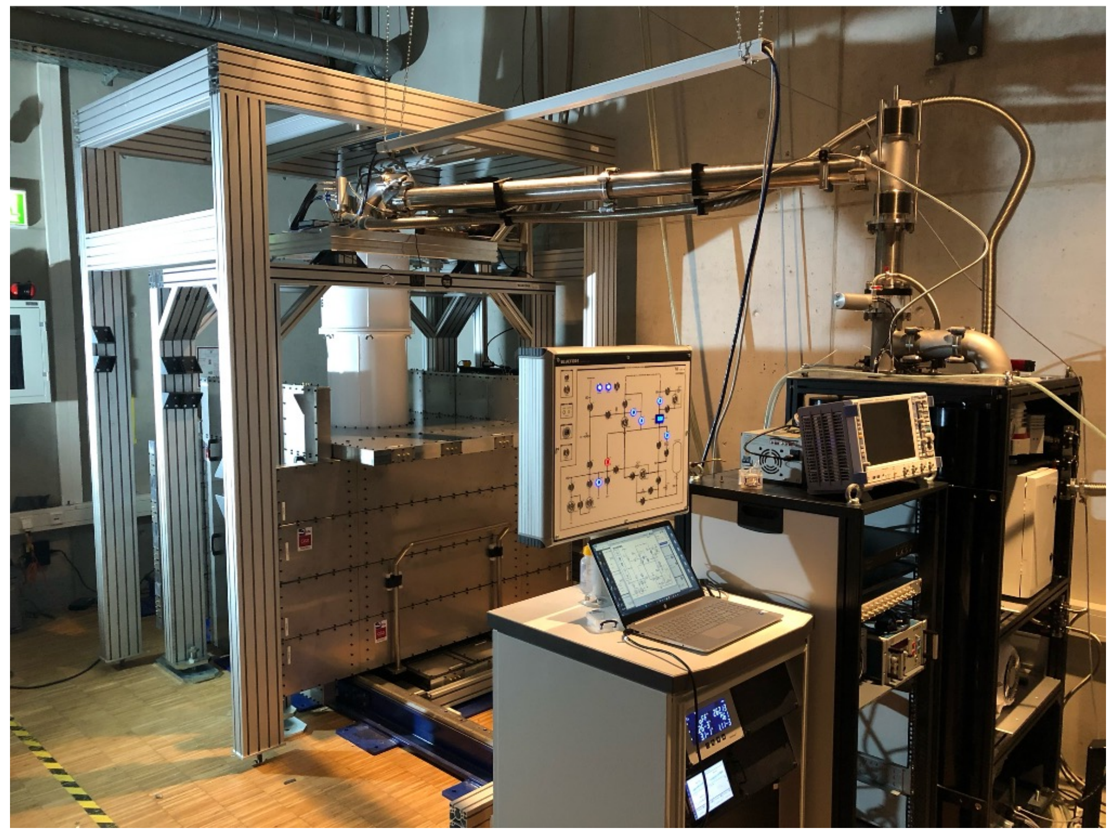
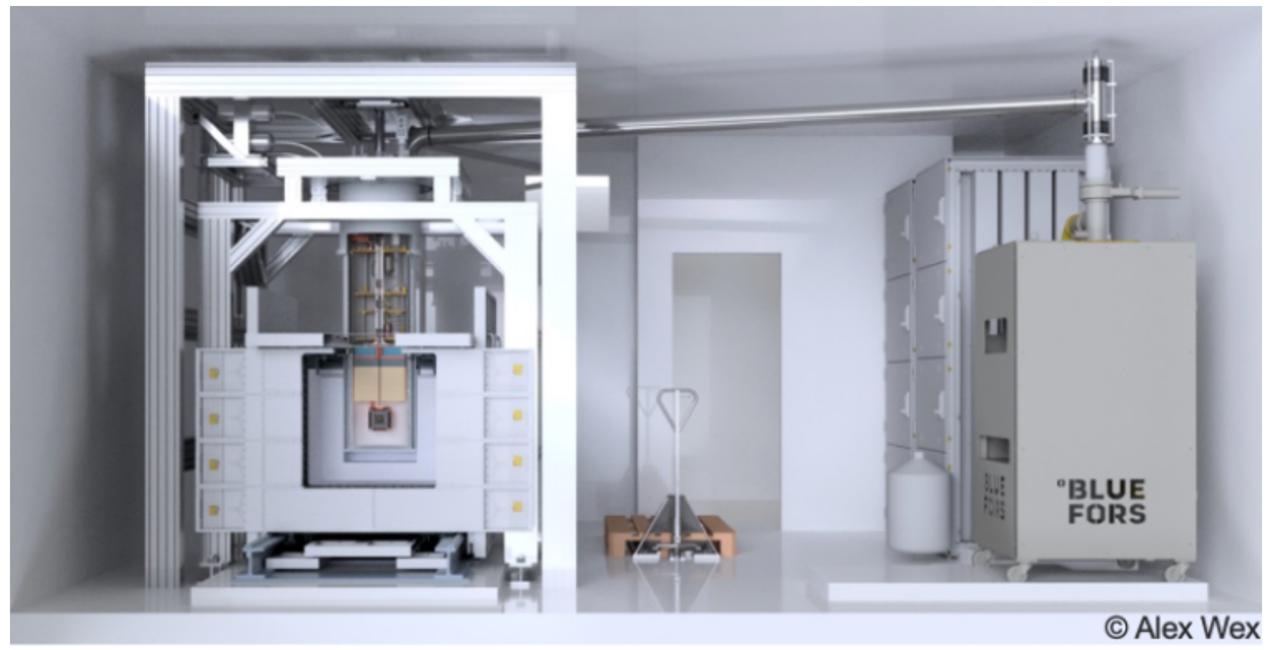
Technical Run @Chooz
- Demonstration of backgrounds
- Validation of LEE mitigation strategy

Physics Run @Chooz
- Neutrino detection with CEvNS





The Long Background Run @TUM

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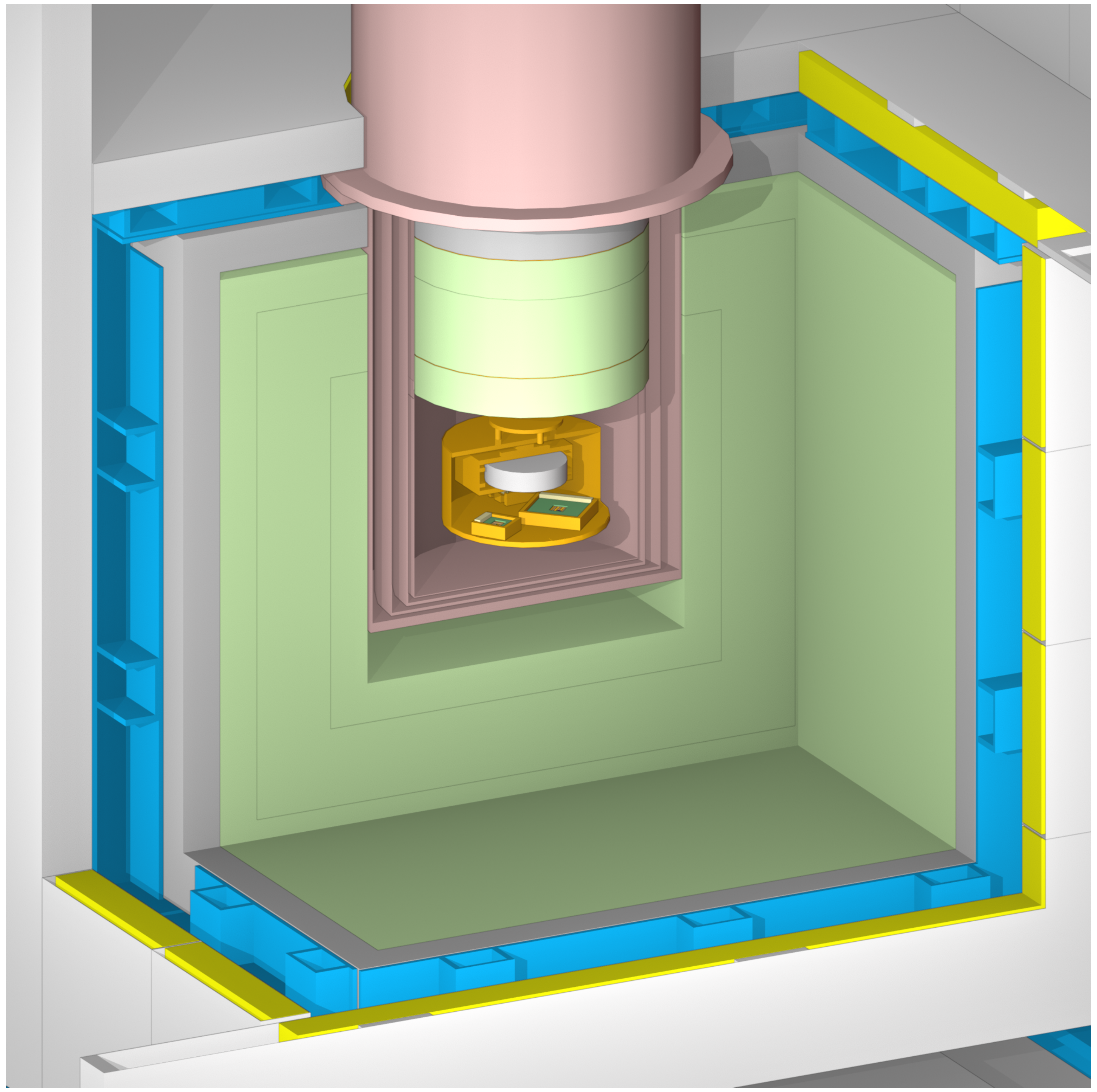

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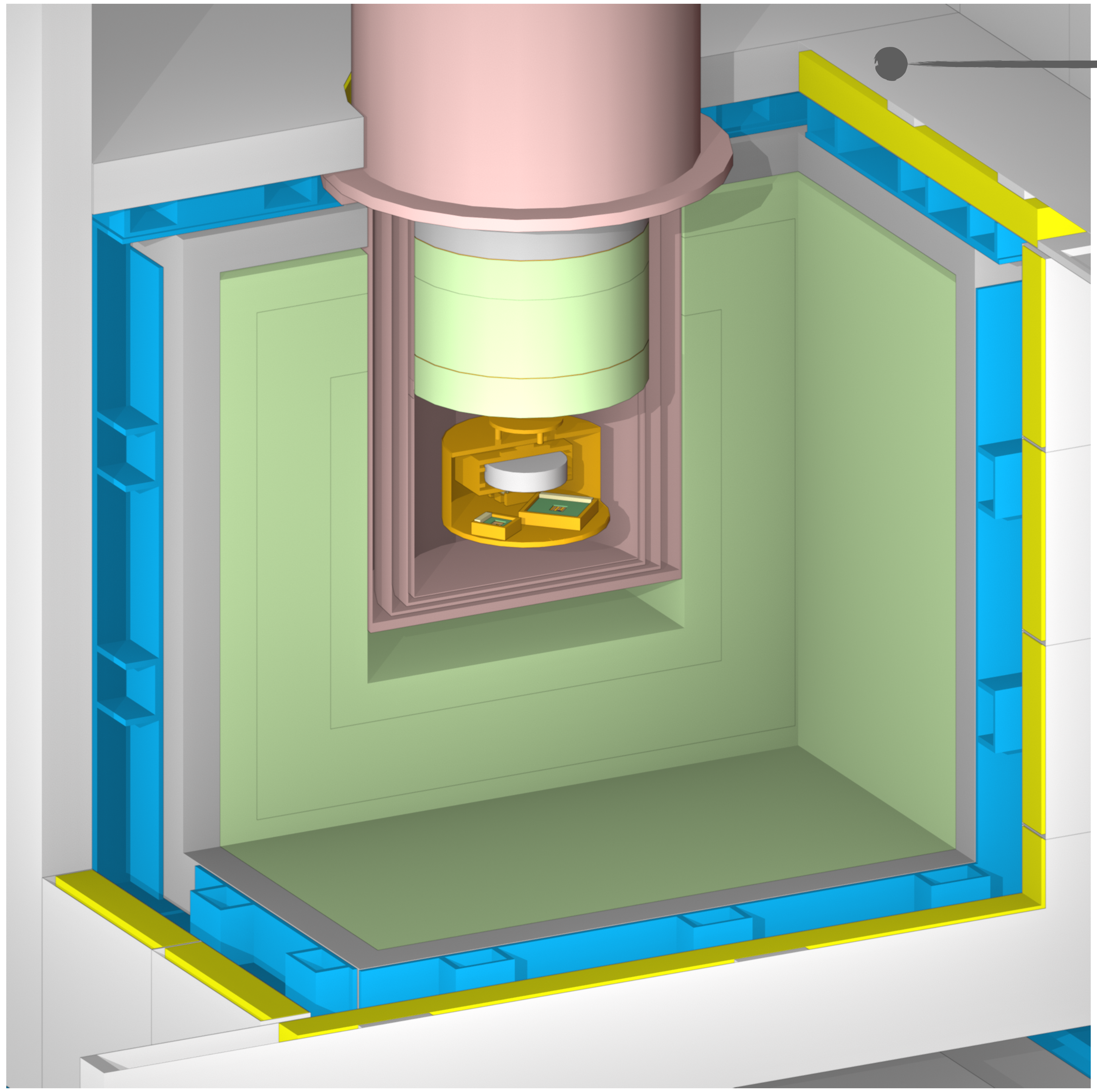

Full Muon Veto: 32 panels + Cold Muon Veto disk

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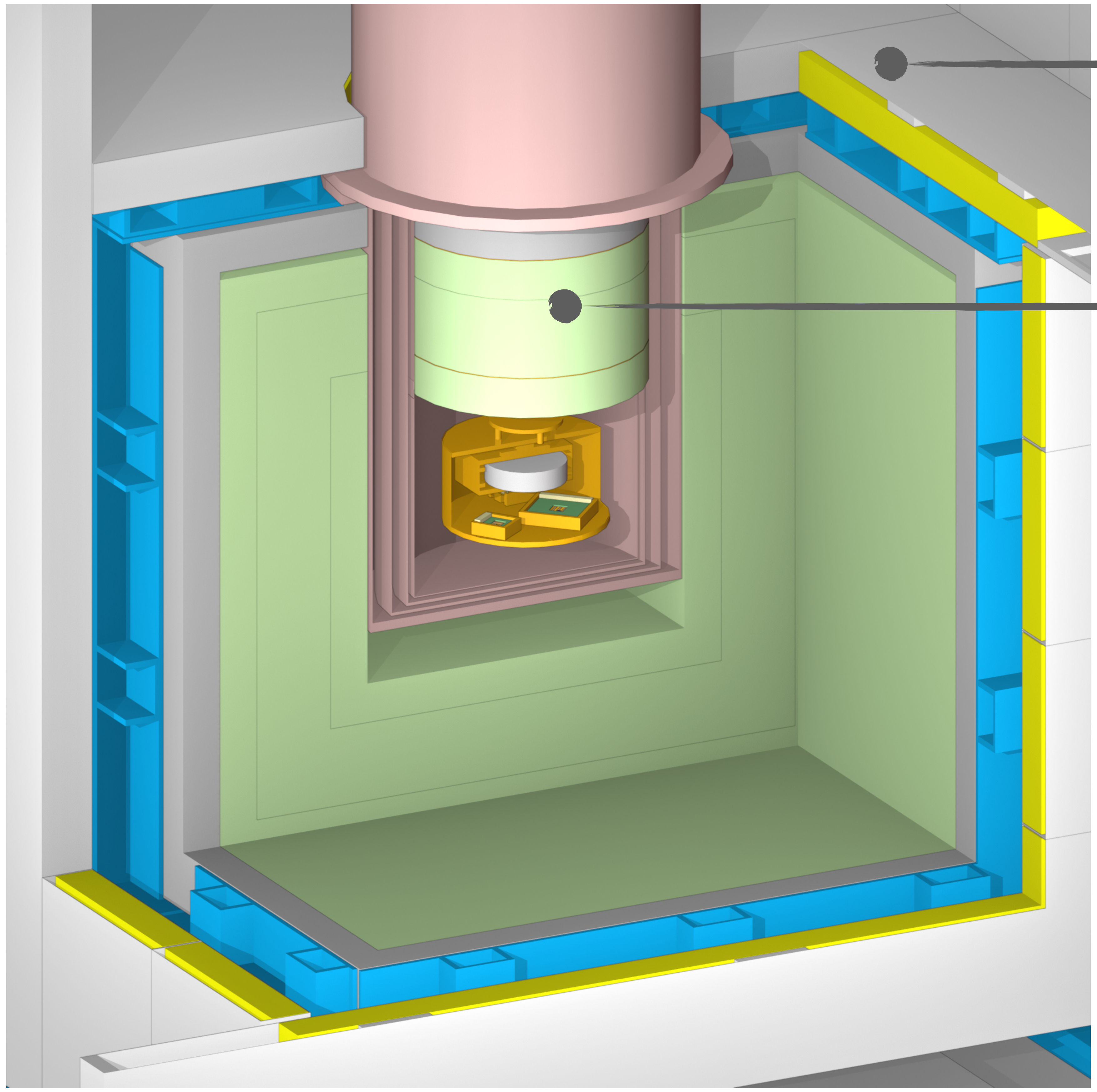

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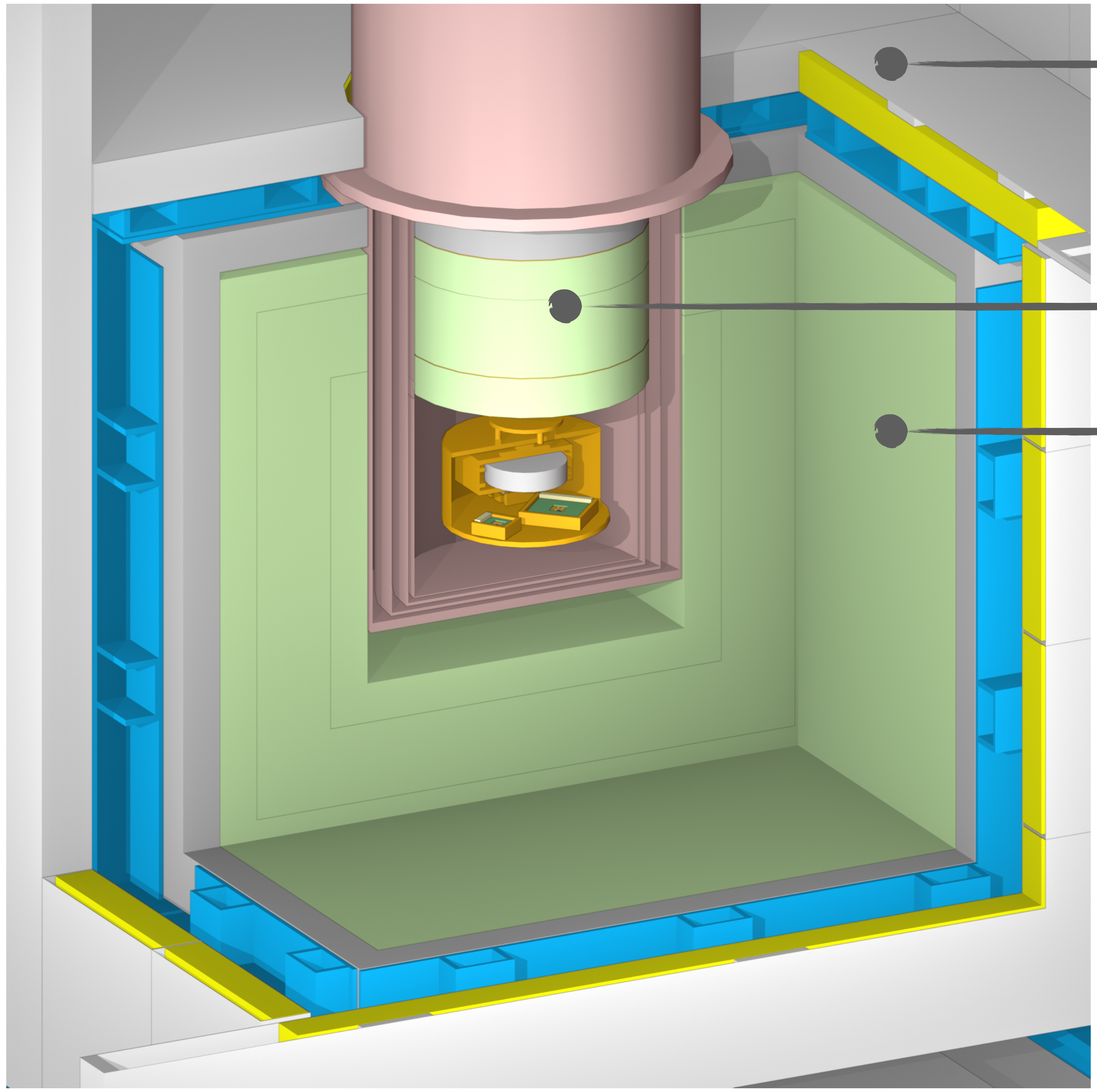

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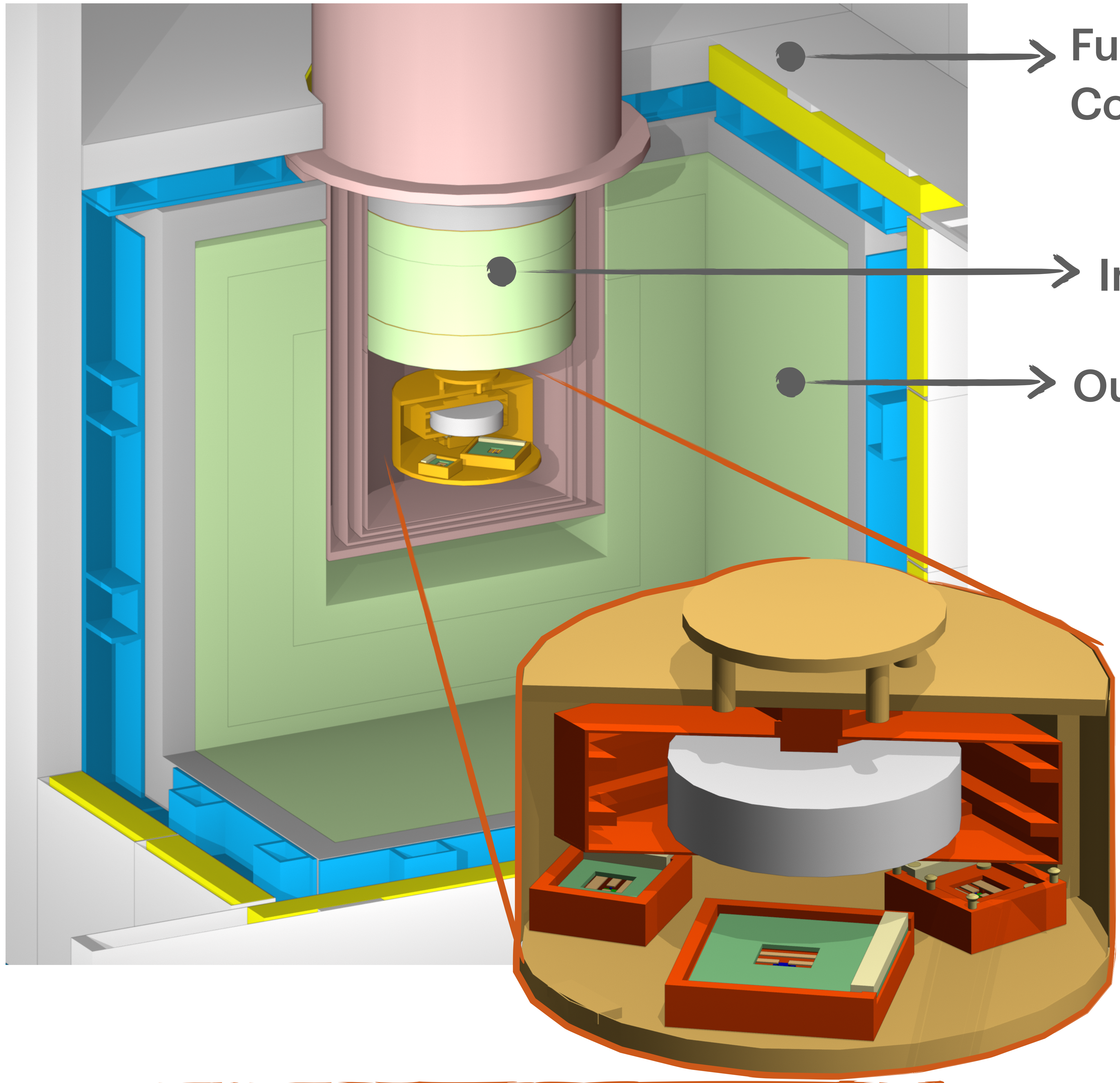

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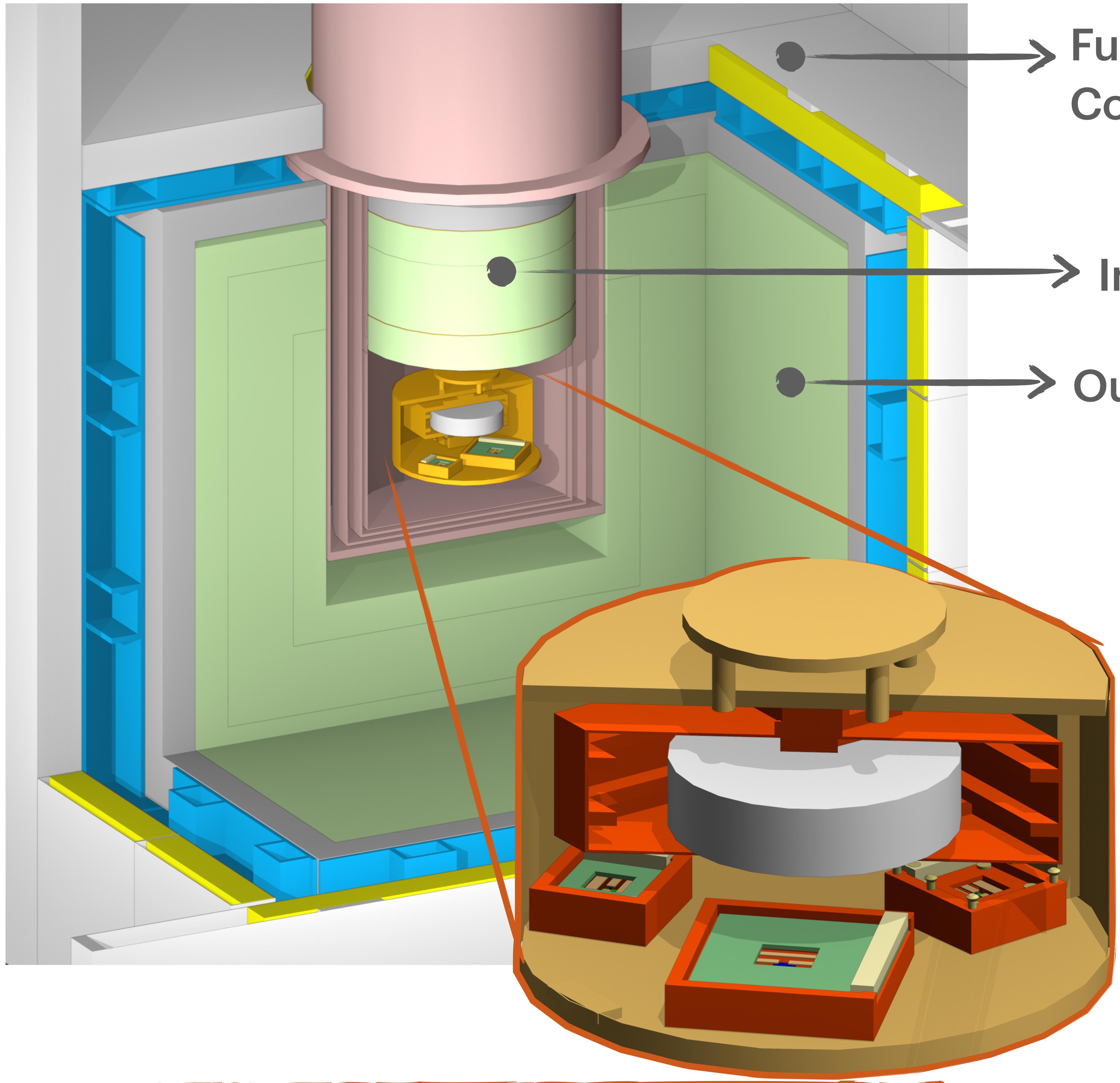

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Simplified cryogenic detectors configuration:

- Cryogenic Outer Veto = 1 out of 6 Germanium detector
- 2x $CaWO_4$ detector (0.76 g)
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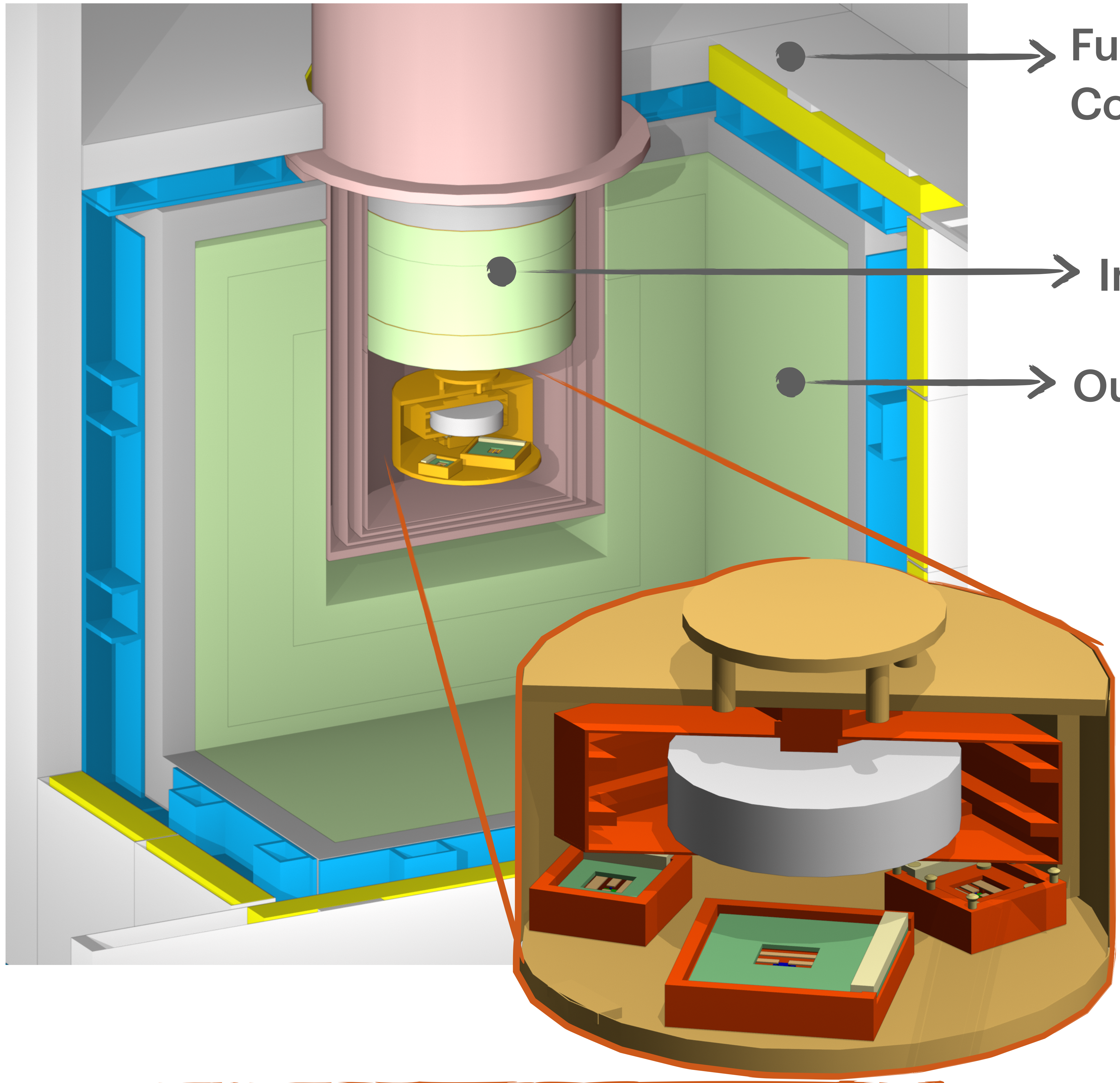

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Physics and technical goals:

- First experience of running the NUCLEUS experiment is a near Chooz-like configuration
- Demonstrate stable detector operation and performance over months-long period
- Validate the shielding strategy: background measurement, tuning of simulation
- Test and validate LED calibration strategy
- Access Low Energy Excess: study time decay of LEE rate, investigate double-TES readout

Clean tent
Inner shielding
© Alexander Wex
© Alexander Wex
Muon Veto
Outer shielding
Cold Muon Veto
Cryogenic
Outer Veto
LED fibers
Detectors
© Alexander Wex
$CaWO_4$
Al_2O_3

The Long Background Run @TUM

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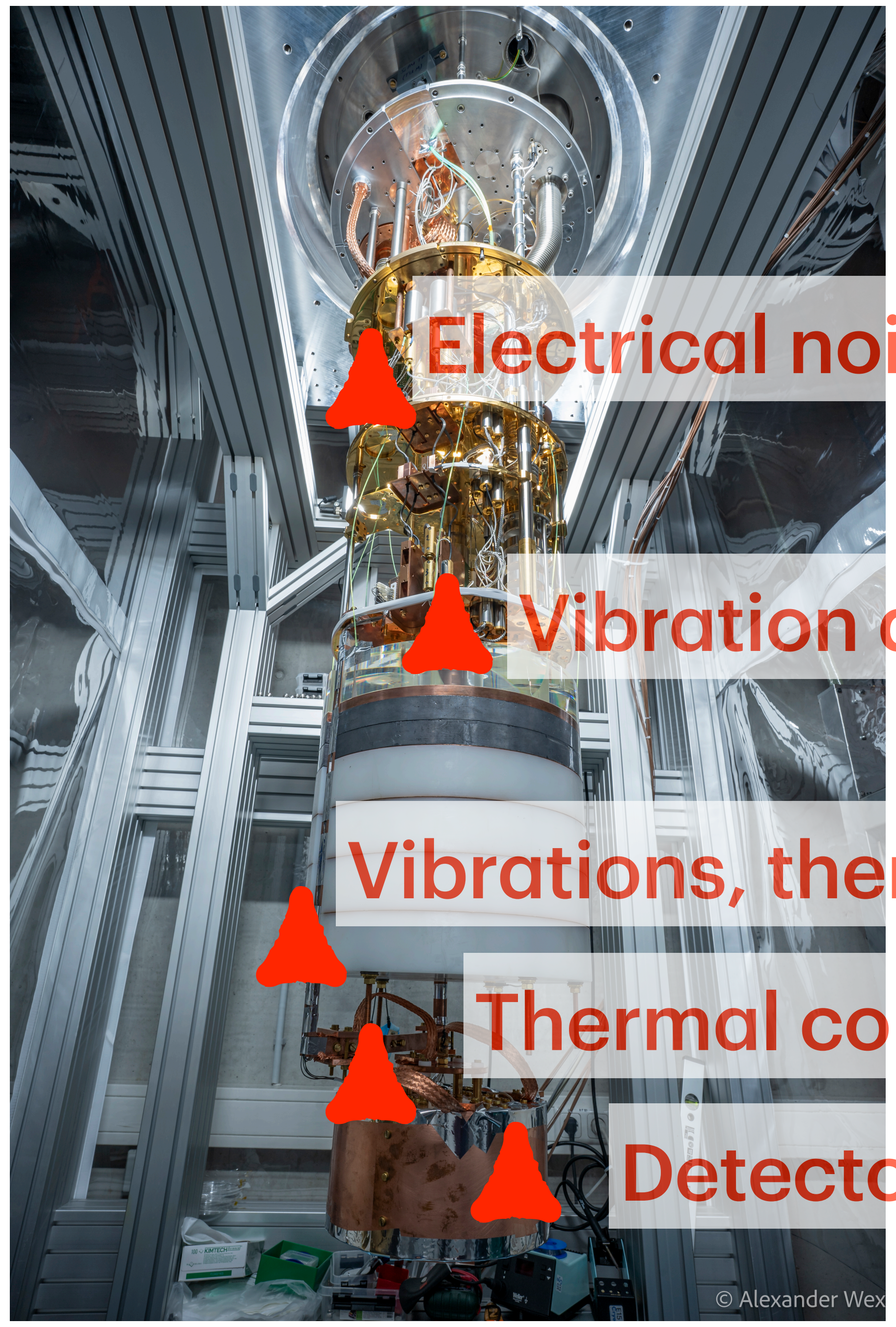
- Lessons learned:
  - Transition to dry cryostat technology extremely challenging
  - Challenging combination of all subsystems: TES + COV + MV



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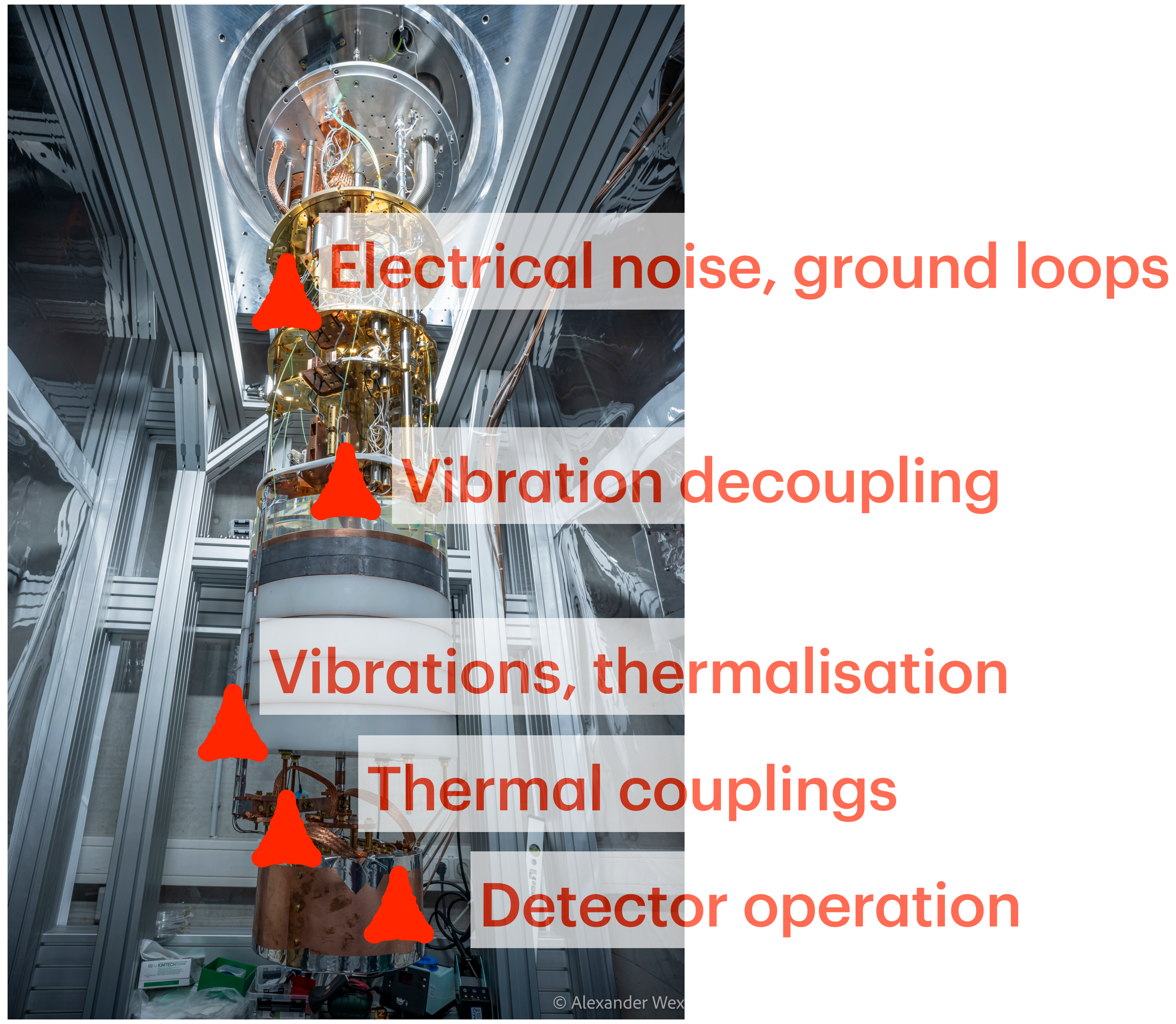
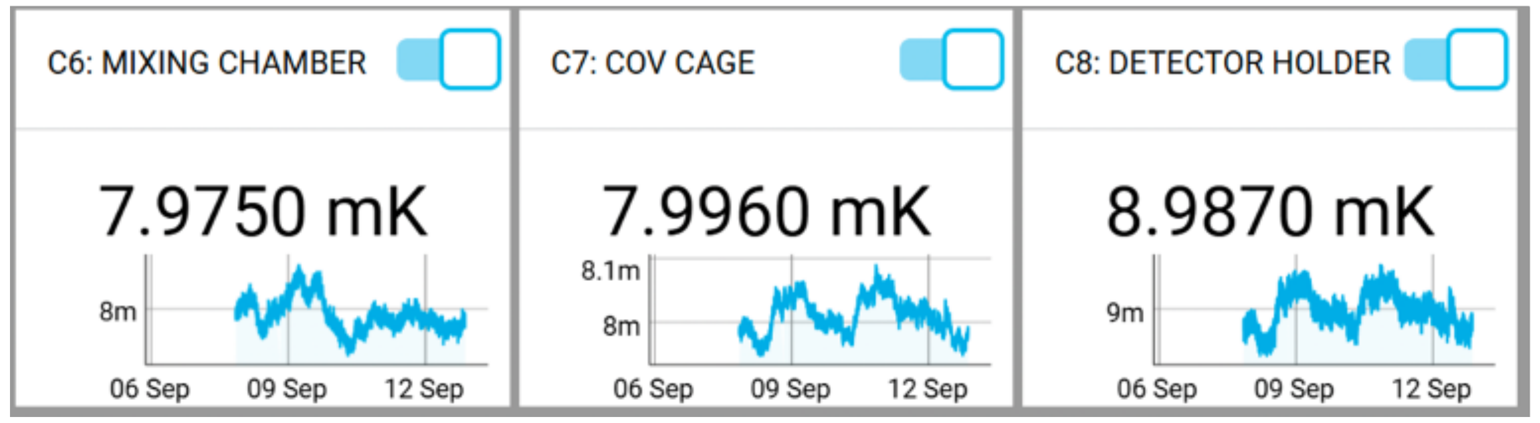


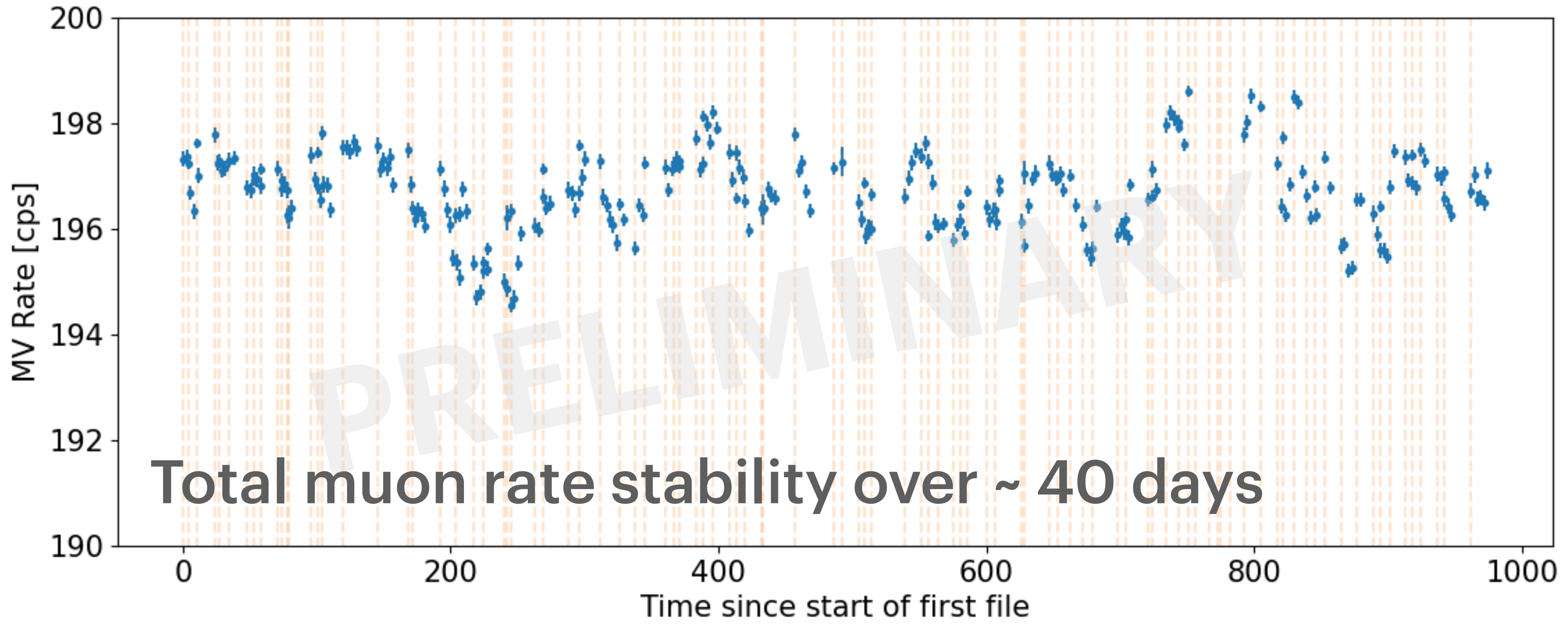
- Successful cool down of more than 70 kg of material in ~13 days
- Excellent temperature levels reached < 9 mK
- Data taking started on August 1st, ongoing for more than 8 weeks
- Smooth data taking with > 80% duty cycle



First Light from the Vetoes

First Light from the Vetoes

The Muon Veto



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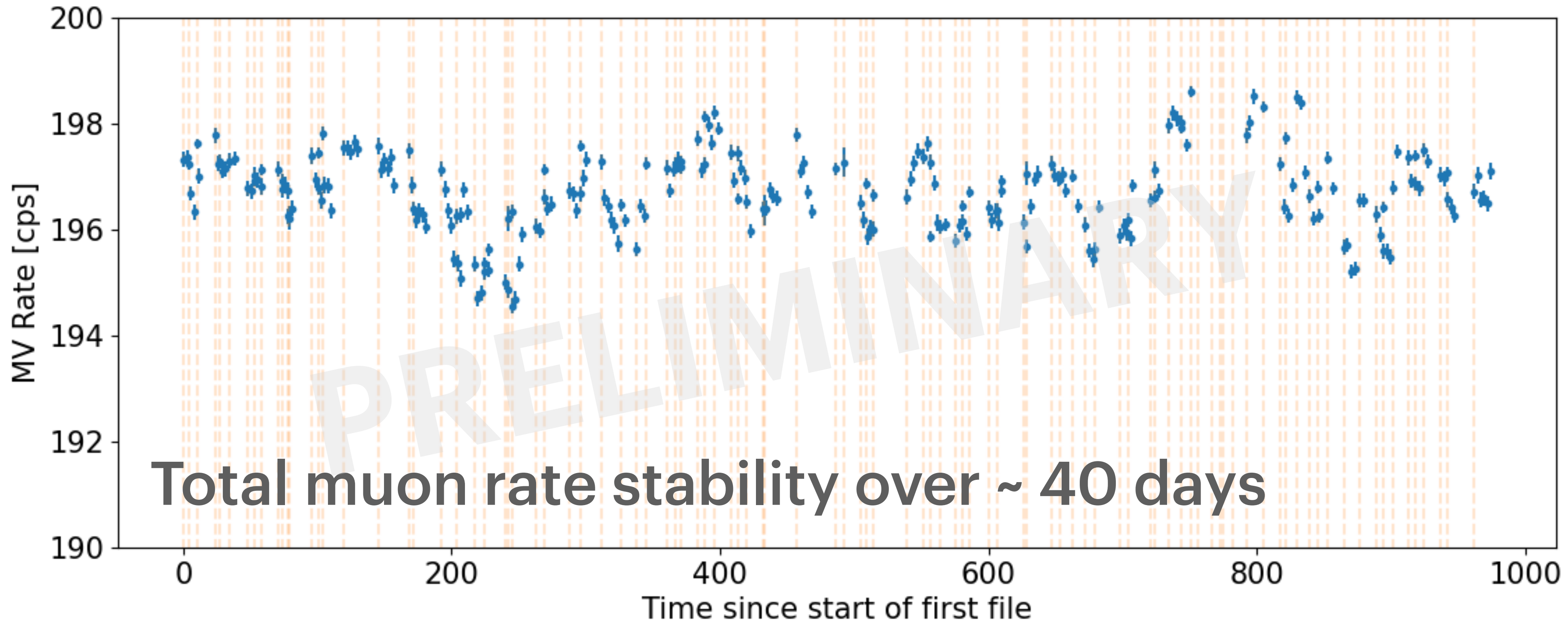

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- Atmospheric pressure variation is the suspected origin for modulation (day/night effect observed)

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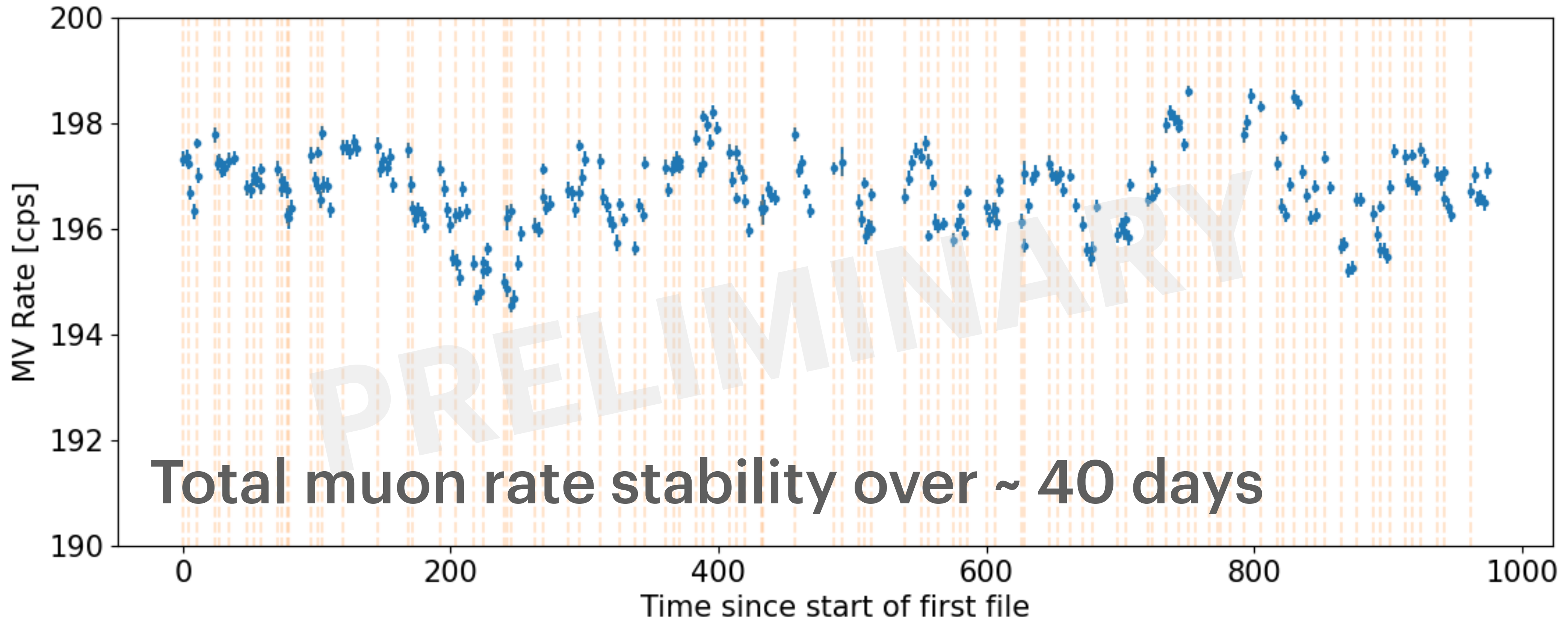

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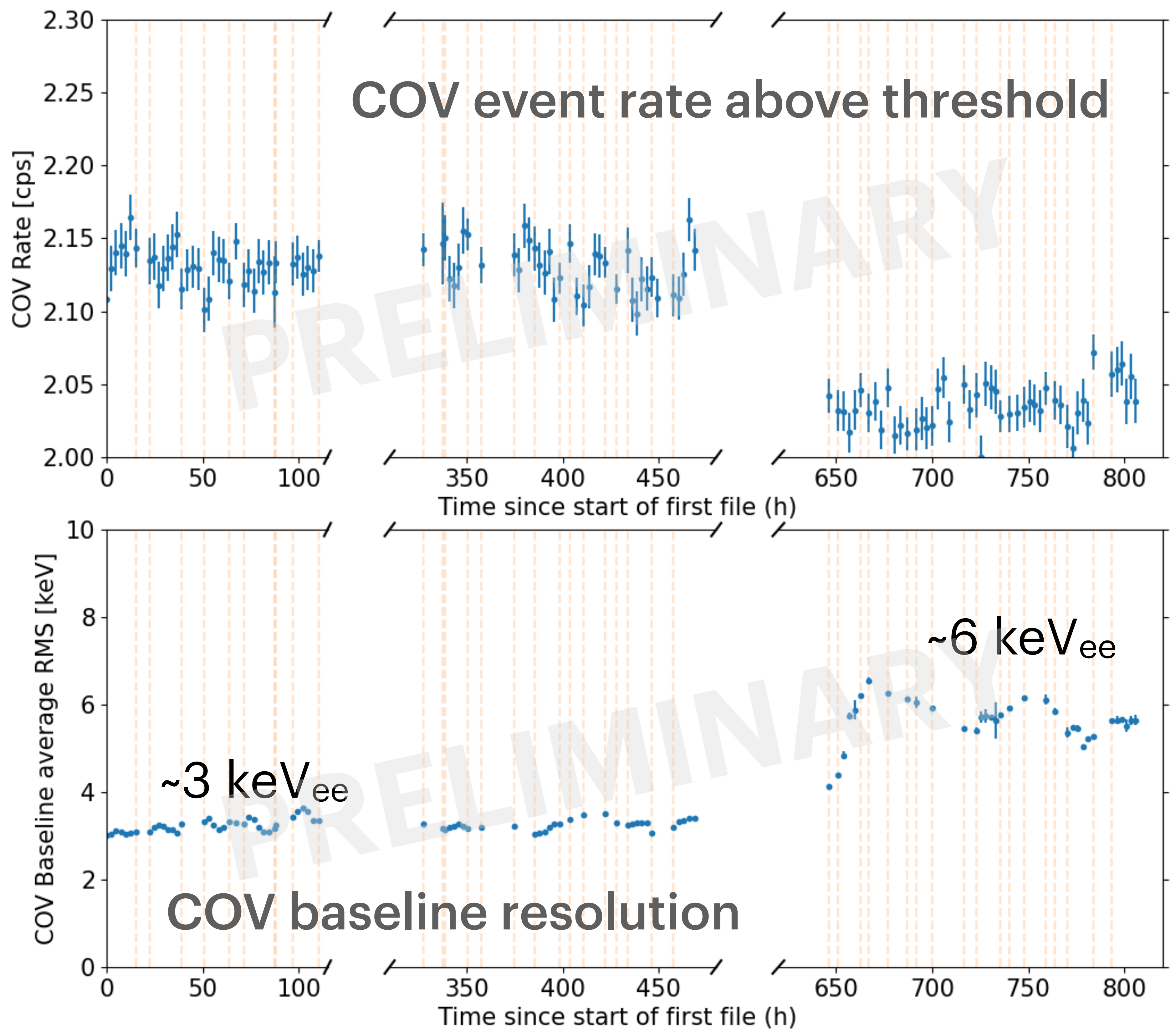
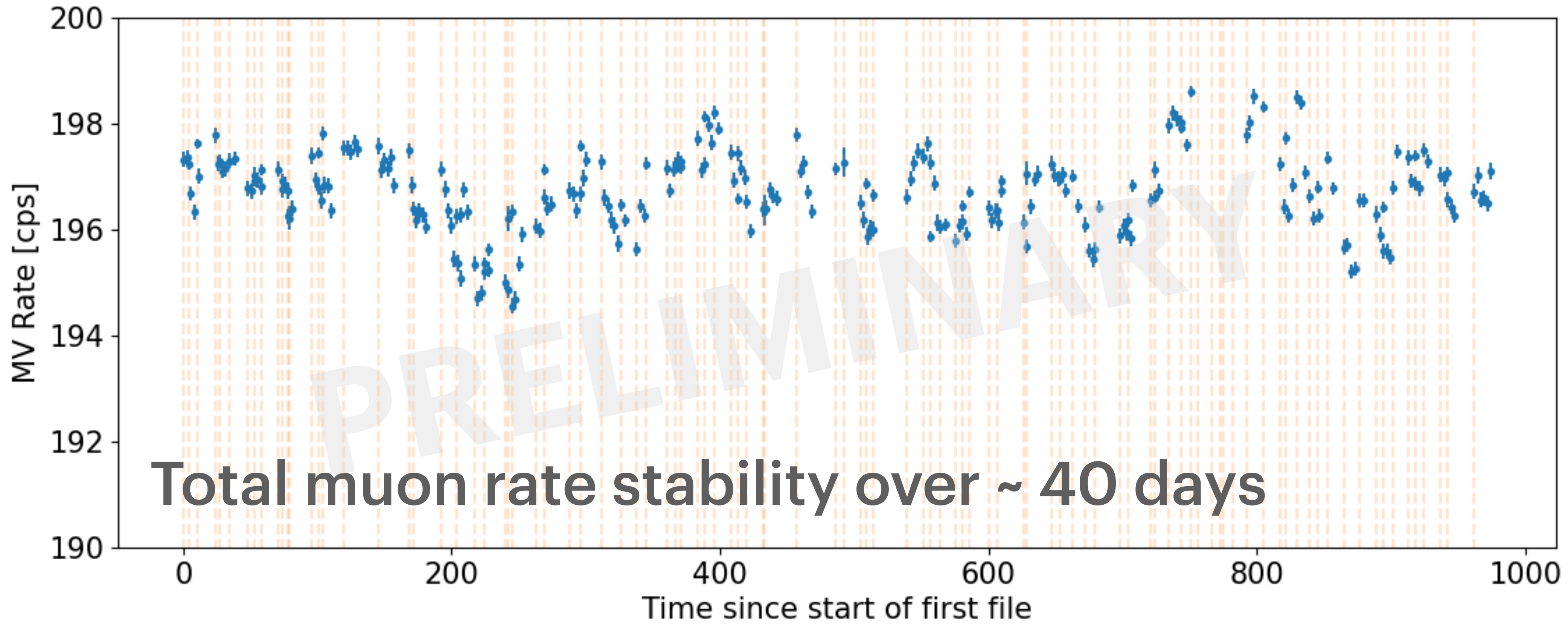
The Cryogenic Outer Veto



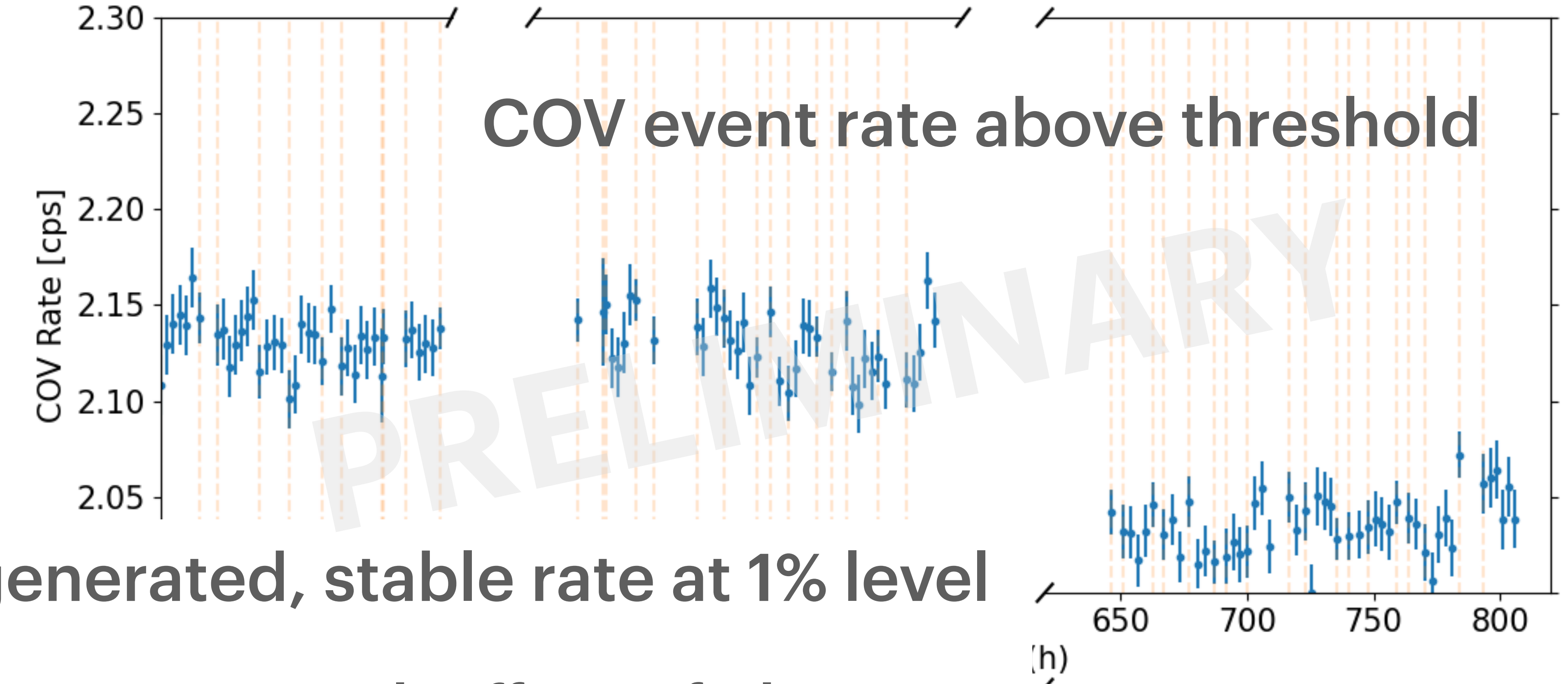
First Light from the Vetoes

The Muon Veto

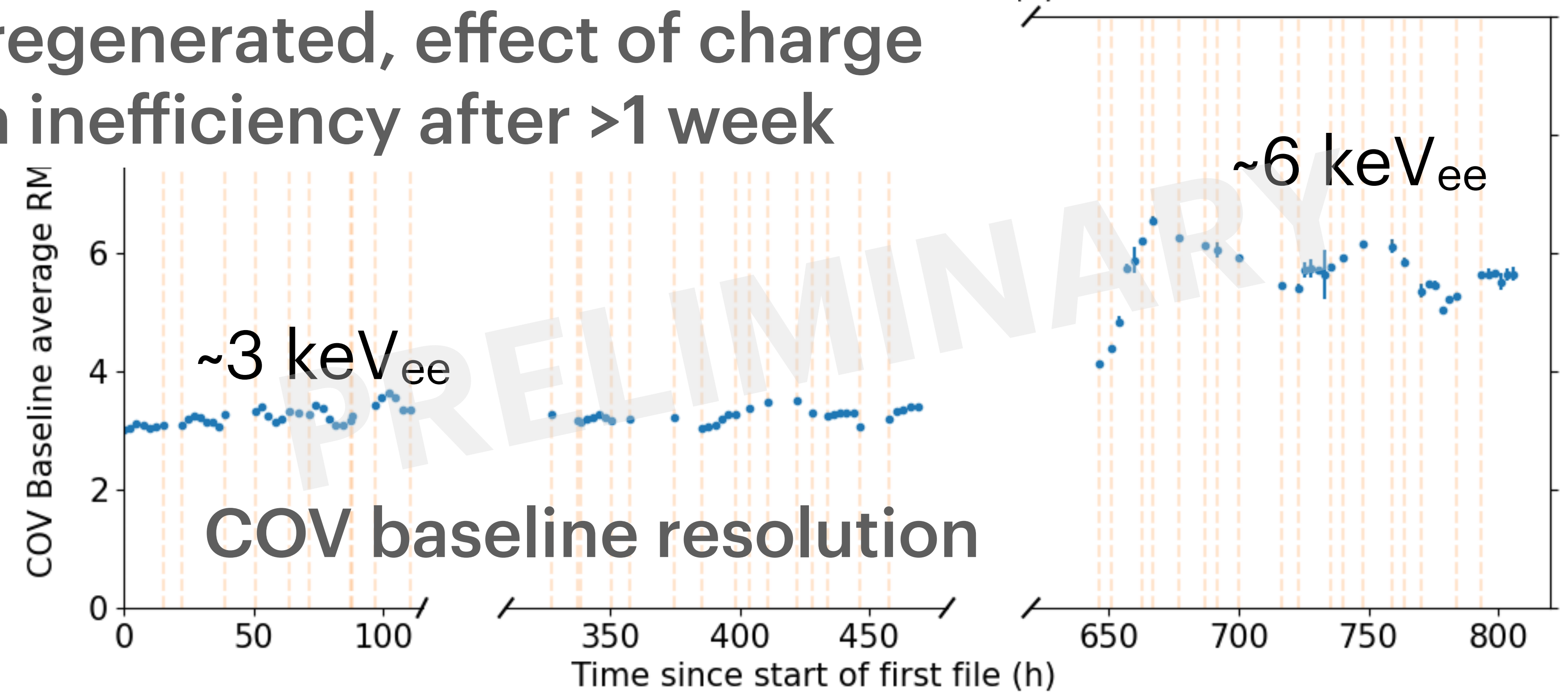


- Stable muon rate at 1% level around 197 Hz
- Atmospheric pressure variation is the suspected origin for modulation (day/night effect observed)

The Cryogenic Outer Veto



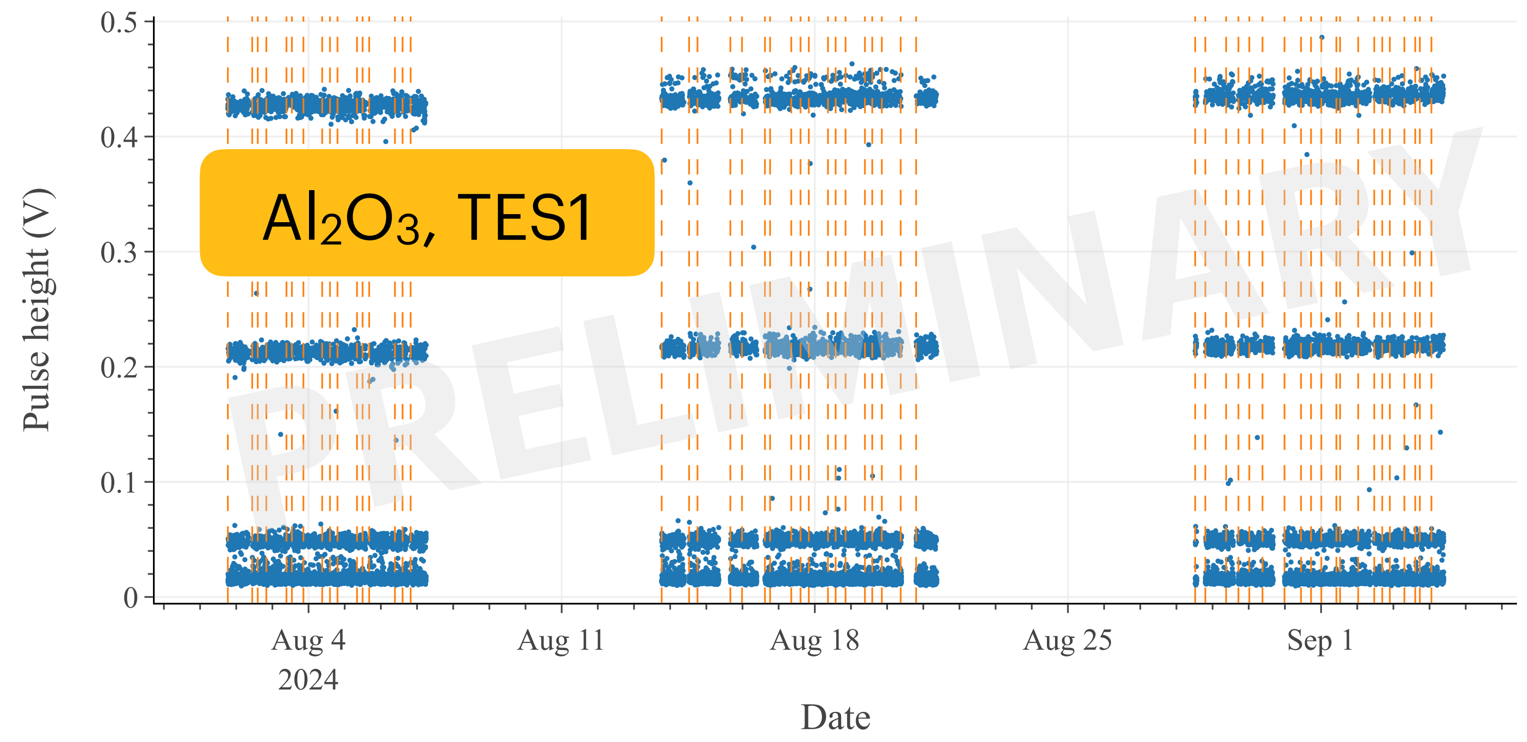
- COV regenerated, stable rate at 1% level
- COV not regenerated, effect of charge collection inefficiency after >1 week

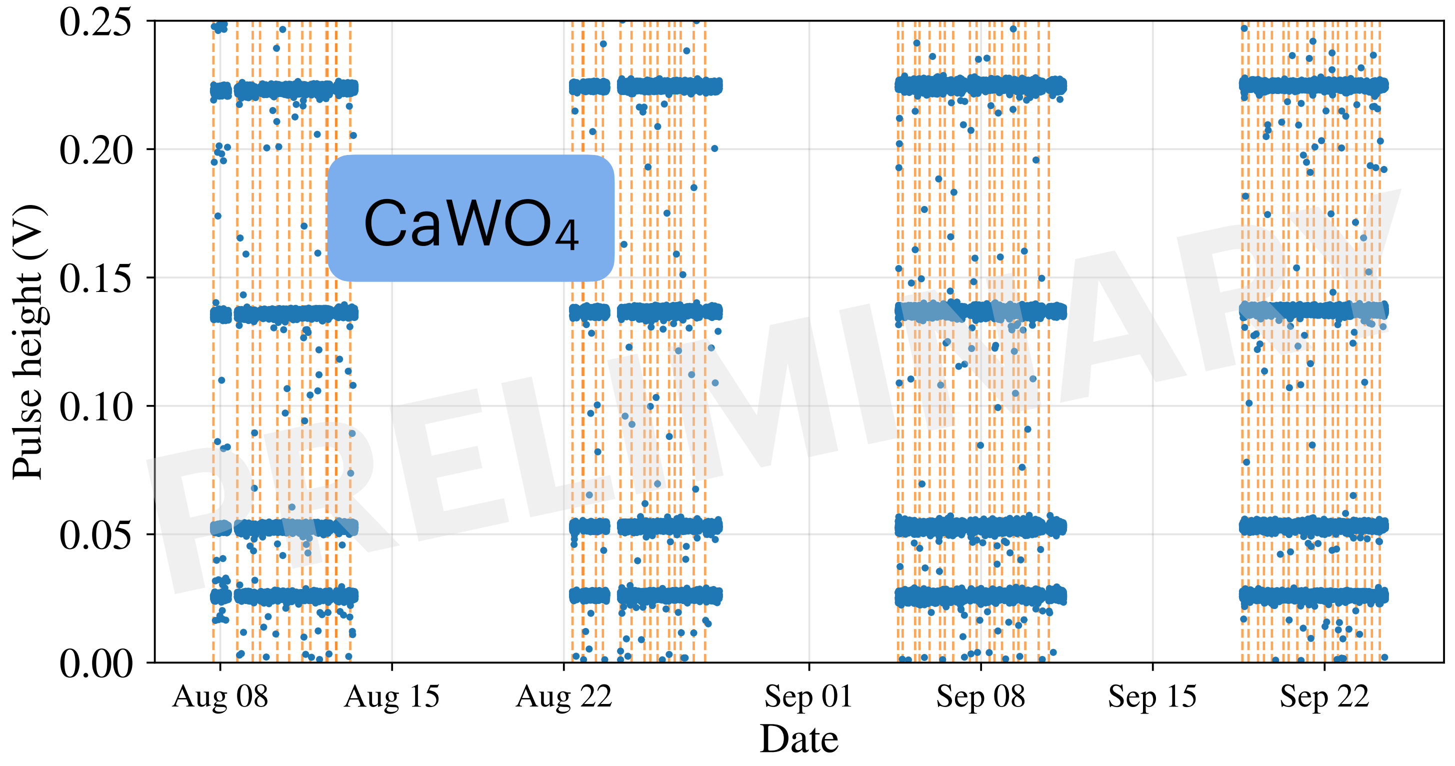


First light from the TES detectors

First light from the TES detectors

- Test Pulses injected periodically in the detectors to monitor their stability
- Better than 1% stability over entire data taking





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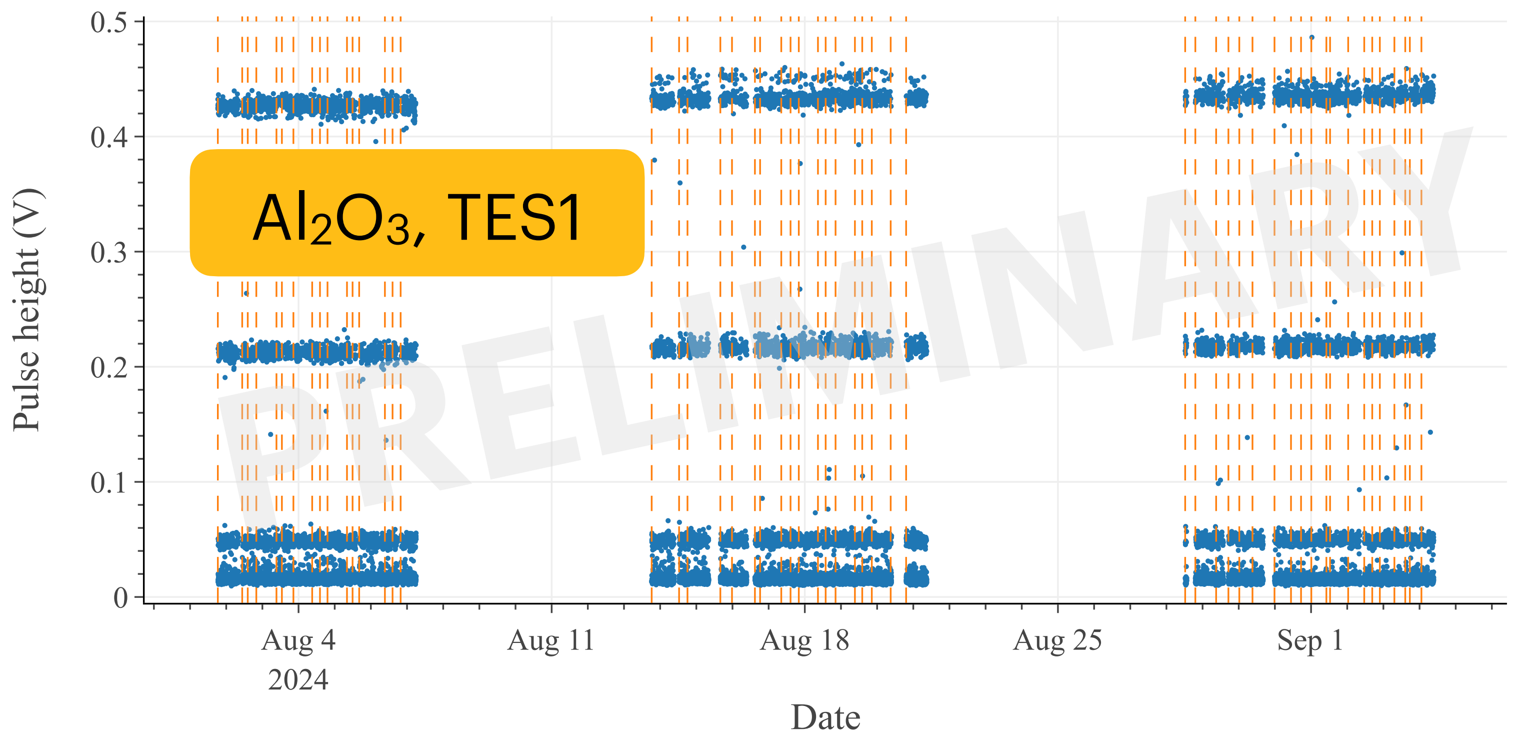
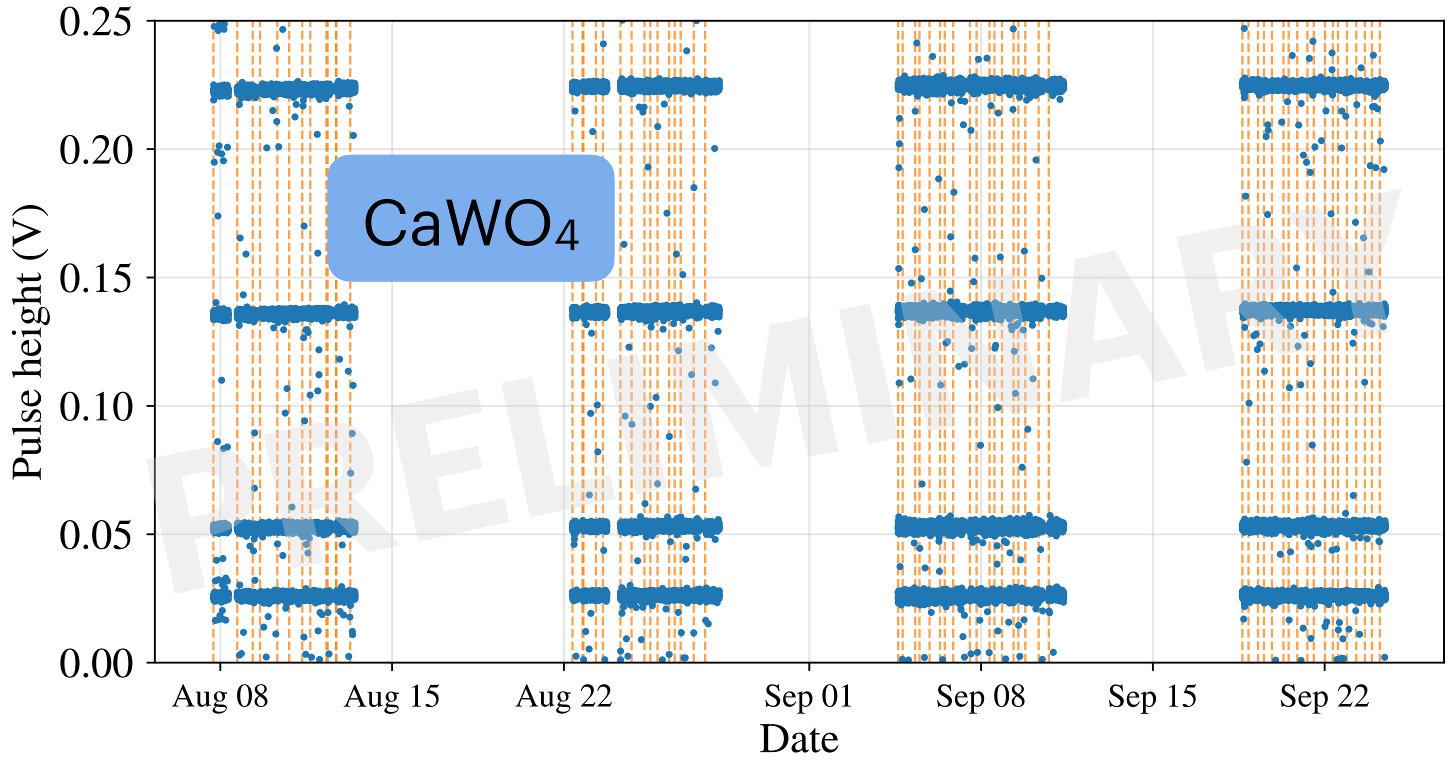
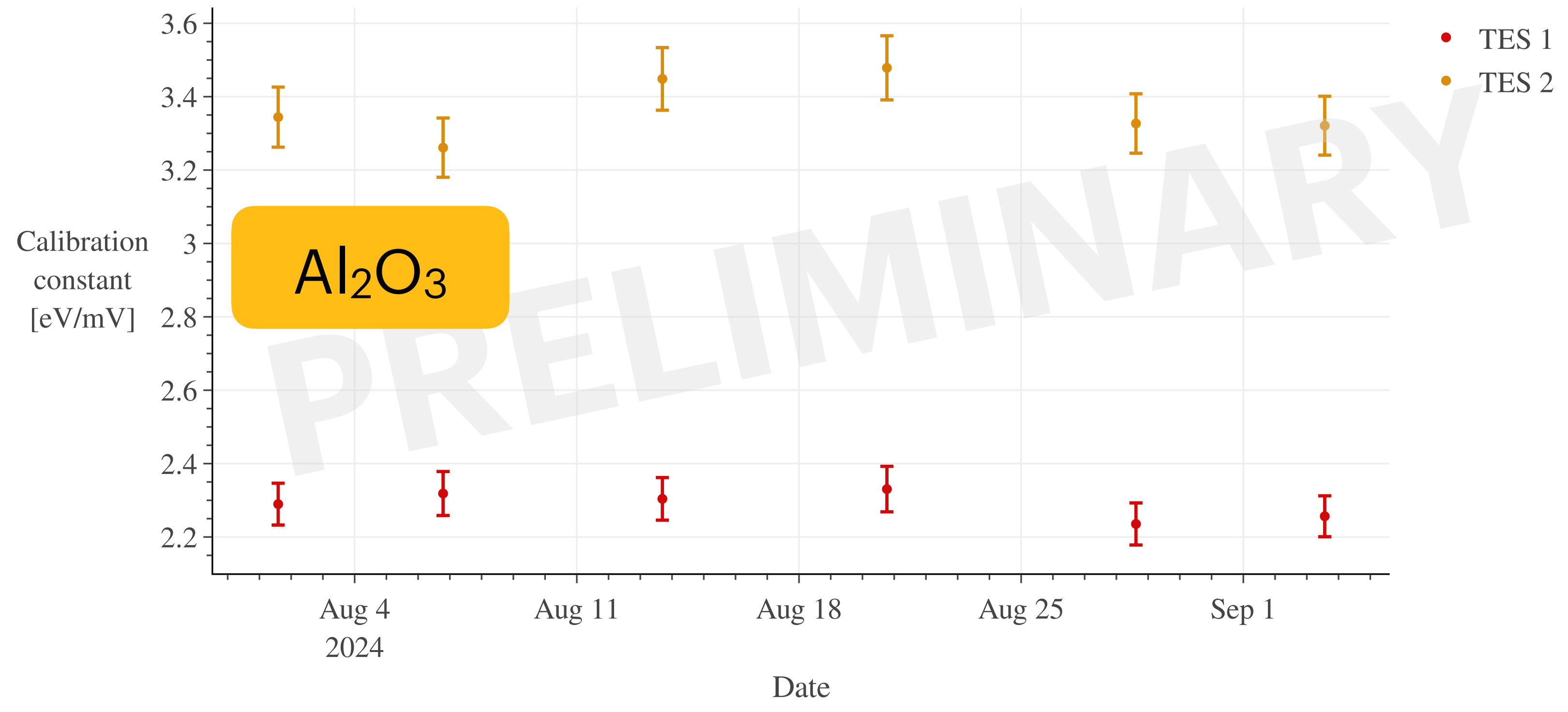
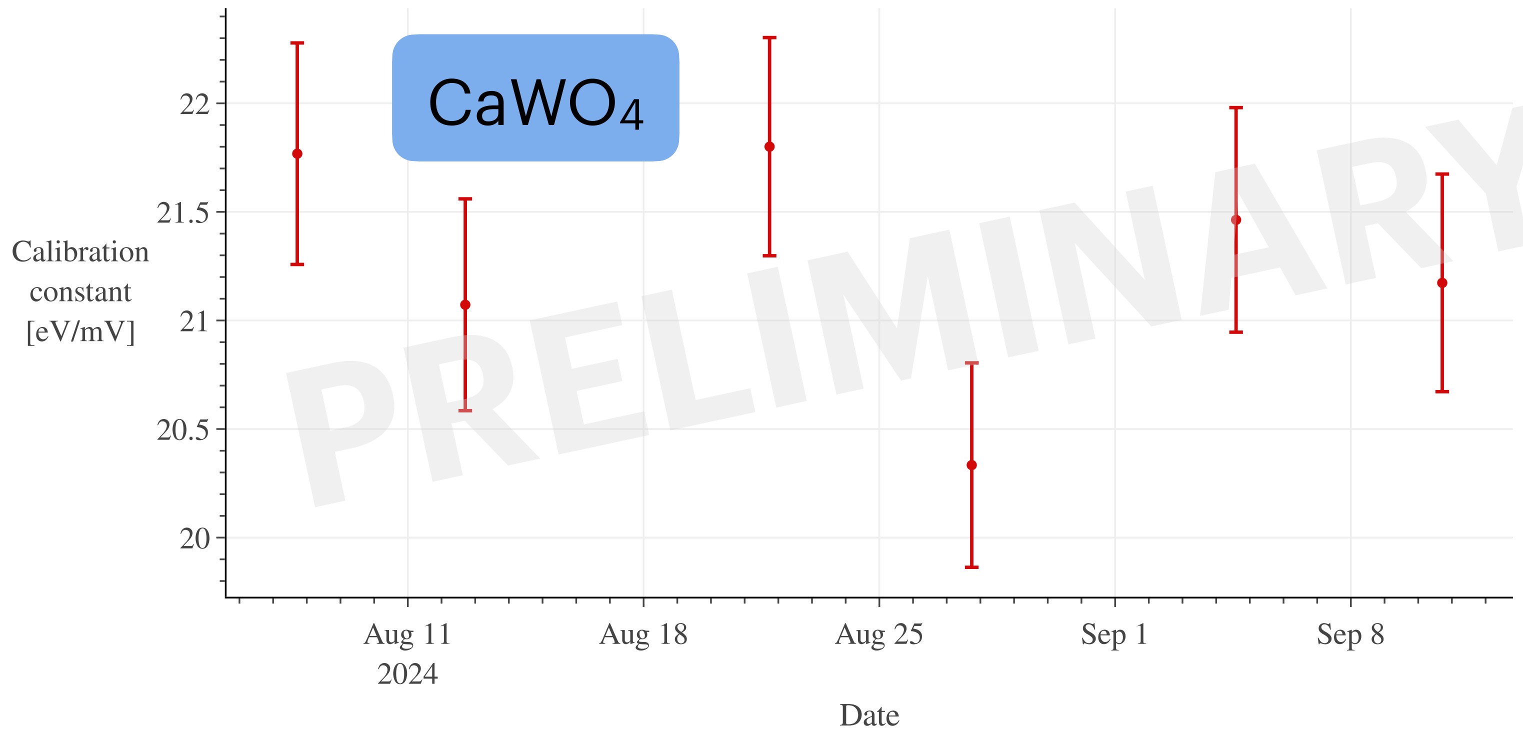




- Regular LED calibration performed to monitor the stability of the detector response
- Good stability and reproducibility within uncertainties





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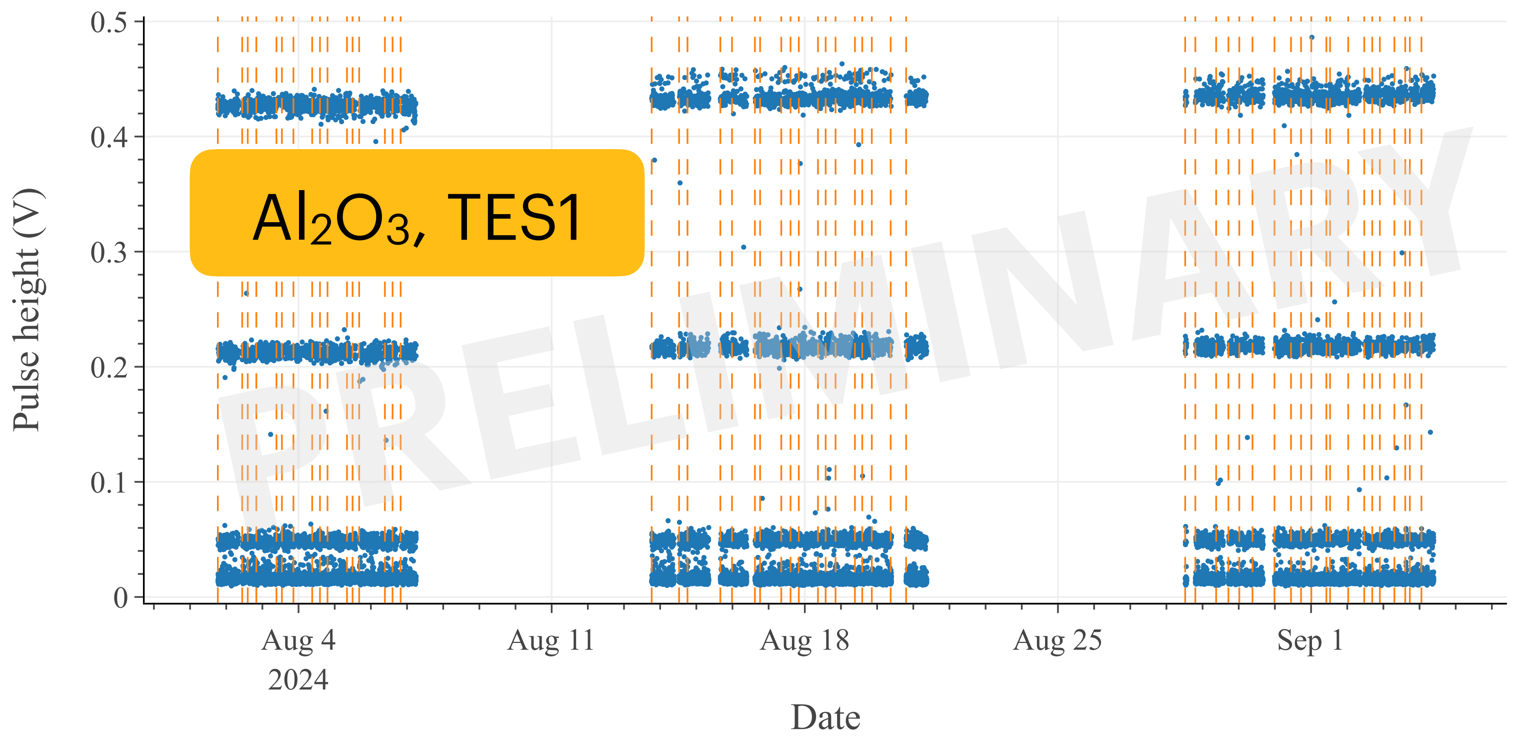

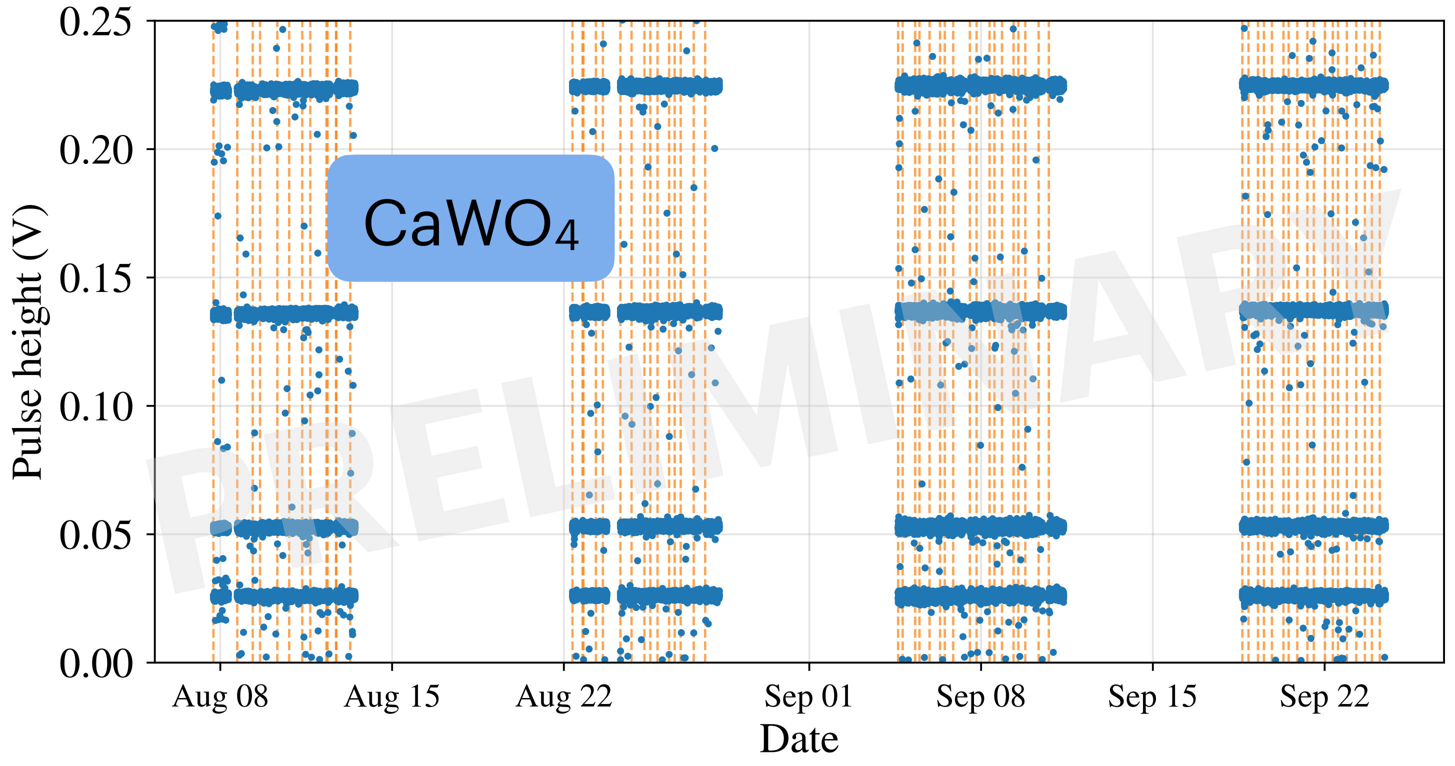

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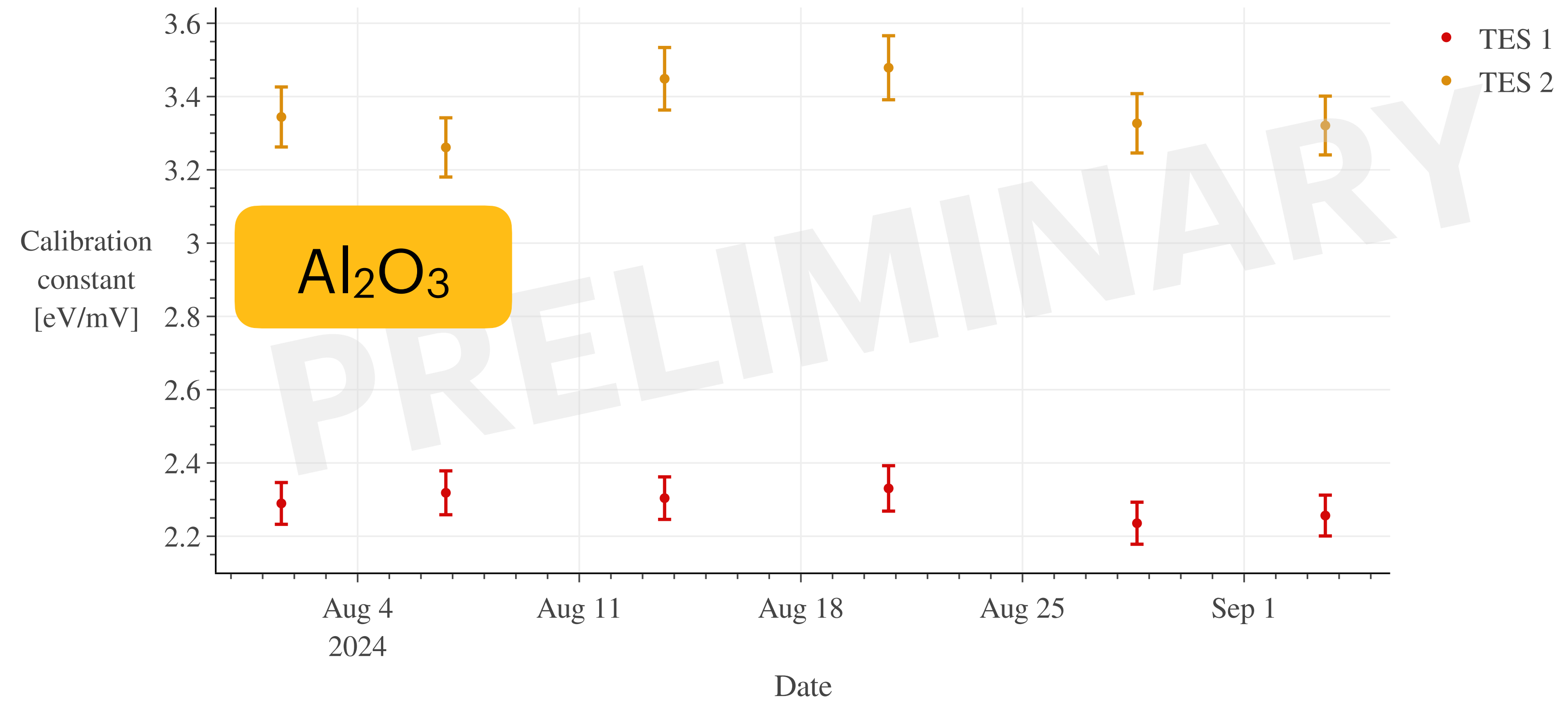
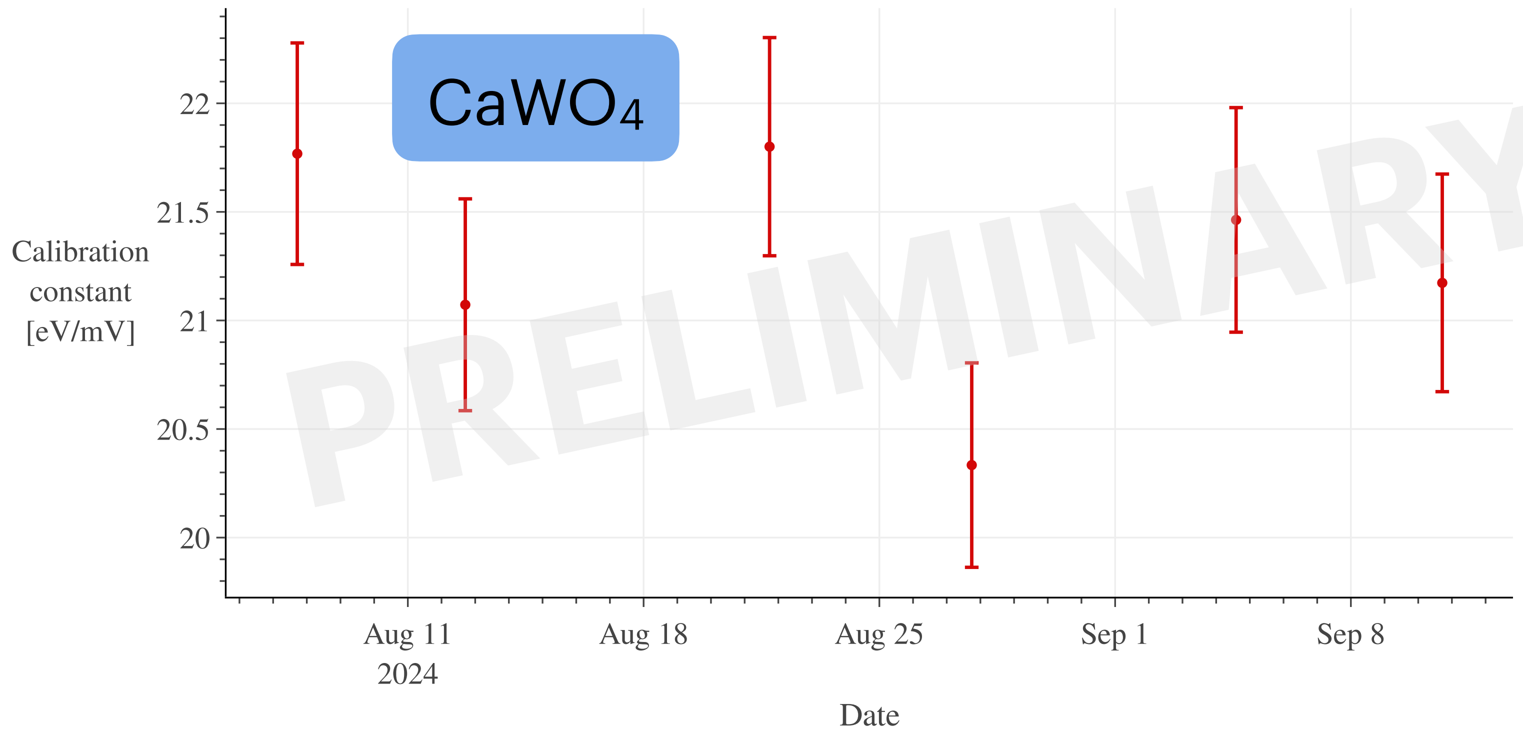
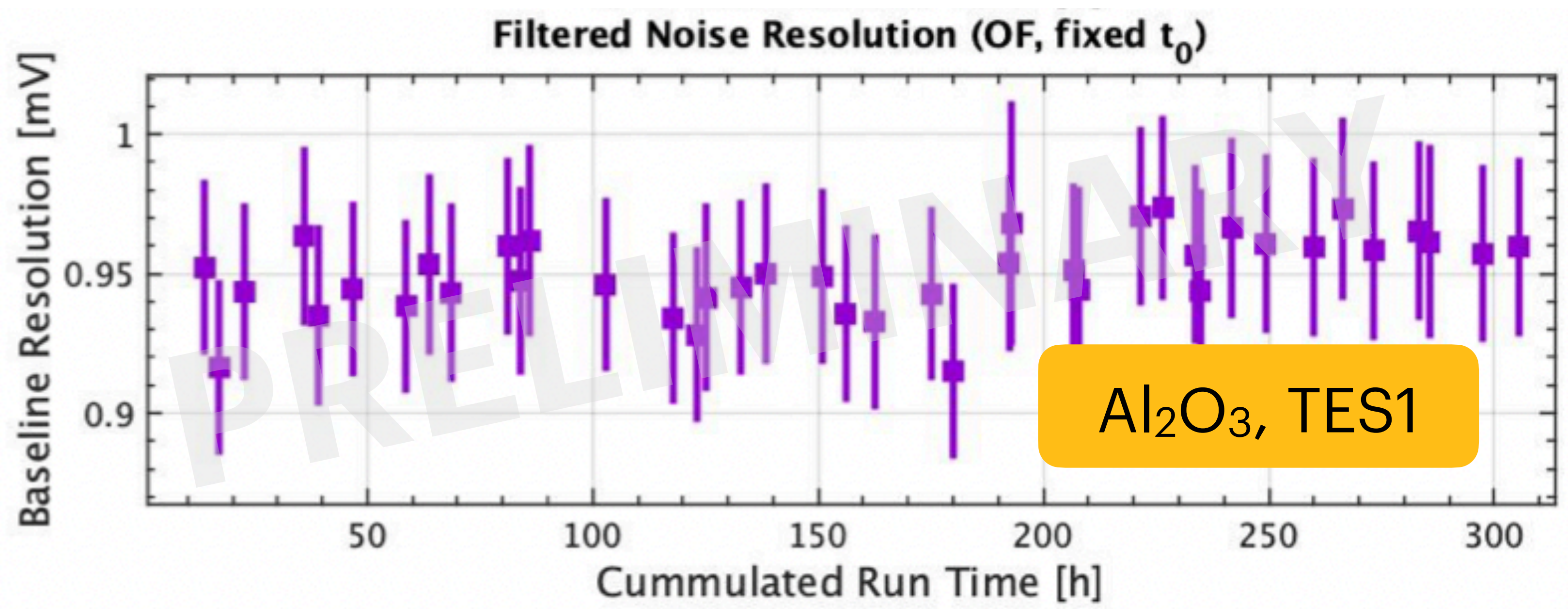
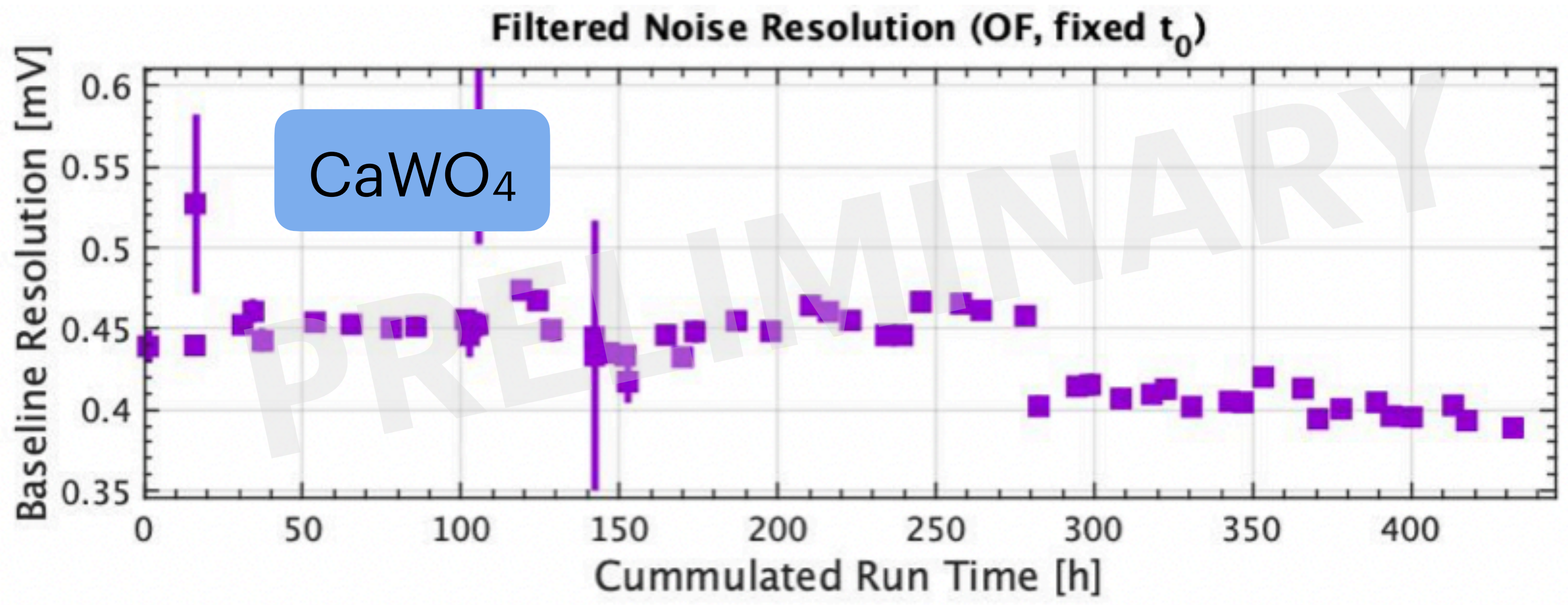




- Stable noise condition over the entire data taking
- Baseline resolution ~ 5.6 eV for Al2O3 and ~ 8.5 eV for $CaWO_4$ (+/- 15% uncertainty from calibration)



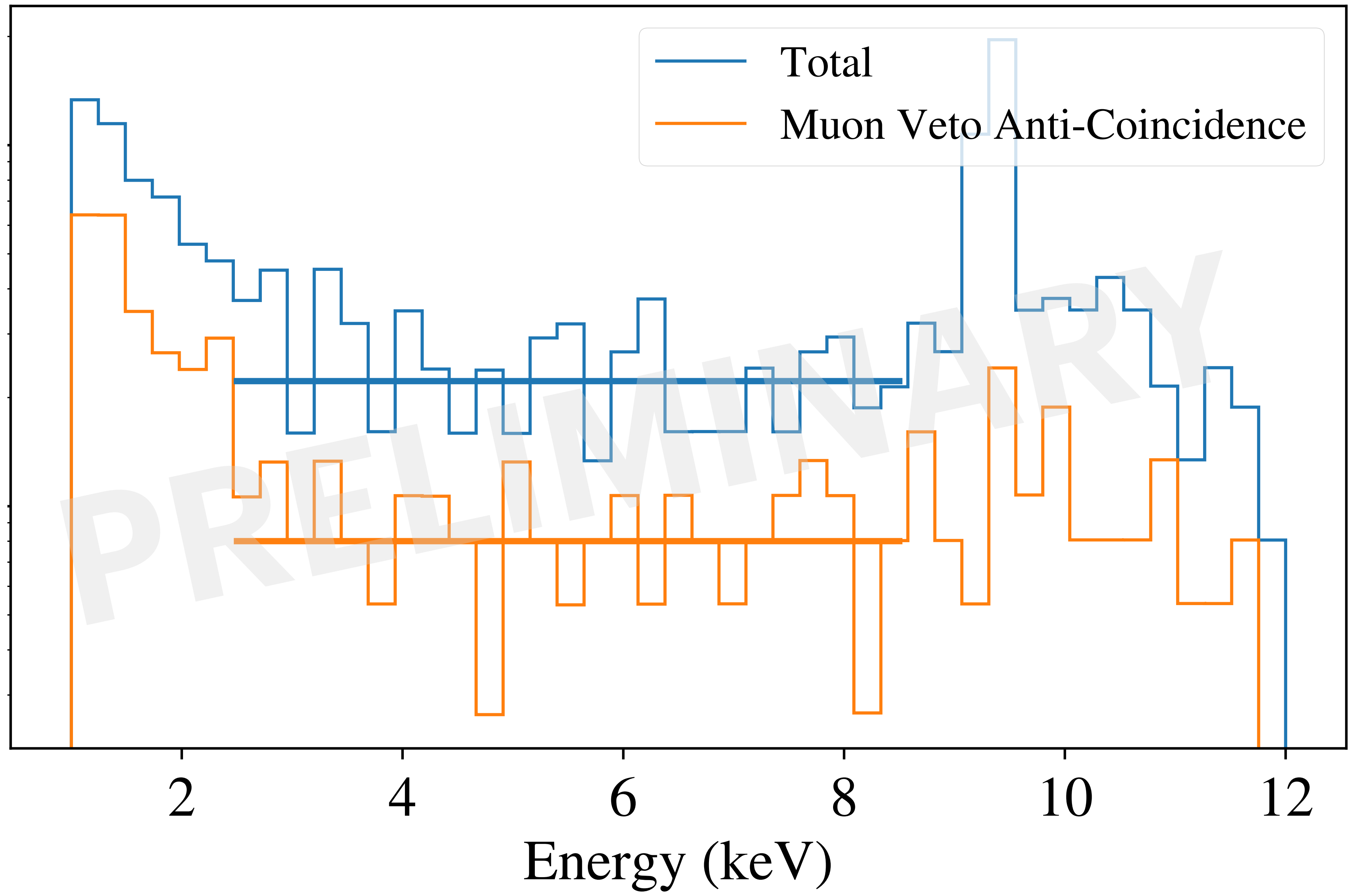


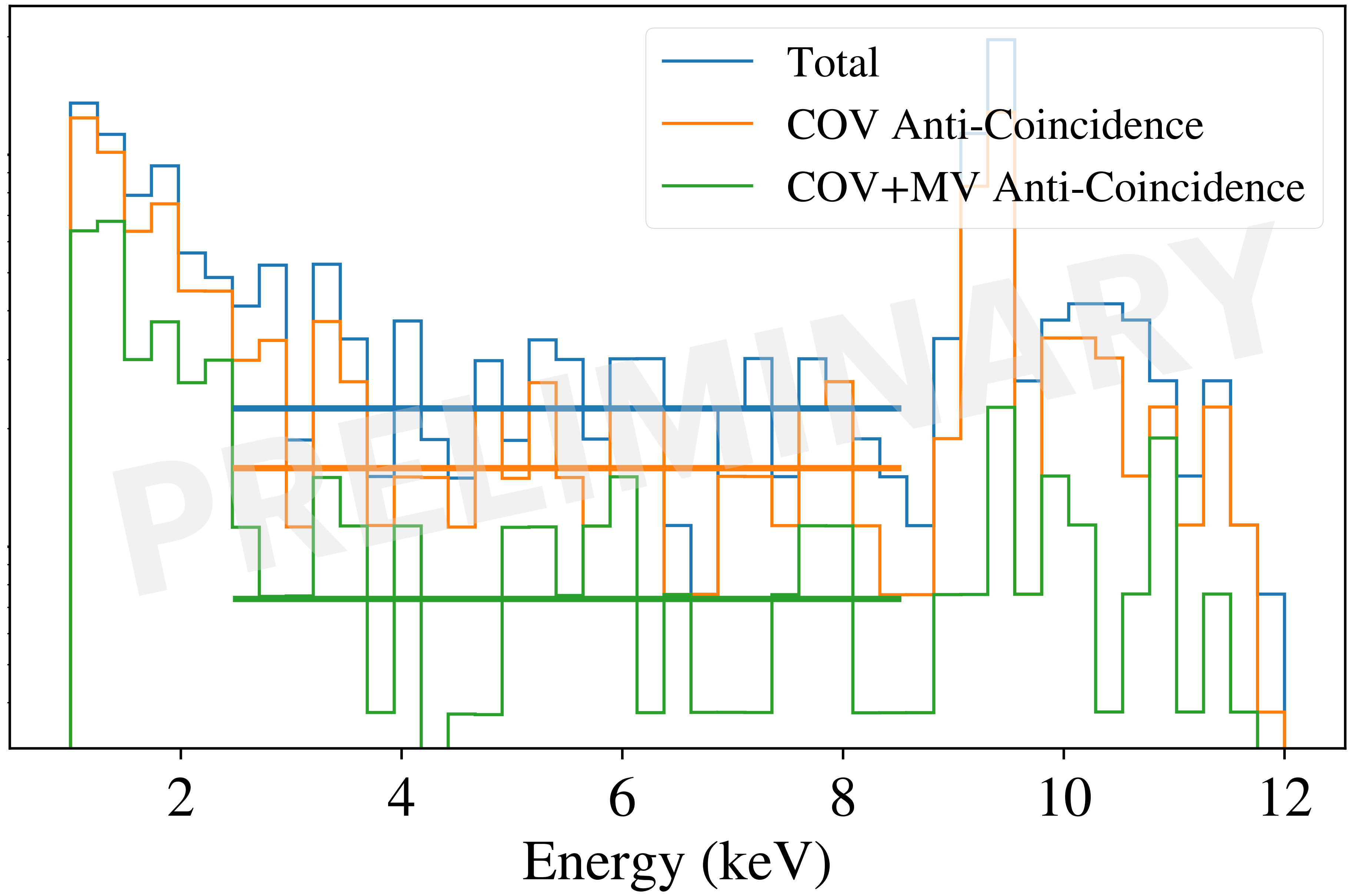
First background data

First background data

CaWO4 + Muon Veto + Cryogenic Outer Veto

- Anti-Coincidence analysis between the TES detector and the two vetoes





*Y-axis removed on purpose, very preliminary results, ongoing analysis

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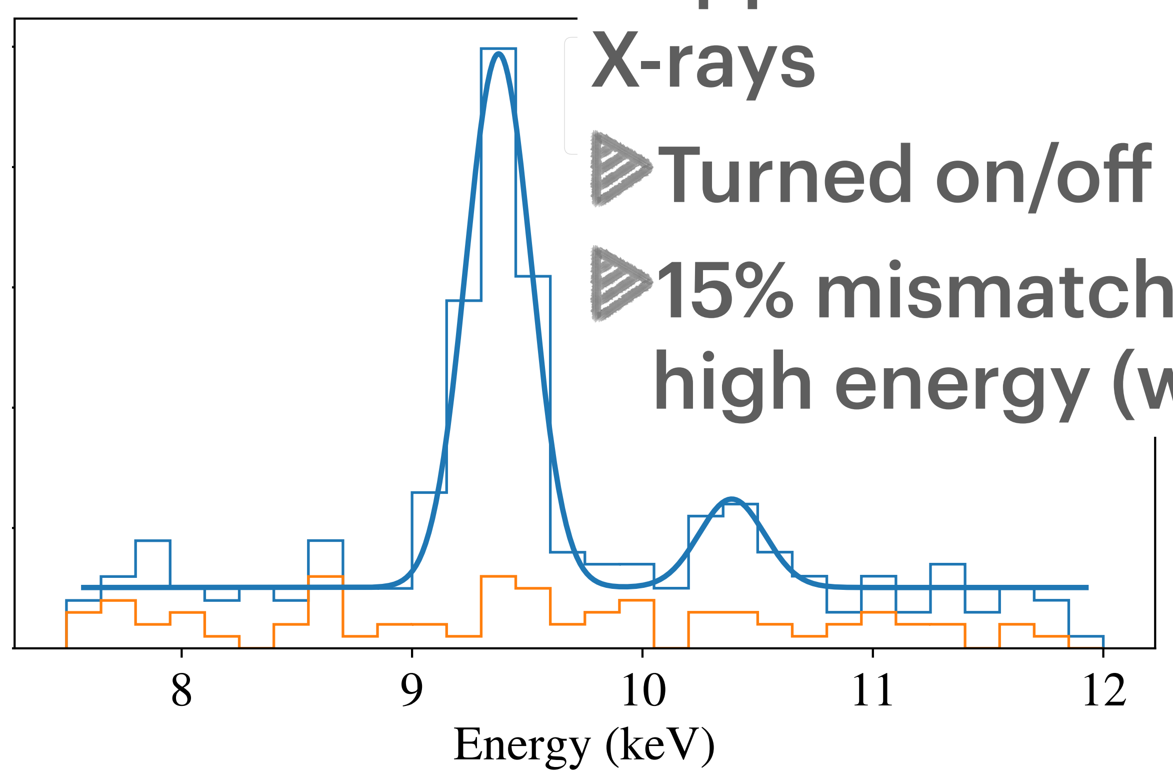
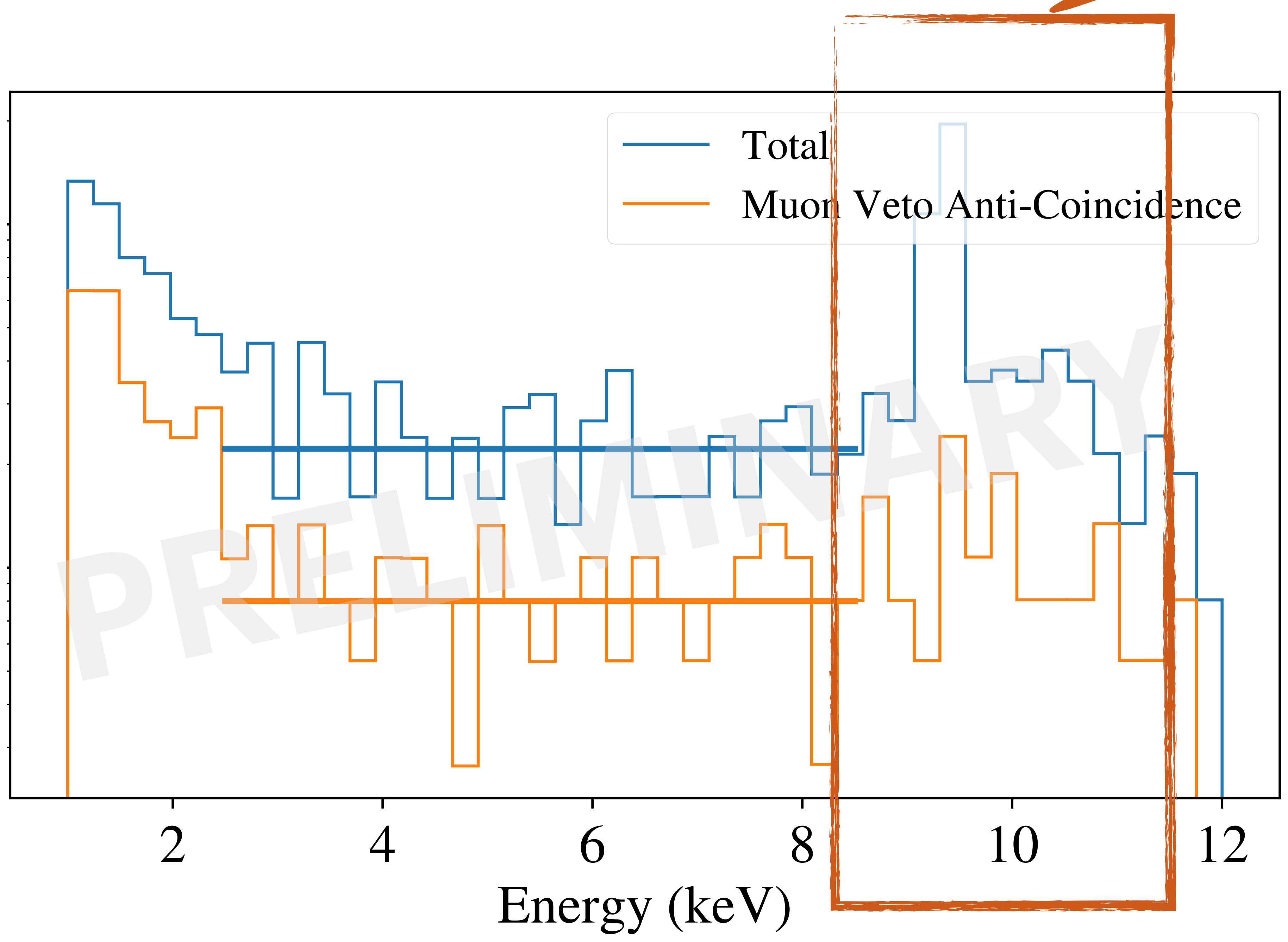
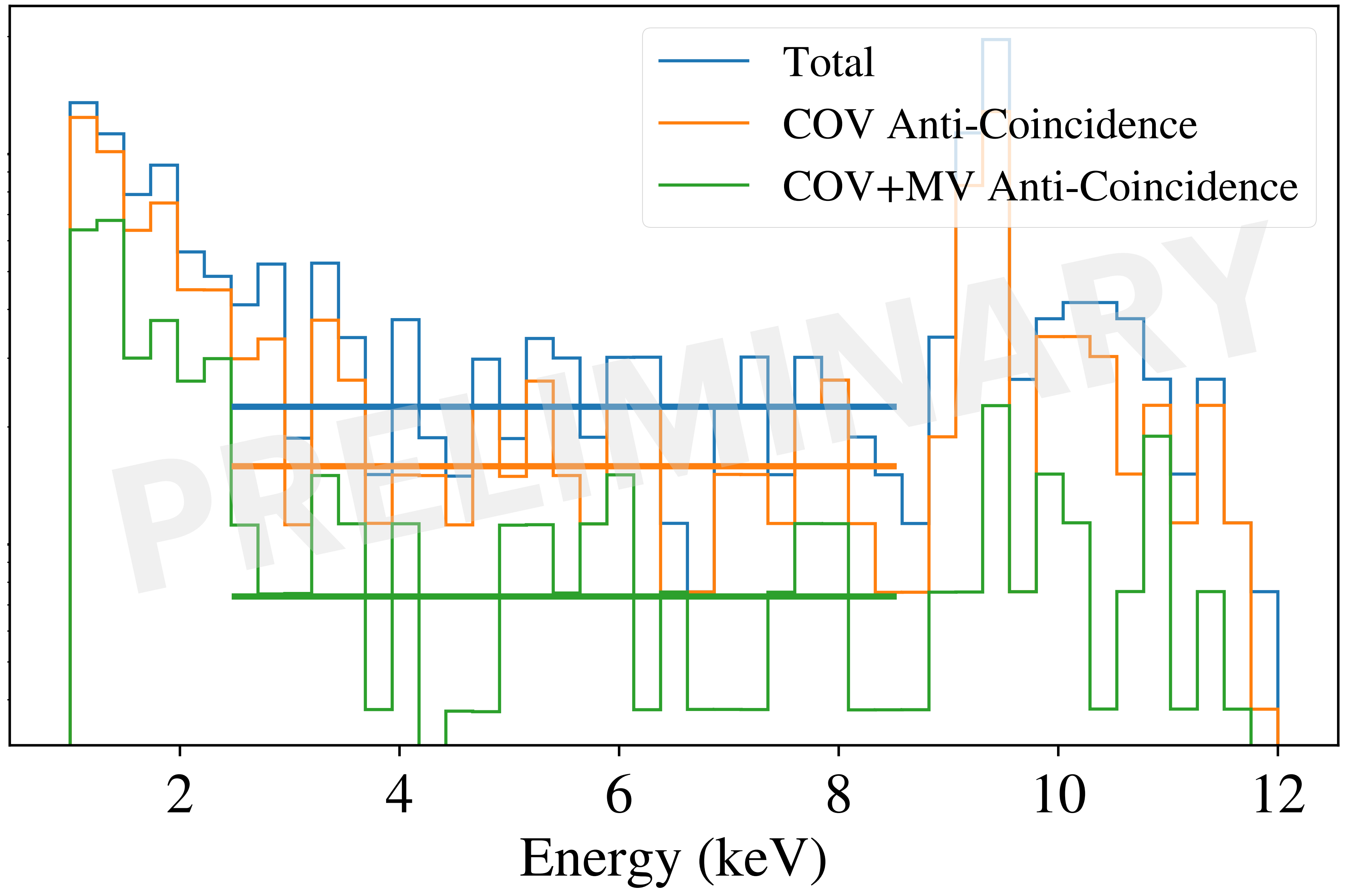


Copper excitation line: 8 keV and 8.9 keV X-rays

- Turned on/off by Muon Veto
- 15% mismatch of LED calibration at high energy (within NUCLEUS specs)





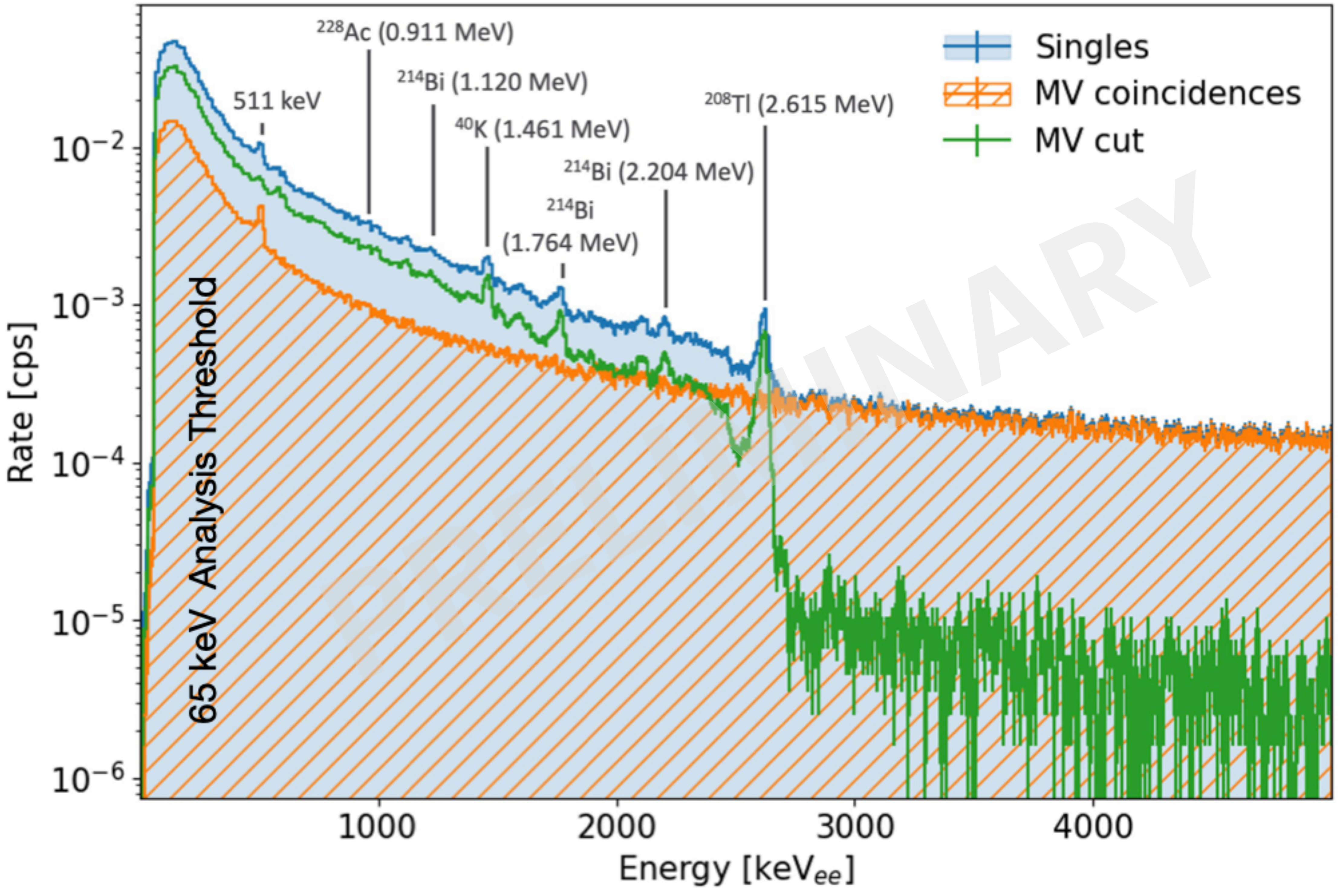
*Y-axis removed on purpose, very preliminary results, ongoing analysis

First background data

First background data

Cryogenic Outer Veto + Muon Veto

- COV also allows a in-situ measurement of the background very close to the target detectors
- Coincidence analysis between COV and MV allows to identify gamma/muon background contributions



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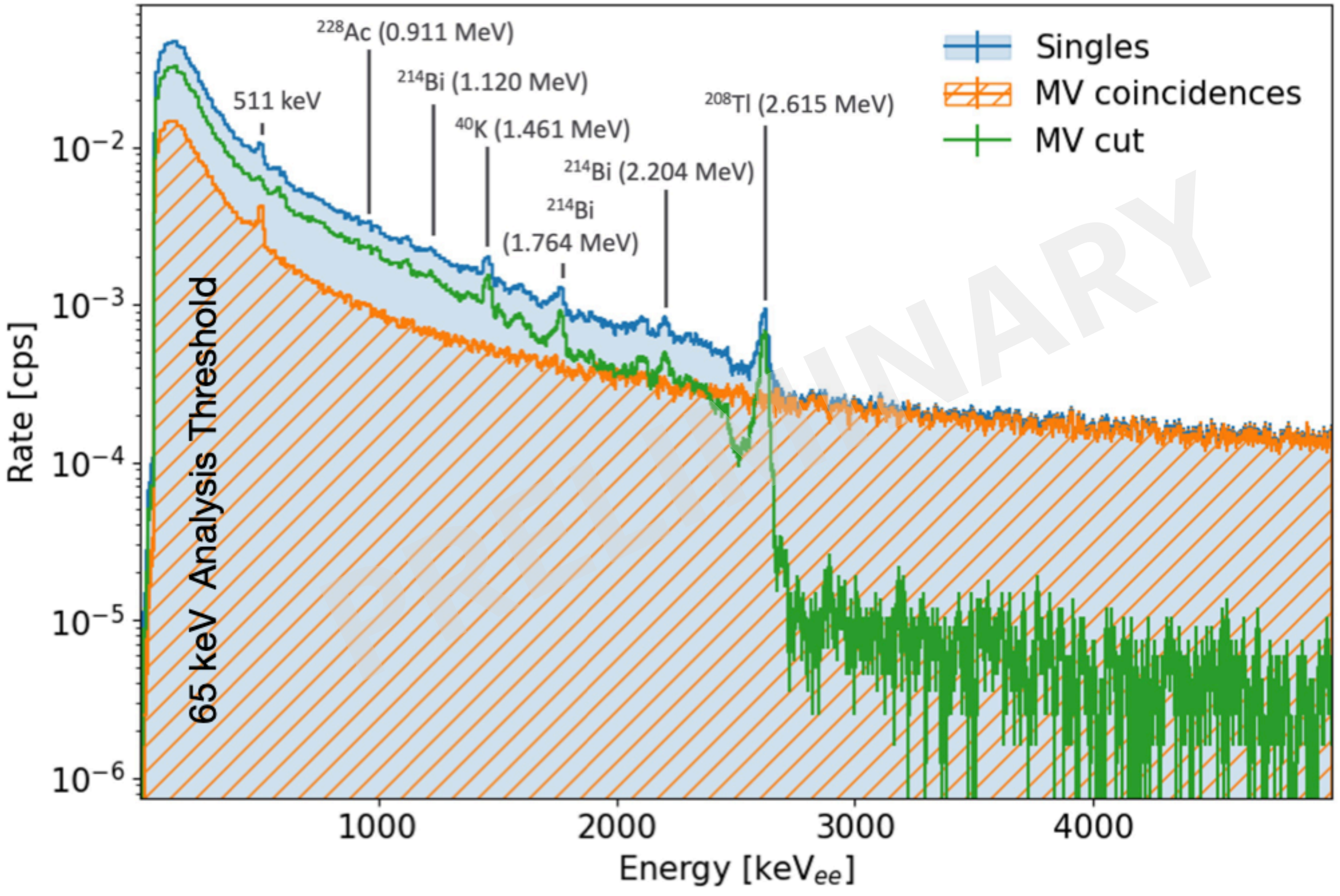
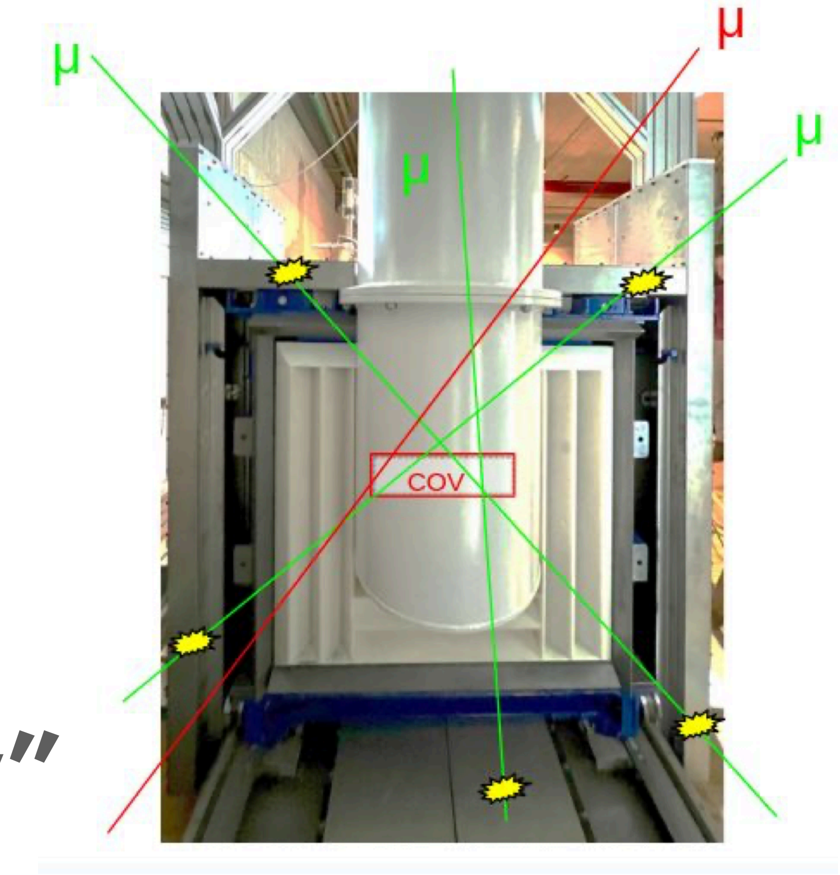
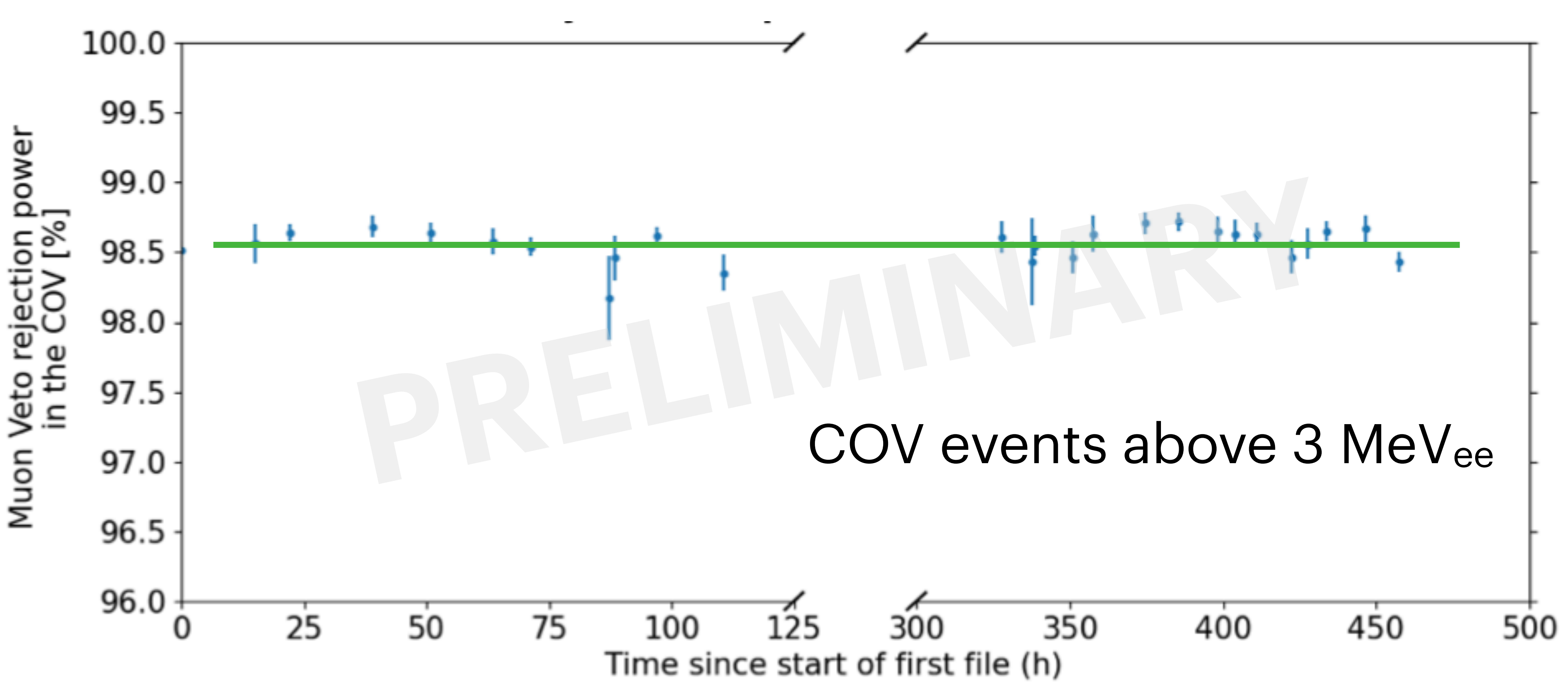




Muon Veto "Efficiency"



Conclusions and Outlook

- Commissioning of the NUCLEUS experiment @TUM successfully completed
- First "Long Background Run" started on August 1st, ongoing for more than 8 weeks
- Stable detector operation and performances demonstrated for all subsystems: TES detectors, Cryogenic Outer Veto and Muon Veto
- LED calibration successfully used over the entire measurement, validated by observed Copper excitation line at ~8 keV
- First background data available: analysis and comparison to simulations ongoing
- Study of Low Energy Excess (LEE) ongoing: investigating time dependence and rejection capabilities of double-TES read-out solution

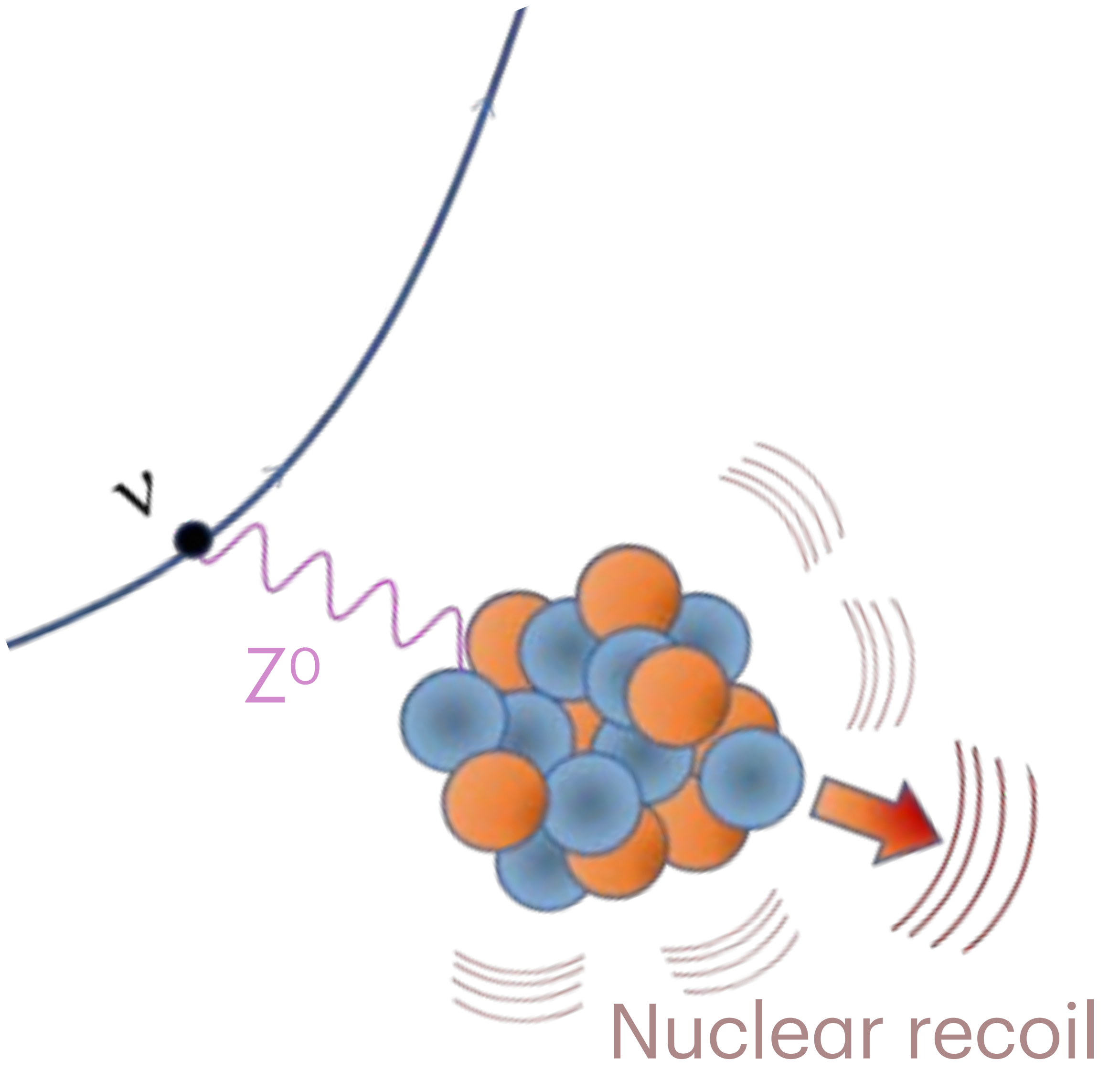
- Outlook:
  - Start soon the upgrade to full setup
  - Relocation and commissioning at Chooz for first technical run to be started in 2025

Thank you for your attention!

NUCLEUS Collaboration

Backup

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

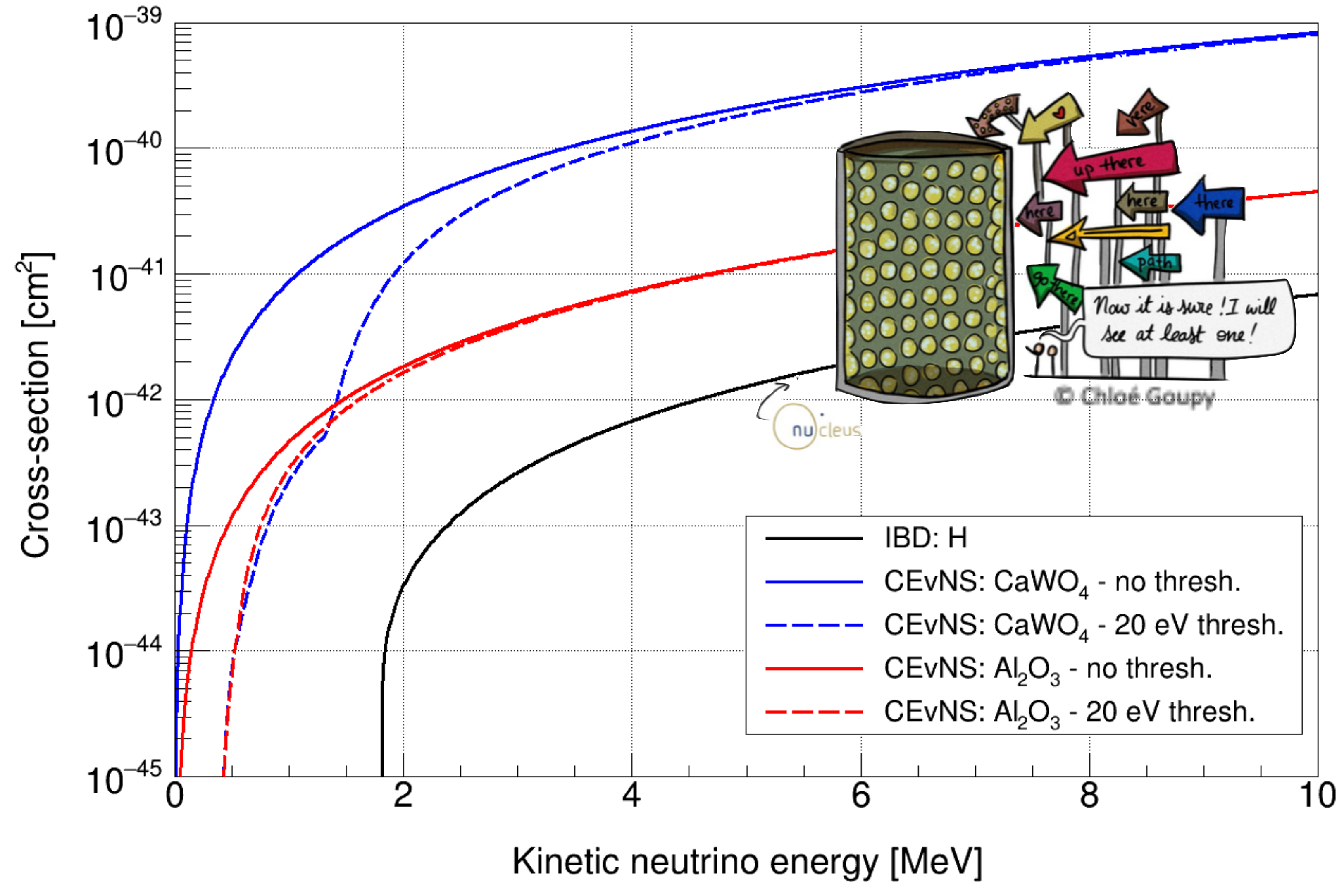


- Predicted by Freedman in 1974
- Dominant neutrino interaction for E_ν ~ 1-100 MeV
- Interesting: large cross-section with N^2 dependence

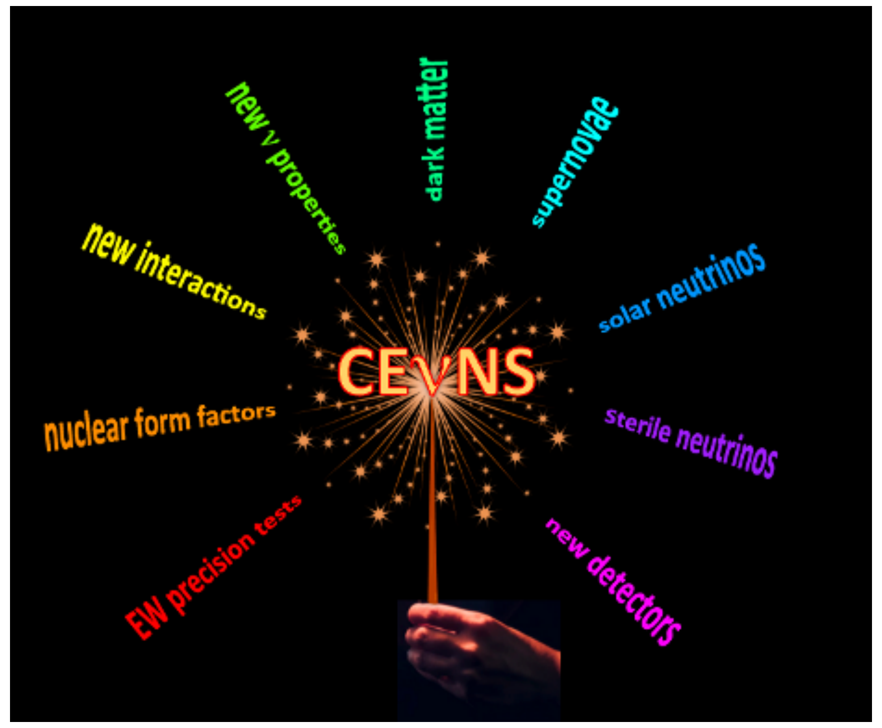
$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi}[Z(1-4\sin^2\theta_W)-N]^2 F^2(q^2)M(1-\frac{ME_R}{2E_\nu^2})$$

- But experimentally very challenging: tiny nuclear recoils

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

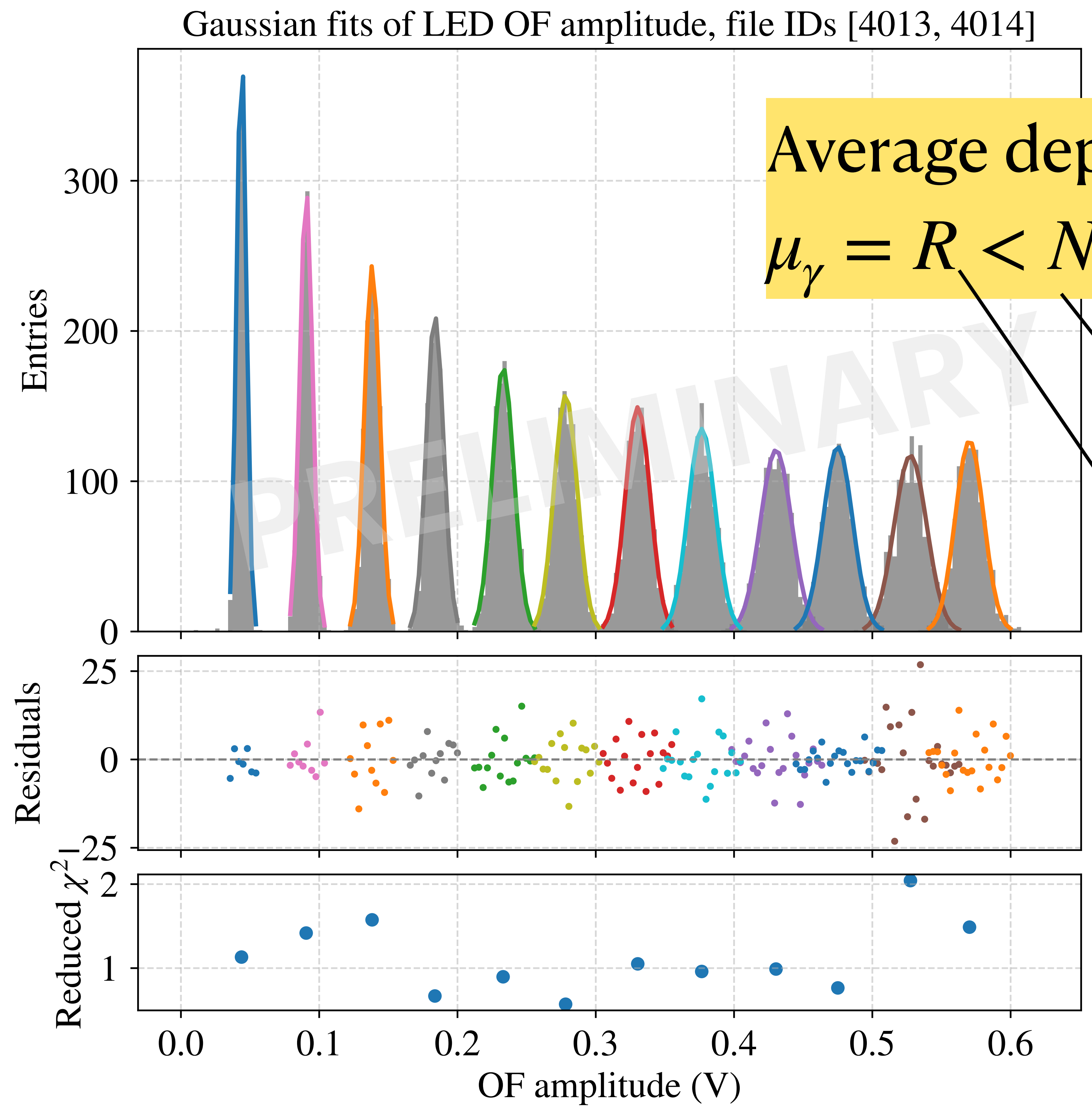


- First experimental observation only in 2017 by COHERENT experiment with neutrinos from Spallation Neutron Source
- To be observed with reactor neutrinos: CONUS, RICOCHET, MINER, NUCLEUS
- Broad physics program: test of the Standard Model and beyond



LED Calibration

- Shine monochromatic LED to the detectors, use phonon statistics to measure the calibration constant
- Advantages: in-situ, continuously available, sub-keV calibration without use of radioactive sources



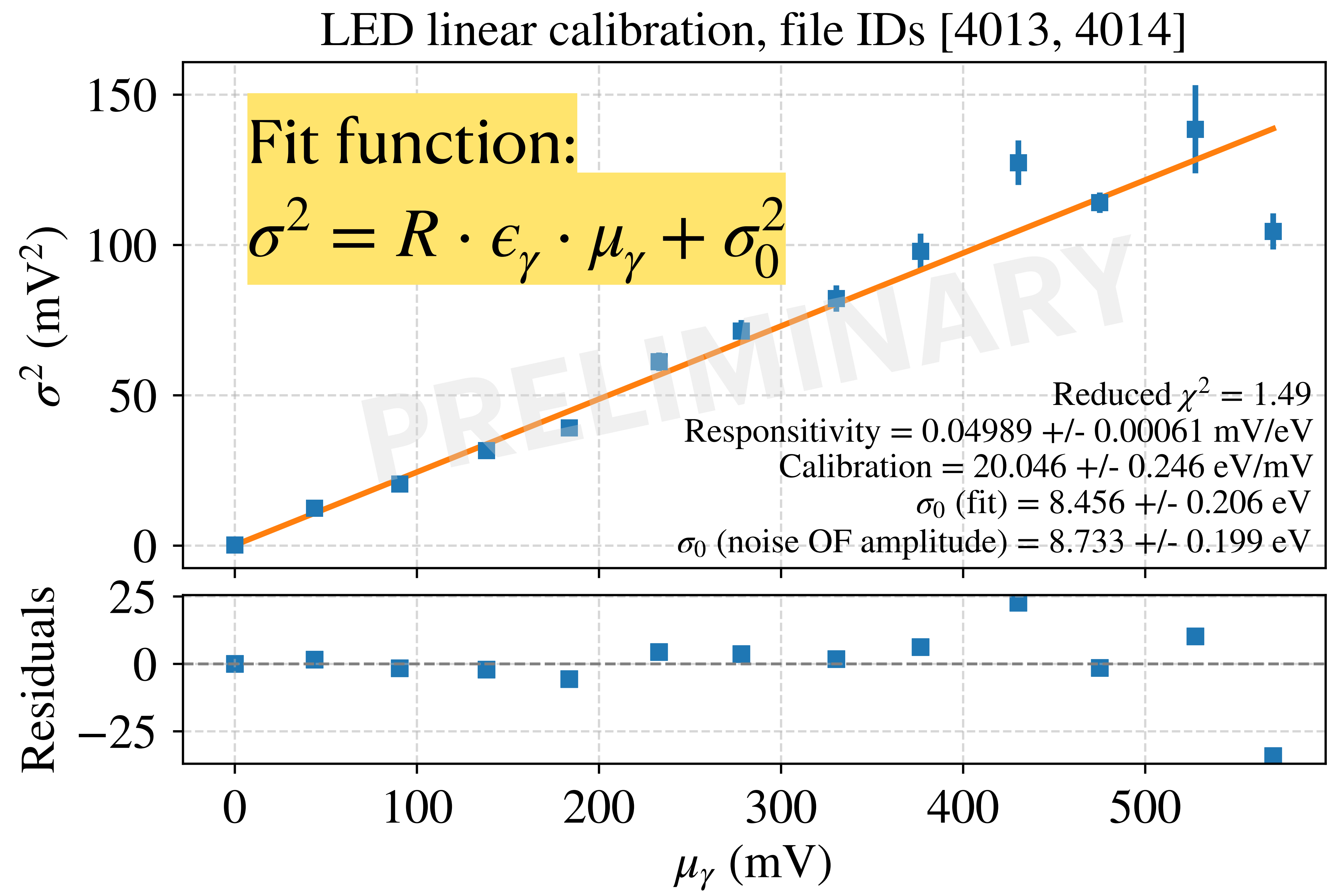
Average deposited amplitude:

$\mu_\gamma = R < N_\gamma > \epsilon_\gamma$

Energy of single photon (depends only on the LED)

Number of deposited photons (can be varied)

Detector responsitivity = 1/calibration

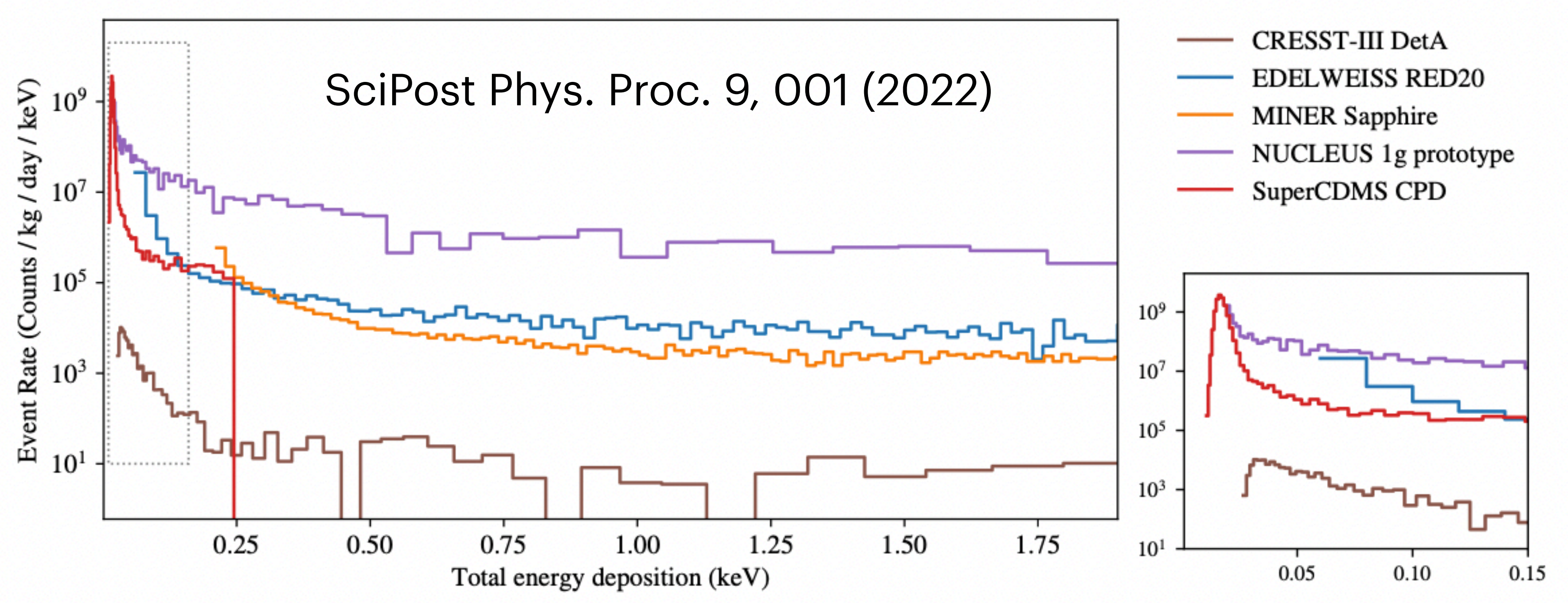


Fit function:

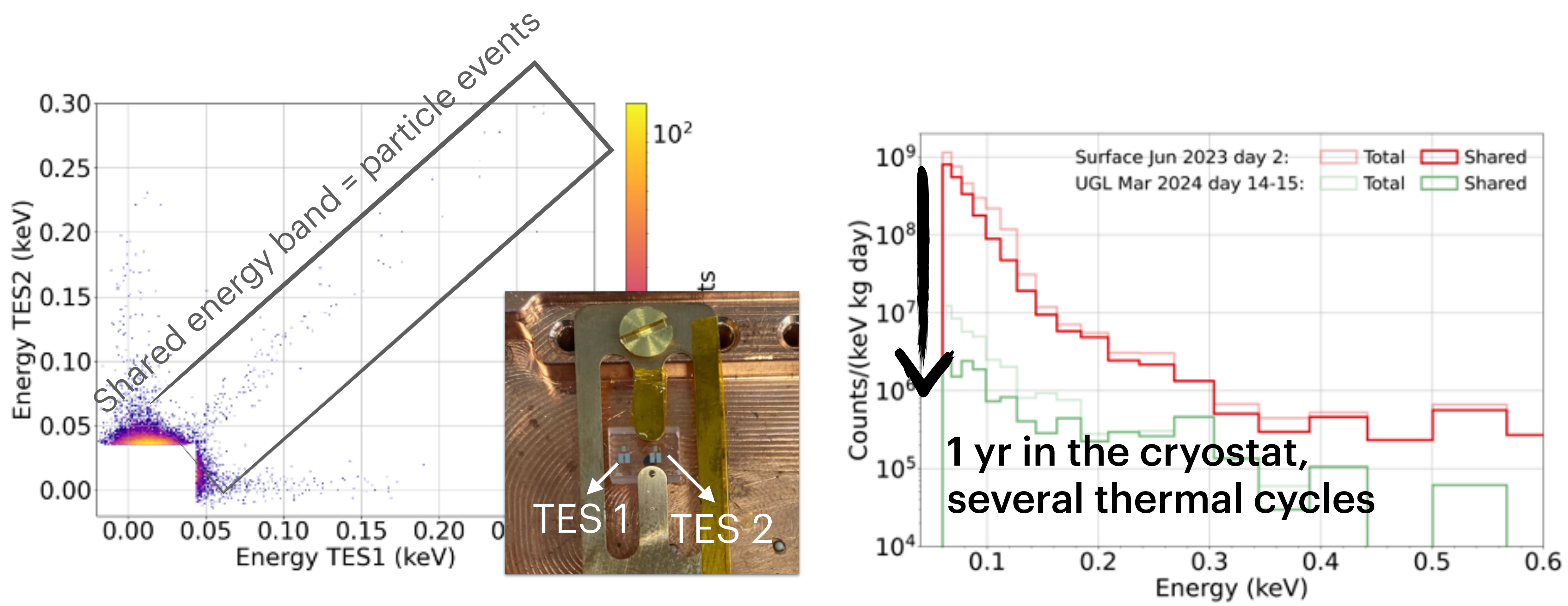
$\sigma^2 = R \cdot \epsilon_\gamma \cdot \mu_\gamma + \sigma_0^2$

The Low Energy Excess

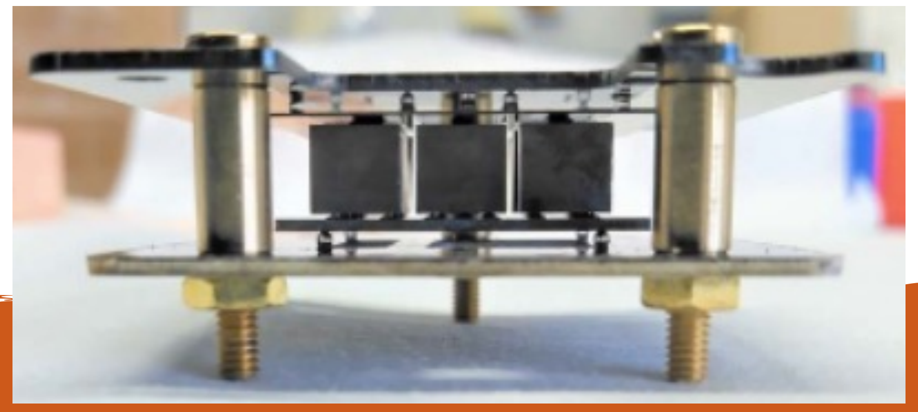
- Many low-threshold experiments observe rising event rates if yet unknown origins below a few hundreds of eV and above the particle background expectations
- Significant impact on CEvNS sensitivity
- What we learned so far in NUCLEUS and in the community:
  - All observations hint towards solid-state effect as origin for the LEE
  - Double-TES detectors show evidence of TES-related LEE
  - Time dependence of LEE rate
  - Reduction of LEE with time and/or thermal cycles
  - Reset of LEE by re-assembing the detectors



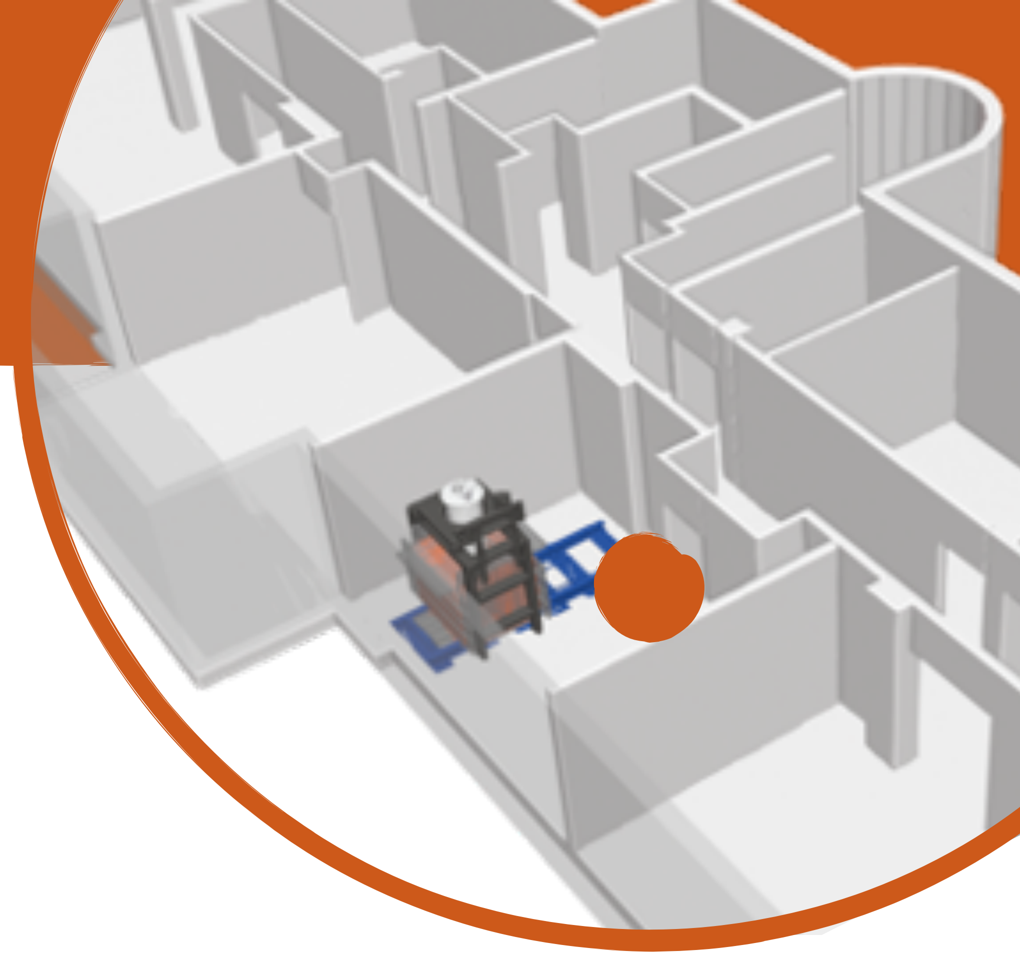
- NUCLEUS track:
  - Double-TES read-out to reject TES-related LEE
  - Results from Long Background Runs on time dependence of LEE
  - Investigate impact of thermal cycles
  - Active holders in the pipeline: strong hints that holder-related LEE contribute to the “shared band”



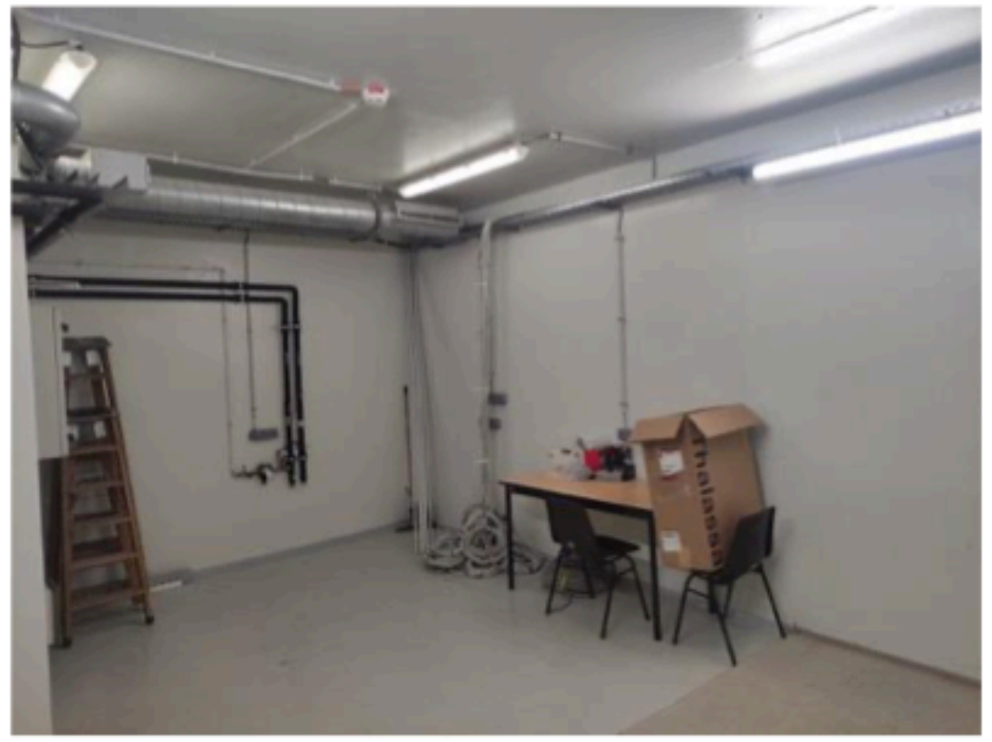
Margarita Kaznacheeva (TUM) at EXCESS24



The VNS



- 24 m^2 basement room (~3 m.w.e.)
- 72 m and 102 m distance from two 4.25 GW_{th} reactor cores
- Expected anti-neutrino flux ~ 1.7 10^{12} $\nu/cm^2/s$
- No reactor related background
- But, very shallow overburden: excellent shielding and vetoing systems are required
- Integration of the experiment at VNS is a logistic challenge (strict access rules, ...)



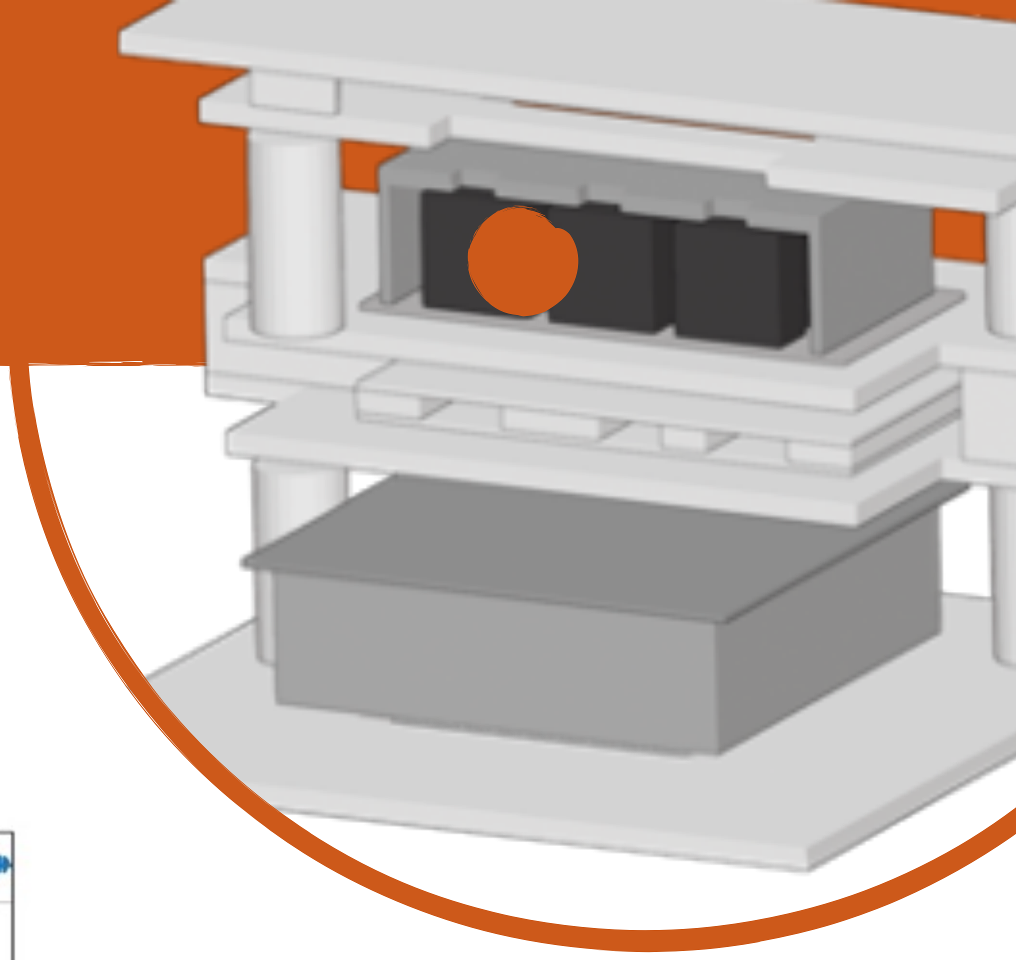
✓ VNS room ready to host the experiment

Setup of network and computing infrastructure ongoing

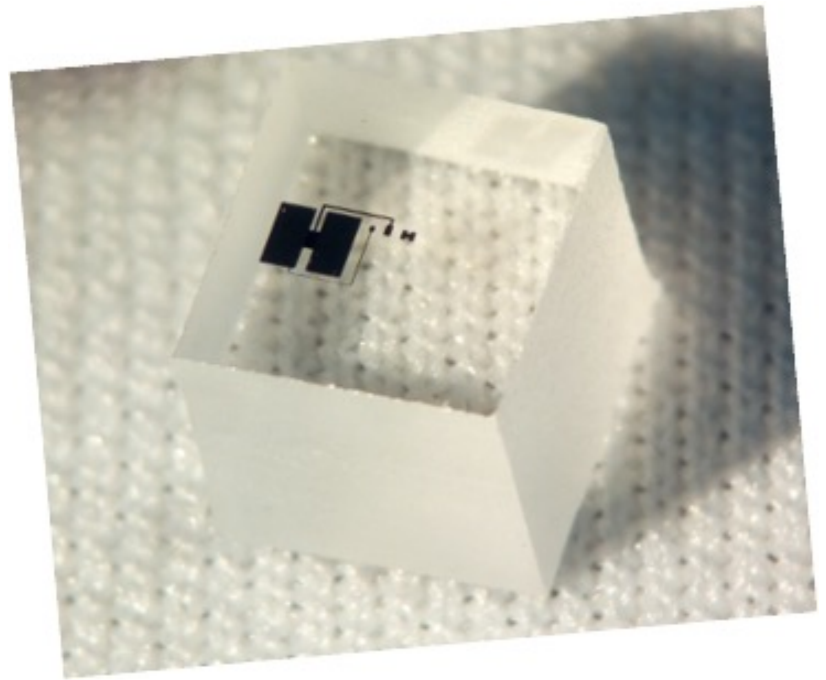
Preview: NUCLEUS@VNS, Chooz 2025

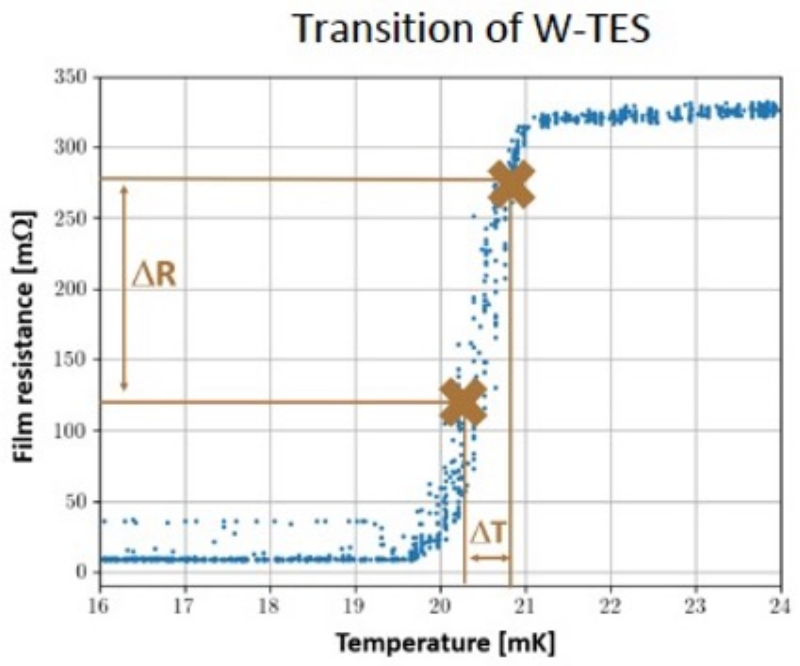
Credit: Loris Scola (CEA)

Target detectors



- Gram-scale cryogenic calorimeters: absorber crystal equipped with Transition Edge Sensor (TES)
- Operated at mK temperatures
- Low threshold & good energy resolution

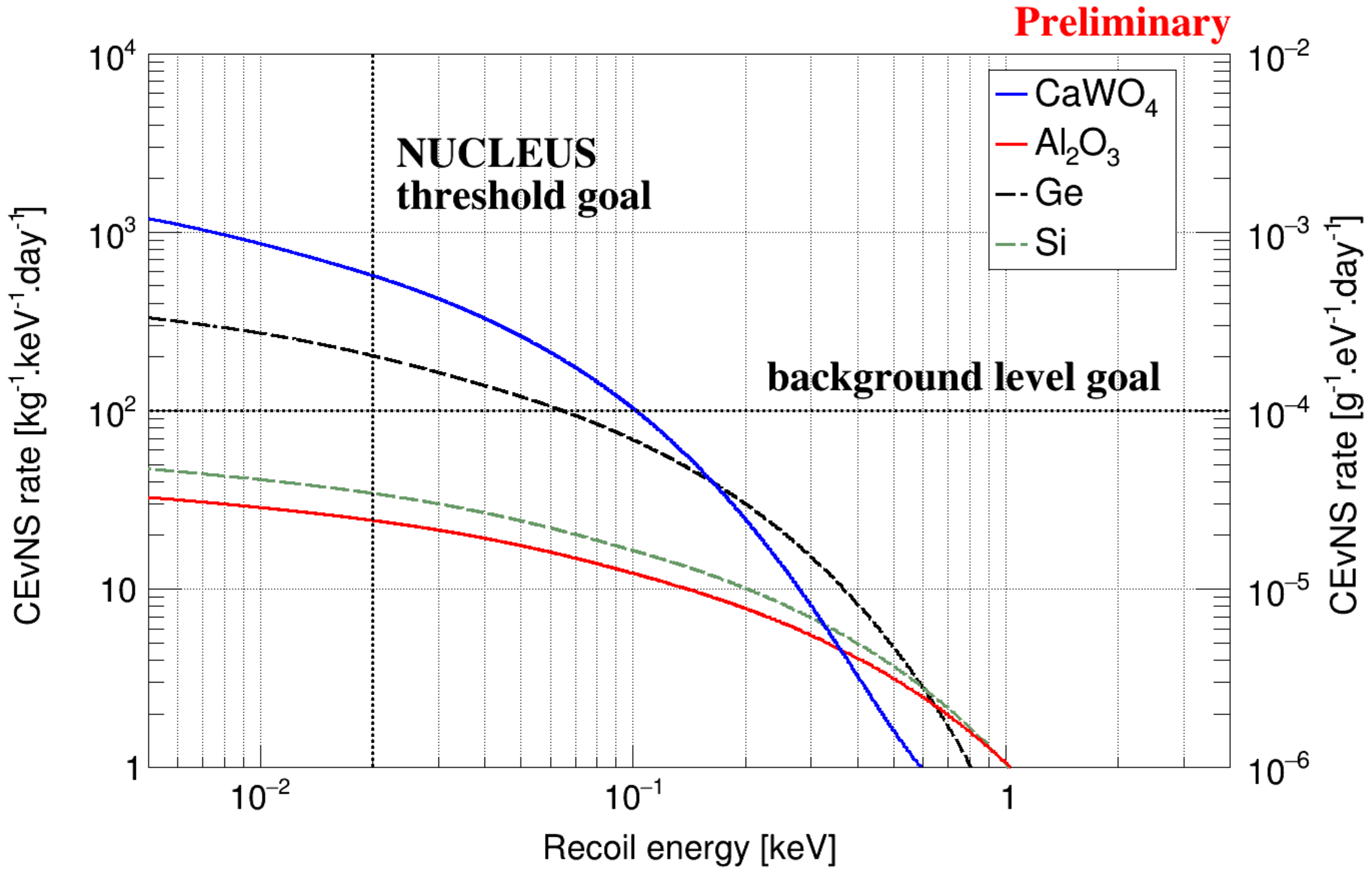




Particle interaction → Phonon production → TES heating → Resistance change → SQUID readout

Multi-target approach for NUCLEUS 10g:

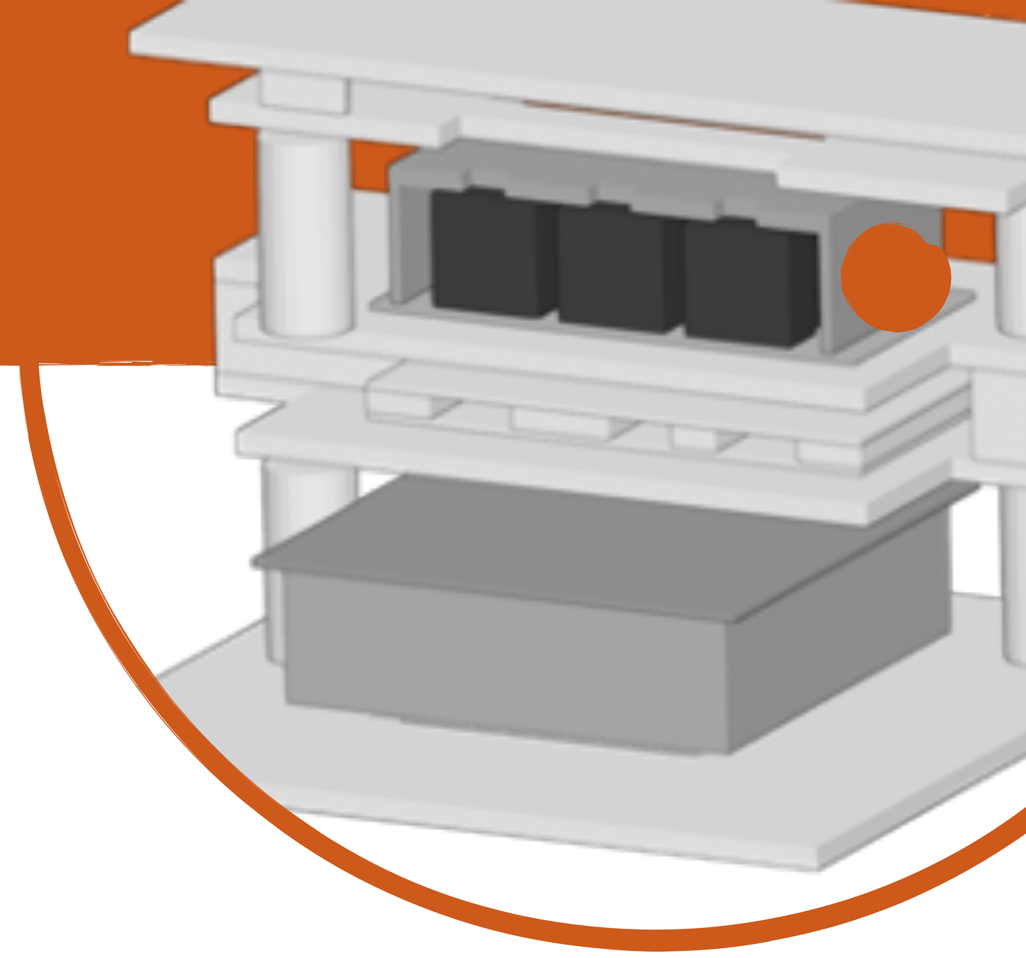
- Al_2O_3 background measurement
- $CaWO_4$ high CEvNS rate



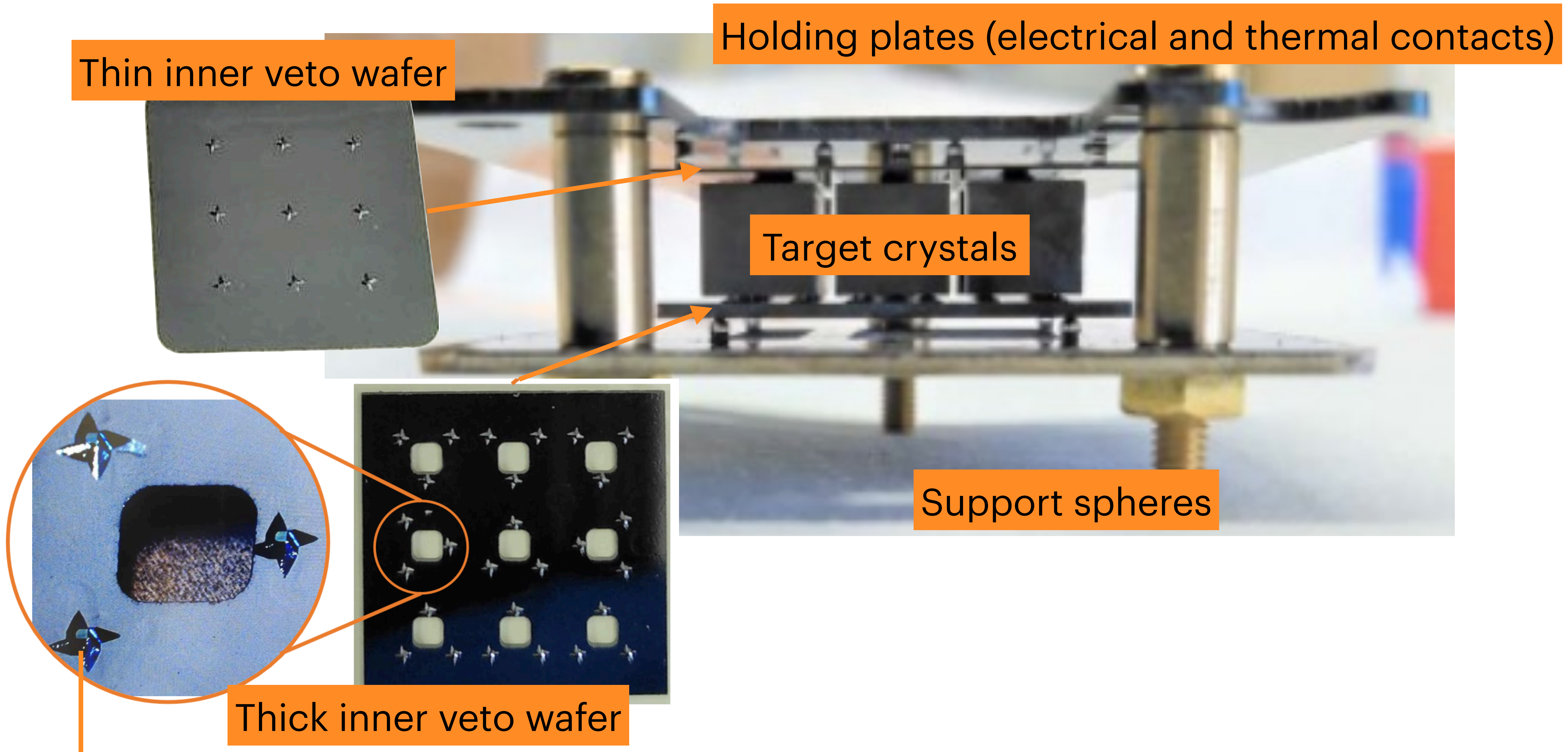
NUCLEUS Al_2O_3 prototype E_{th}=(19.7 +/- 0.8) eV [*Phys. Rev. D* **96**, 022009 (2017)]

✓ Good performances demonstrated over multiple measurements & in ongoing commissioning @TUM

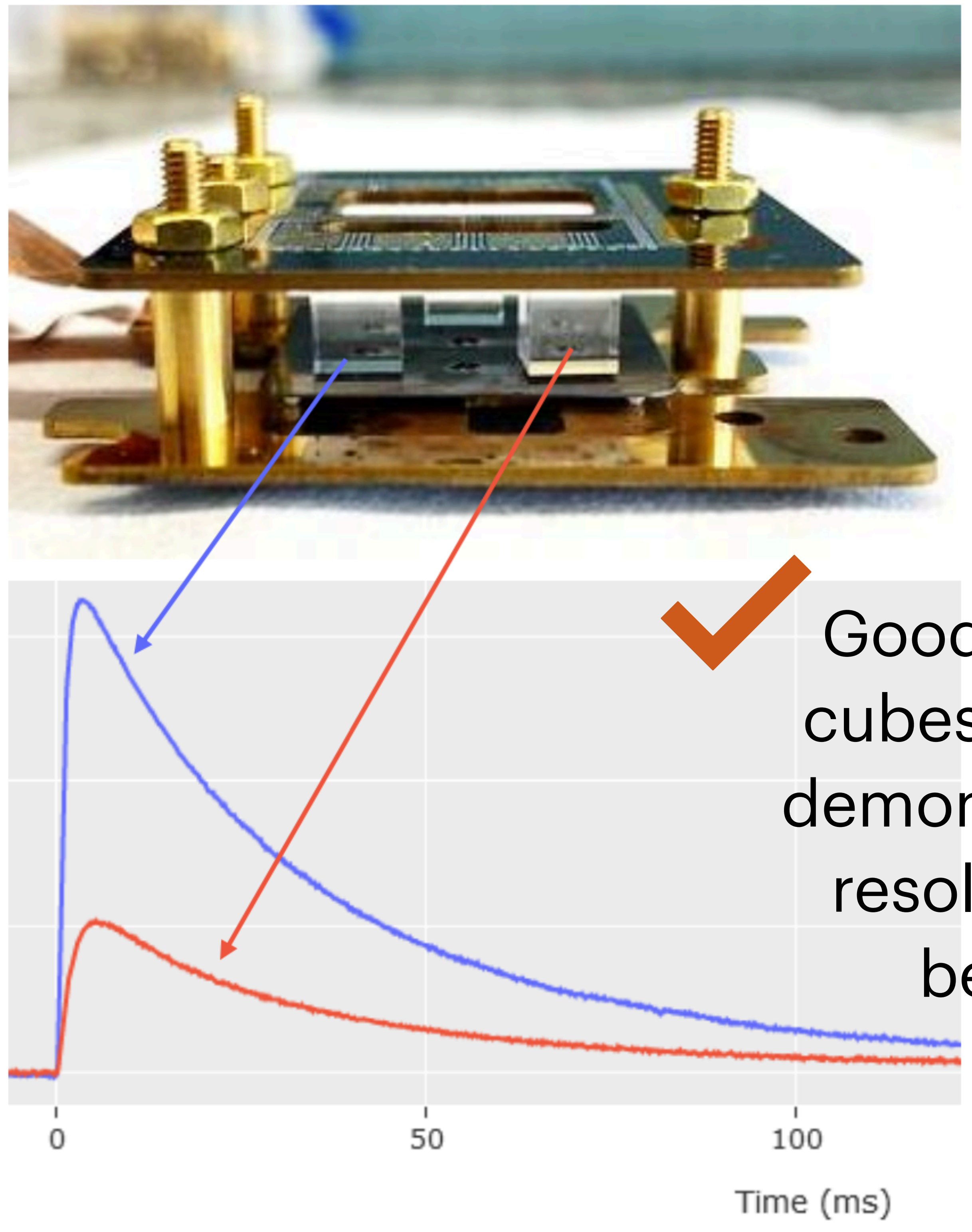
Inner veto



- Instrumented holder for target detectors: Silicon wafers equipped with TES
- Veto of surface events and mechanical stress relaxation-induced events (Low Energy Excess)



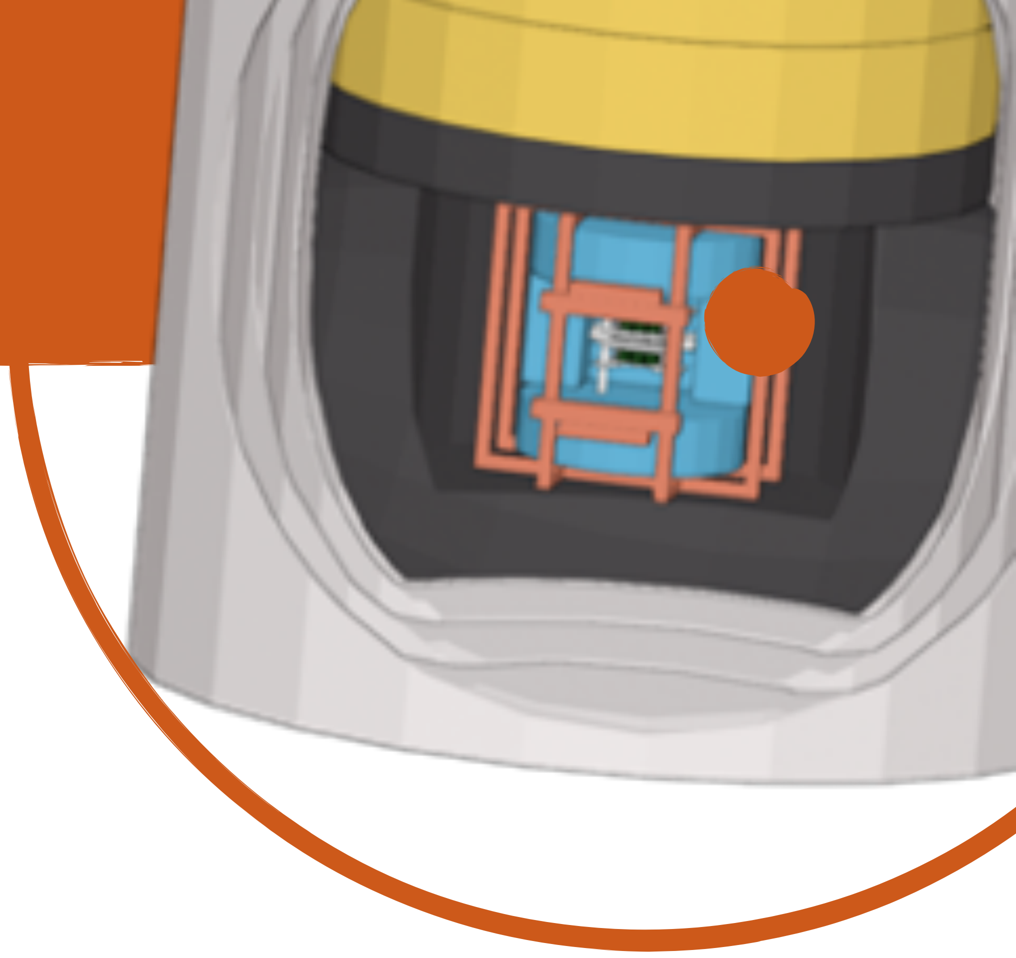
Point-like contact between crystals and Silicon wafers via pyramids for low phonon dispersion



✔ Good performance of two cubes in inner veto module demonstrated: 6 eV baseline resolution & no cross-talk between detectors!

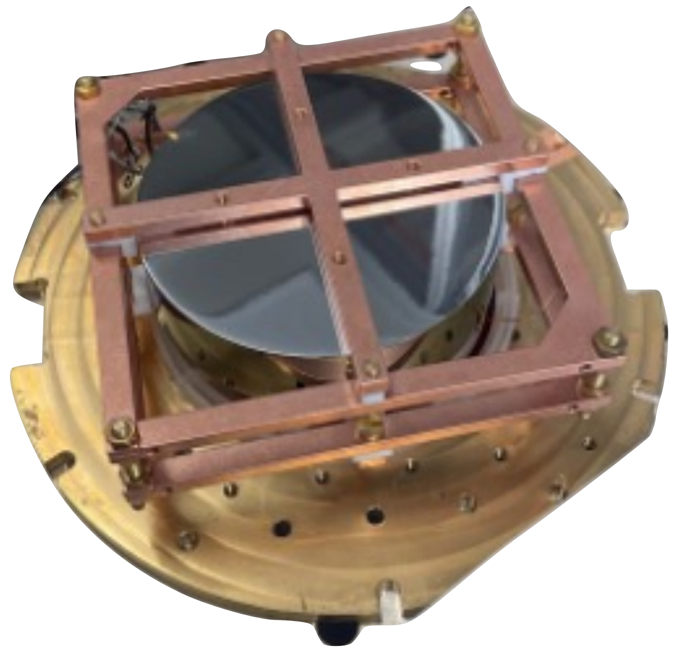
Ongoing optimisation of inner veto TES design & validation of veto capabilities

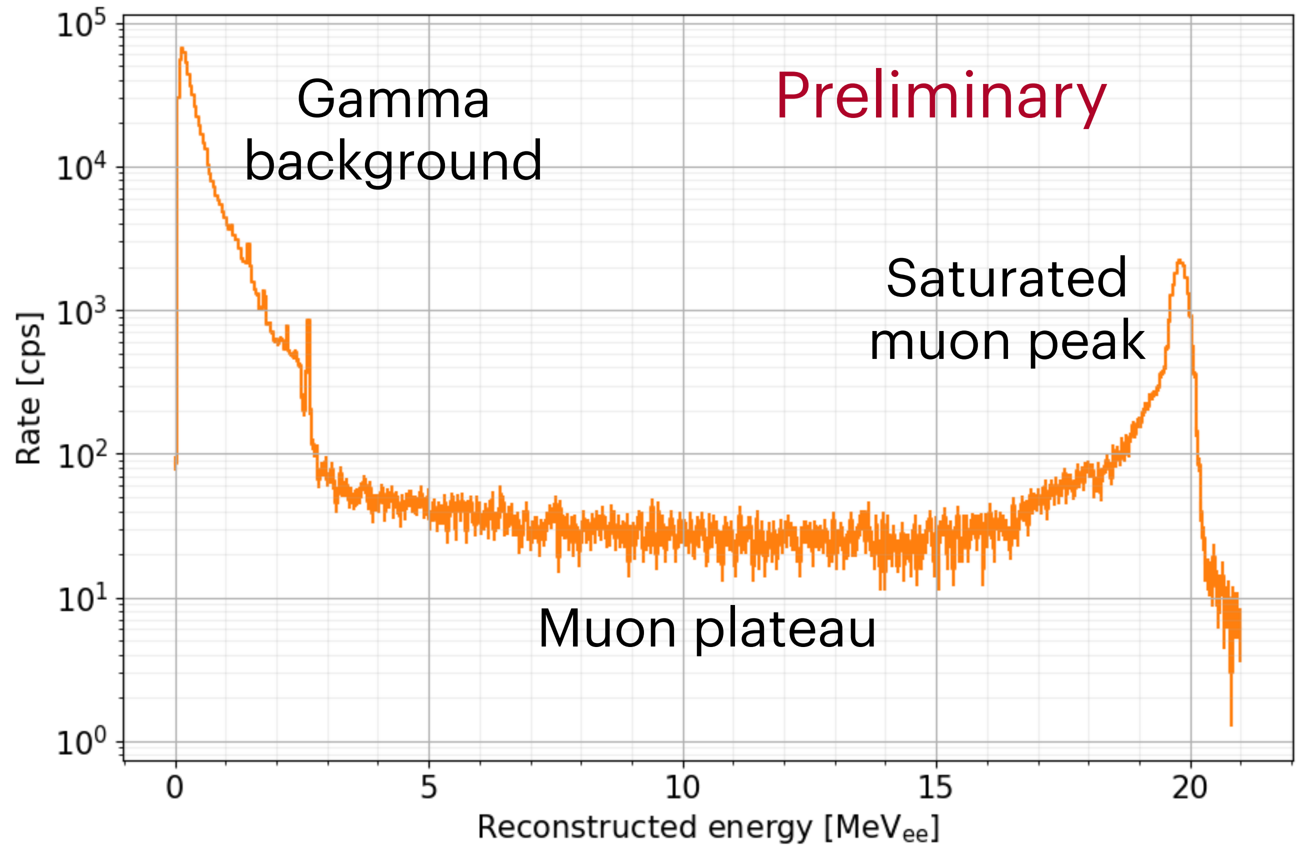
Cryogenic Outer Veto



- 6 High purity Germanium detectors (4 kg, 2.5 cm thickness) with threshold ~O(1-10 keV) with 4π coverage of target detectors
- Background suppression of external gammas

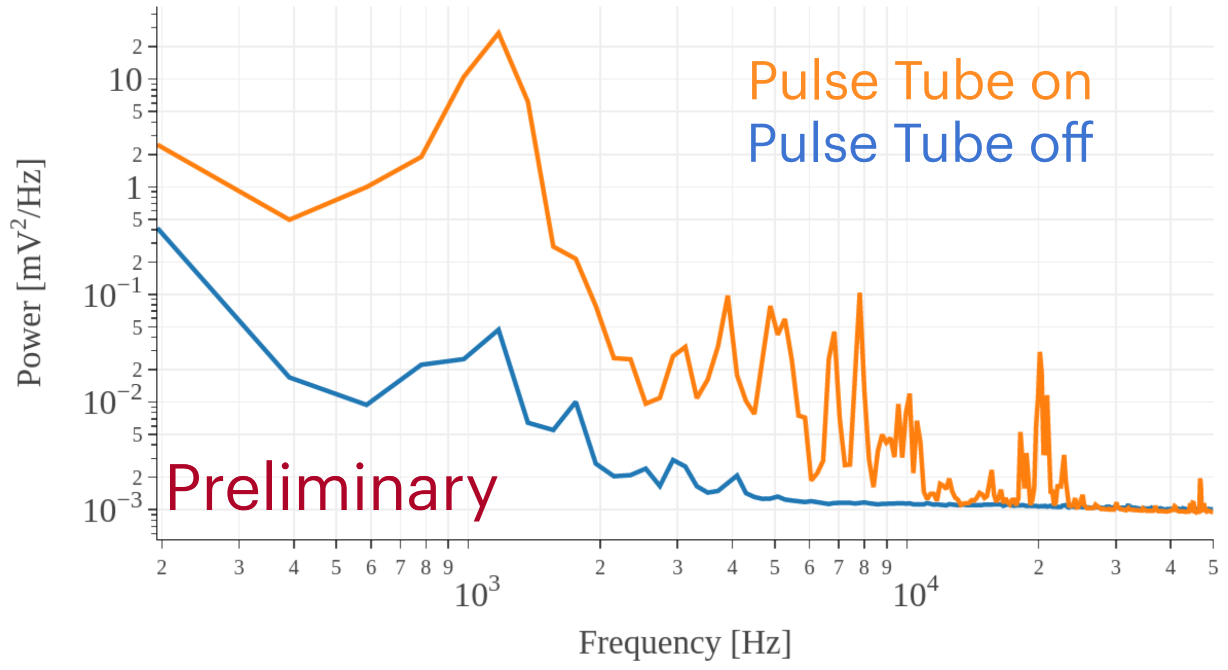
One cylindrical crystal currently operated in the NUCLEUS cryostat @TUM



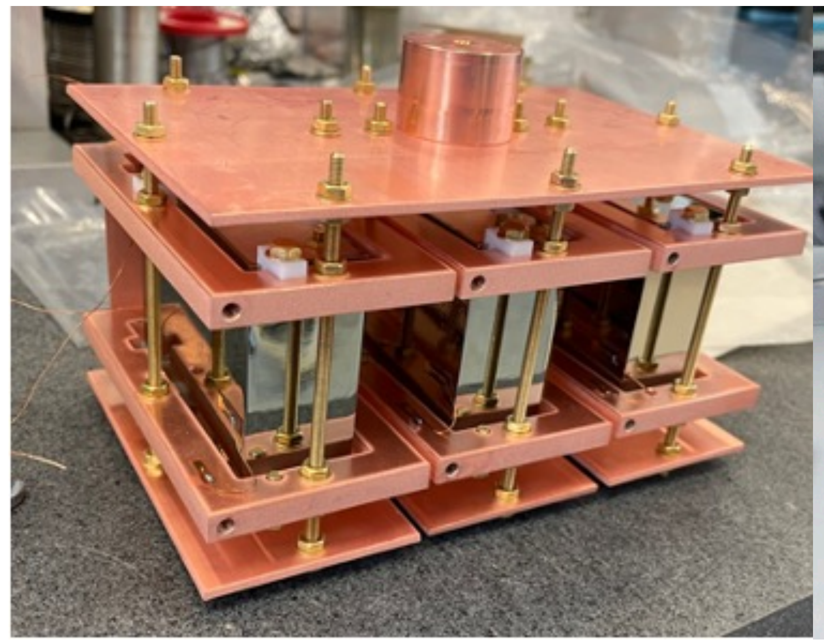


Threshold of ~25 keV achieved with one-electrode readout (improvement to be expected with double readout)

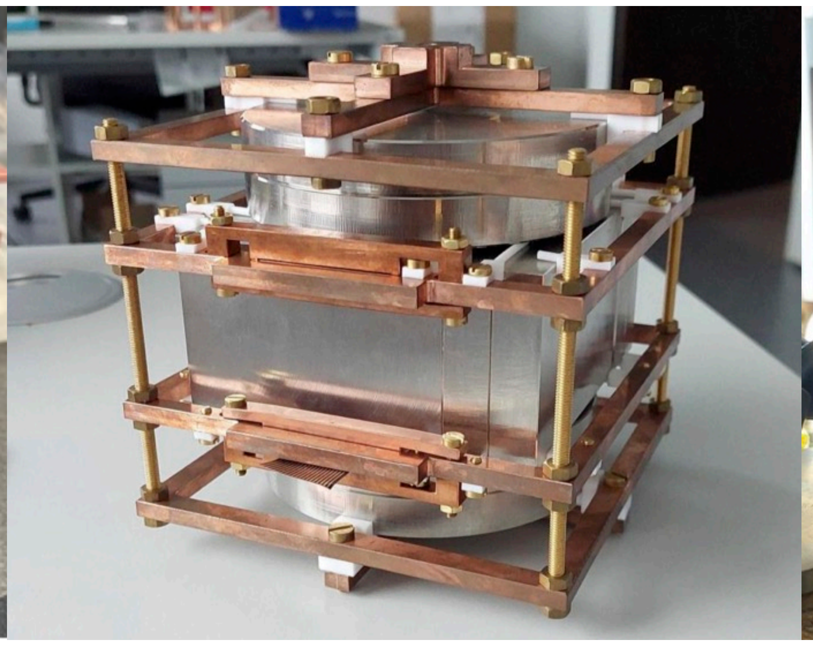
Ongoing optimisation of electronic chain: vibrations are a challenge



Next steps:
- Test of rectangular crystals (ongoing)
- Scale up to 6 crystals and 12 channels version of electronic chain



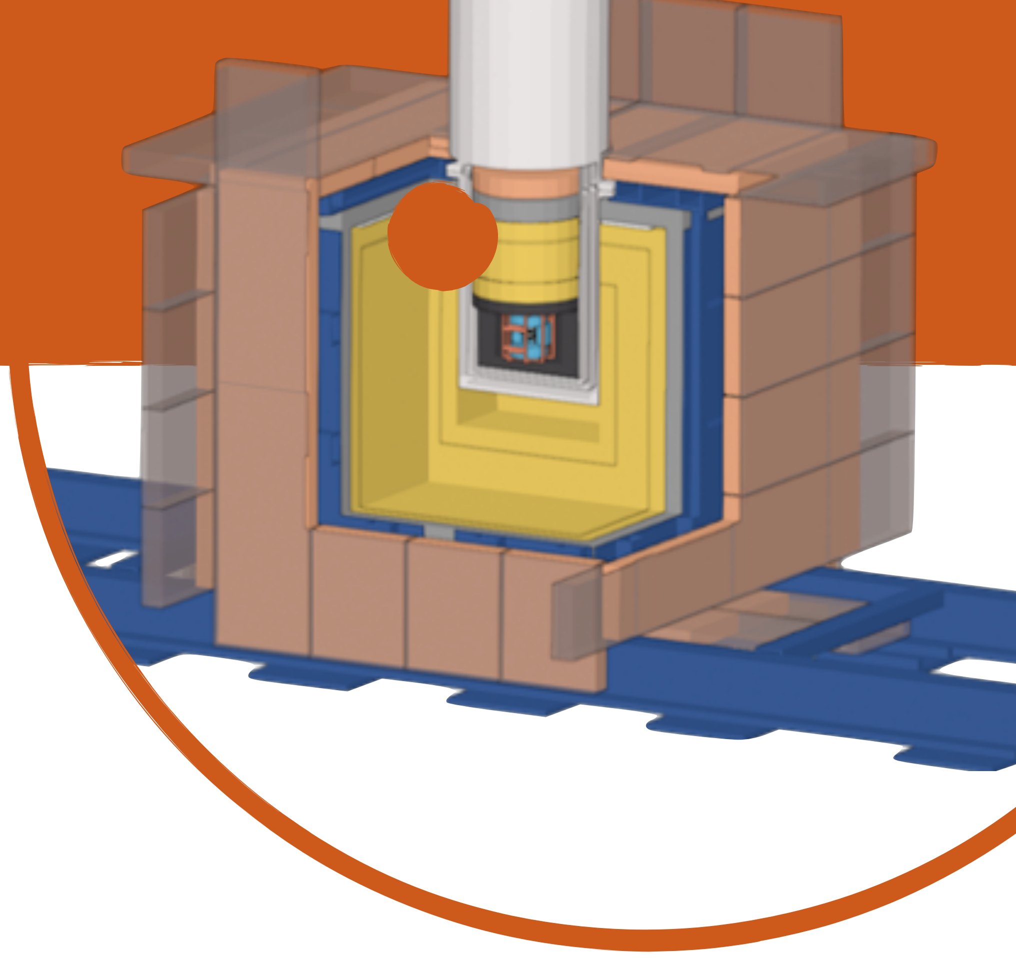
Rectangular crystals



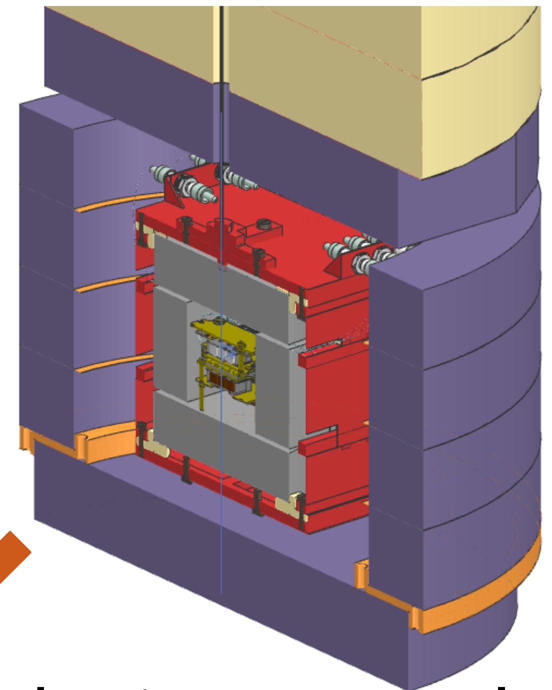
Holding mechanics

Multi-channel 4K box

Passive shielding

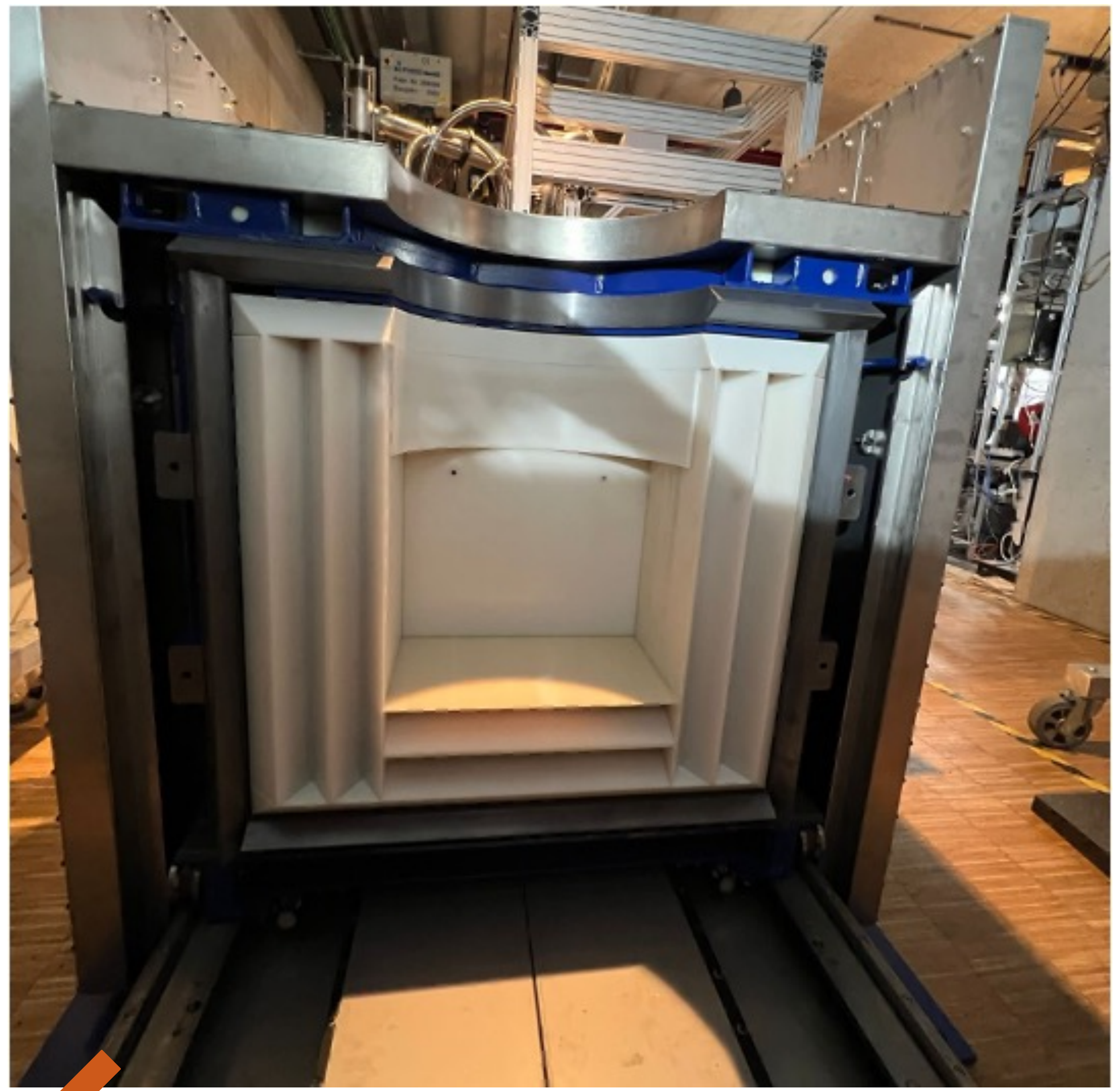


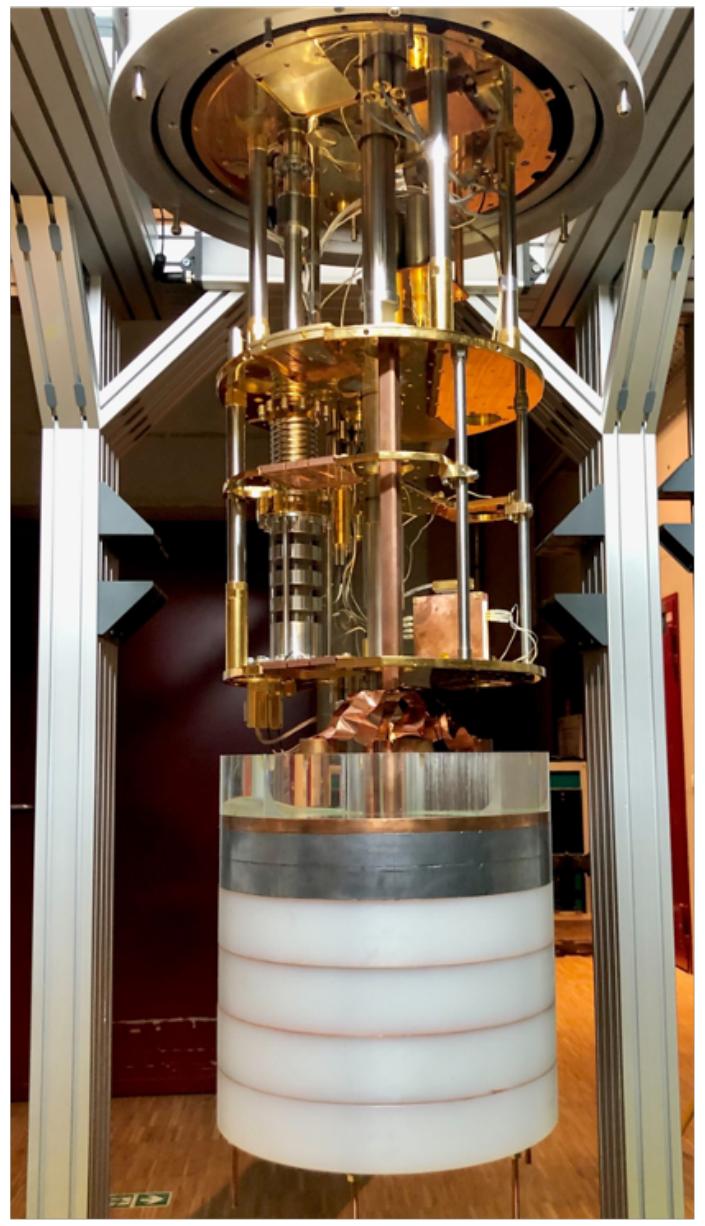
- **Outer shielding:**
  - 5 cm lead + 20 cm borated polyethylene
  - Movable mechanical structure to allow easy access to cryostat
  - Background reduction of ambient gammas, atmospheric and secondary neutrons
- **Inner shielding:**
  - Extension of the outer shielding inside the cryostat: cryogenic muon veto + lead + borated polyethylene
  - Additional 4 cm boron carbide (B_4C) layer around detectors for slow and thermal neutron reduction



B_4C design completed

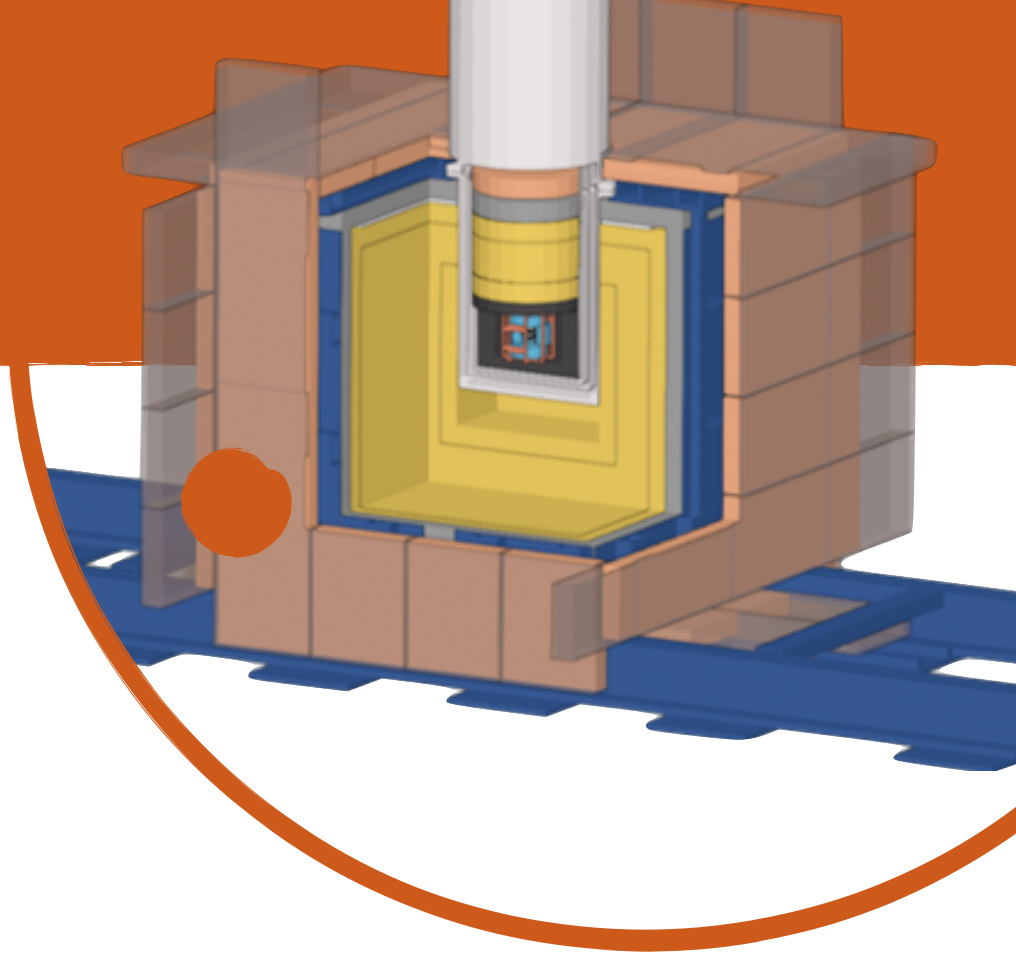
Production ongoing @Wintrustek (China)
First parts delivered and being tested for mechanical integration



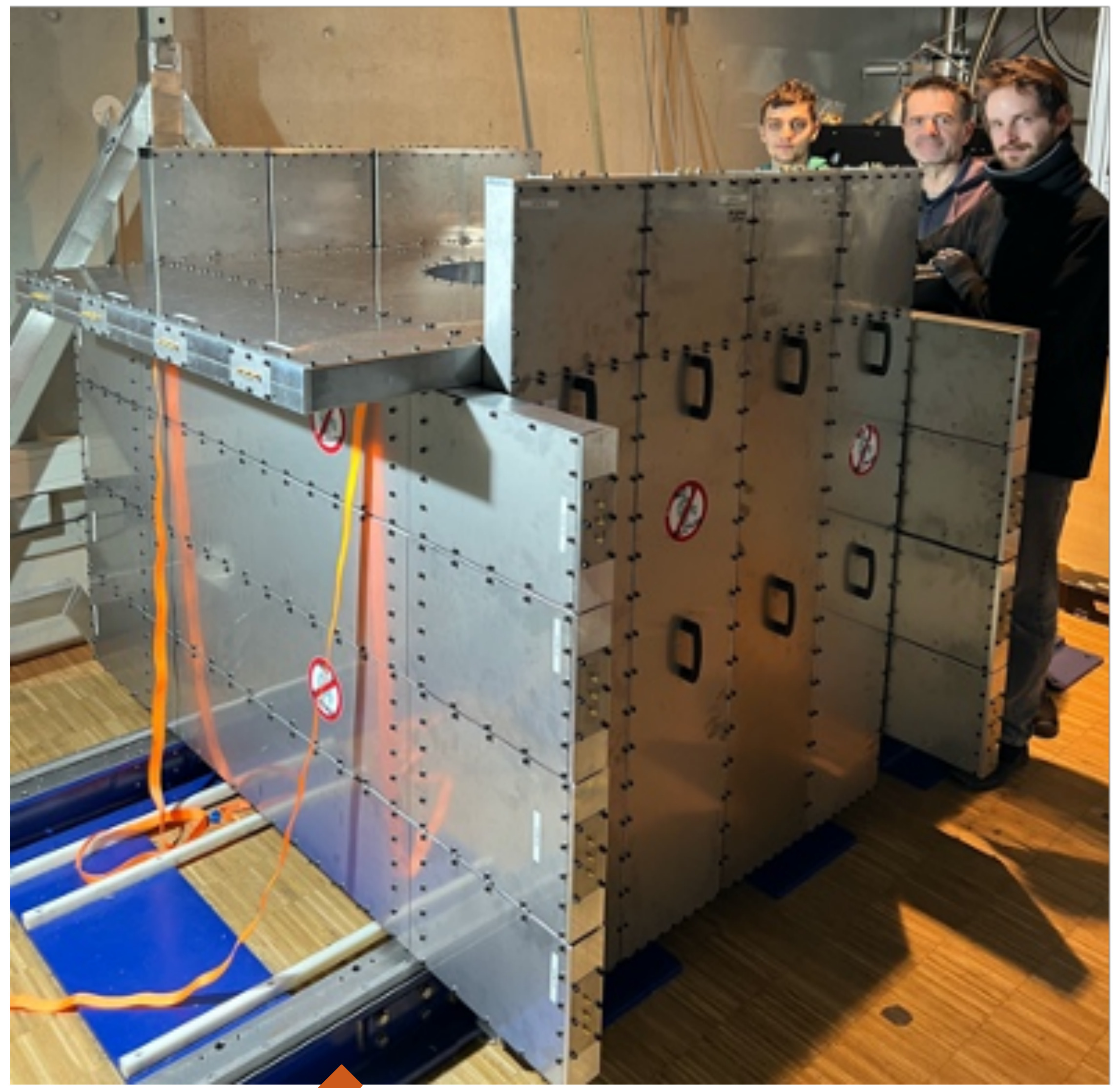


External shielding fully commissioned and in place
Full thermalisation of internal shielding (~50 kg of PE, Pb, Cu, CMV) achieved within 11 days.

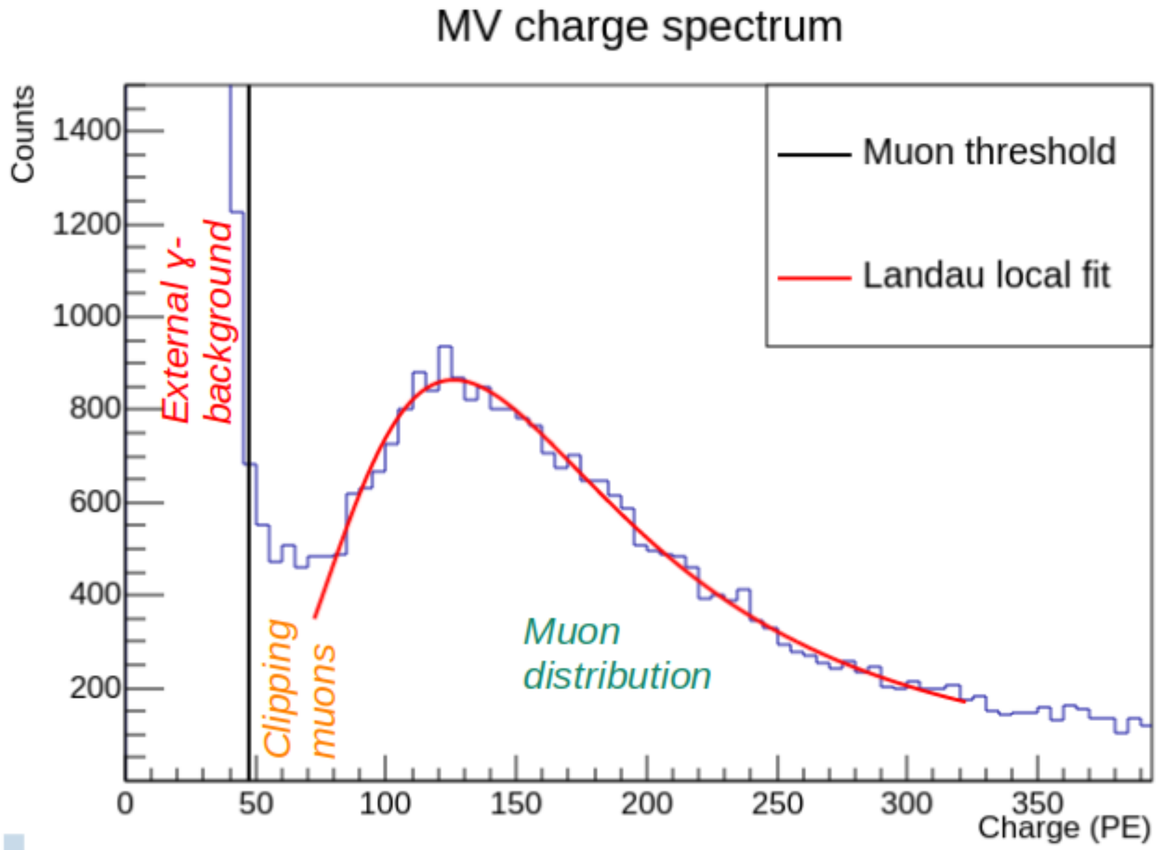
The Muon Veto



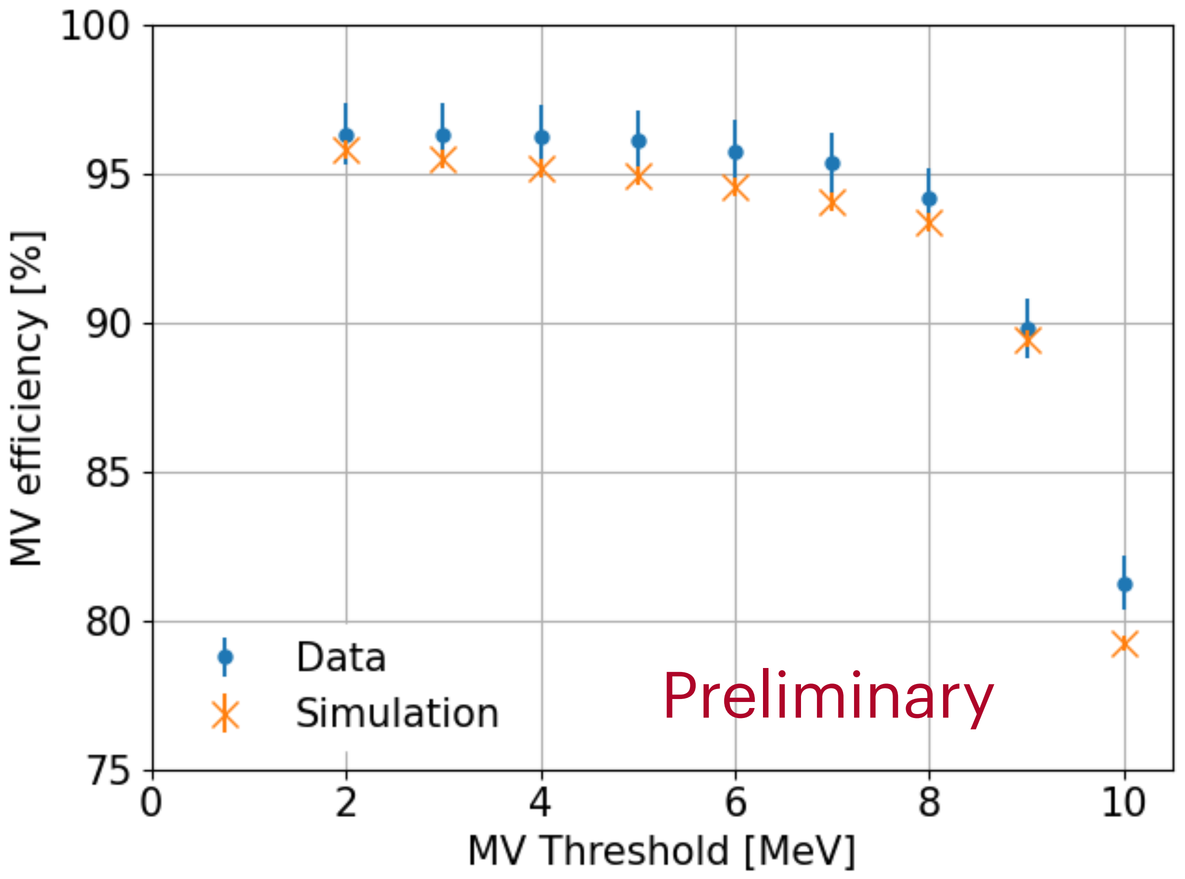
- 28x5cm thick plastic scintillator plates with SiPMs and WLS-fiber readout [V. Wagner et al 2022 JINST 17 T05020]
- Cryogenic extension for 4π coverage (>99% geometrical efficiency) [A. Erhart et al Eur. Phys. J. C 84, 70 (2024)]



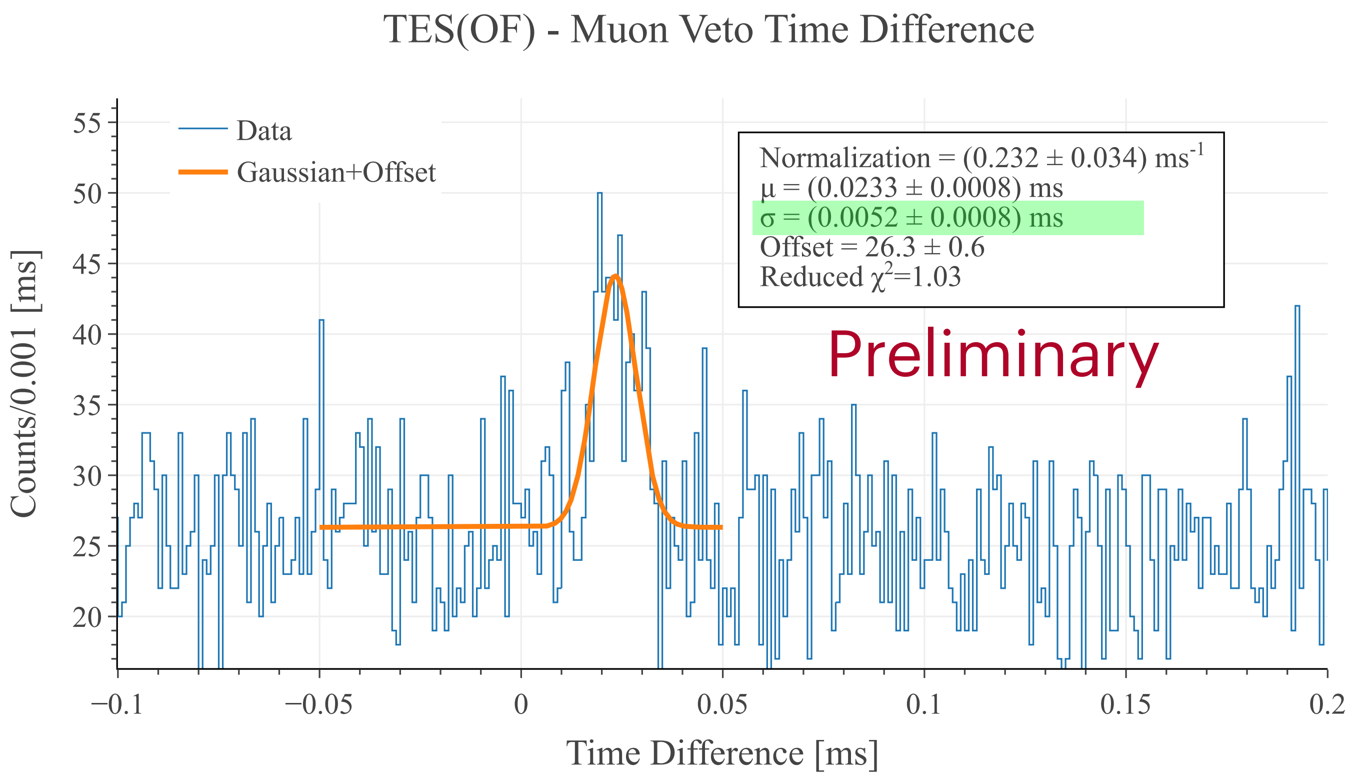
✔ Assembling and commissioning @TUM completed



MV efficiency (w/o CMV) with muon events seen in COV = 96.3 %

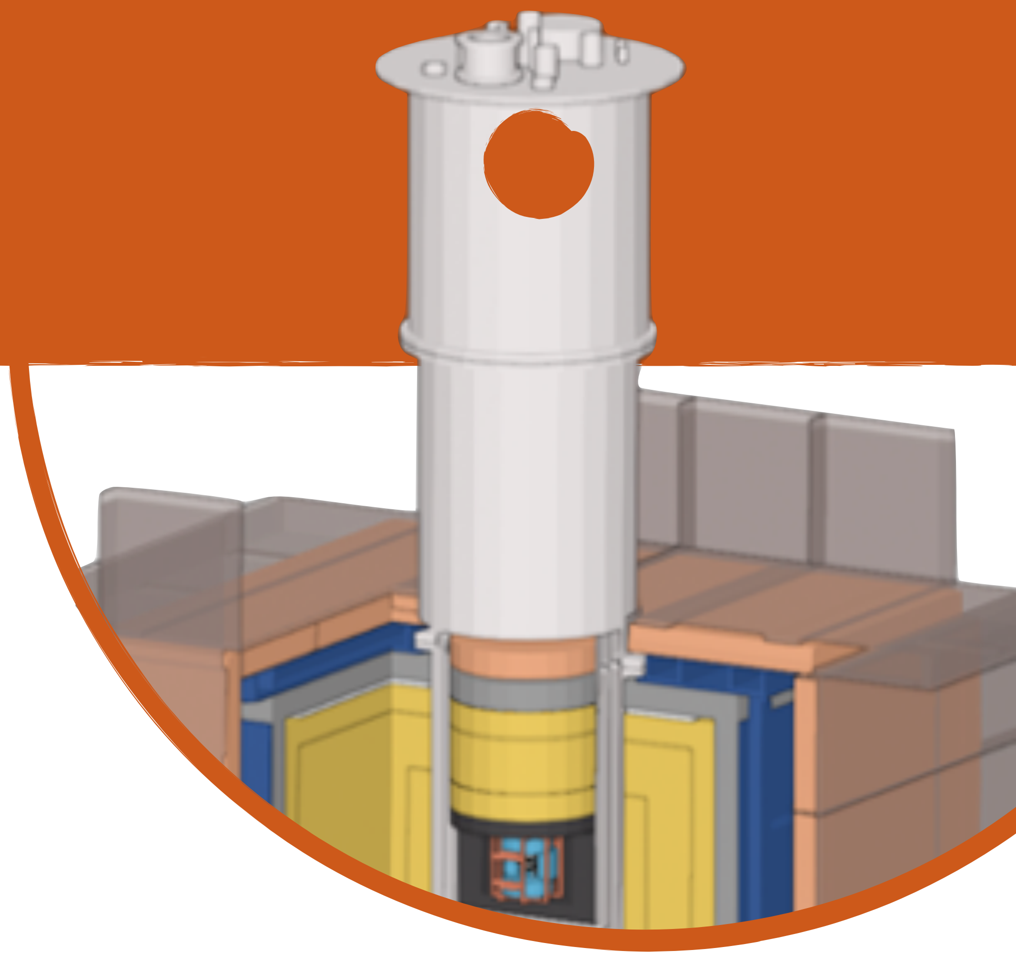


~1% dead time with 325 Hz @VNS

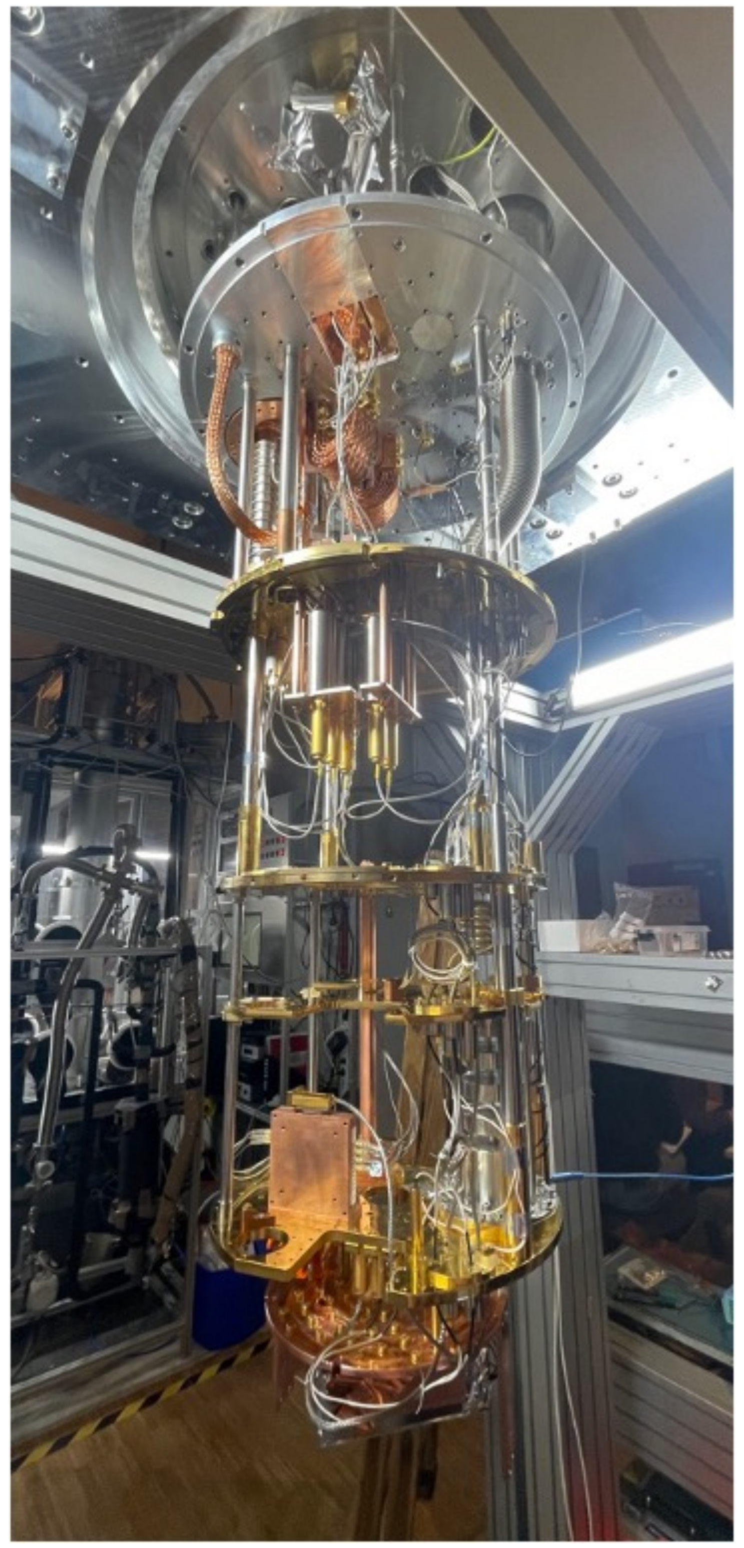


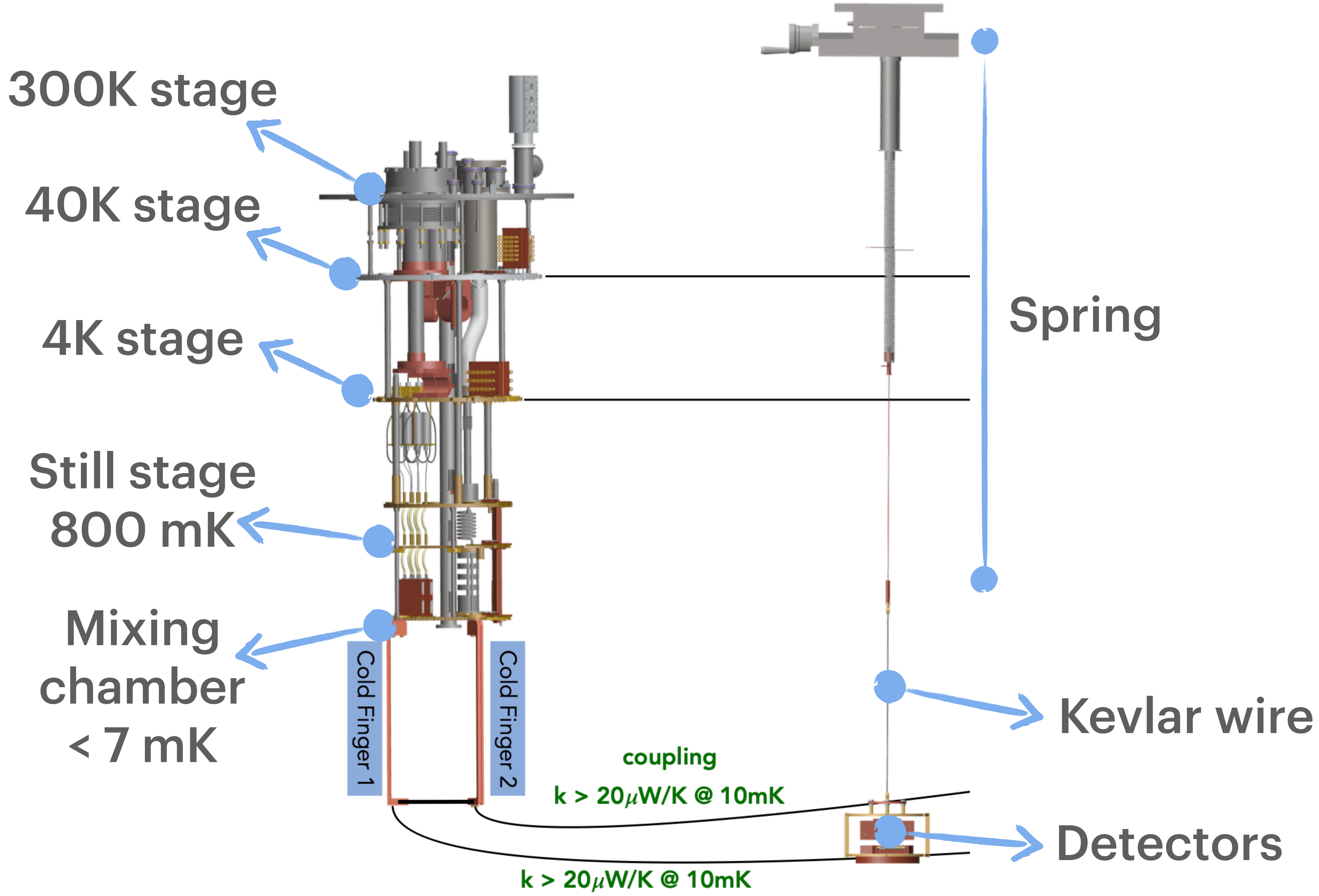
✔ Muon Veto operational and fully validated in terms of rates, spectral shape, calibration, efficiency, dead time.

Cryogenic detector operation



- Dry dilution refrigerator to avoid handling of cryogenic liquids (BlueFors LD400 cryogen-free)
- Base temperature O(10 mK)
- Pulsed tube cryo-cooler: challenging vibration environment
- Custom-made vibration decoupling system deployed and validated (patent protected)





More than 4 weeks stable continuous operation of NUCLEUS $CaWO_4$ crystal. Target detector operation largely independent of Pulse Tube vibrations. Noise reduction by a factor ~30.