

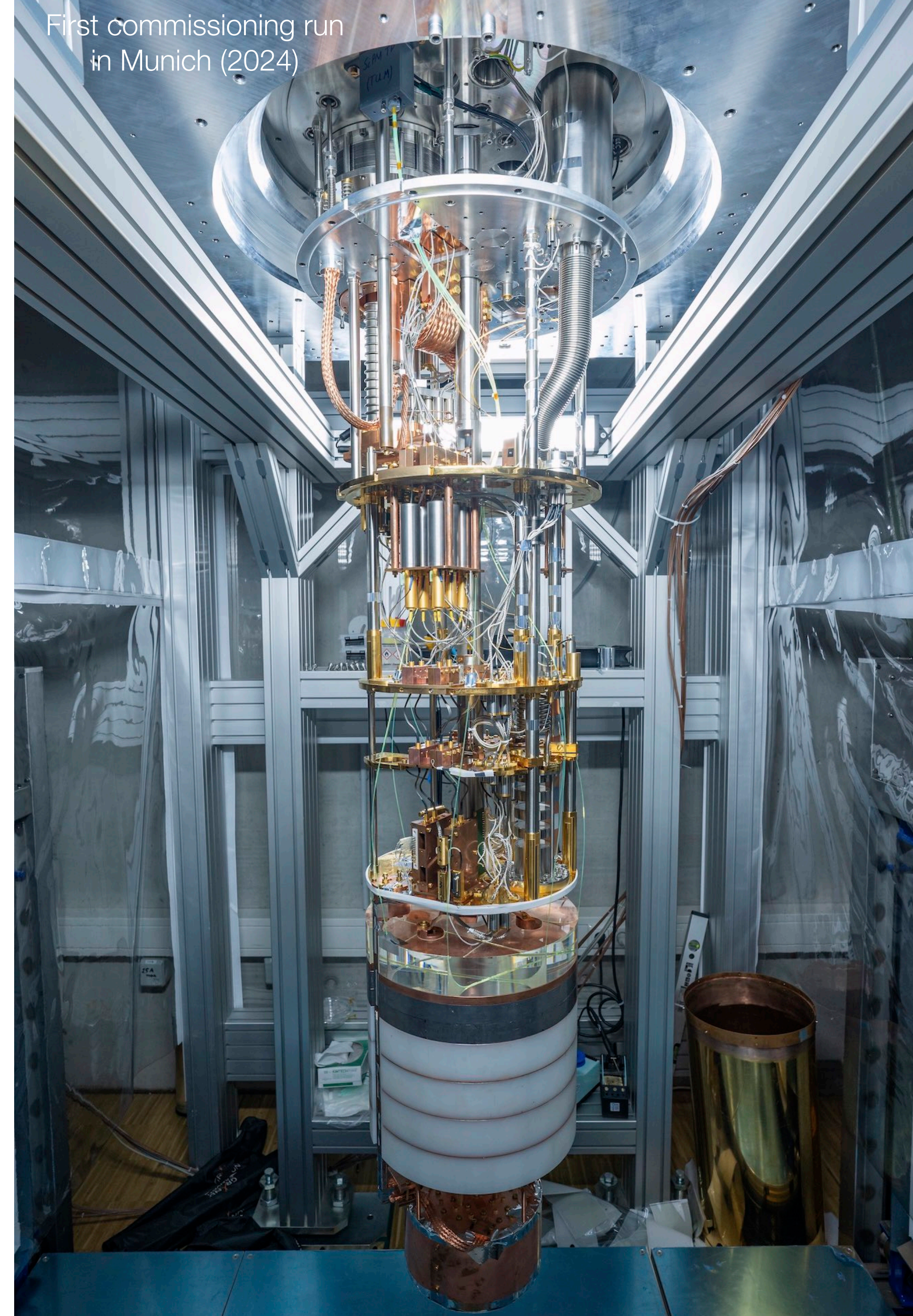


Cryogenic Detection of Reactor Antineutrinos with NUCLEUS

Status Report

Matthieu Vivier
CSTD DPhP (07/10/2026)

First commissioning run
in Munich (2024)



Outline

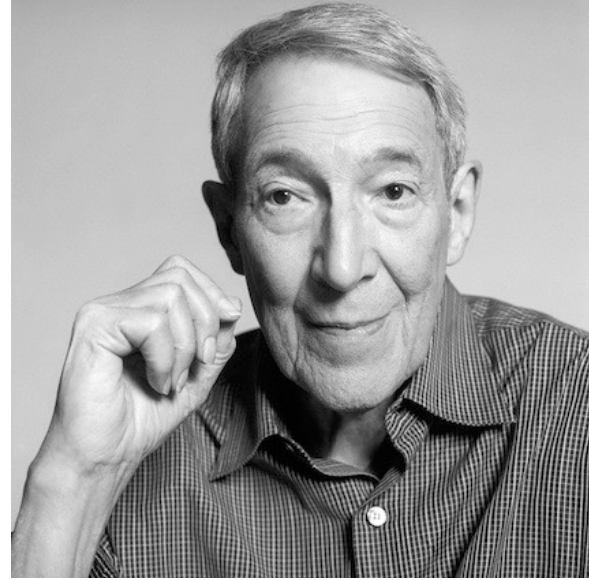
- ▶ Science Case: Why NUCLEUS?
- ▶ The NUCLEUS Experiment: Overview and Status
- ▶ Summary and Outlooks

Science Case

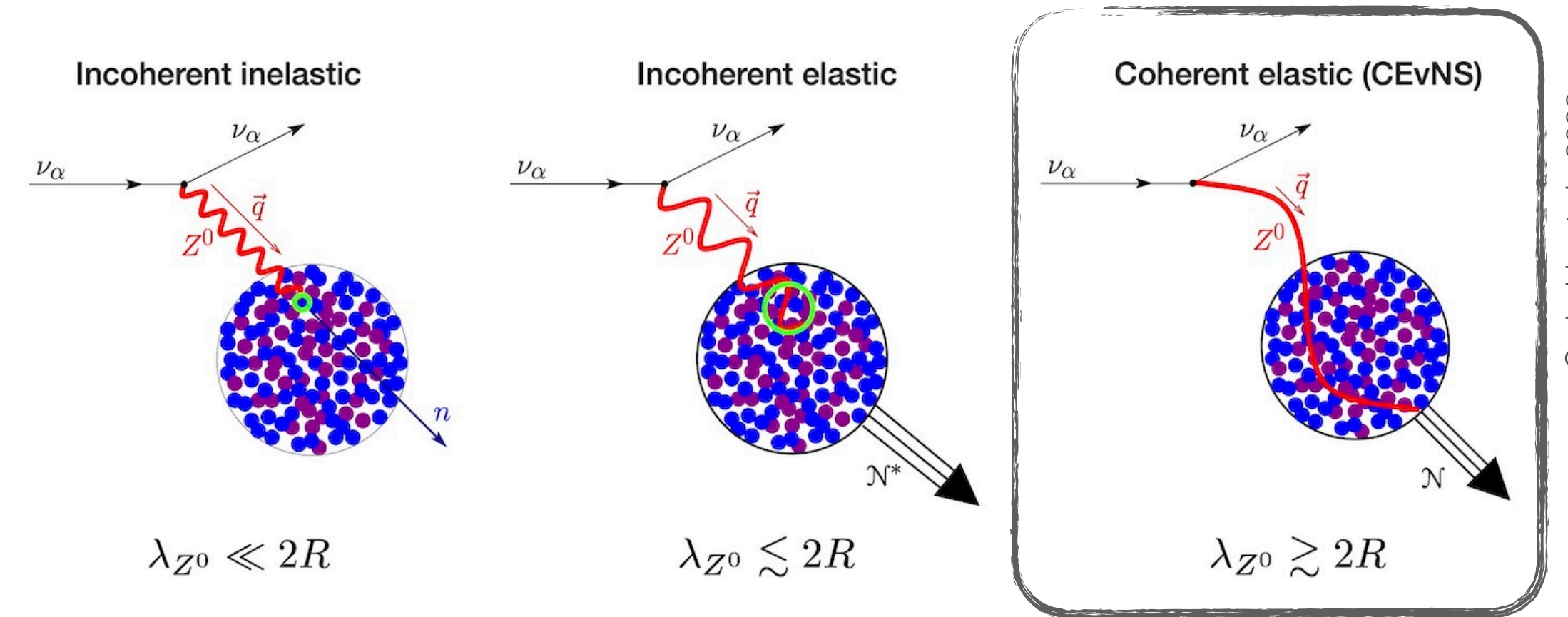
Why NUCLEUS ?

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

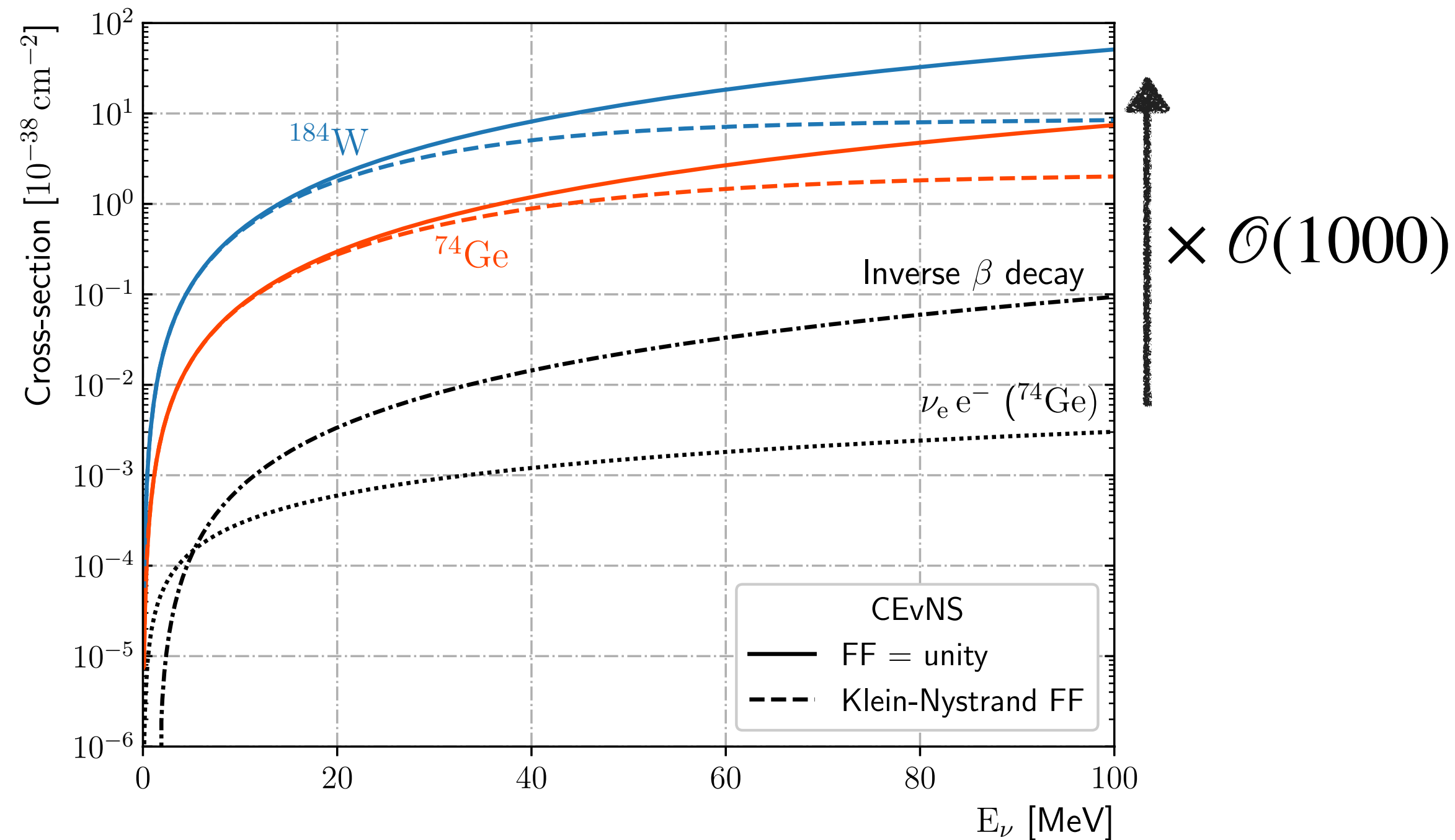
D. Z. Freedman (1974)



- Neutral current, flavor blind process
- Coherent interaction over a nucleus as a whole
 - N^2 -enhancement of the cross-section
 - No kinematic threshold
 - Experimental signature = low-energy nuclear recoil



Cadeddu et al., 2023

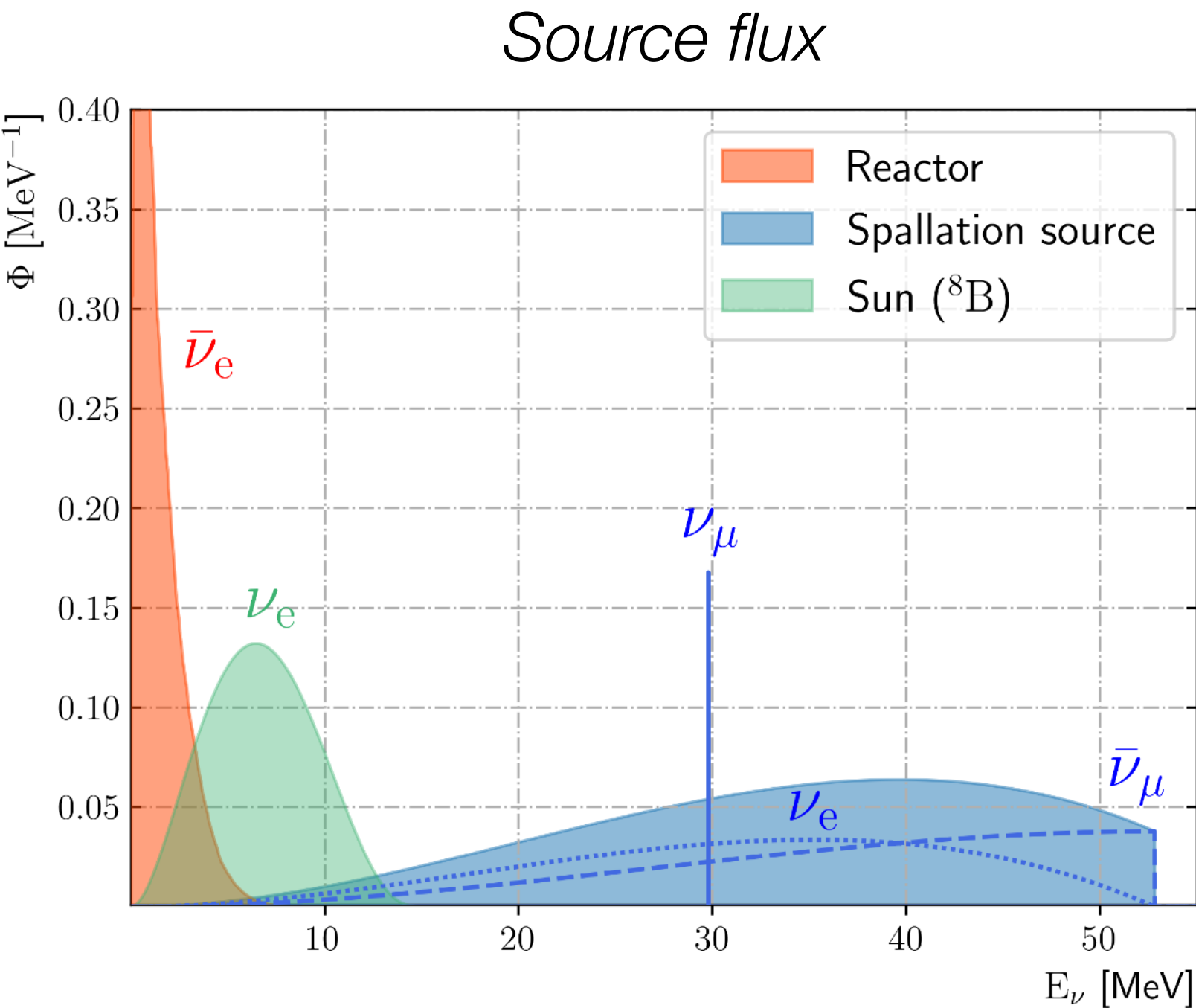


$$\frac{d\sigma}{dT} \propto \underbrace{[Z(1 - 4 \sin^2 \theta_W) - N]^2}_{\text{Electroweak physics}} \underbrace{F^2(q^2)}_{\text{Nuclear physics}}$$

- Electroweak physics and BSM searches at low energies
- New probe for nuclear matter
- Miniaturization of detectors: many potential applications
 - Nuclear reactor safeguarding
 - Synergies with neutrino astronomy, DM detection, etc.

CEvNS Detection: Experimental Challenges

► Low-energy “controllable” neutrino source (coherent regime)



$$T_{max} = \frac{2E_\nu^2}{M + 2E_\nu}$$

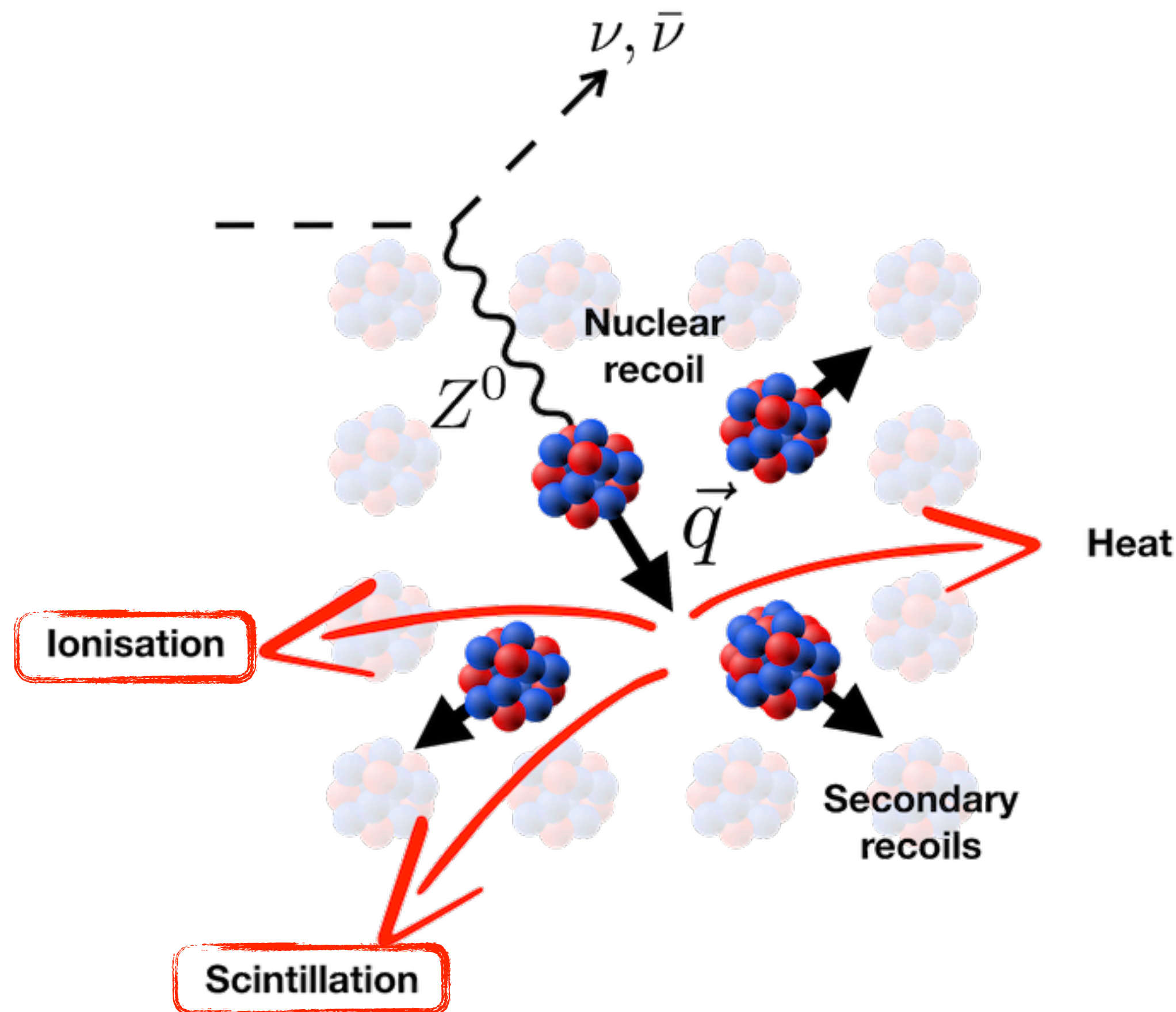
Low-energy nuclear recoils

Complementary !

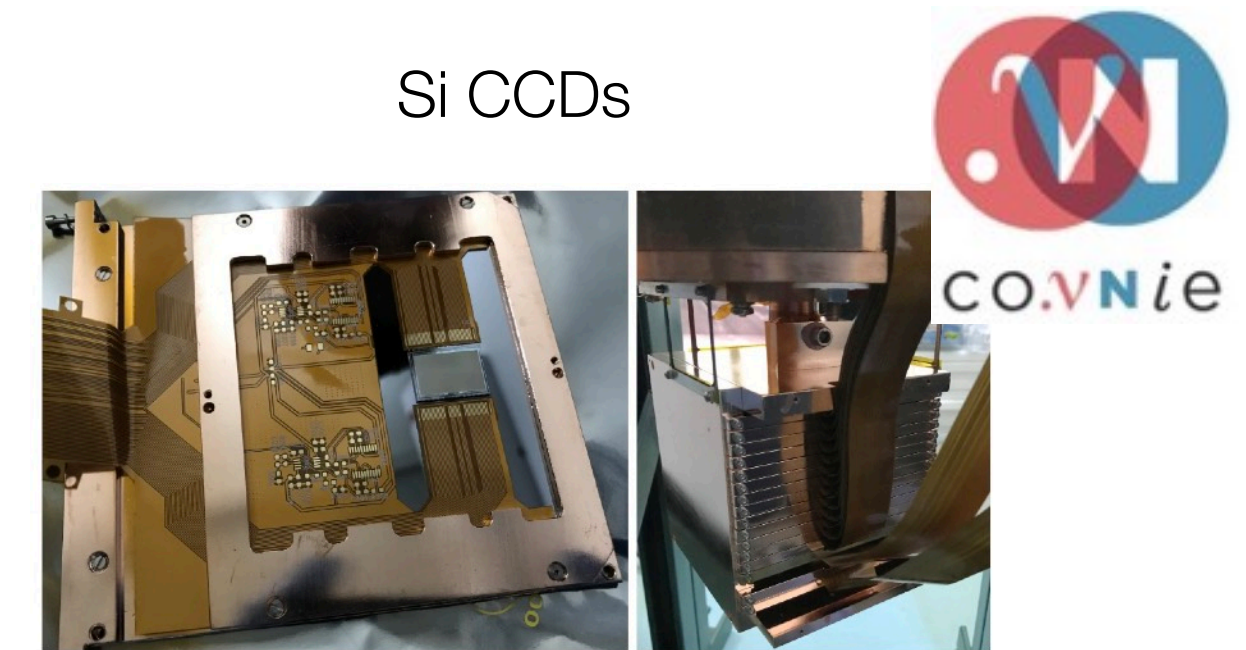
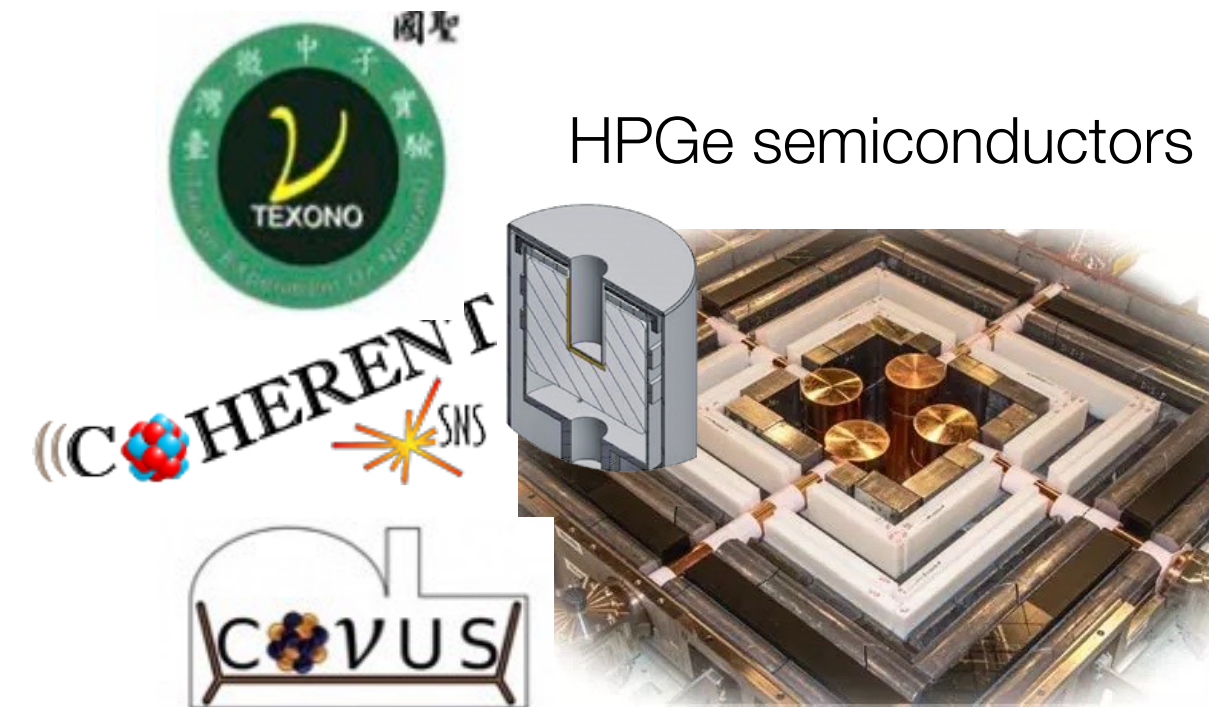
	Spallation	Reactor
Neutrino flavors	Multiple	Single (electronic)
Flux at O(10 m) [cm ⁻² s ⁻¹]	~ 10 ⁷ -10 ⁸	~ 10 ¹² -10 ¹³
Cross-section [10 ⁻⁴⁰ cm ²]	10-100	0.1-1
Mean energy [MeV] Coherence	~ 30 F(q ²) < 1	~ 3 F(q ²) ≈ 1
Recoil energies [keV]	≲ 100 keV	≲ 1 keV
Timing	Pulsed	~ steady

CEvNS Detection: Experimental Challenges

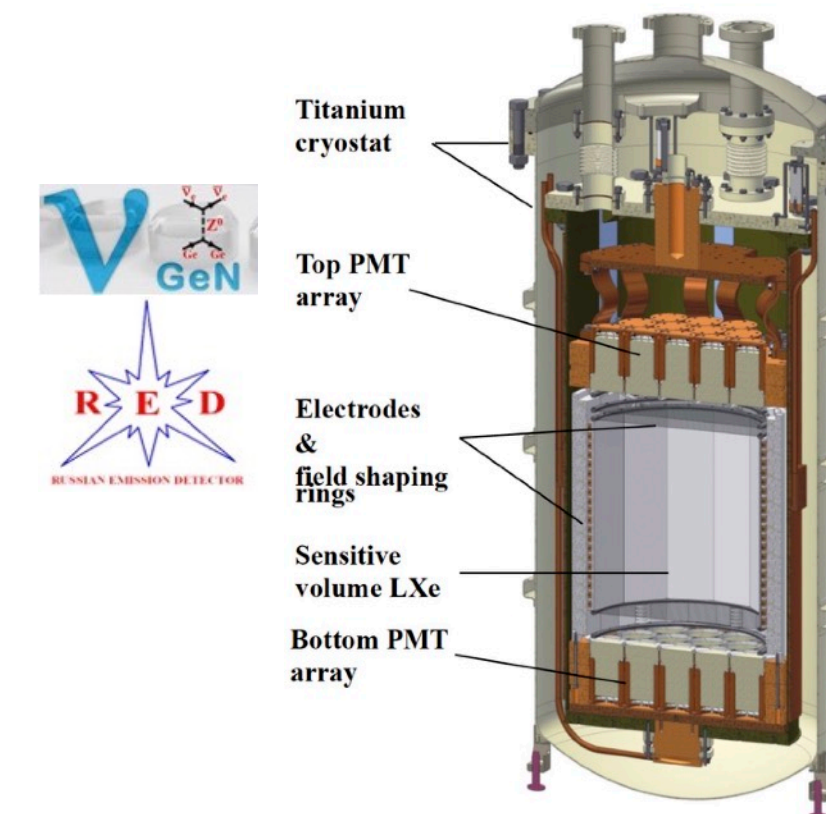
► Ultra low energy threshold detectors



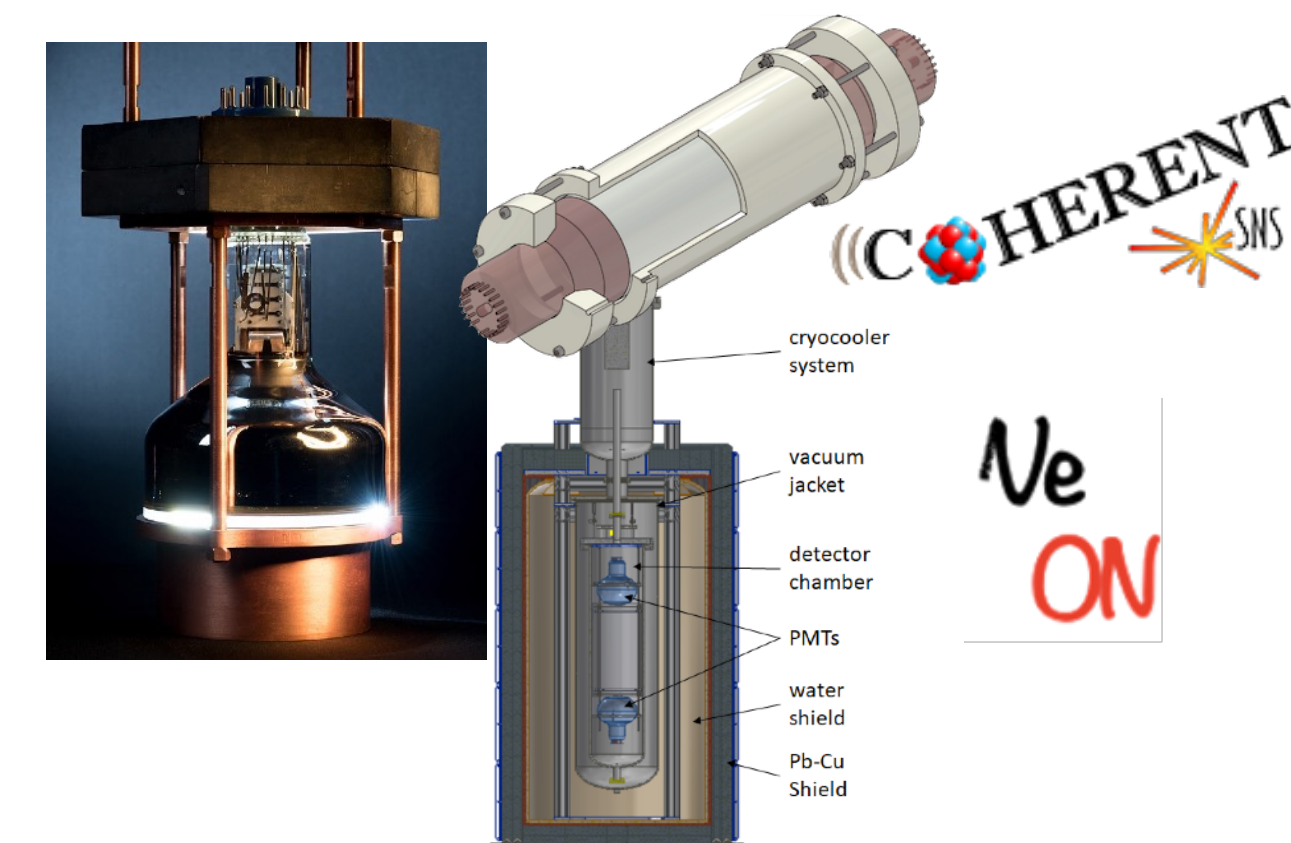
Conventional detection techniques



Dual phase noble liquid TPC

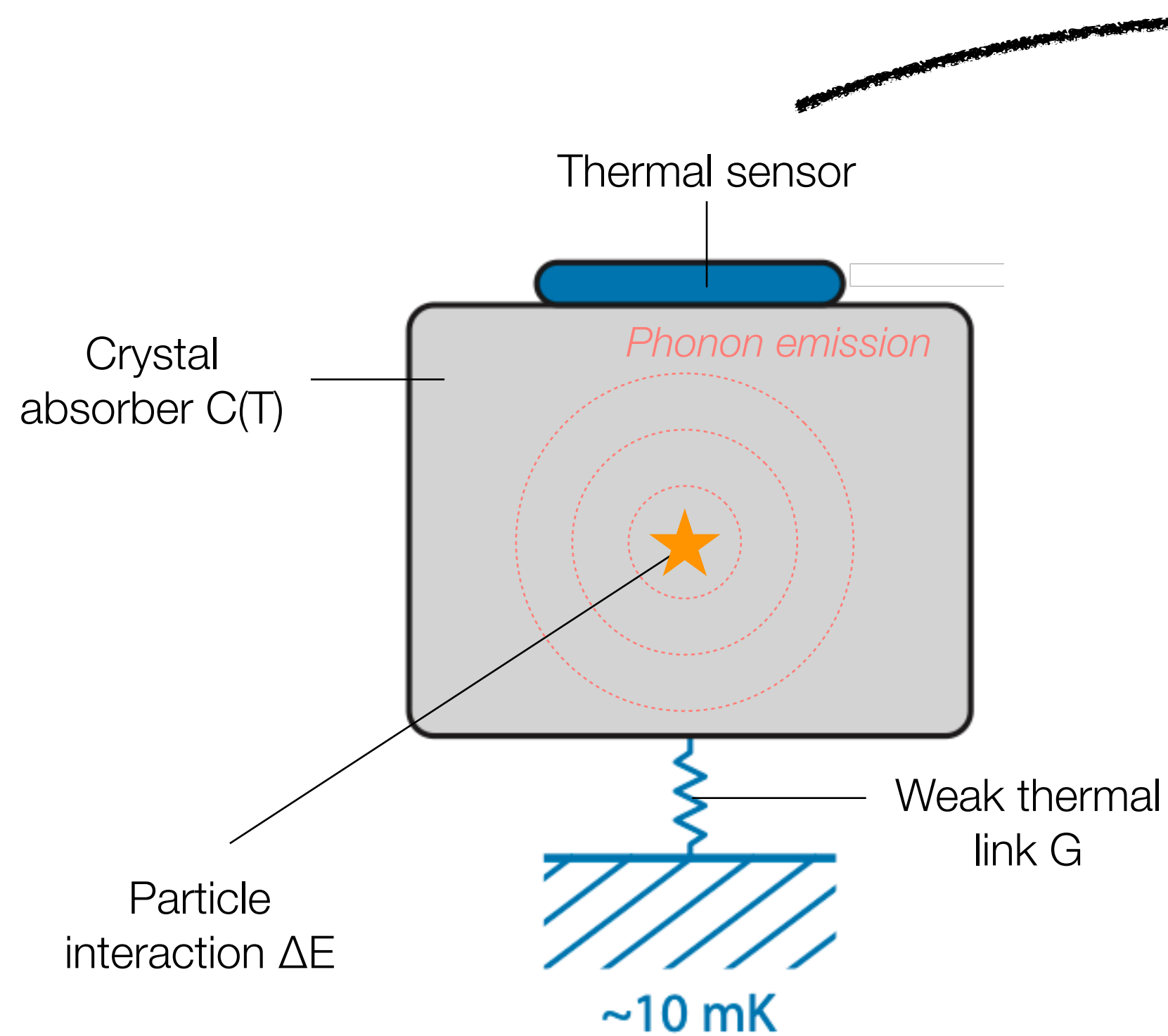


Liquid & crystal scintillators

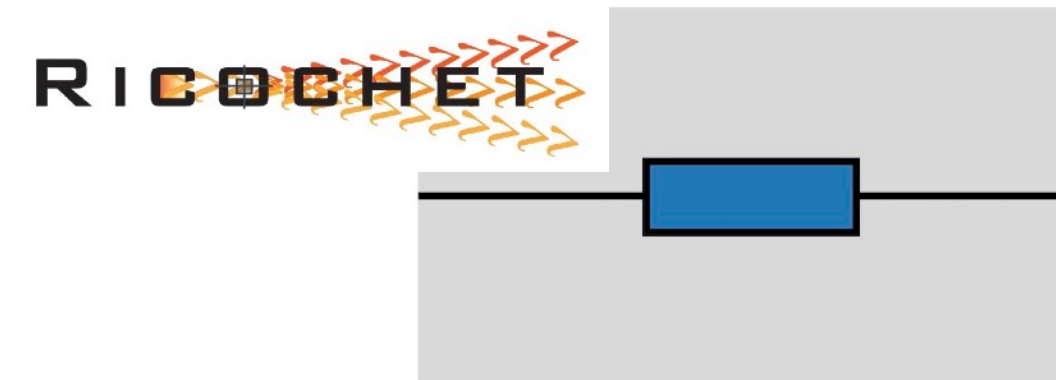


- Fundamentally limited: energy required to create a light/charge quantum $\sim O(10 \text{ eV}) \rightarrow O(1 \text{ keV})$ thresholds
- Quenching characterization issues at low recoils !

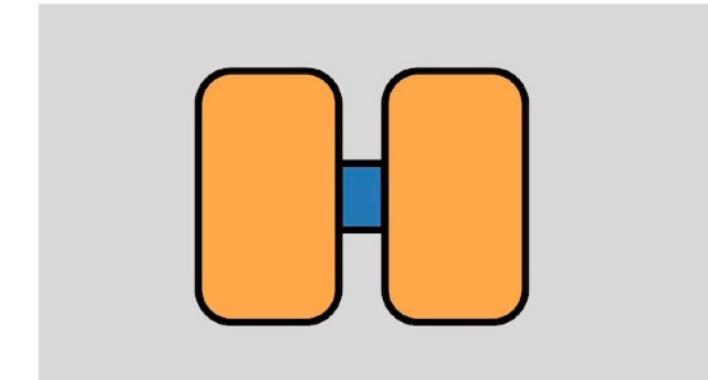
Phonon-Mediated Detectors



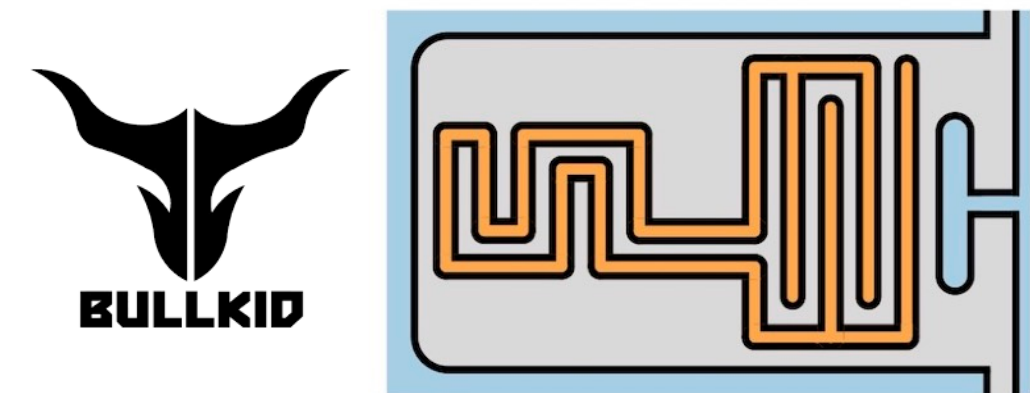
Neutron-transmutation
doped sensor (NTD)



Superconducting transition
edge sensor (TES)



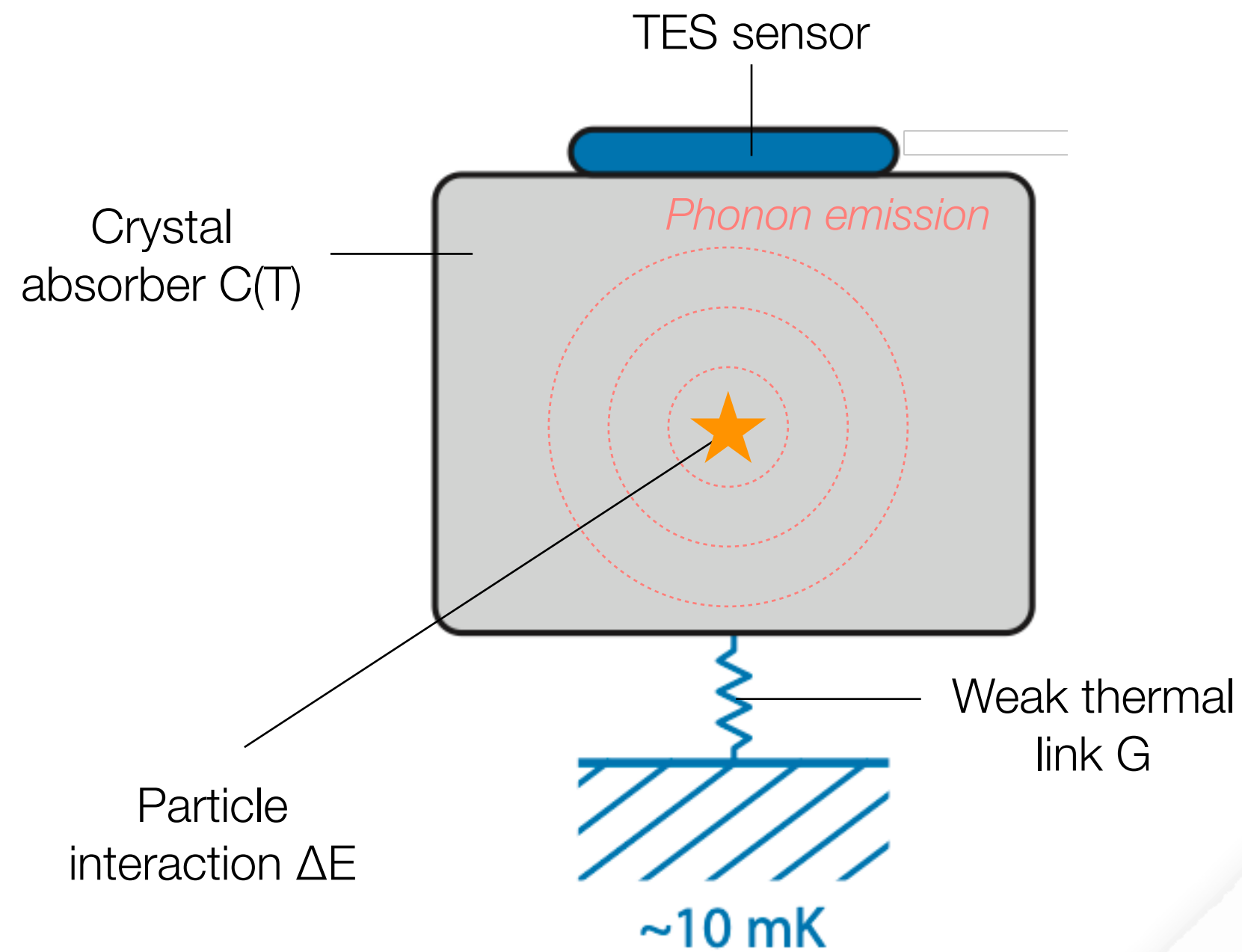
Kinetic inductance
detector (KID)



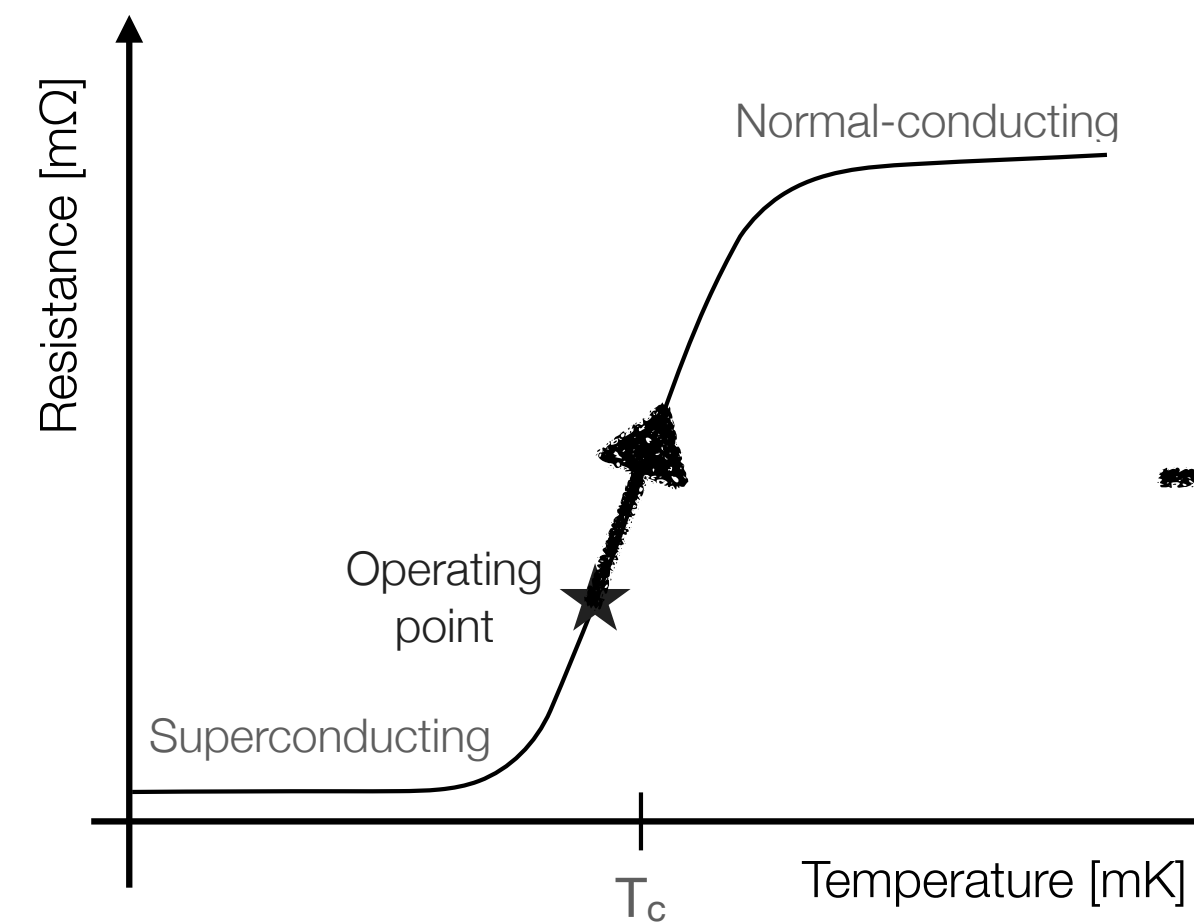
- ▶ Very low-threshold, high energy resolution, etc.
- ▶ But very slow (> 10 - 100 μ s decay time)
- ▶ Cryogenics highly constraining and challenging

O(100 eV) thresholds achieved with O(10 g) detectors $\rightarrow$ very relevant for CEvNS at reactors !

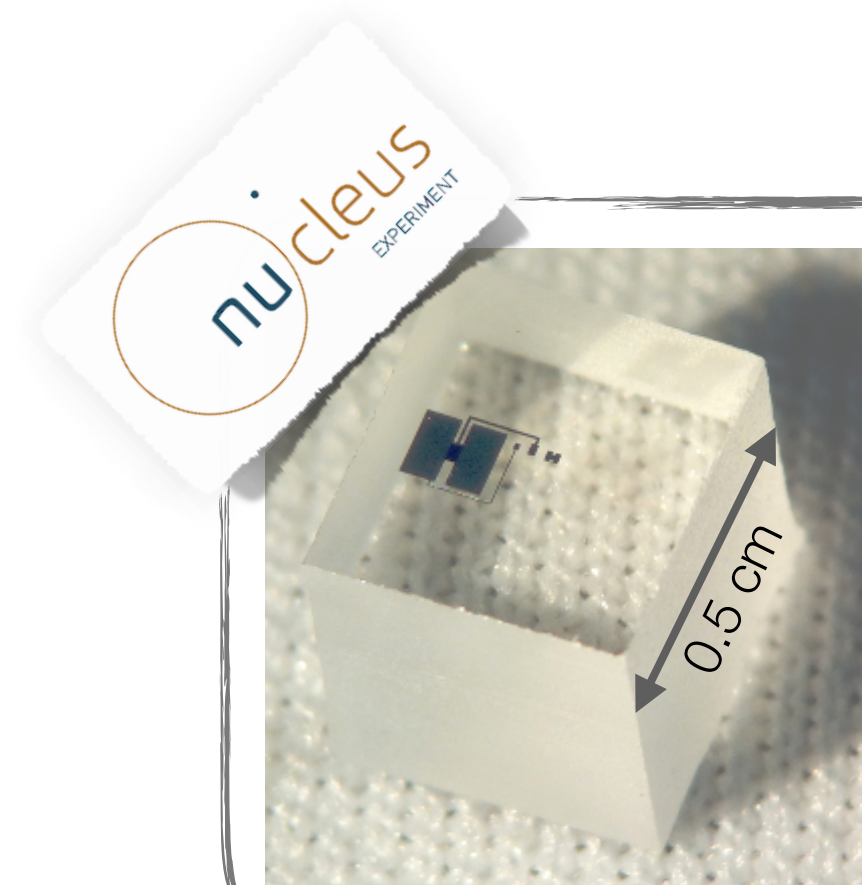
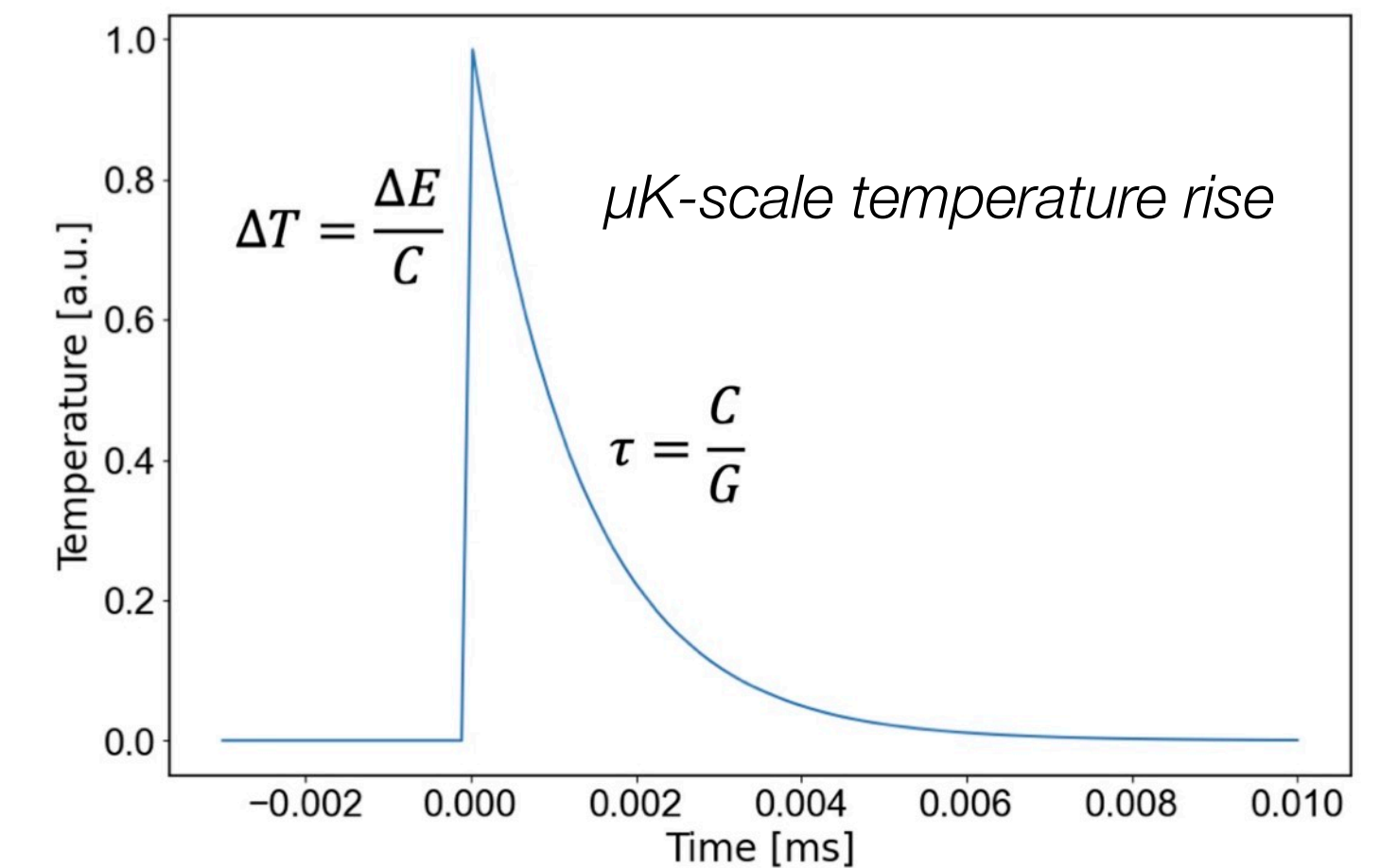
TES-based Cryogenic Detectors



TES transition curve



Simplified TES response

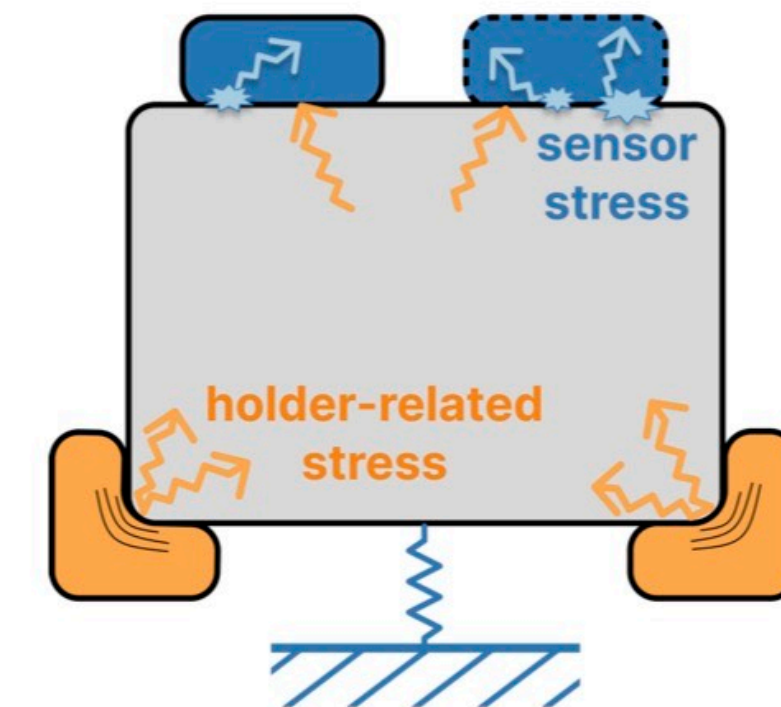
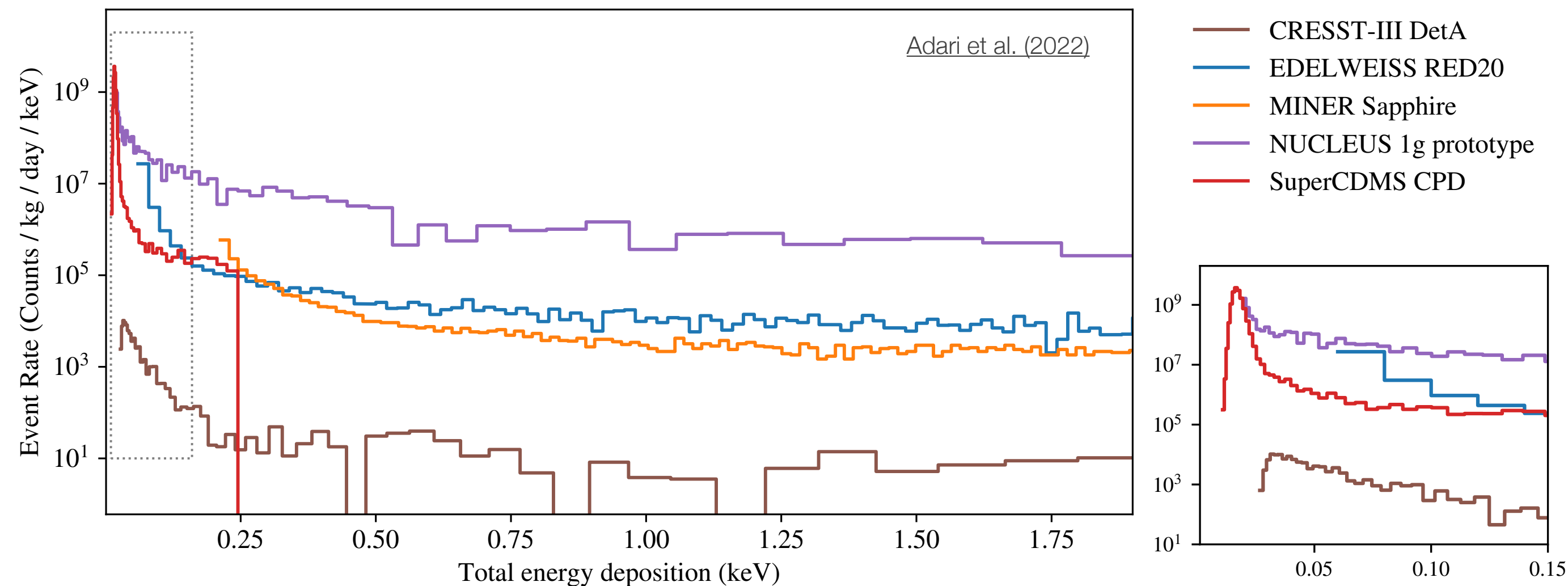


- Absorber mass set to gram scale $\rightarrow$ gain in energy threshold & time response
- Unprecedented ≤ 20 eV thresholds routinely achieved
- Insensitive to quenching effects !

Low-Energy Excess (LEE)

- ▶ Exponential rise of event rate close to threshold → severely affects searches for low-mass DM and CEvNS at reactors
- ▶ Unknown origin, likely linked to solid-state physics phenomena upon thermal cycles of detectors:
 - **External mechanical stress** effects at crystal-holder and crystal-TES film interfaces
 - Relaxation of internal stress energy: **rearrangement of crystalline defects** such as dislocations

LEE close to threshold in several cryogenic detection experiments



Active R&D in the cryogenic detector community
(see, e.g., EXCESS workshop series)

- Not particle-related & non-ionizing
- Not scaling with mass ?
- Time-dependent decay

The NUCLEUS Experiment

Overview and Status

Chooz nuclear power station

- ▶ 2 x N₄ pressurized water reactors (4.25 GW_{th})
- ▶ Former host of the CHOOZ and Double Chooz experiments

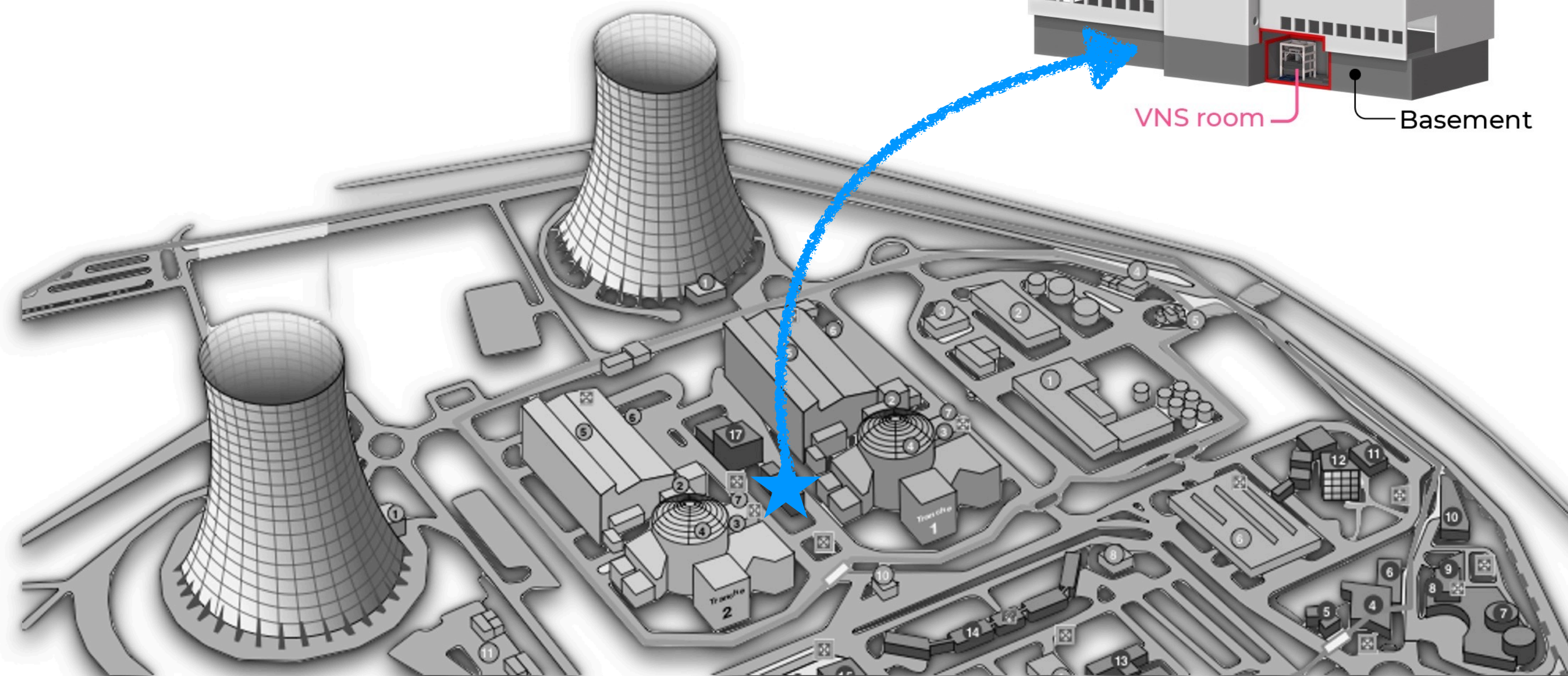
Very Near Site (VNS)

- ▶ $D_{\text{eff}} \sim 59 \text{ m}$
- ▶ $\Phi_\nu \sim 2.2 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$
- ▶ 3 m.w.e overburden (challenging !)



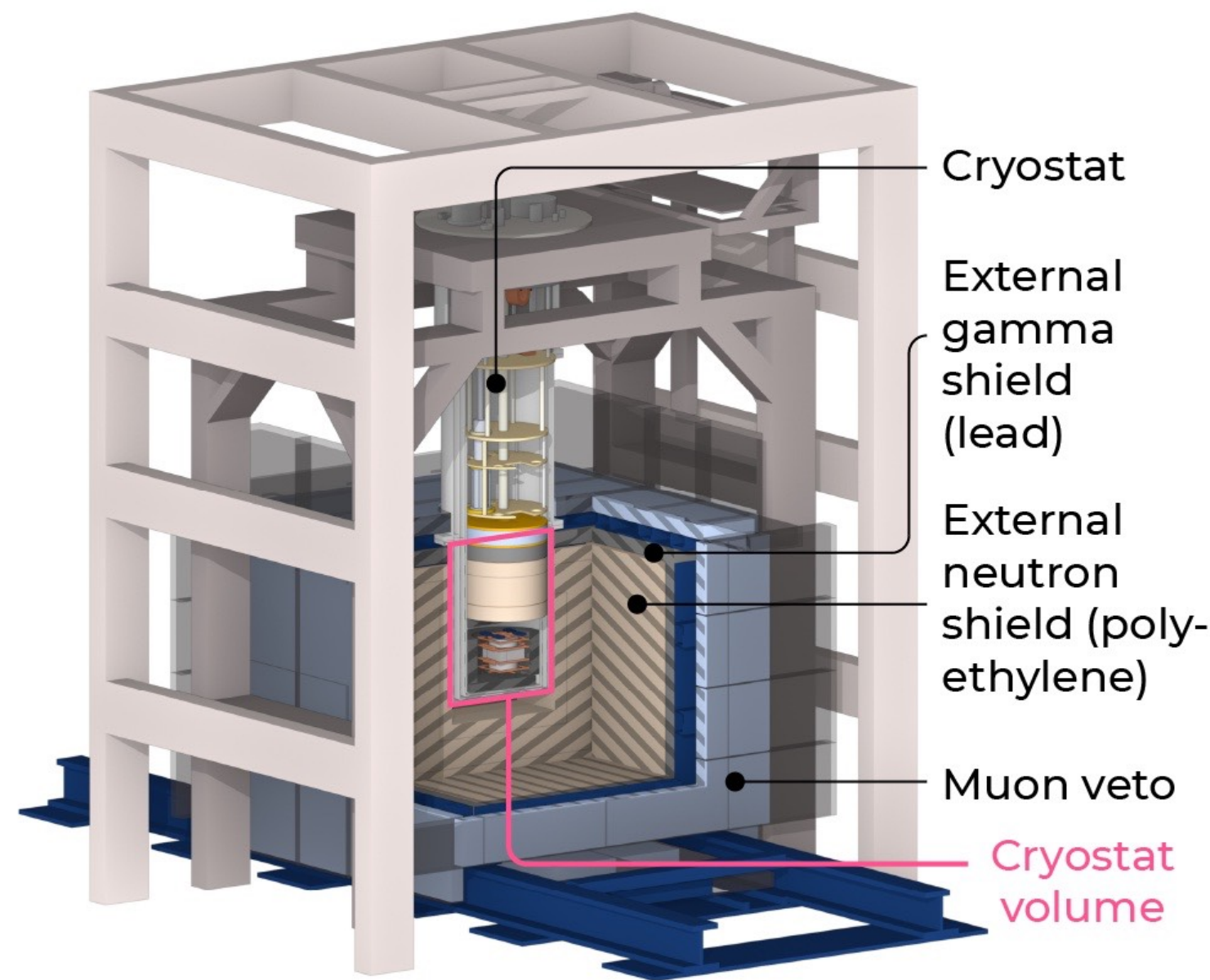
VNS room

Basement



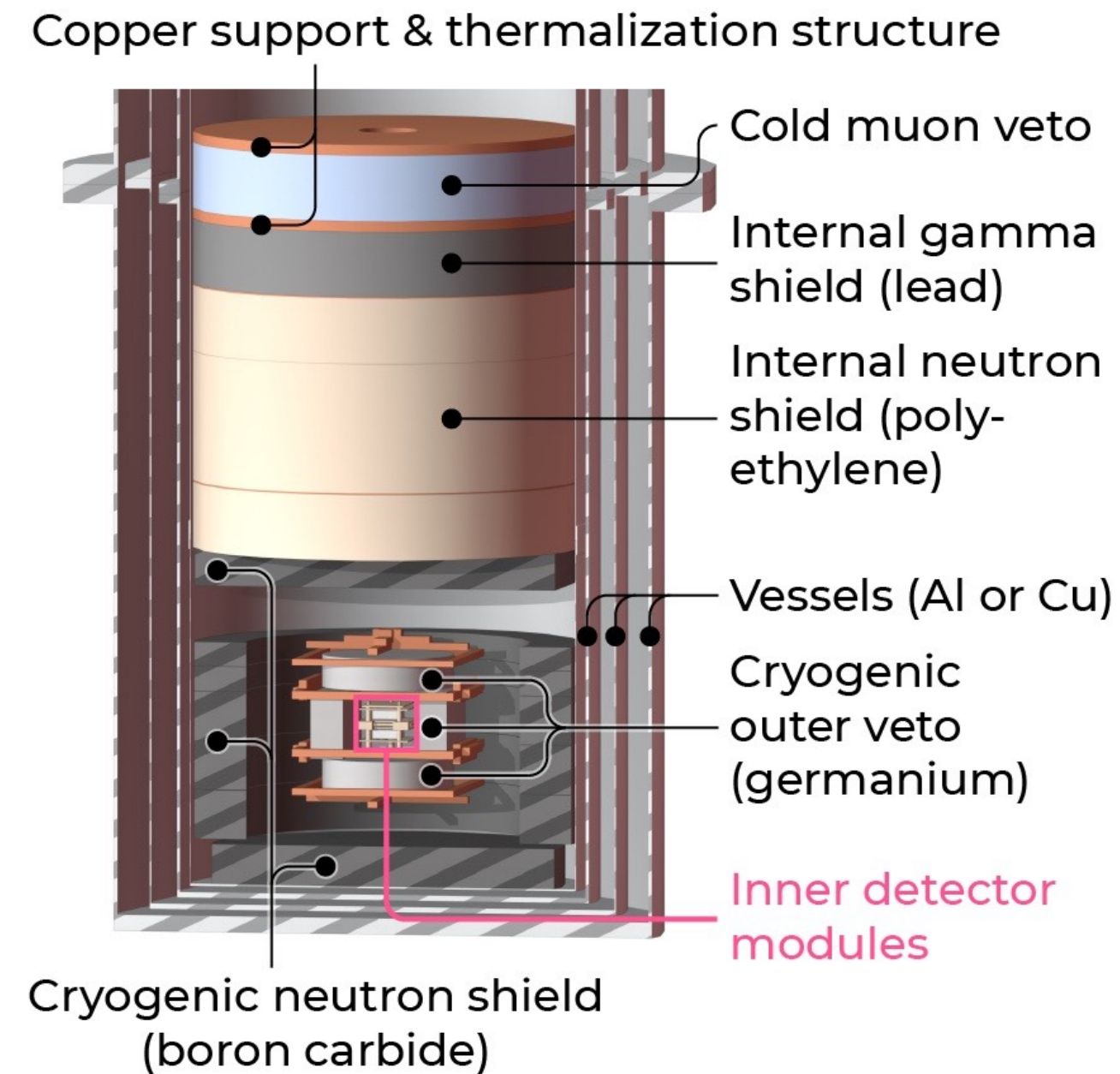
A highly sophisticated (cryogenic) design...

Experimental setup



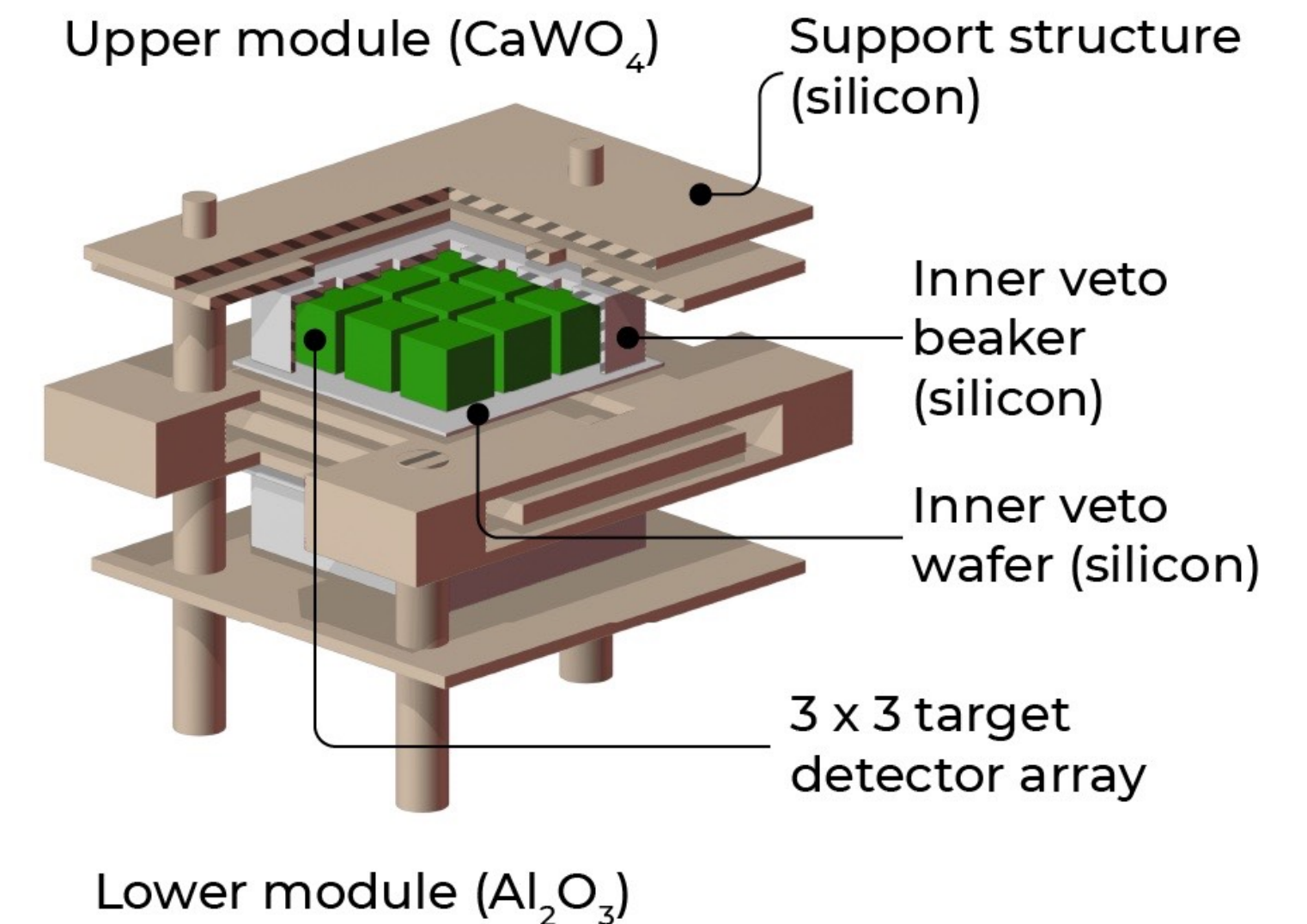
- Cryogen-free dry dilution refrigerator (DDR)
- Vibration decoupling system (VDS)
- External active & passive shieldings

Cryostat volume (10 mK)



- Cryogenic passive & active shields
- TES-based cryogenic detectors

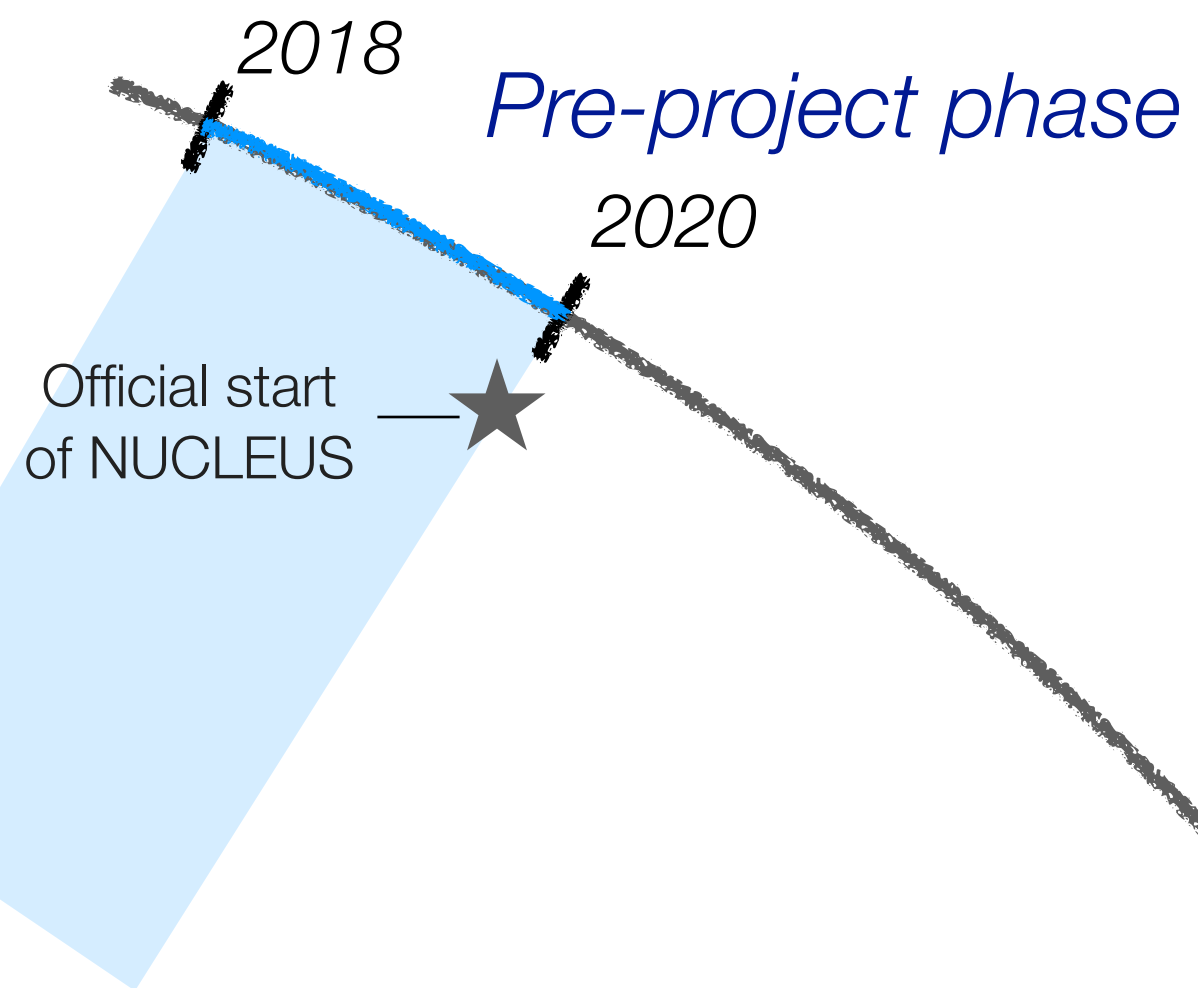
TES-based cryogenic detectors



- CaWO_4 (6.8 g) & Al_2O_3 (4.5 g) arrays as ν detectors
- Instrumented holder (inner veto) to mitigate LEE

Project Timeline & Contributions from CEA/Irfu

DPhP
DIS

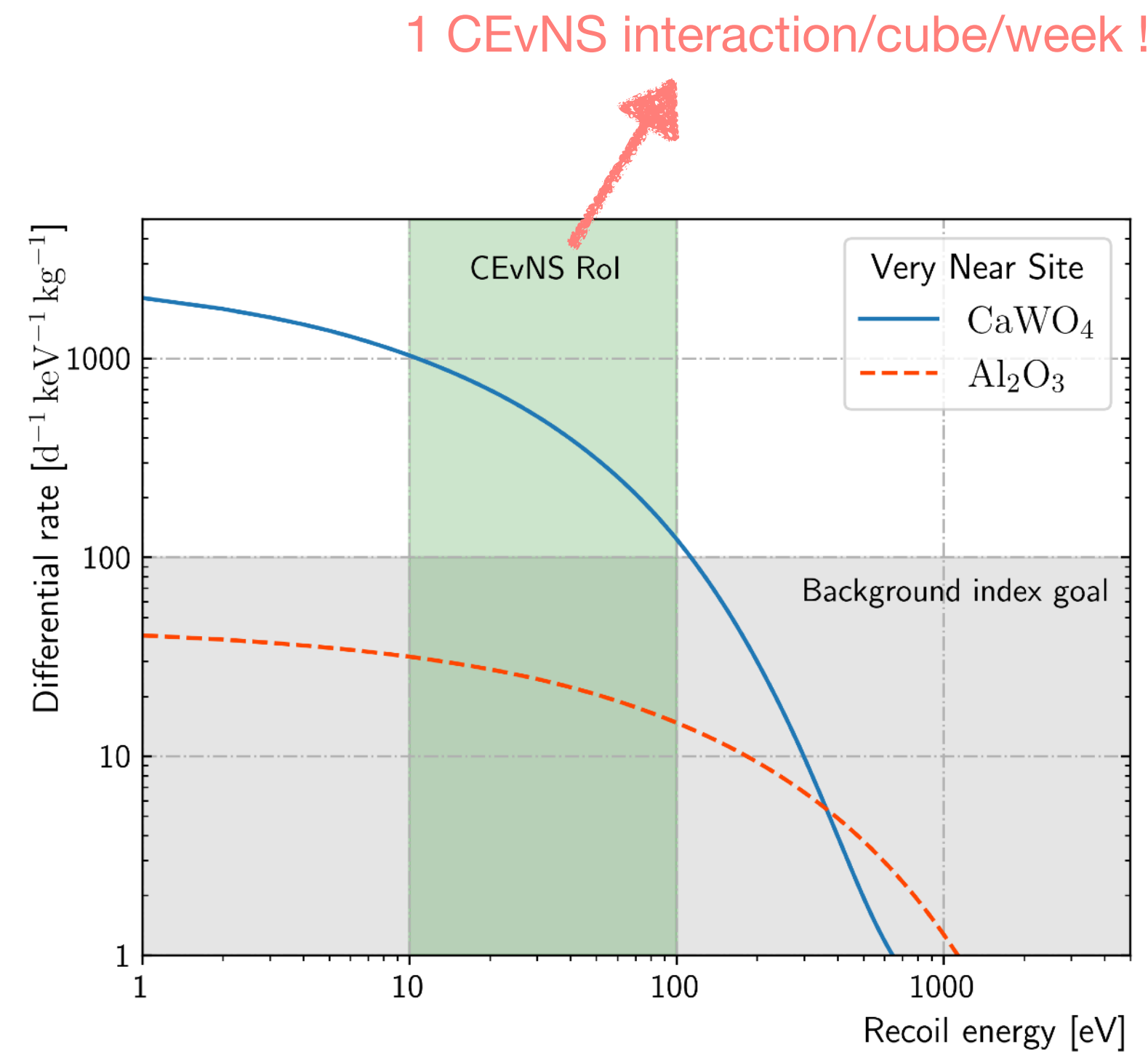


- Identification of Very Near Site
- Preliminary background measurements
- Crude sensitivity estimates
- Formation of collaboration & funding requests

Surface μ measurements (2018)



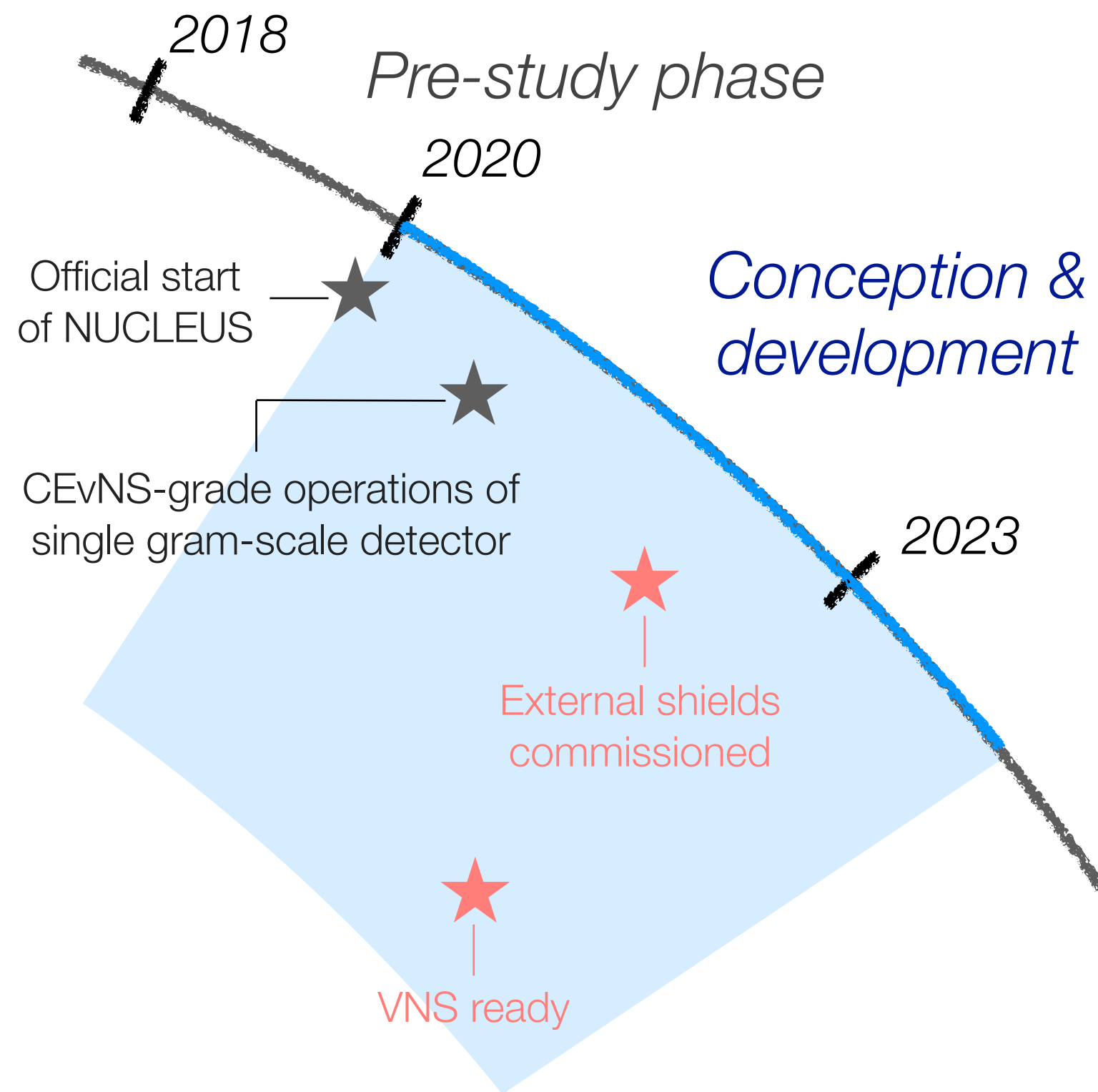
Collaboration steering
Technical coordination



[EPJC 2019]

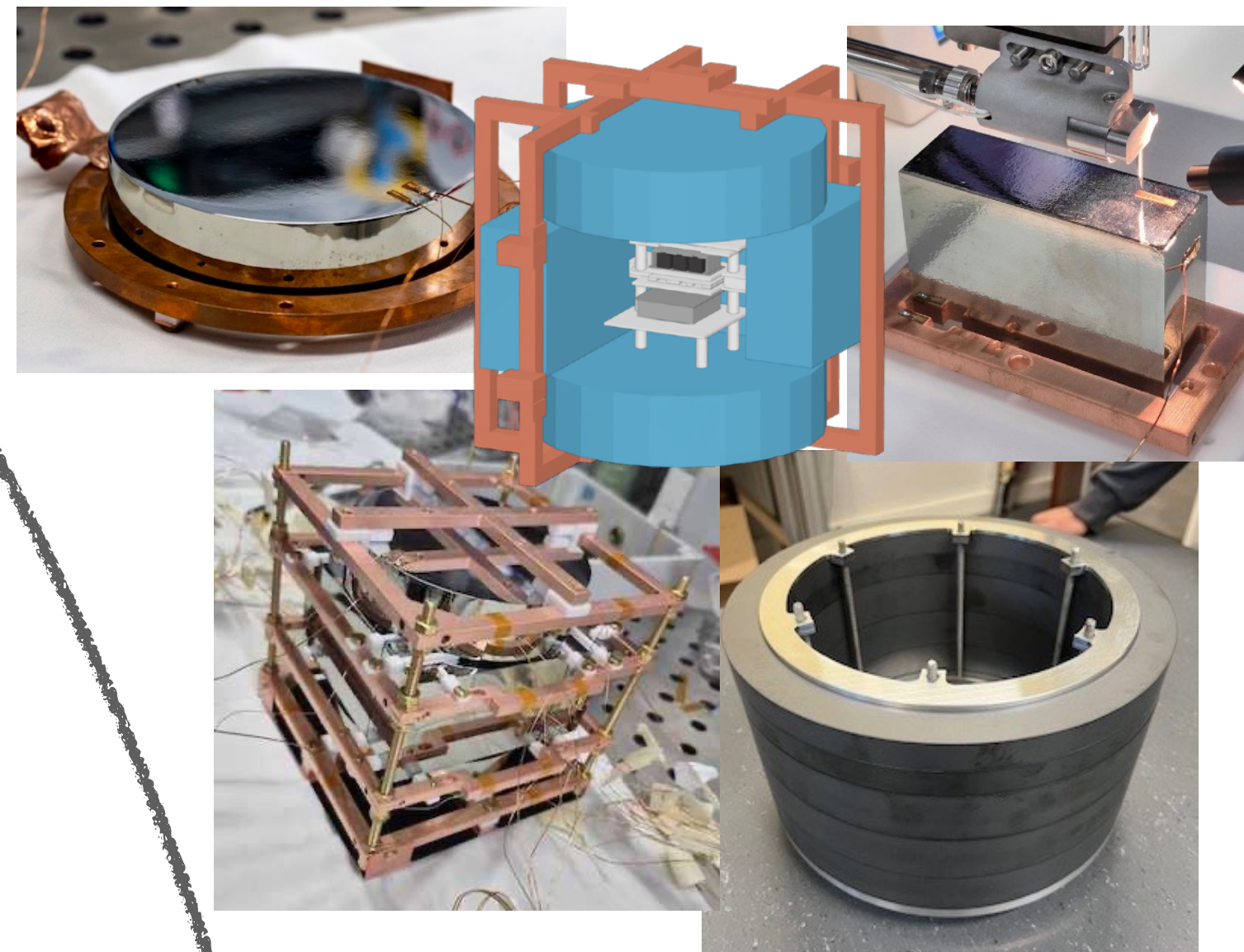
Project Timeline & Contributions from CEA/Irfu

DPHP
DPhN
DEDIP
DIS

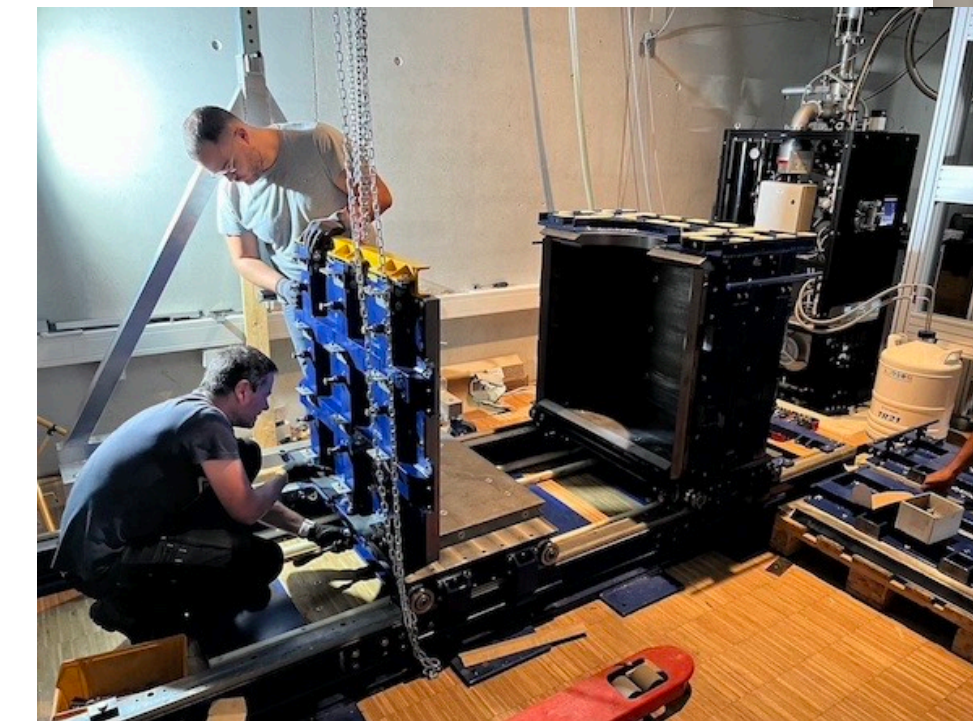


- ▶ Experimental site preparation
- ▶ Design of shielding strategy + particle background modeling
 - ◉ Delivery of external shielding + μ veto
 - ◉ Development of cryogenic outer veto (COV) & B₄C cryogenic shield

COV and B₄C developments



Shielding delivered in Munich

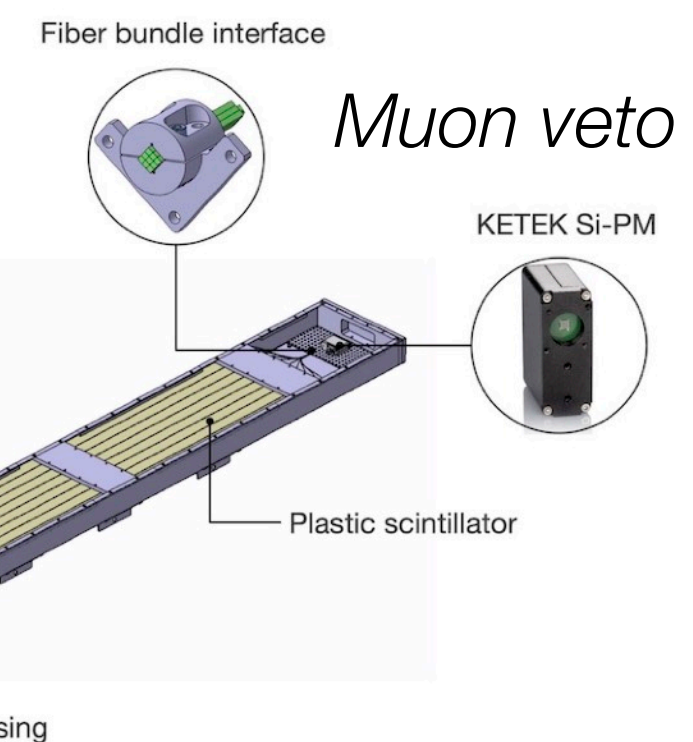


VNS ready



Collaboration steering
Technical coordination

[JINST 2022]
R. Rogly (PhD, 2022)



Particle Background Modeling

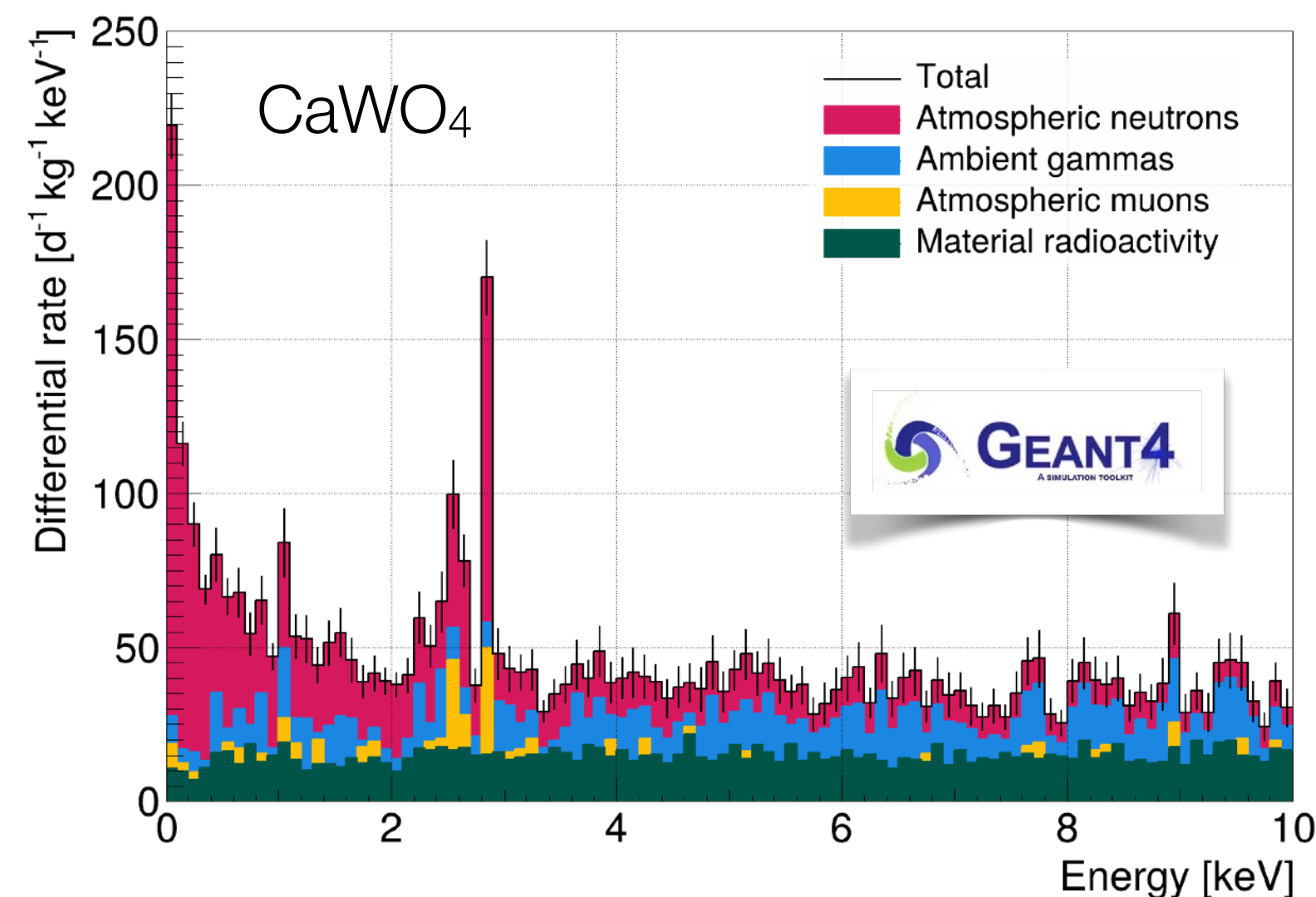
DPhP
DIS

- On-site background characterization campaigns (ambient gammas, cosmic ray-induced neutrons & muons)
- Full Geant4 shielding design optimization
- Comprehensive modeling of particle backgrounds

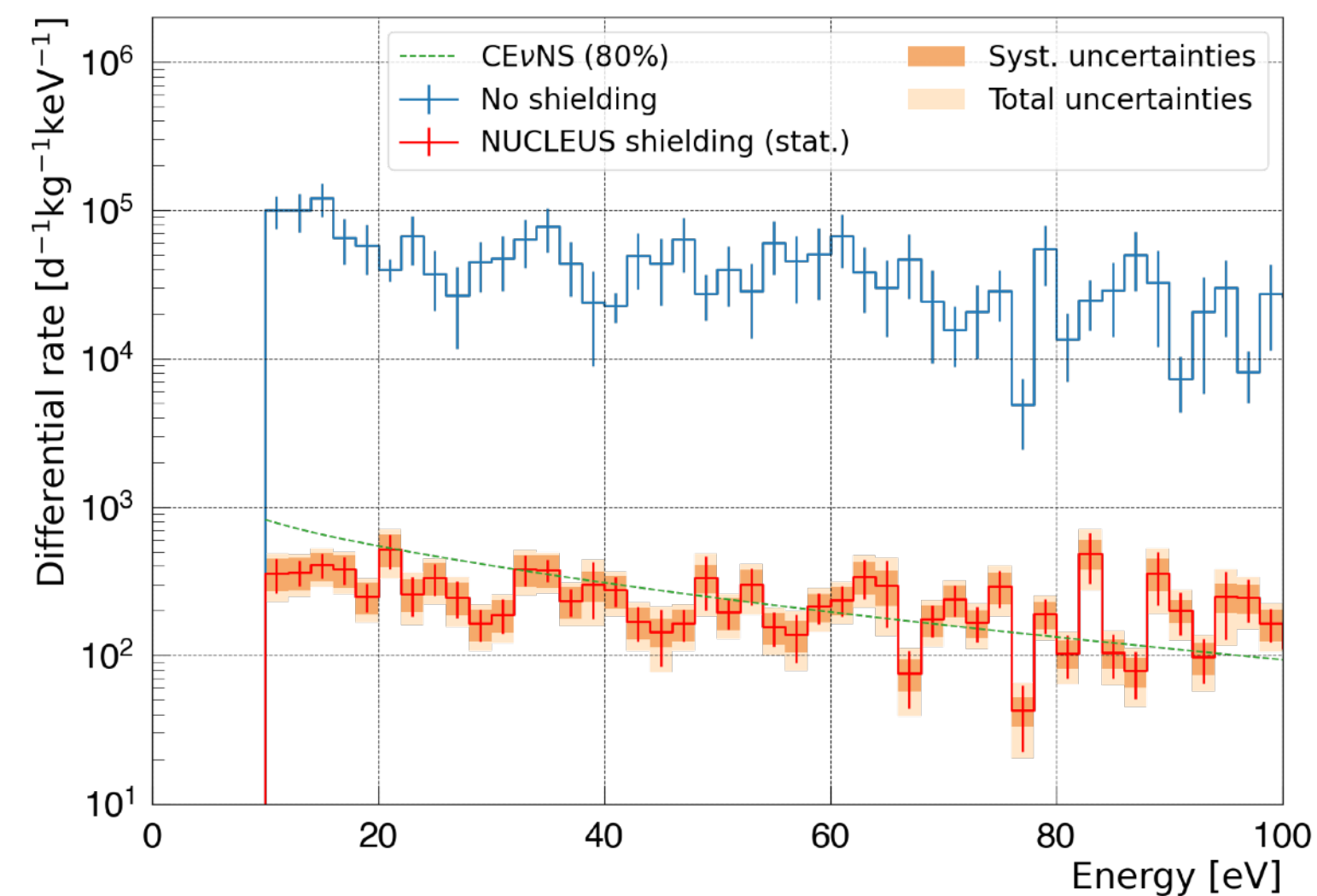
C. Goupy (PhD, 2024)
[EPJC 2026a]



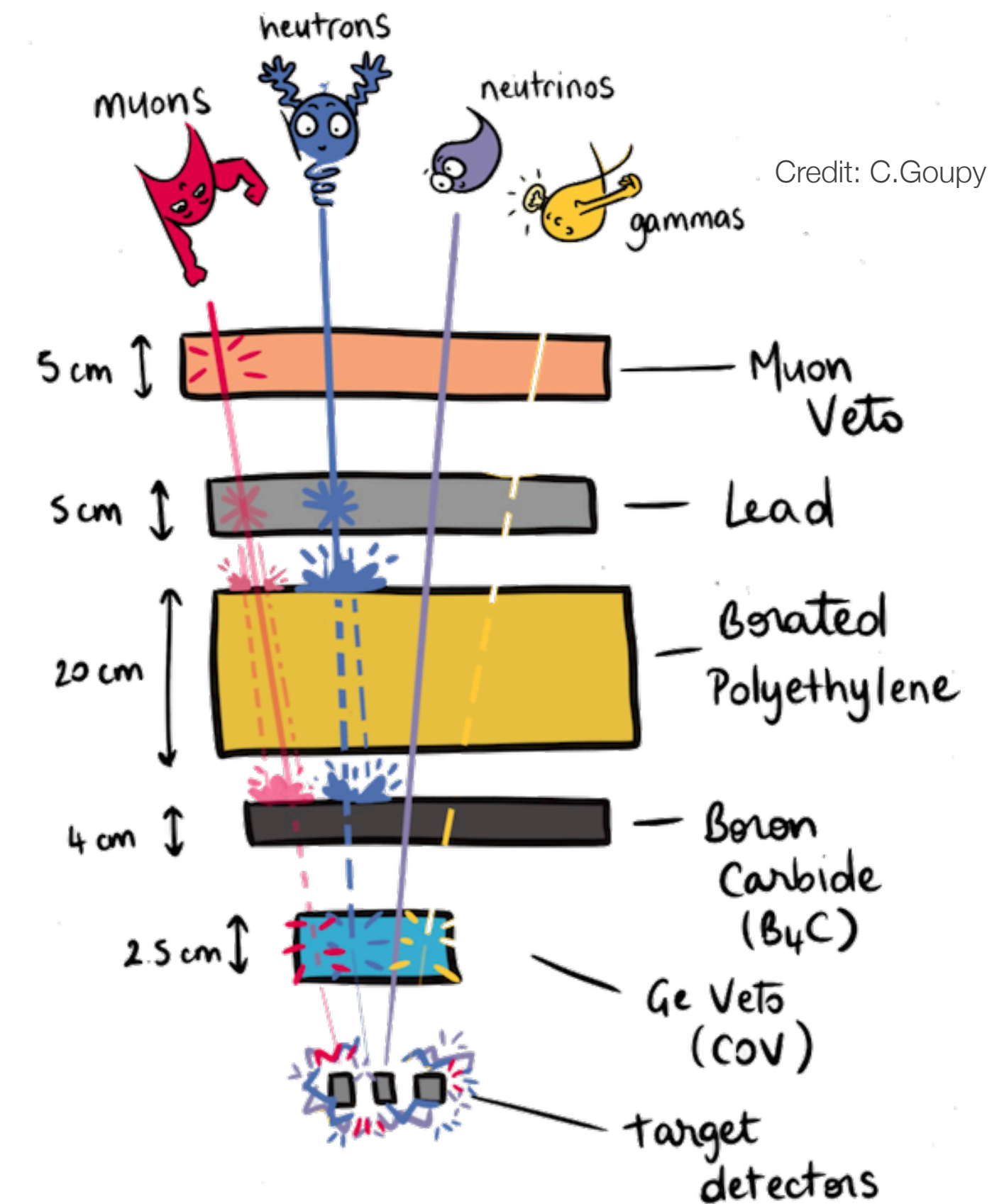
Breakdown of particle background contributions



Expected $S/B \geq 1$ in CEvNS RoI



Multi-layered (and sophisticated) passive and active design

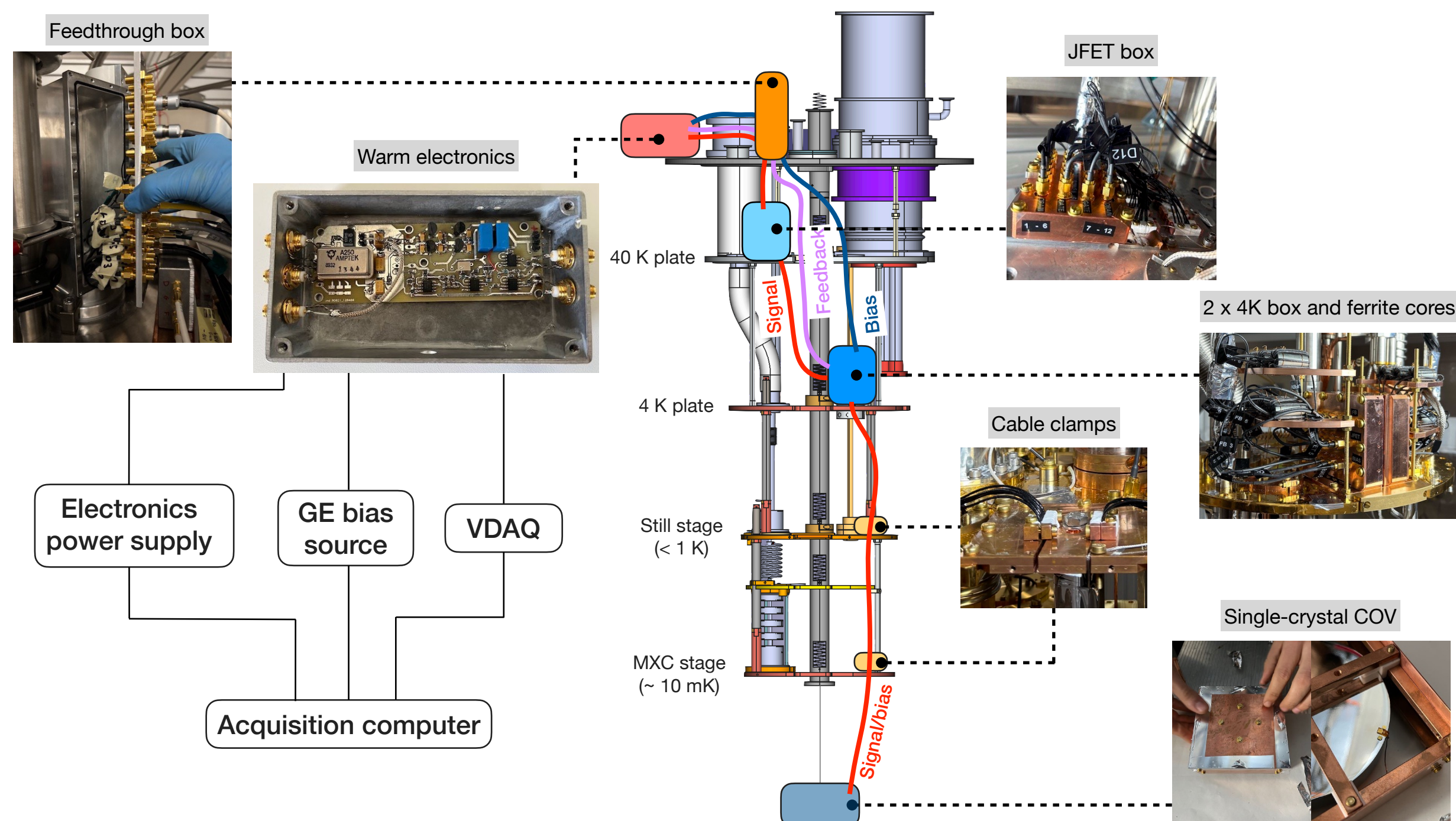


Cryogenic Outer Veto (COV)

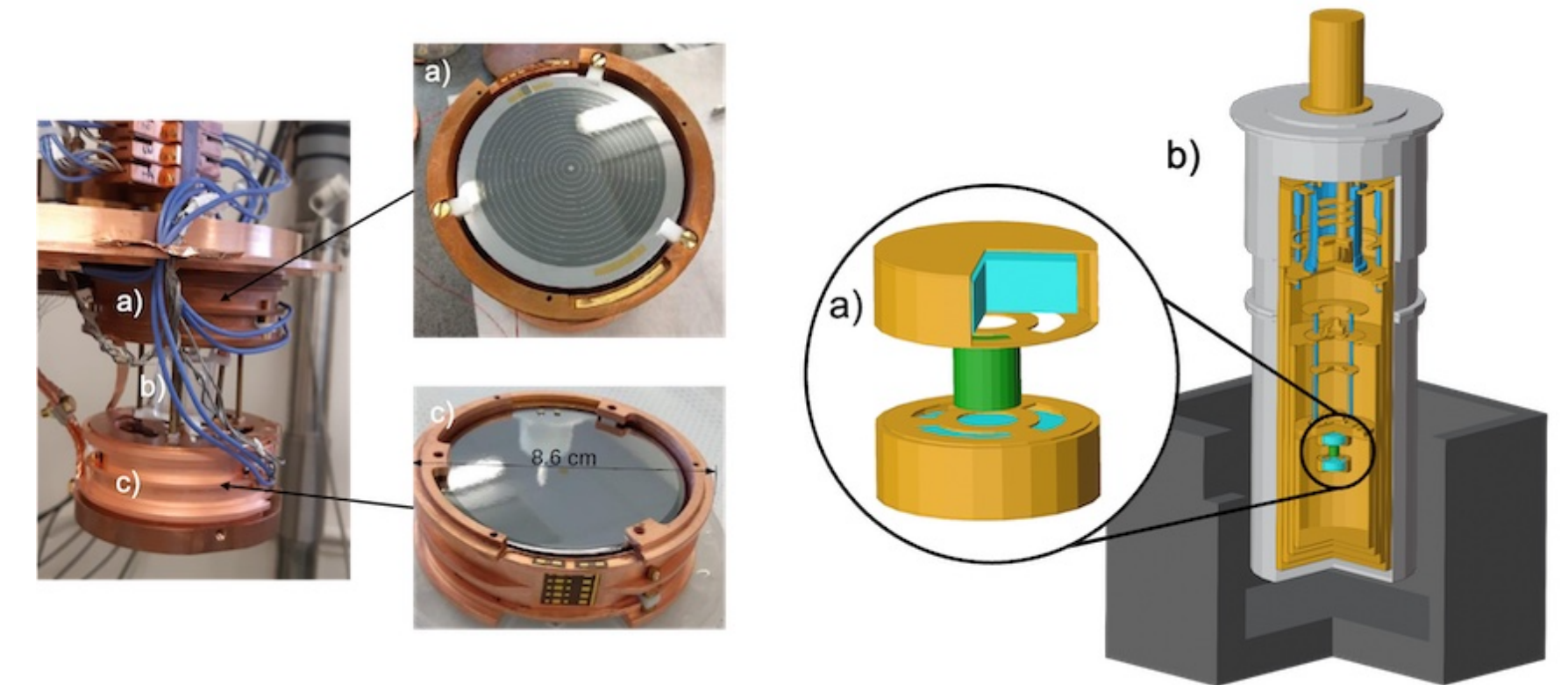
DPhP
(Support from IJCLab)

- Concept & proof-of-principle
- Crystal procurement & preparation
- Integration work in NUCLEUS cryostat at TUM

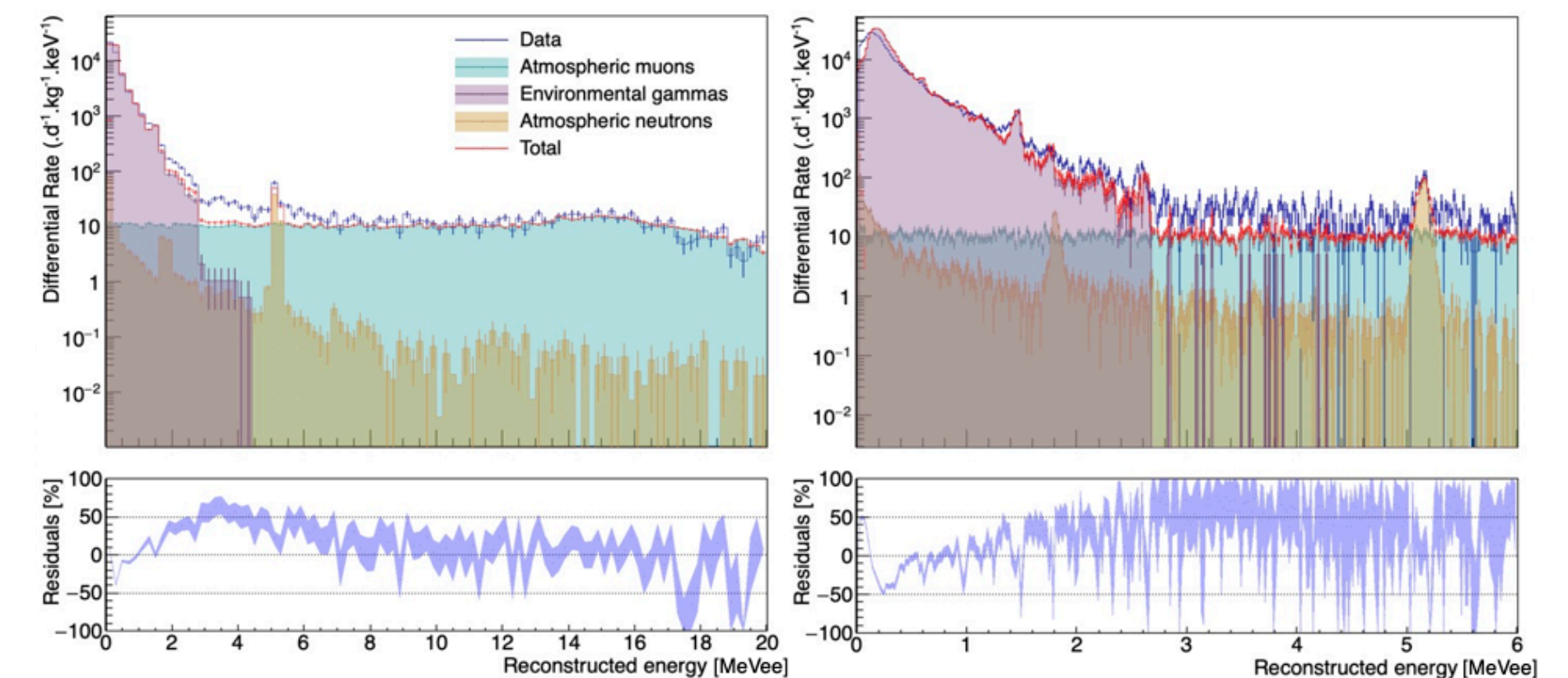
*First integration of COV in NUCLEUS' cryostat at TUM (2023)
EDELWEISS-style ionization readout*



Prototyping work: Li_2WO_4 bolometer sandwiched between two HPGe



*Full data-MC comparison validating particle surface
background modeling*



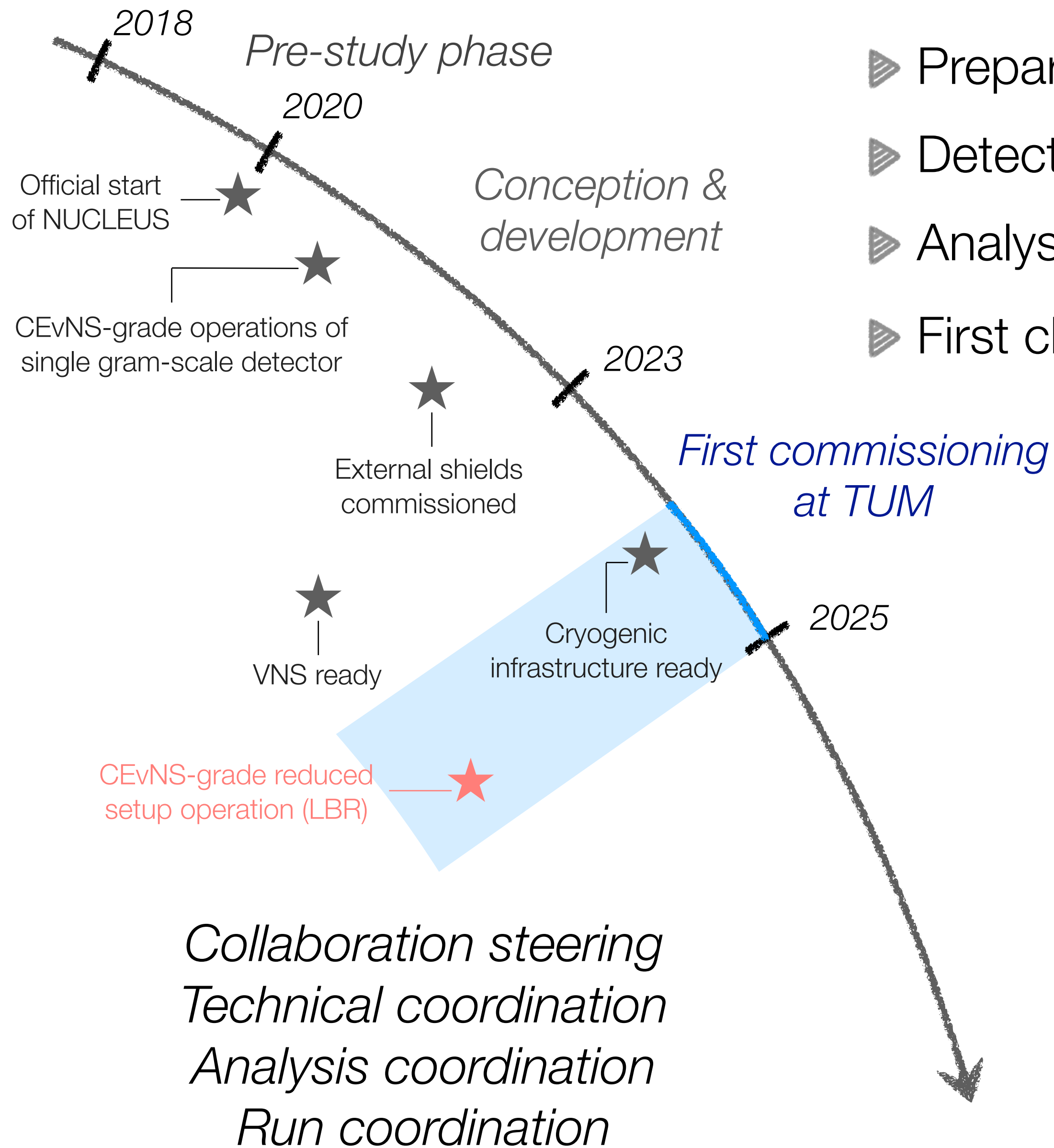
B. Mauri (PhD, 2022)

[NIM A 2024]

C. Goupy (PhD, 2024)

Project Timeline & Contributions from CEA/Irfu

DPH
DPHN
DEDIP

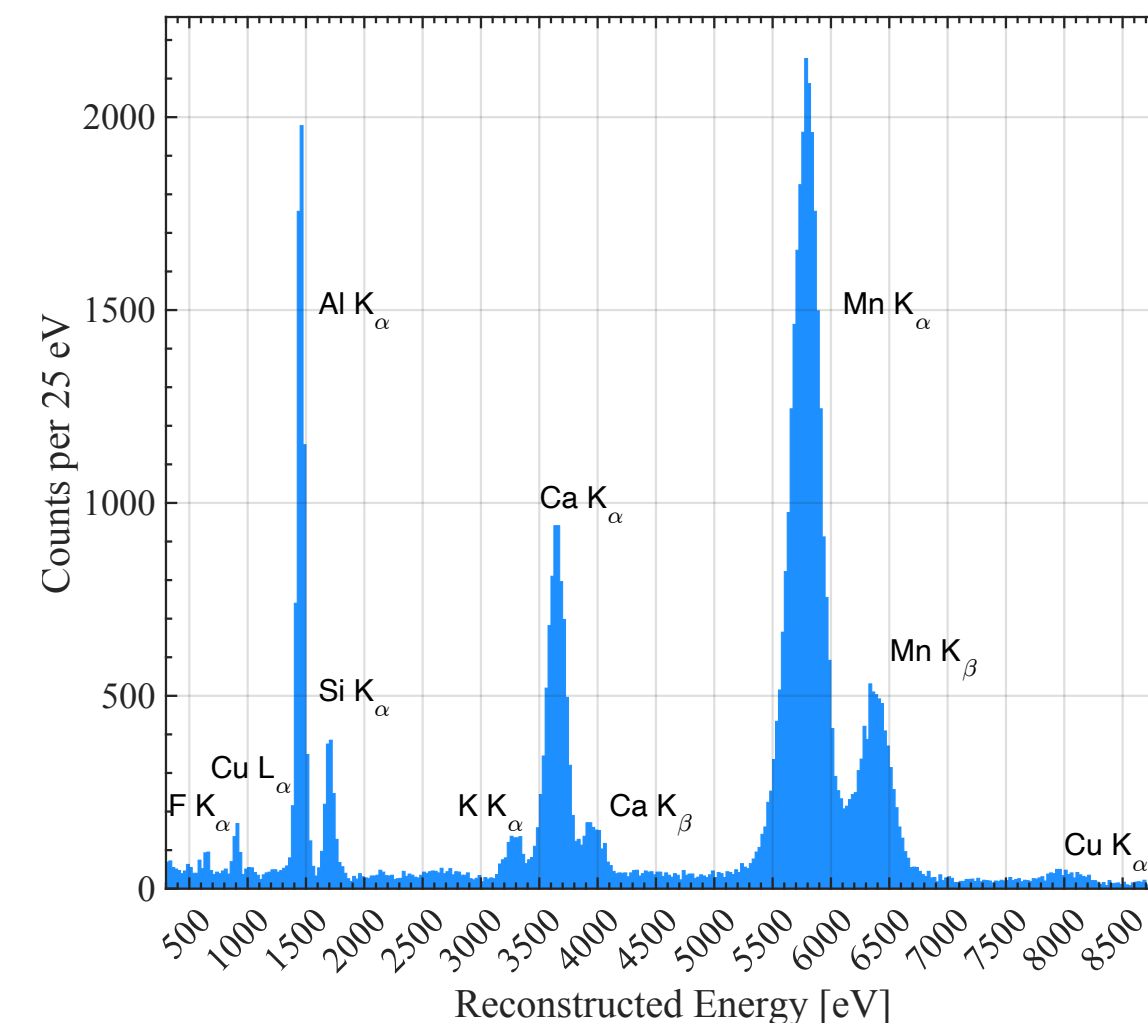


- Preparation & execution of the *Long Background Run* (LBR)
- Detector calibration, time & energy response studies
- Analysis & simulation of data, first validation of particle backgrounds
- First characterization of LEE

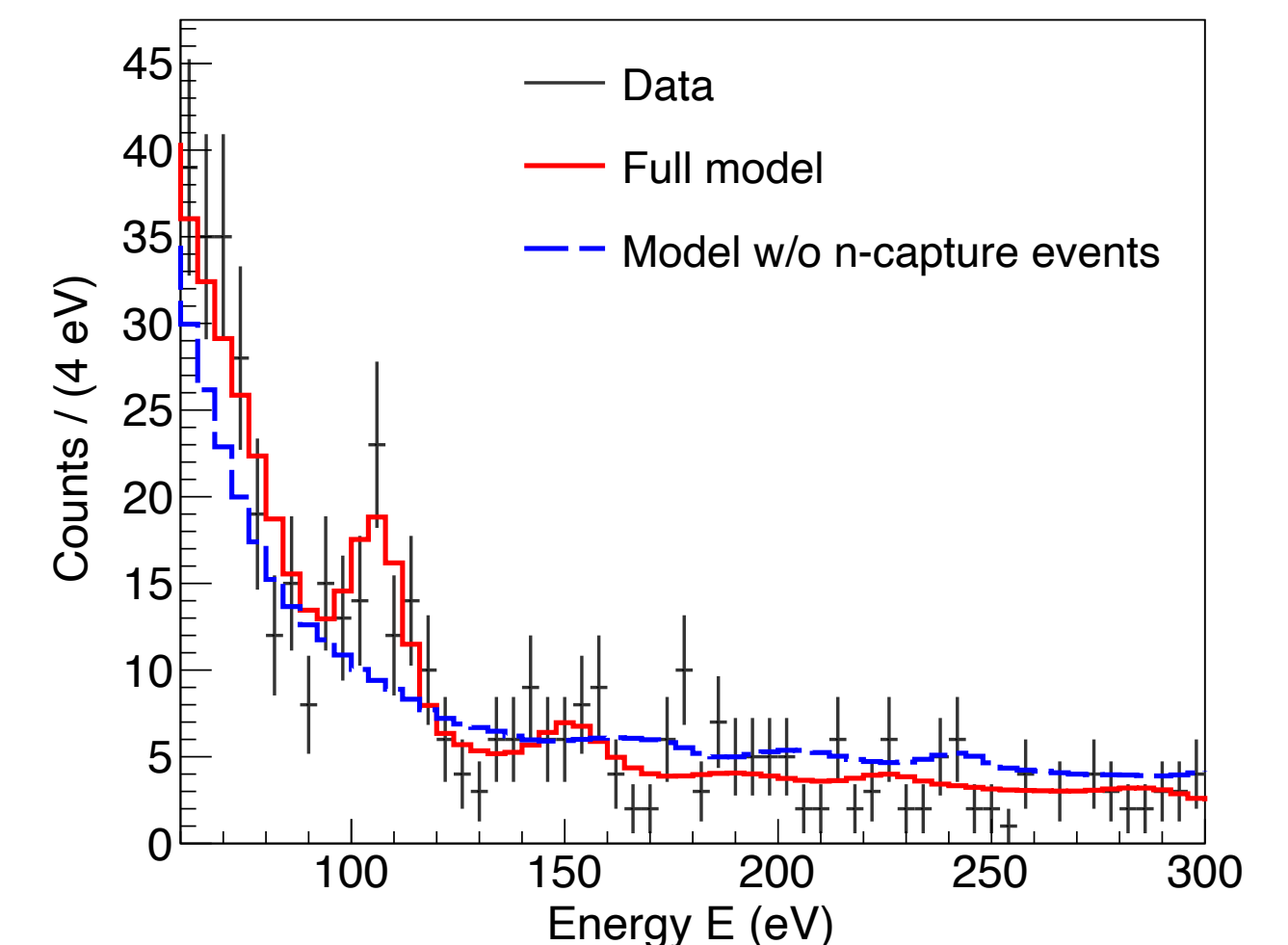
[PRL 2023]

[JLTP 2025]

Low-energy X-ray source calibration



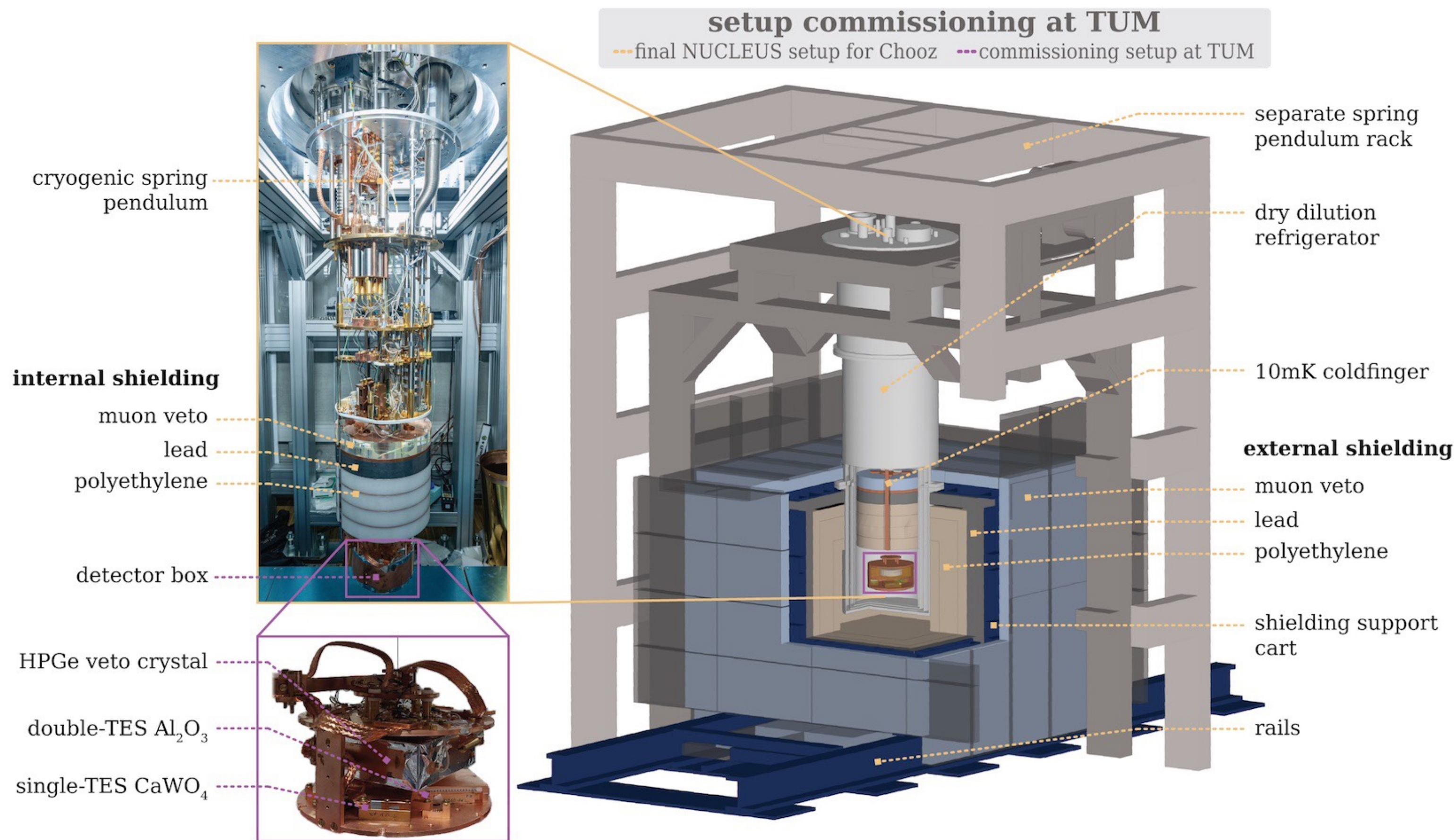
Demonstration of direct nuclear recoil calibration (CRAB)



First Commissioning at TUM

DPhP
DPhN

Long Background Run (2024)



- ▶ Reduced version of cryogenic detector module
- ▶ Simultaneous operation of all sub-systems
- ▶ Prolonged data acquisition under near-VNS conditions

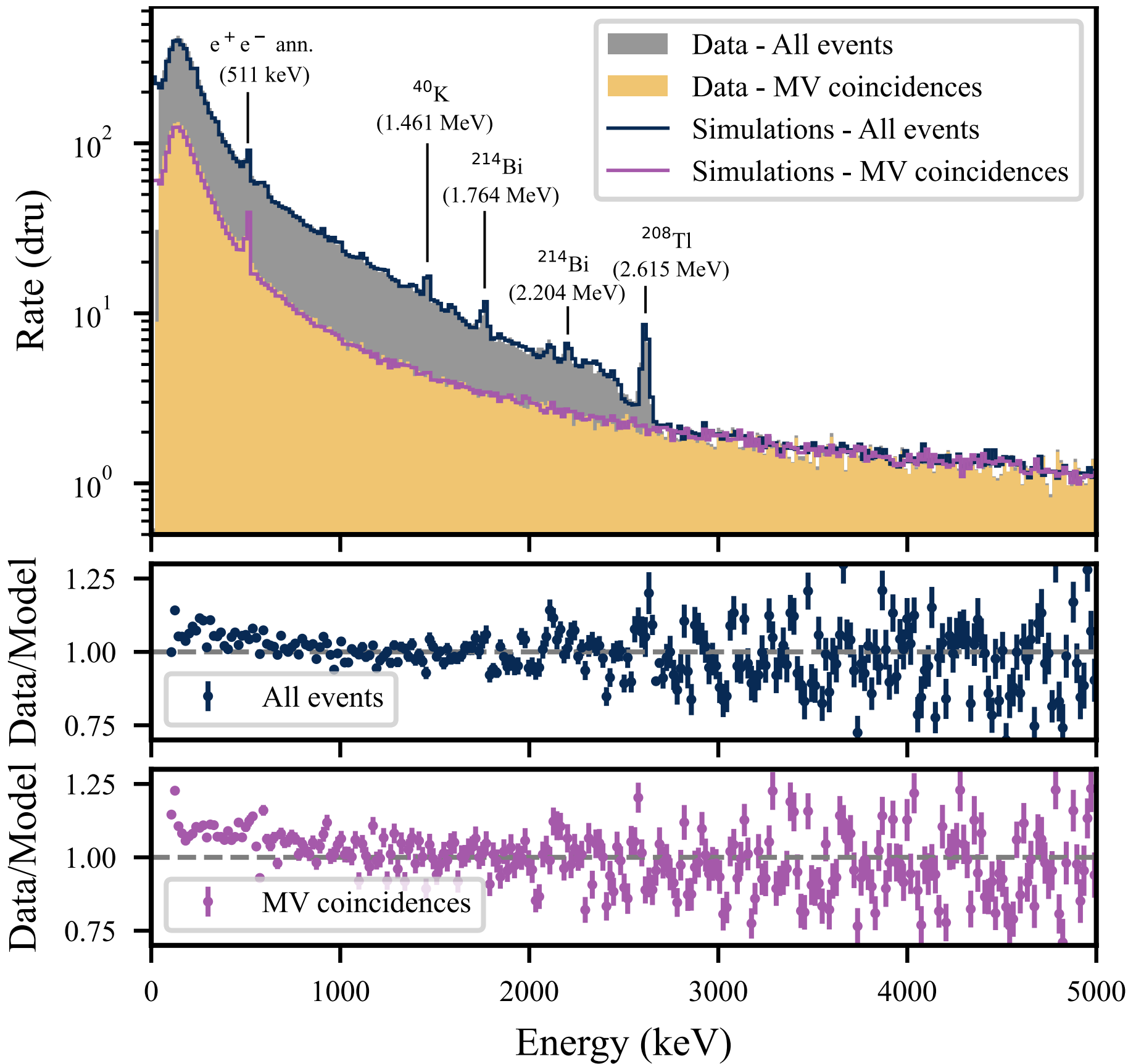
[PRD 2025]

Technical readiness of experiment



Commissioning at TUM: Particle Backgrounds

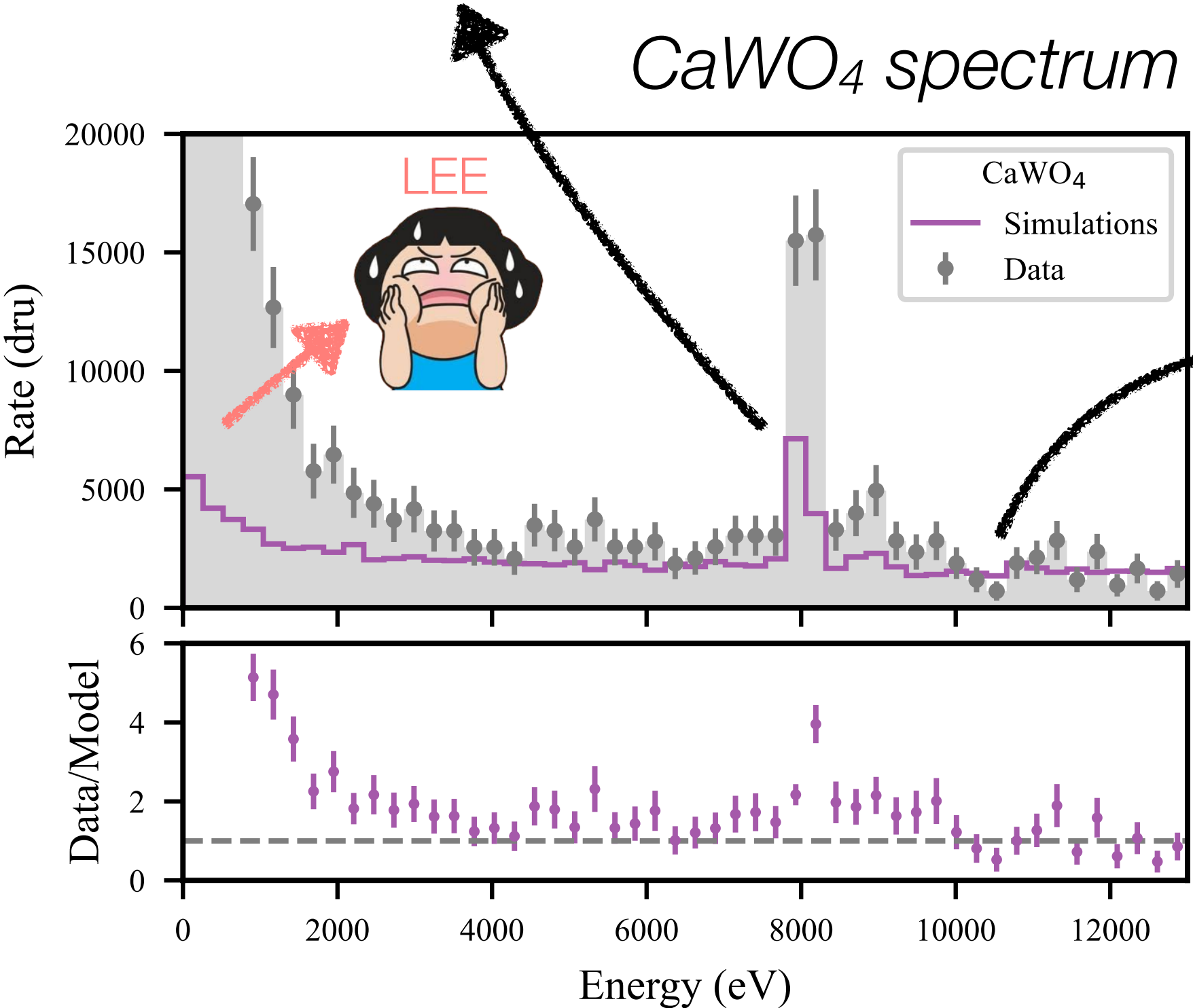
COV spectrum



Discrepancies at low-energies
(G4 tuning on-going)

Long Background Run (2024)

CaWO₄ spectrum



Background modeling
validated ≥ 10 keV

[PRD 2025]

Particle background modeling & mitigation

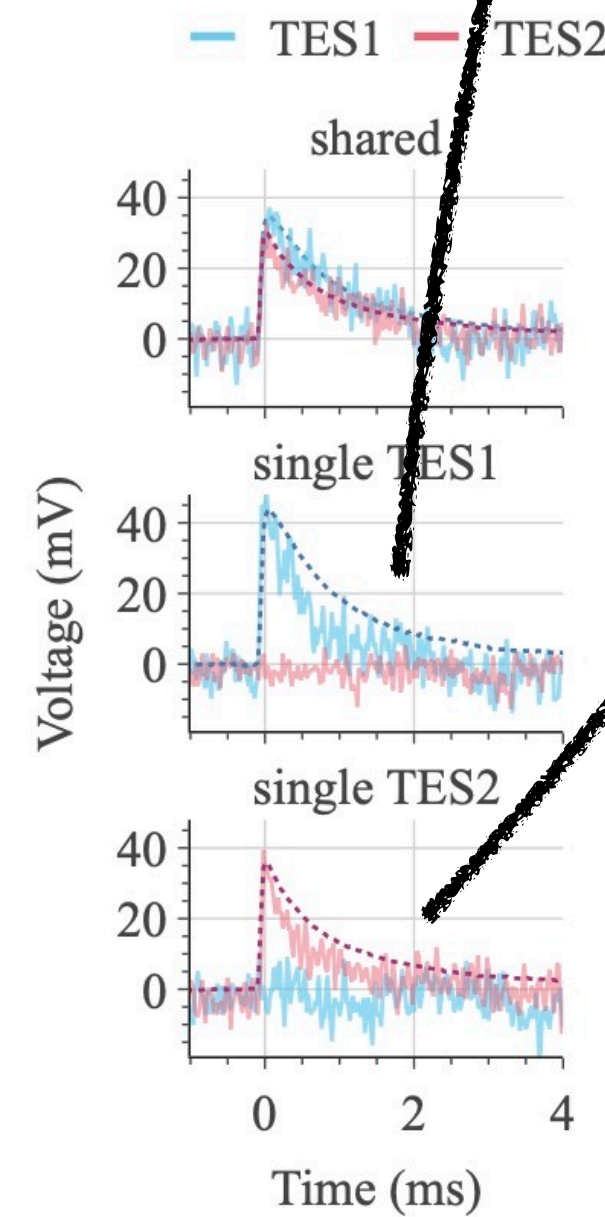
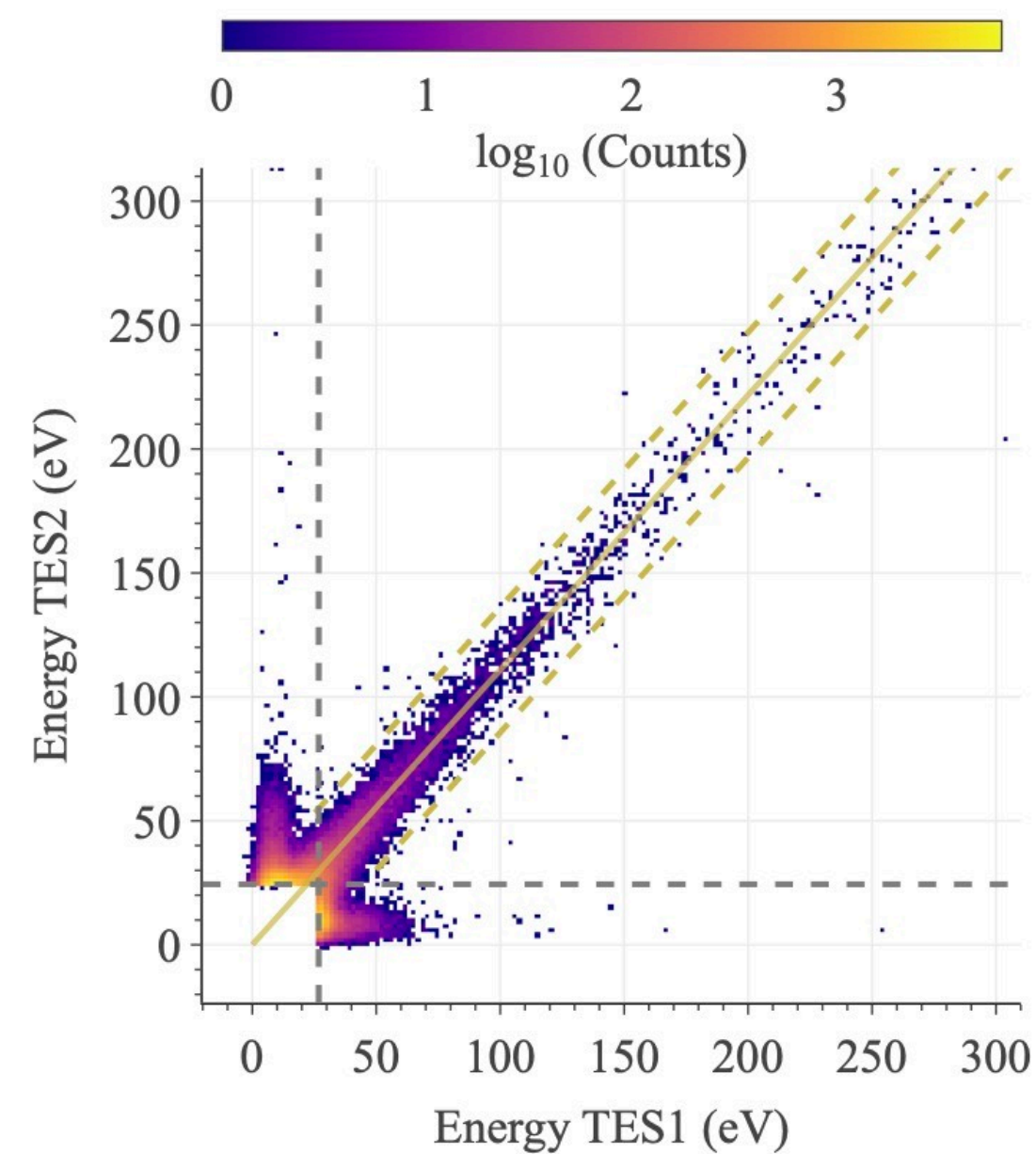
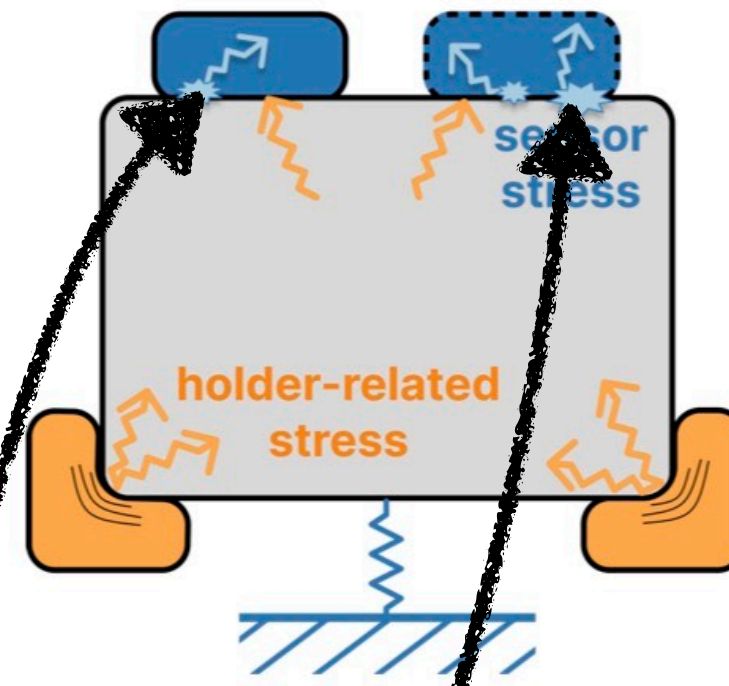
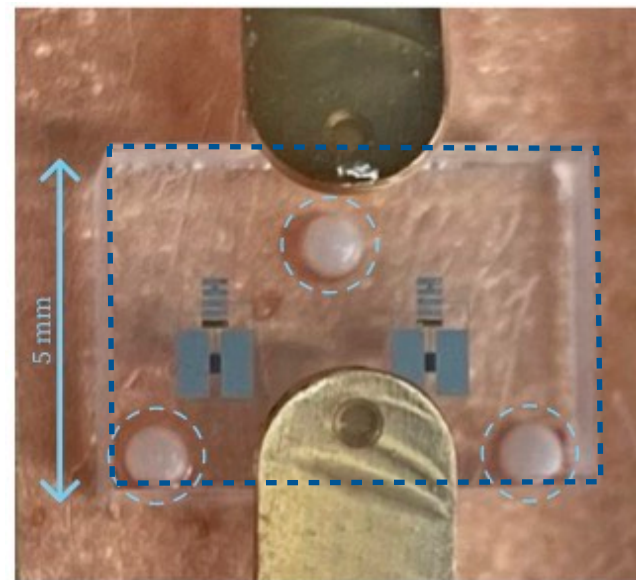


First Commissioning at TUM: LEE characterization

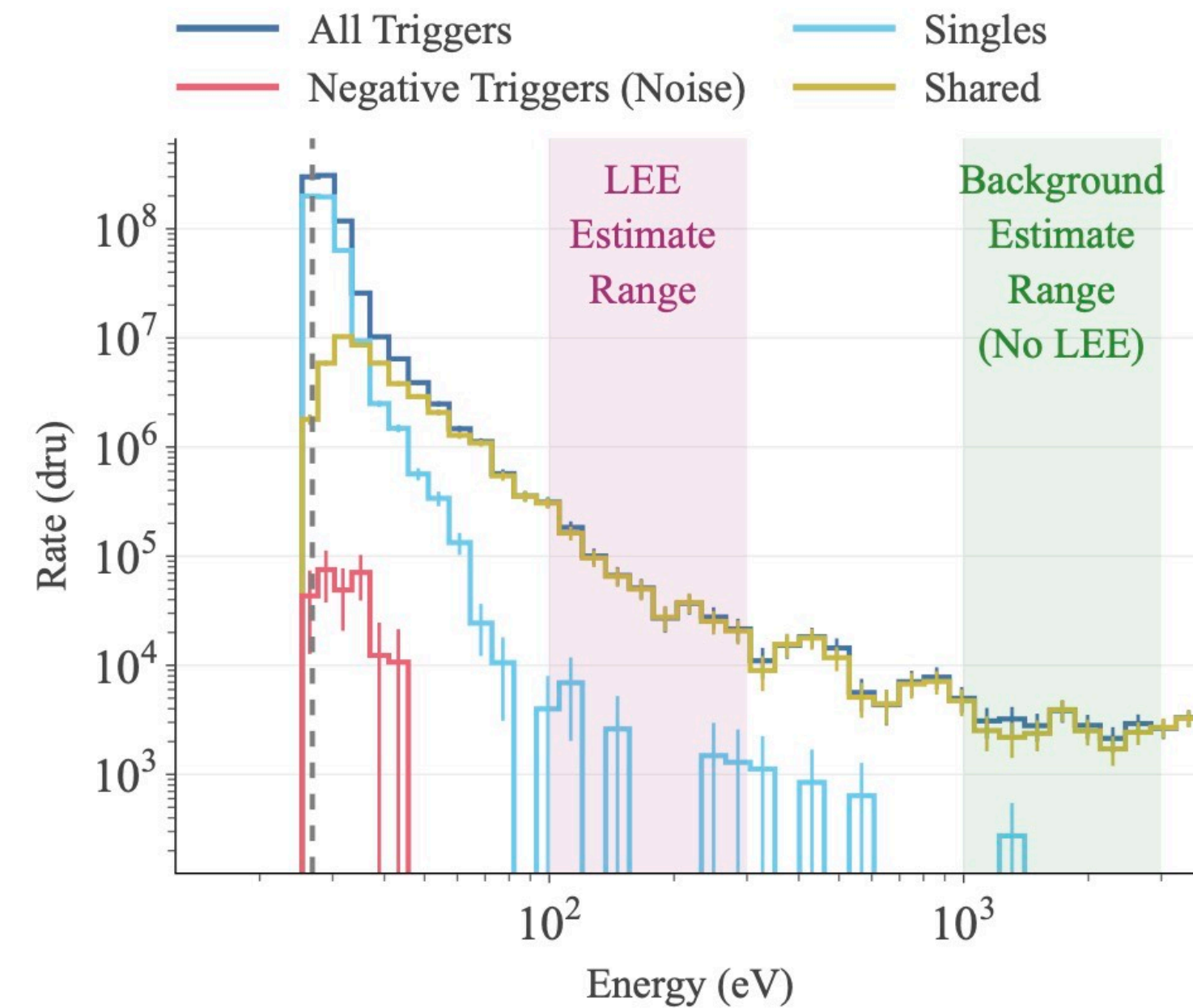
DPhP
DPhN

[EPJC 2026b]

Double-TES
 Al_2O_3 detector



$$R_{LEE} = R_{[100-300]eV}^{shared} - R_{[1-3]keV}^{shared}$$

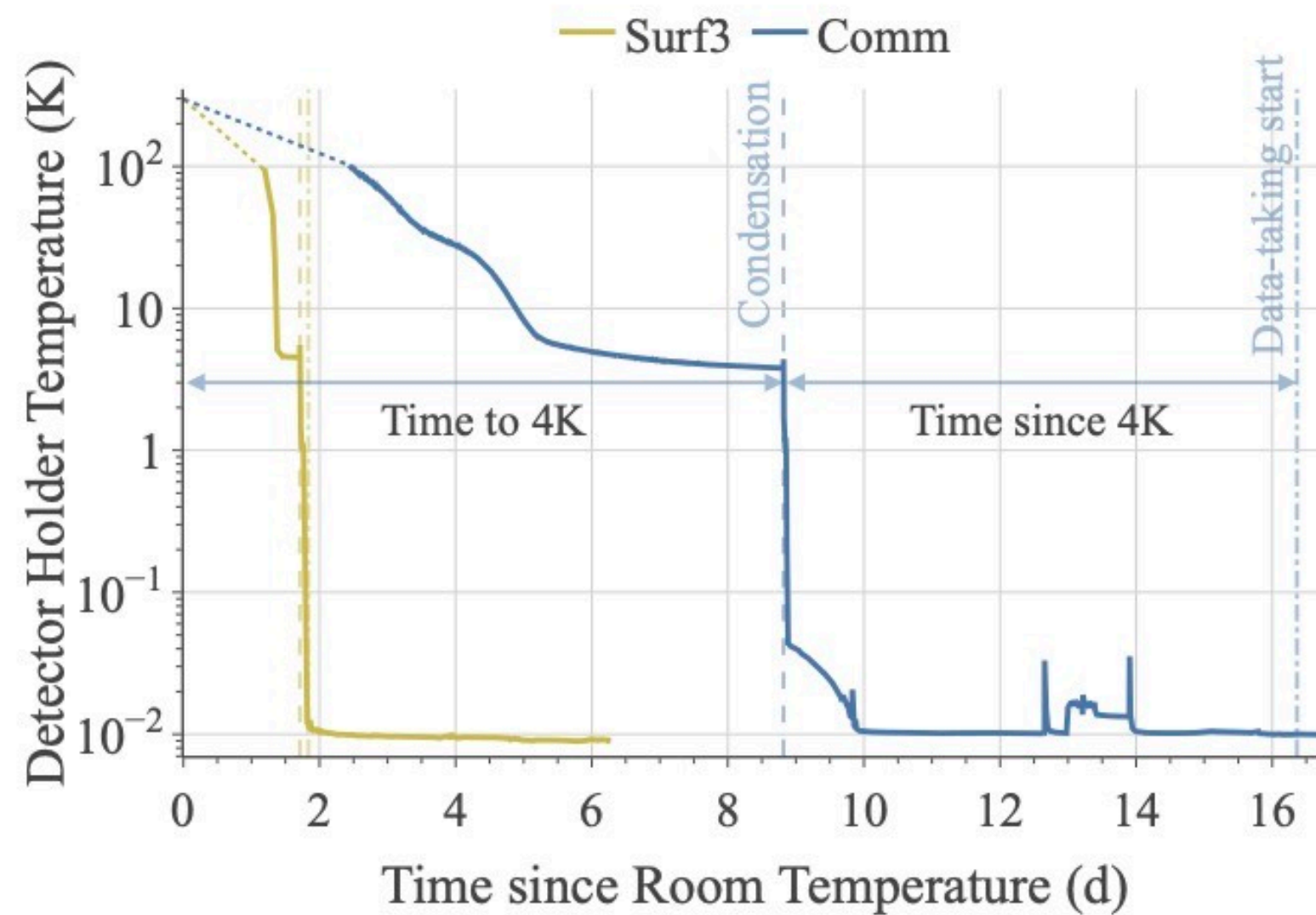


- Sensor-related stress origin validated...
- ... but other source(s) contributing too!

First Commissioning at TUM: LEE characterization

DPhP
DPhN

Cryostat cooldown profiles

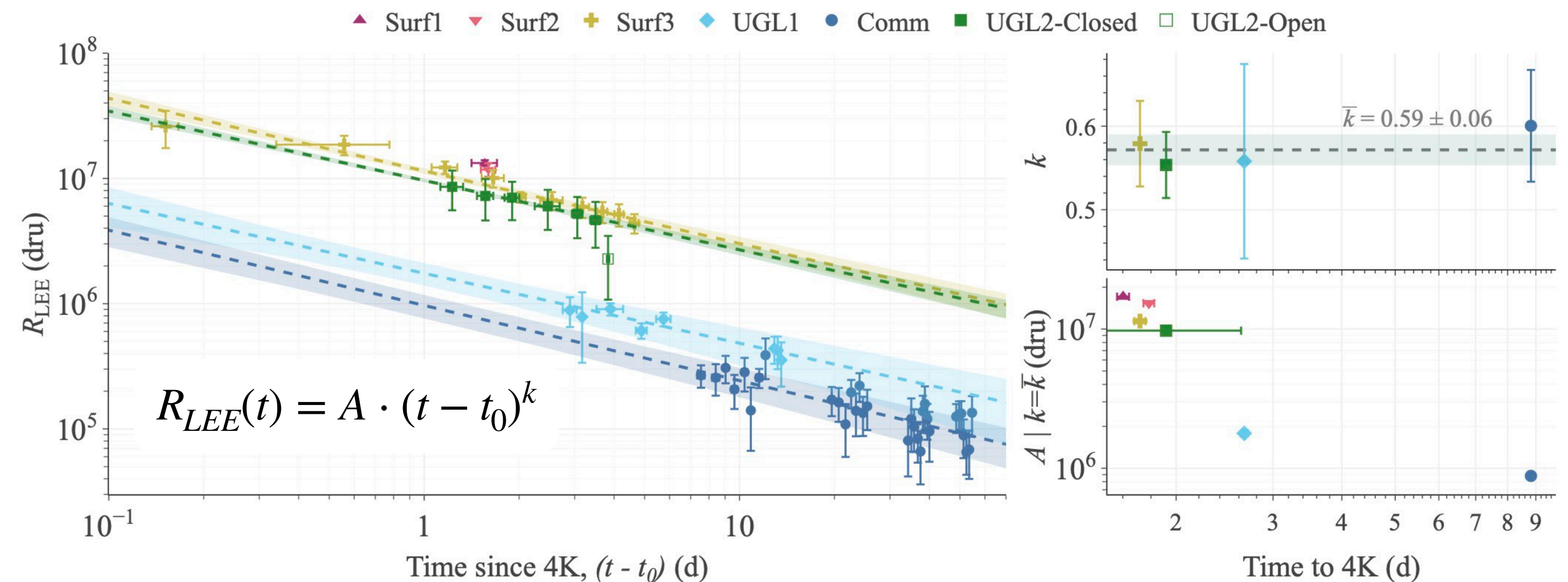


Solid-state physics origin favored !

LEE time-dependence

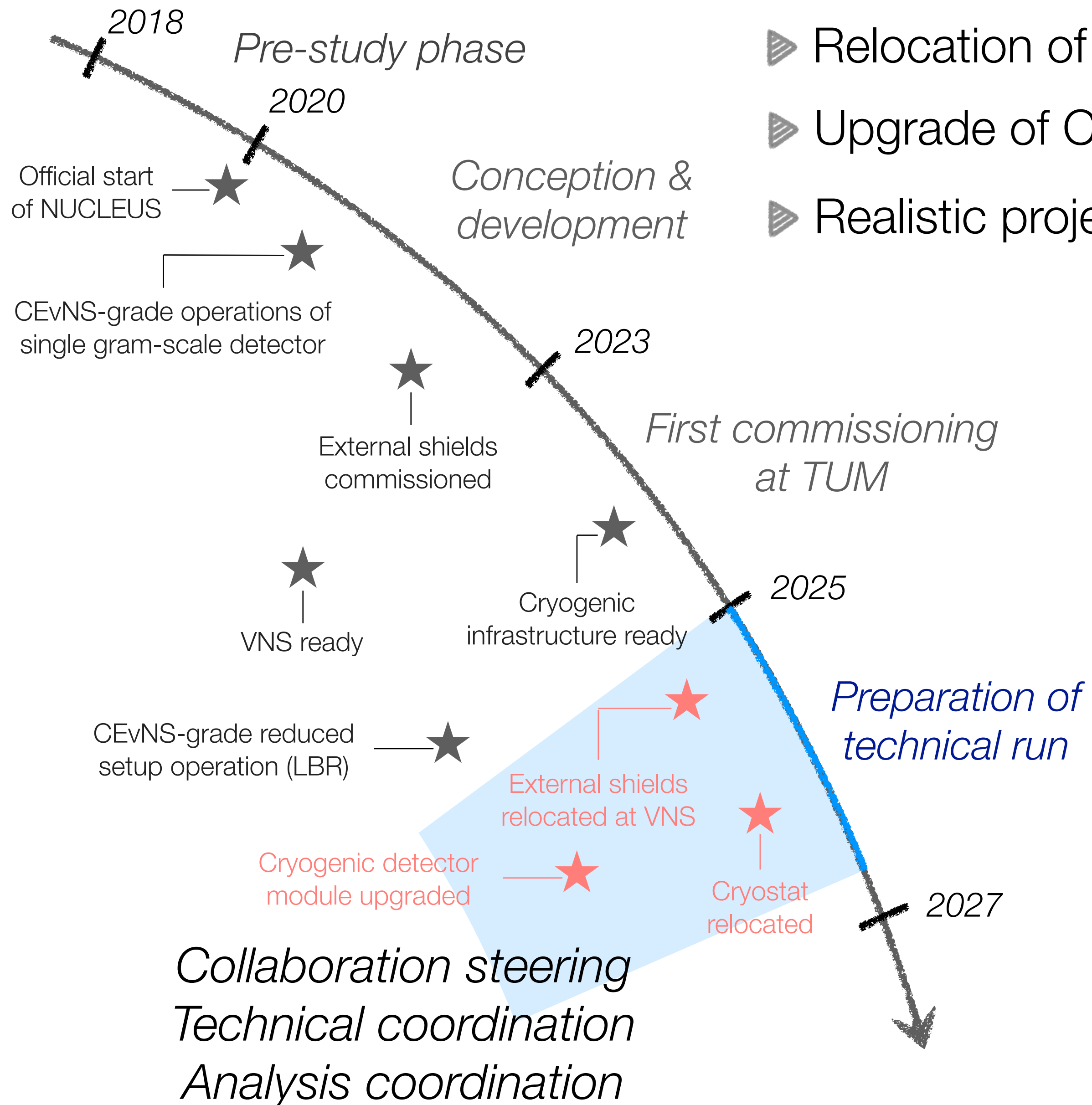
- ▶ Power-law decrease with time since 4K
- ▶ Initial normalization dependence on cooldown time to 4K
- ▶ Both particle & instrumental noise origins excluded

Measured LEE rates for various experimental conditions follow a common power law

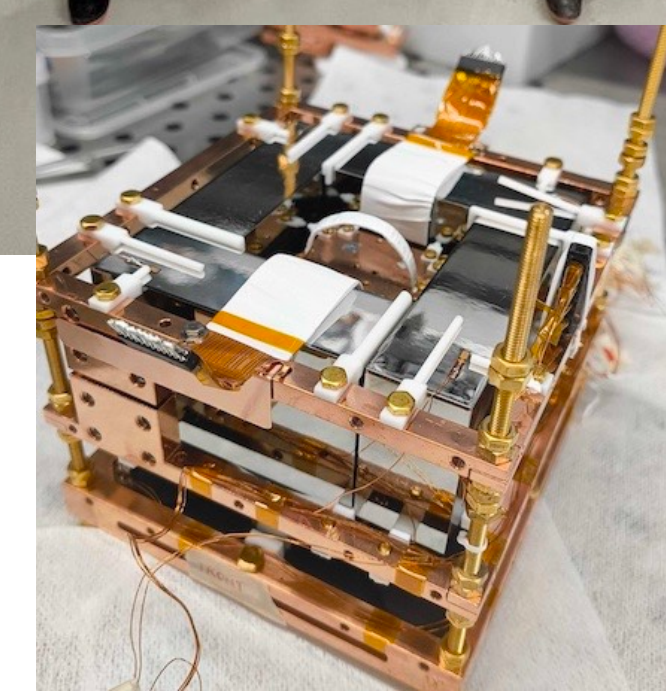


Project Timeline & Contributions from CEA/Irfu

DPhP
DPhN
DEDIP
DIS

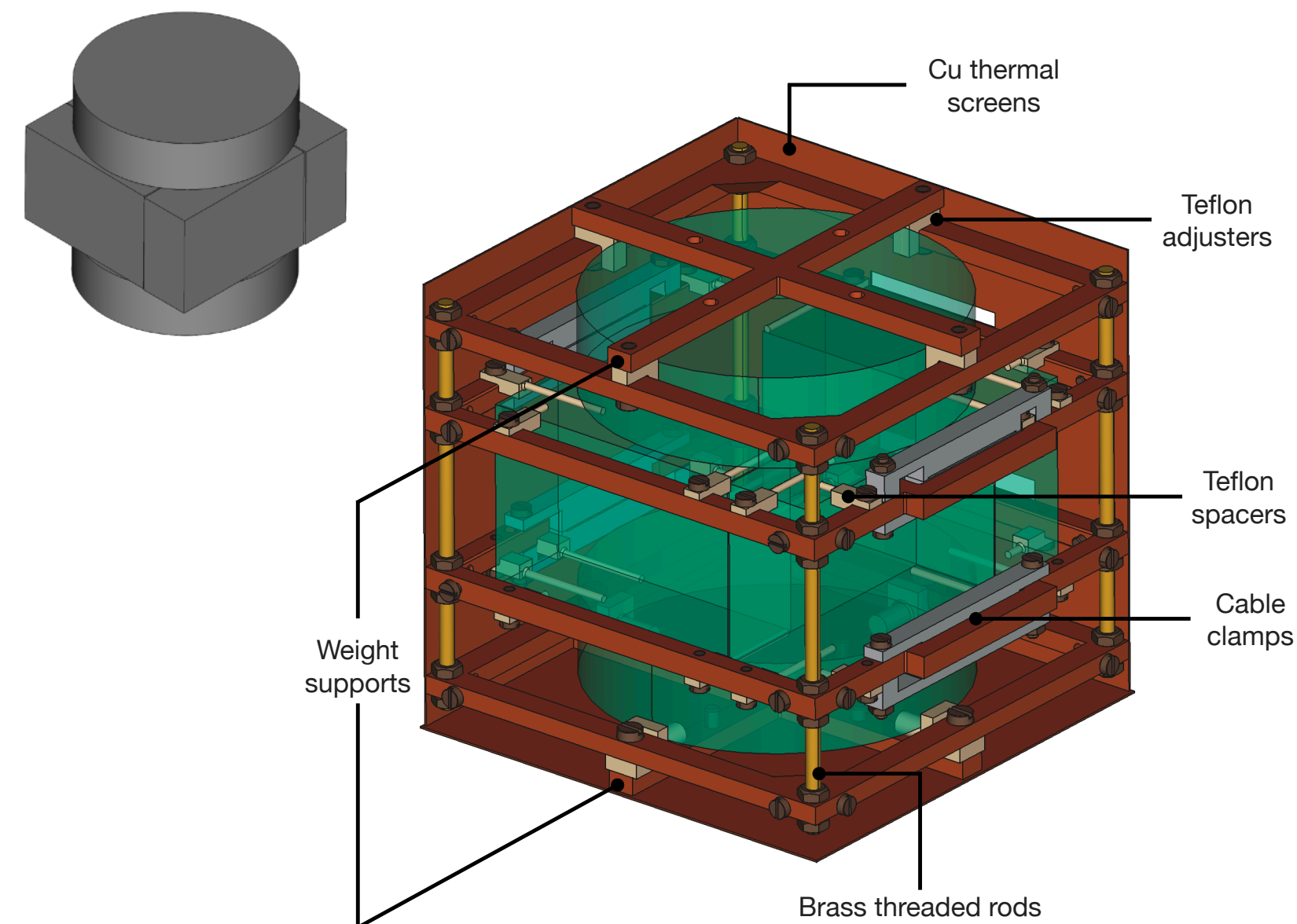


- Relocation of external shields + cryostat at VNS
- Upgrade of COV & cryogenic detector module preparation at TUM
- Realistic projections for neutrino detection & sensitivity to new physics

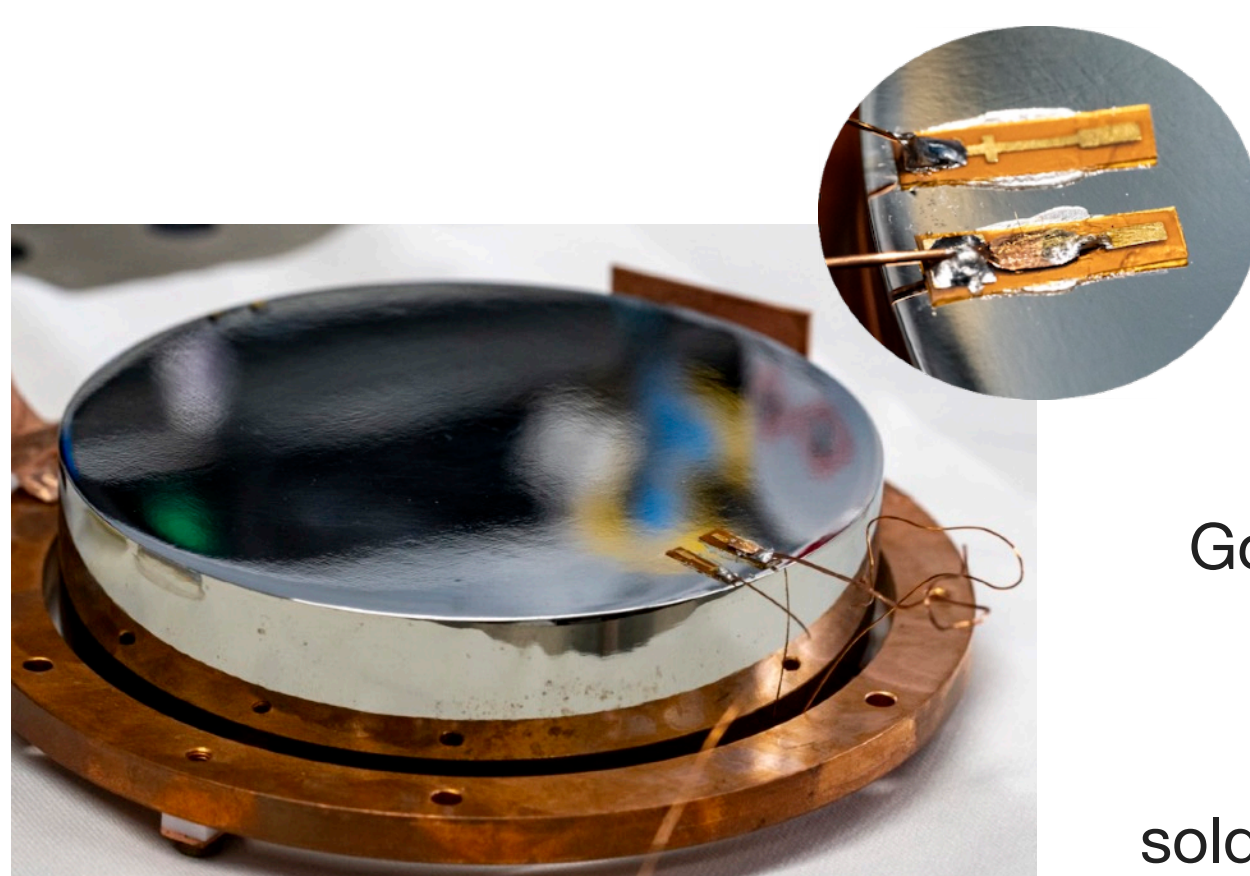
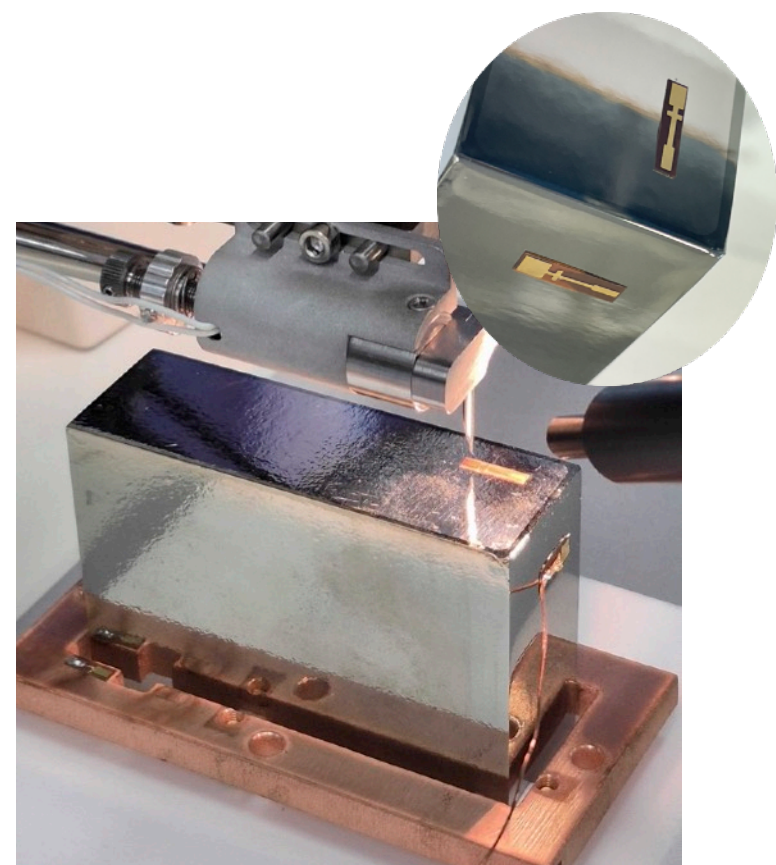


COV Upgrade Work at TUM (2025)

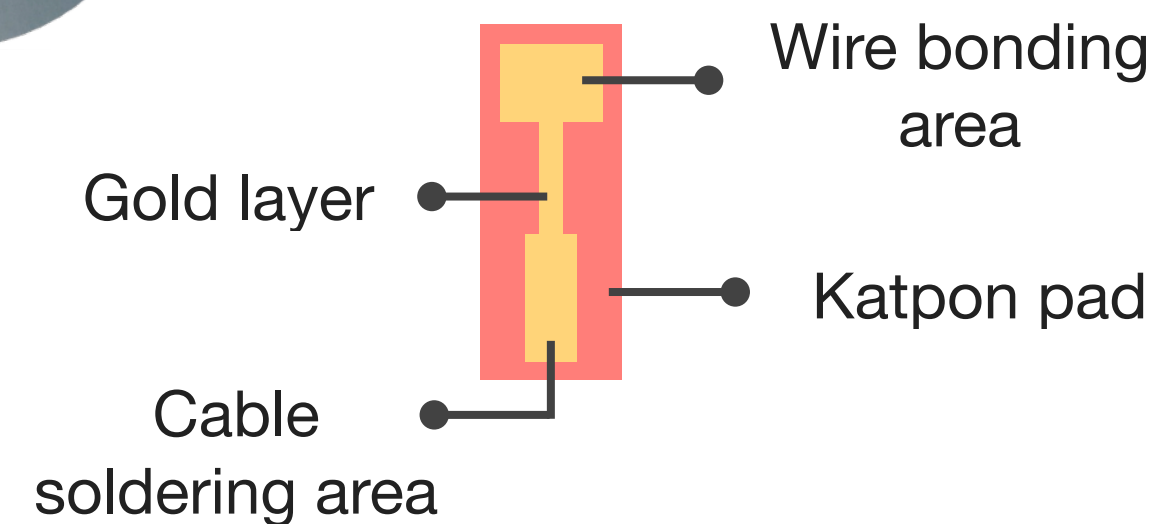
COV mechanical design



- Complicated and compact mechanical design (tedious assembly constraints, many cables, interfacing with TES detectors)
- Readout and thermal connexions via bond pads glued on each crystal to ease assembly and cable routing

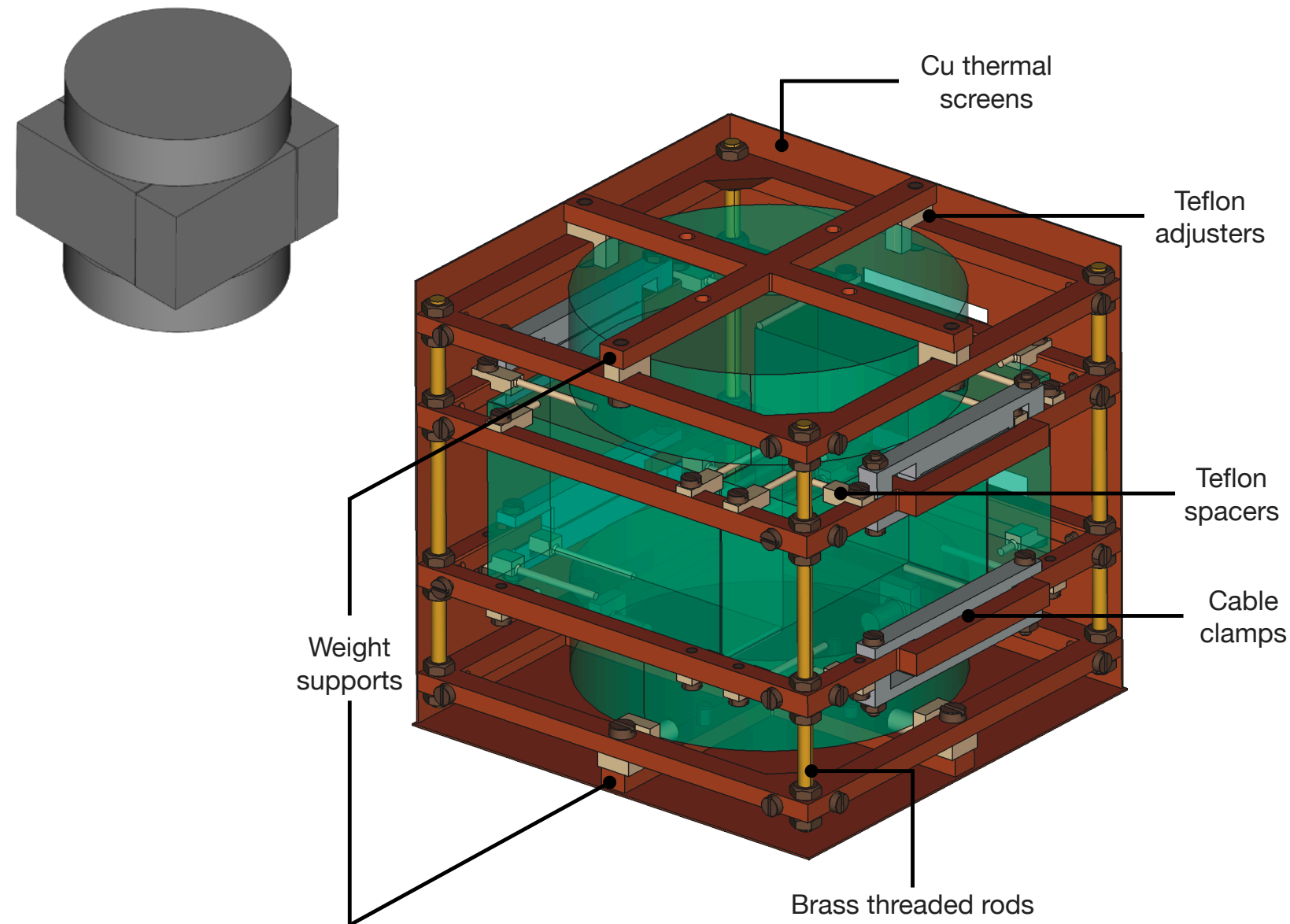


Bond pads



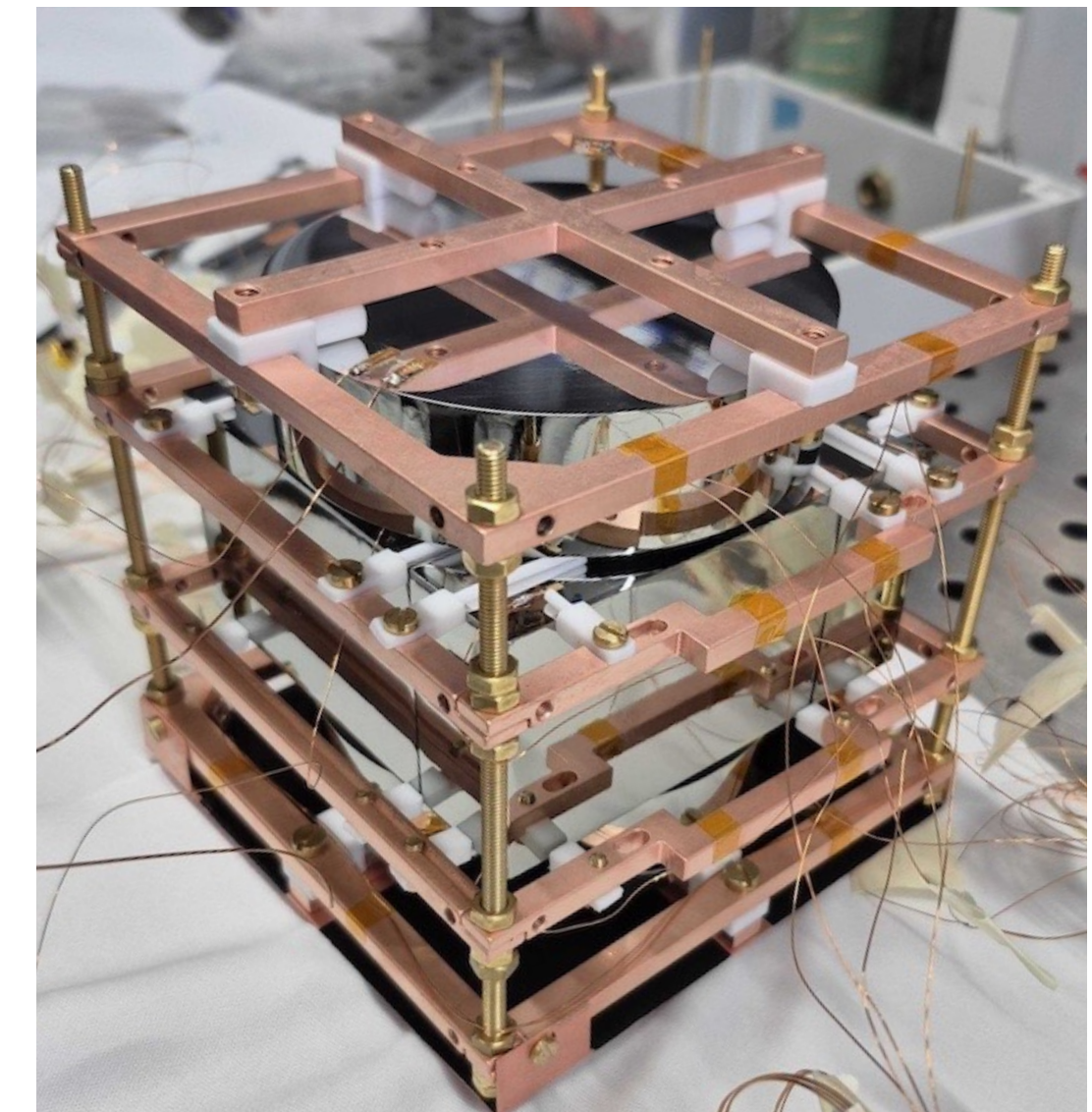
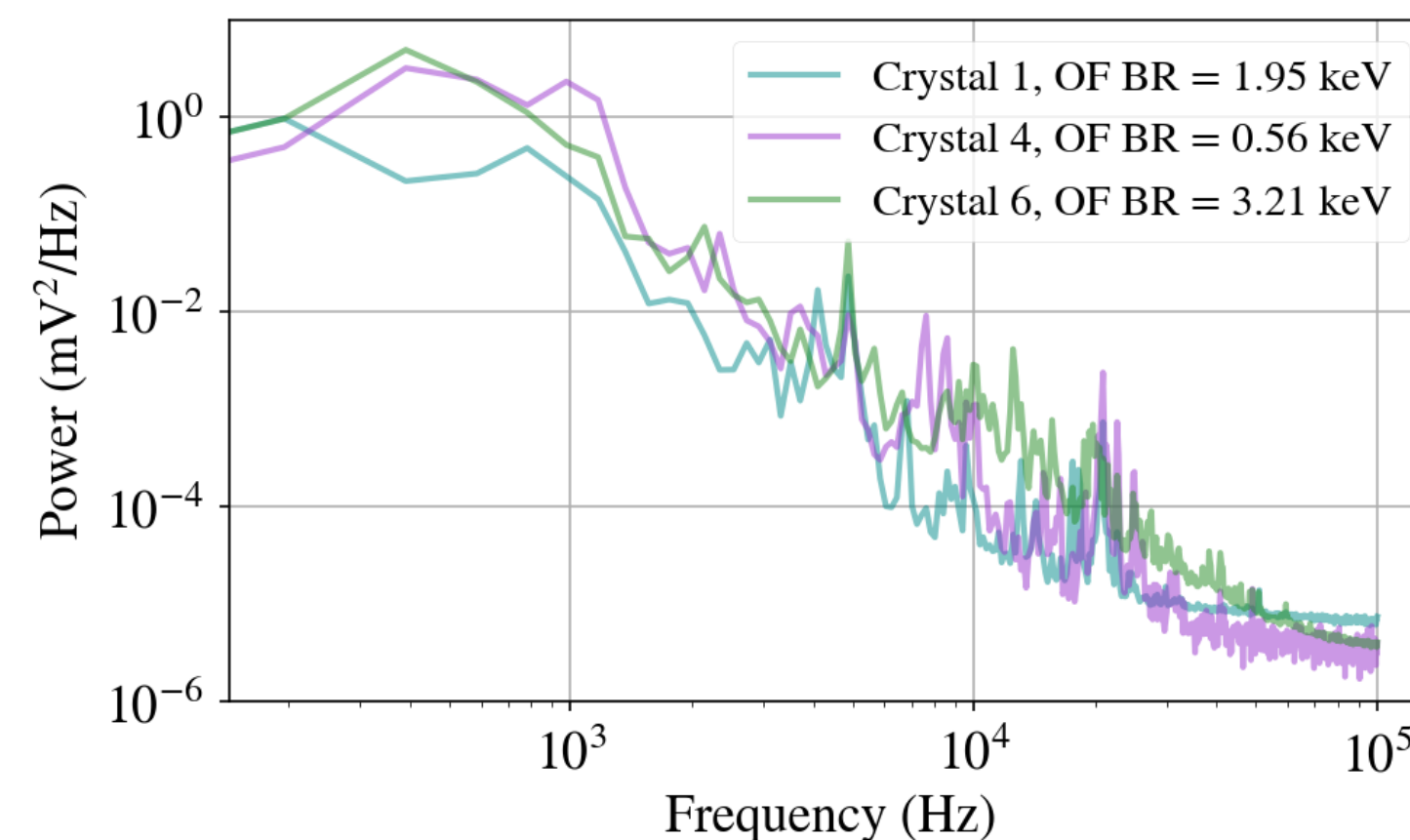
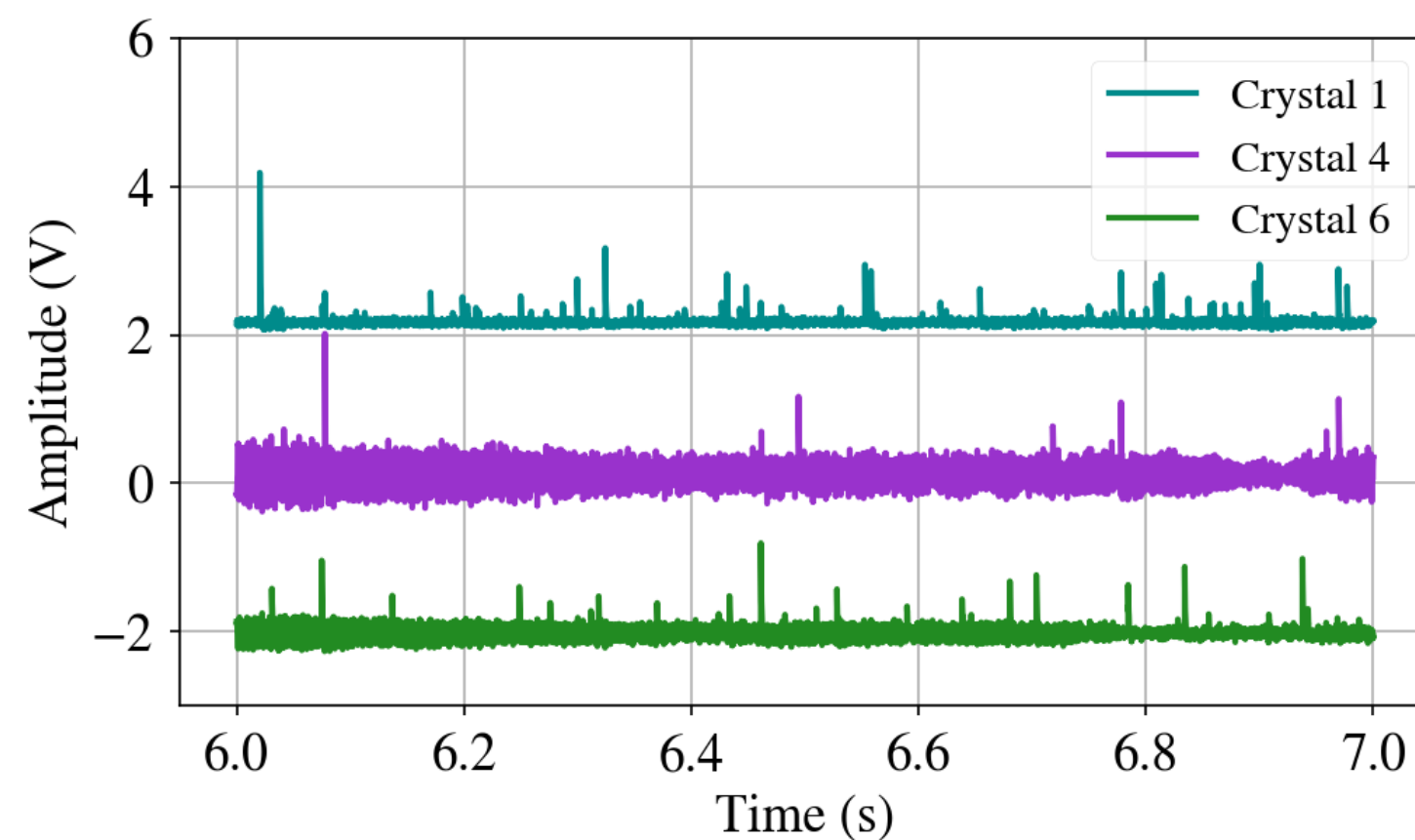
COV Upgrade Work at TUM (2025)

COV mechanical design



- Complicated and compact mechanical design (tedious assembly constraints, many cables, interfacing with TES detectors)
- Readout and thermal connexions via bond pads glued on each crystal to ease assembly and cable routing
- Successful assembly, thermalization and readout test with half of the electronics → O(10 keV) thresholds achieved

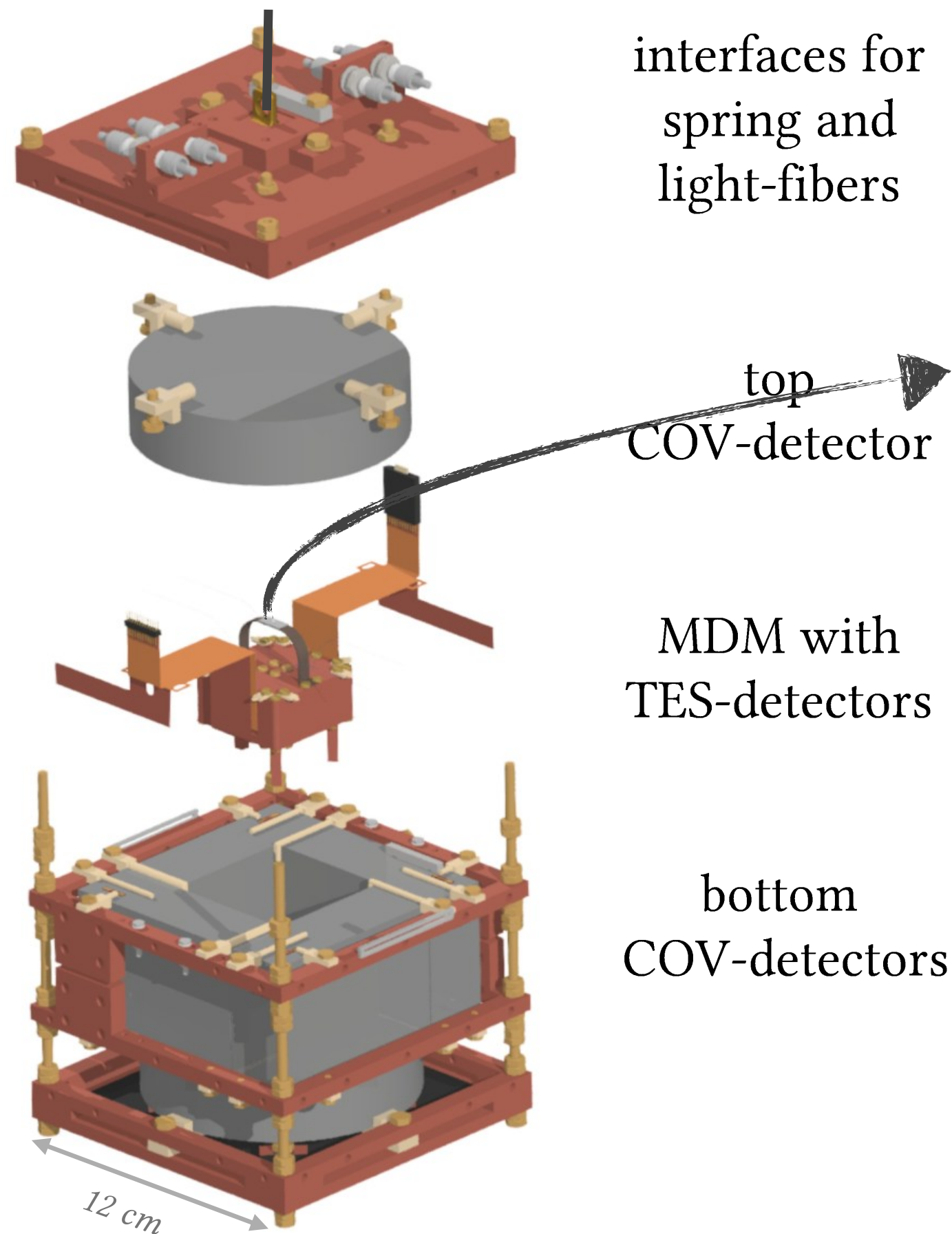
COV readout streams and noise performances



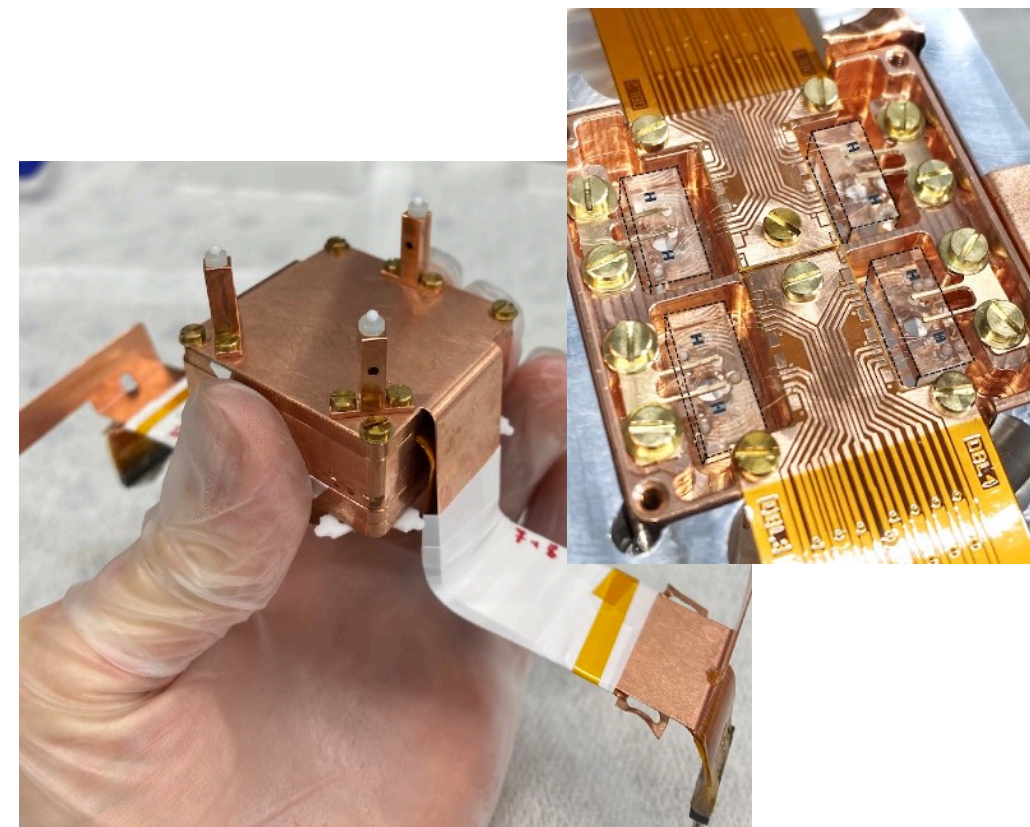
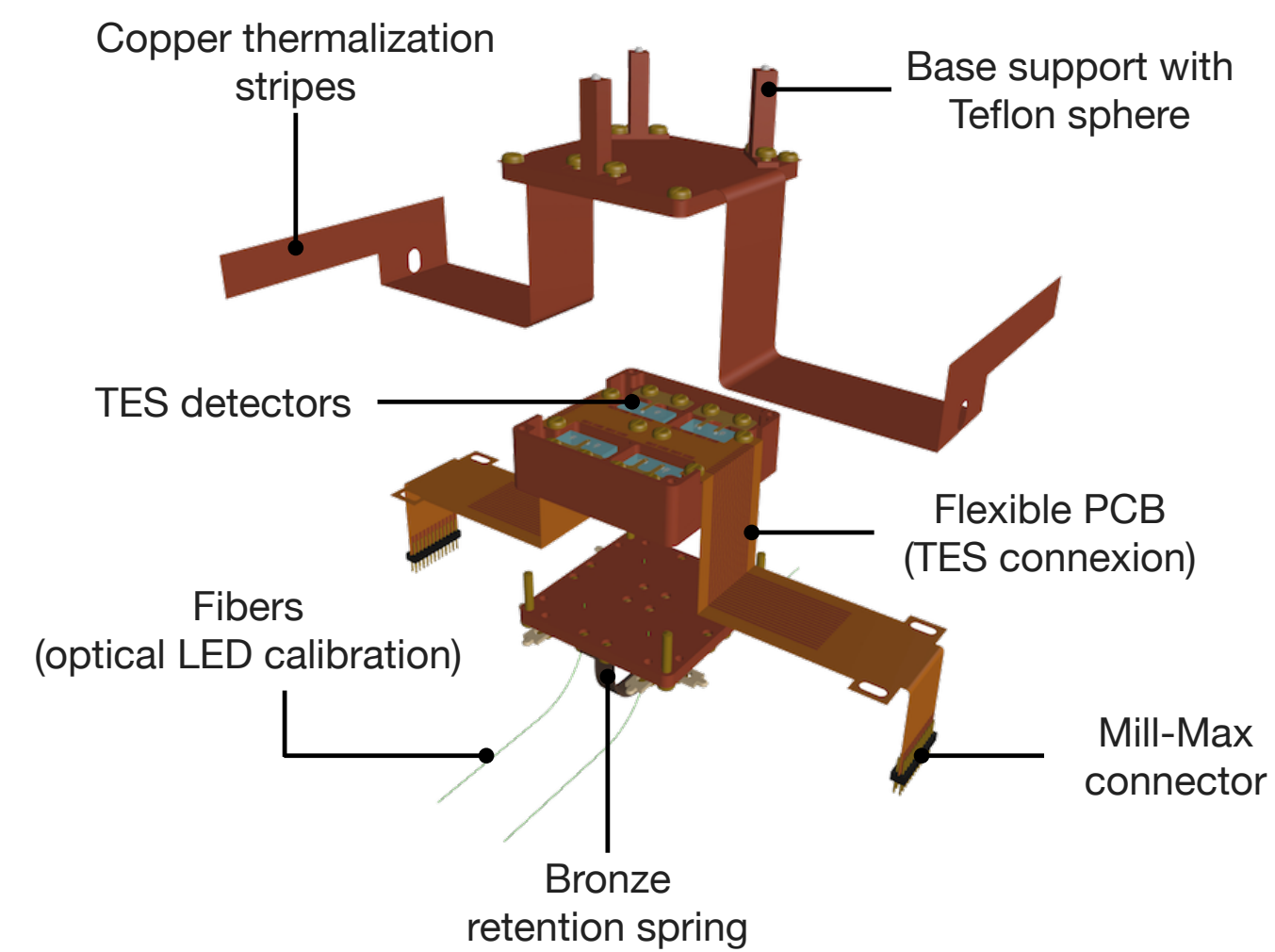
Cryogenic Detector Module Preparation (2025)

DPhP

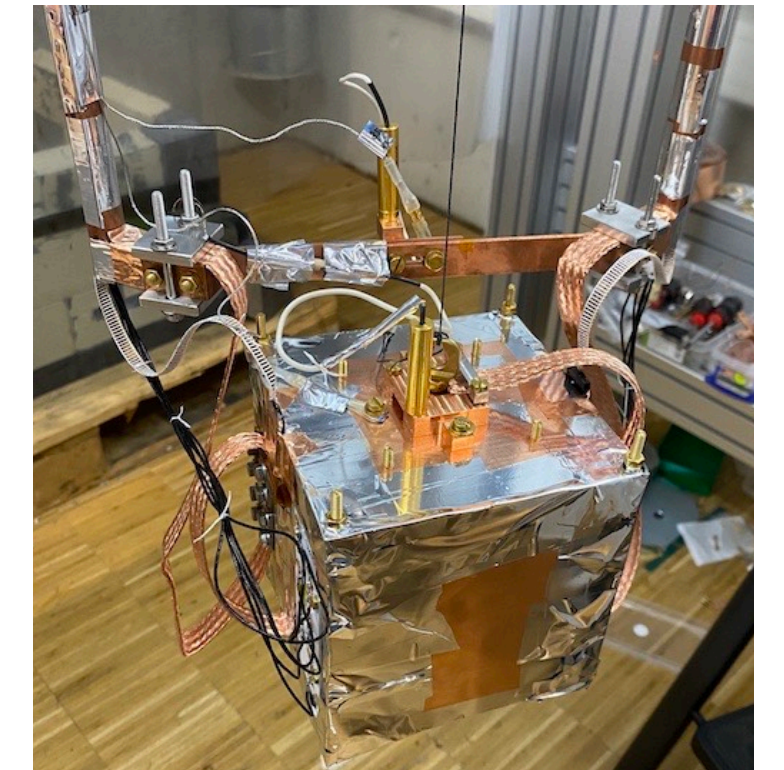
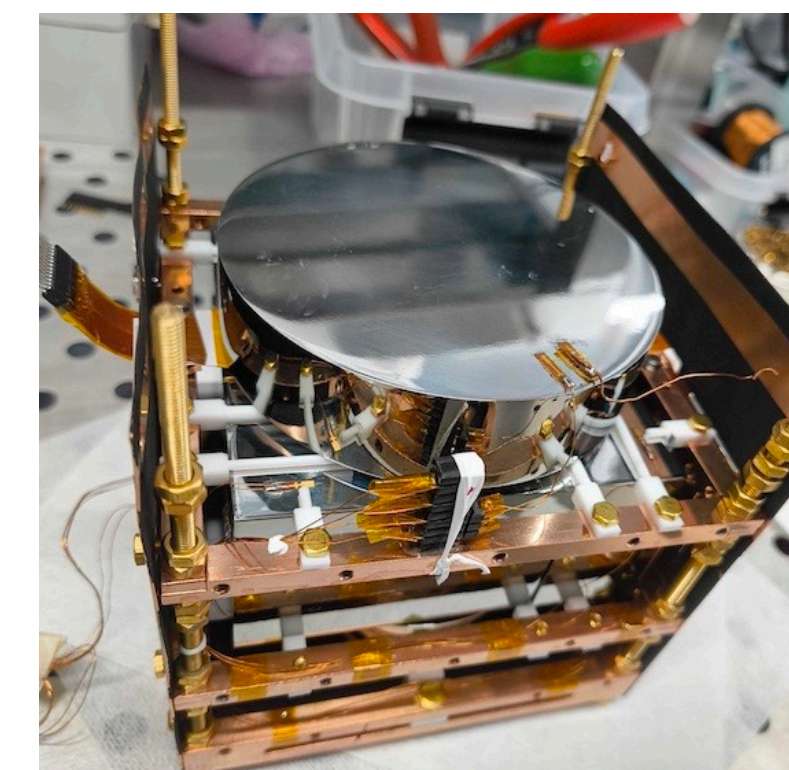
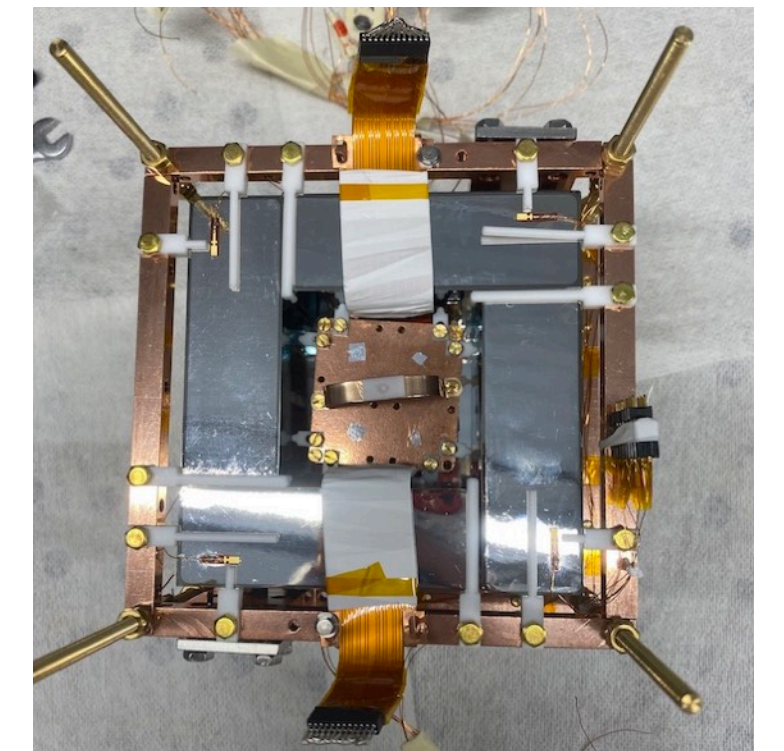
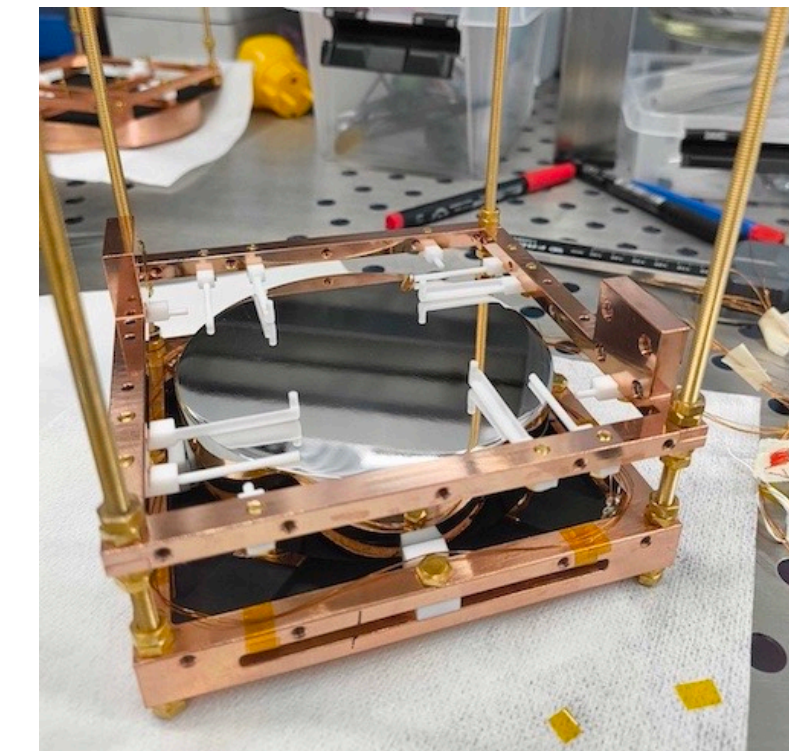
Detector module exploded view



Minimal Detector Module (MDM)
4 x 1.7-g CaWO_4 detectors with
double TES readout

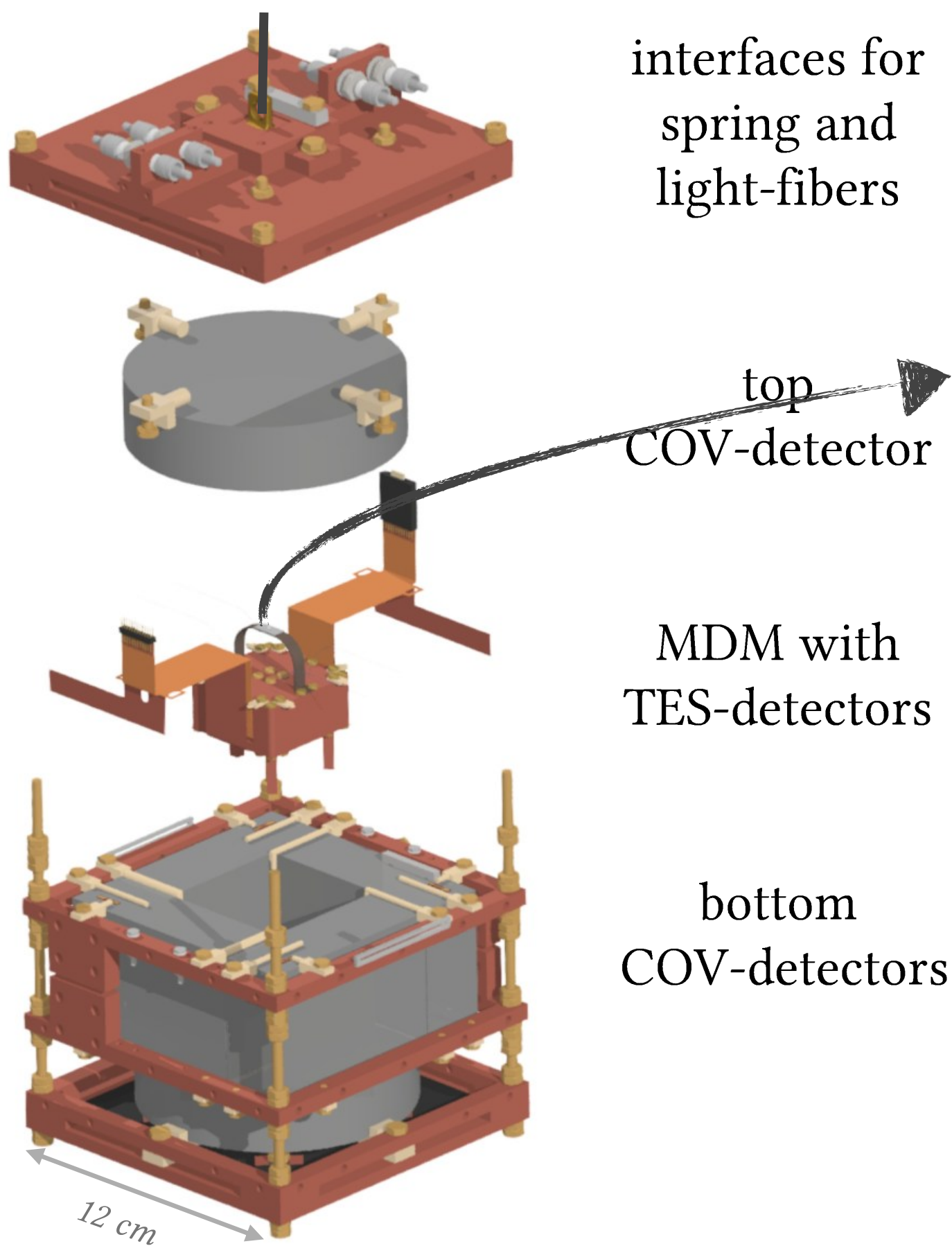


► Successful assembly + thermalization in Munich

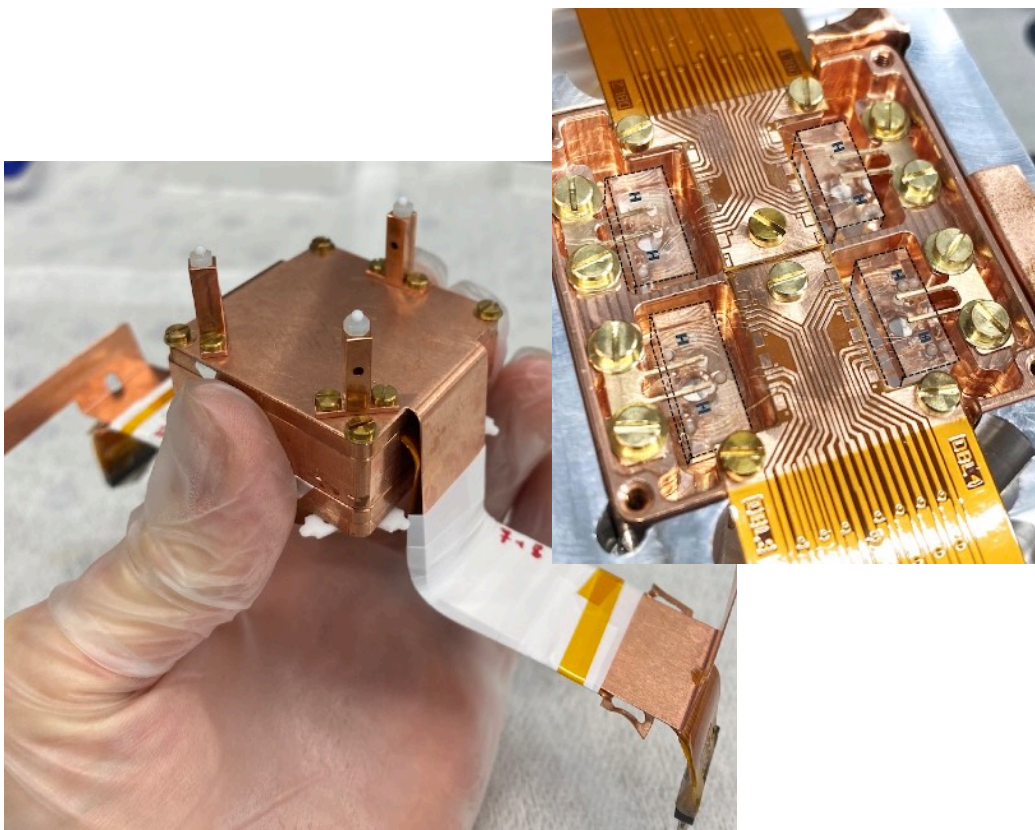
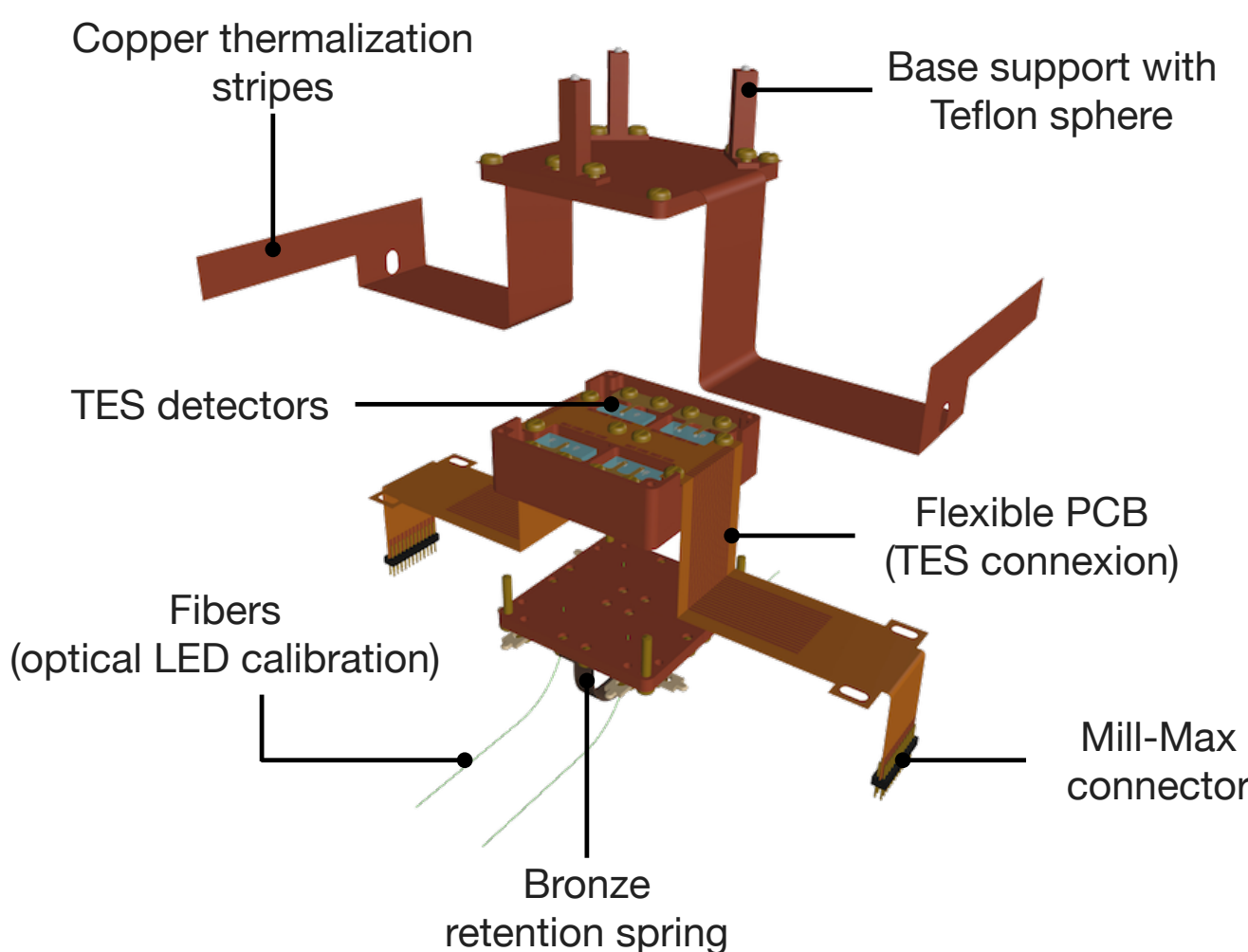


Cryogenic Detector Module Preparation (2025)

Detector module exploded view



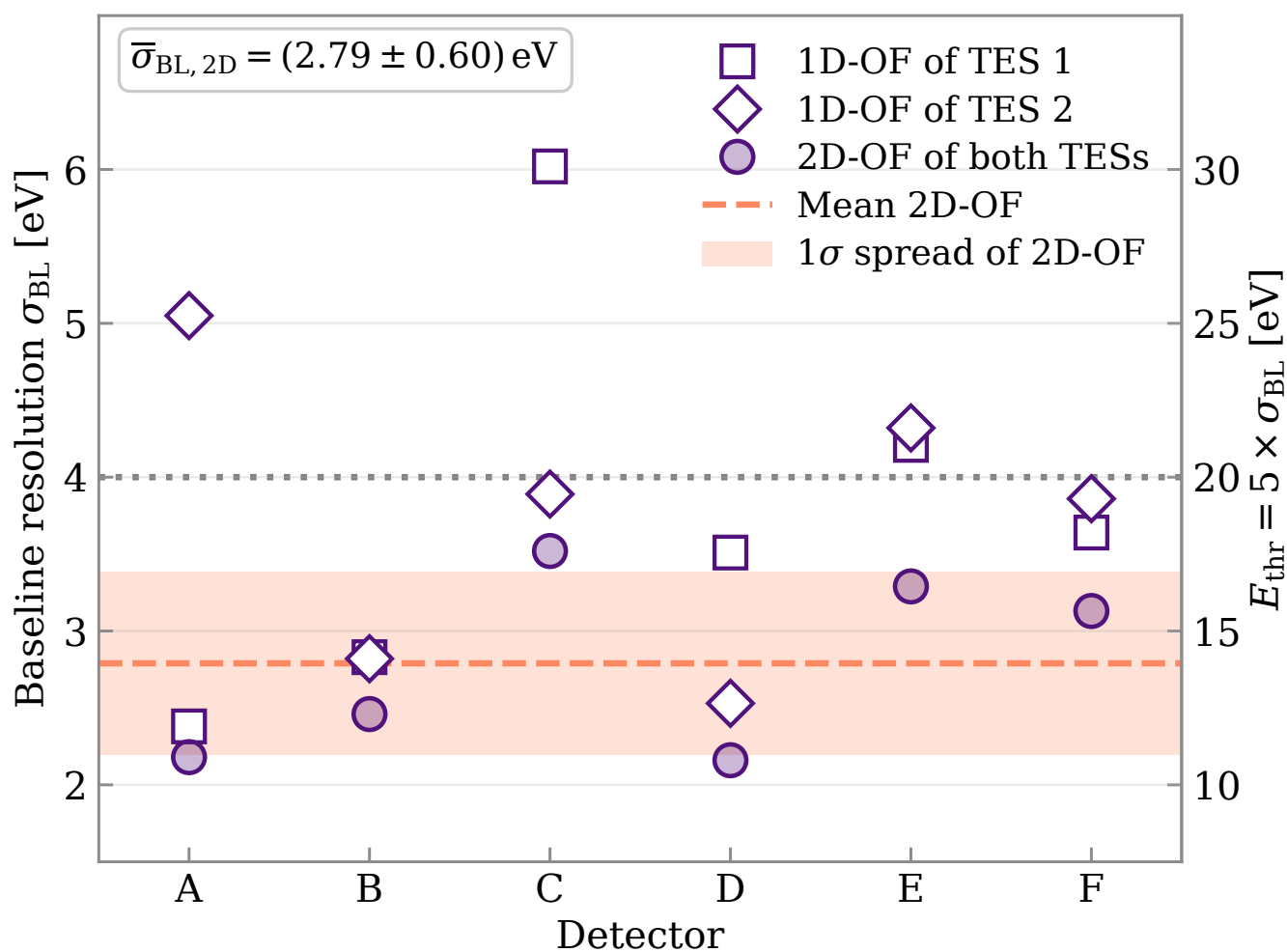
Minimal Detector Module (MDM)
4 x 1.7-g CaWO_4 detectors with
double TES readout



- ▶ Successful assembly + thermalization in Munich
- ▶ Inter-operability of MDM with COV demonstrated
- ▶ TES detectors reached CEvNS-grade specifications:

- Operating point optimization procedure to maximize S/N + advanced filtering technique
- < 20 eV thresholds achieved for all sensors !

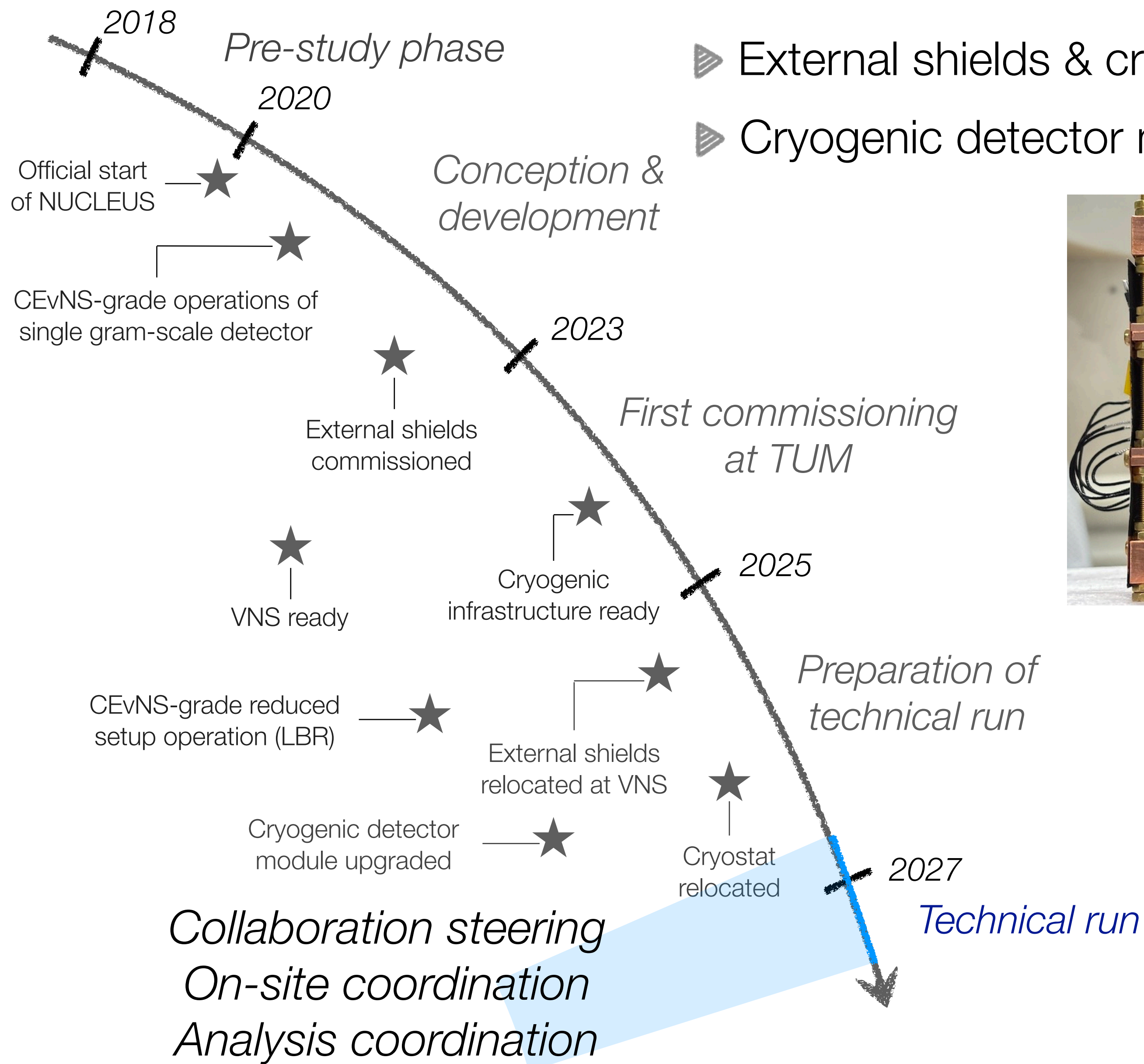
Achieved TES baseline resolutions



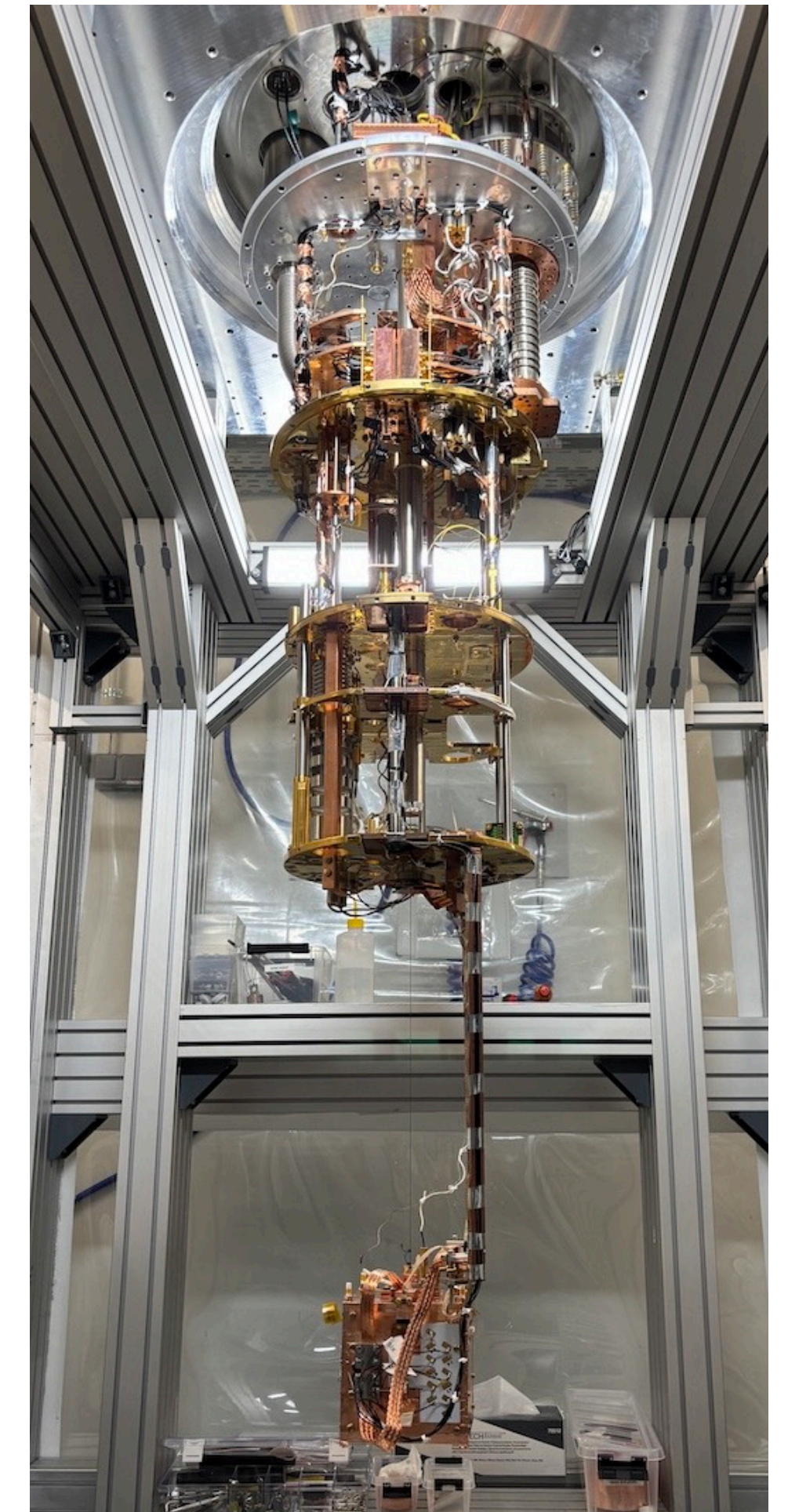
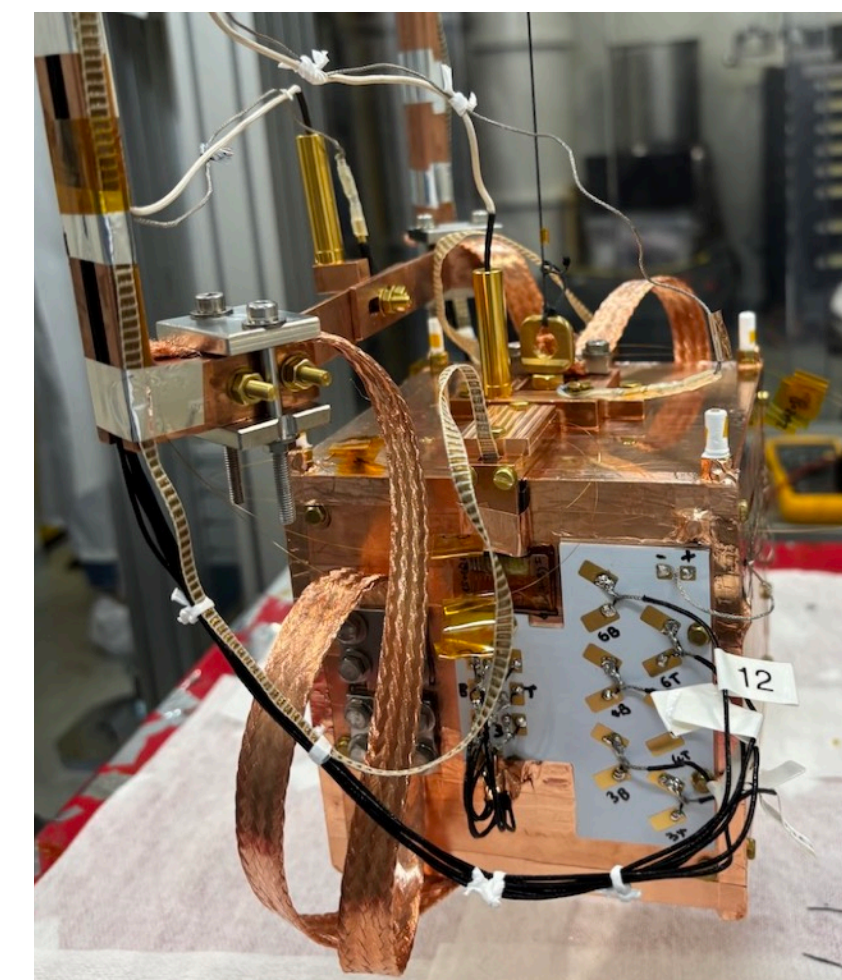
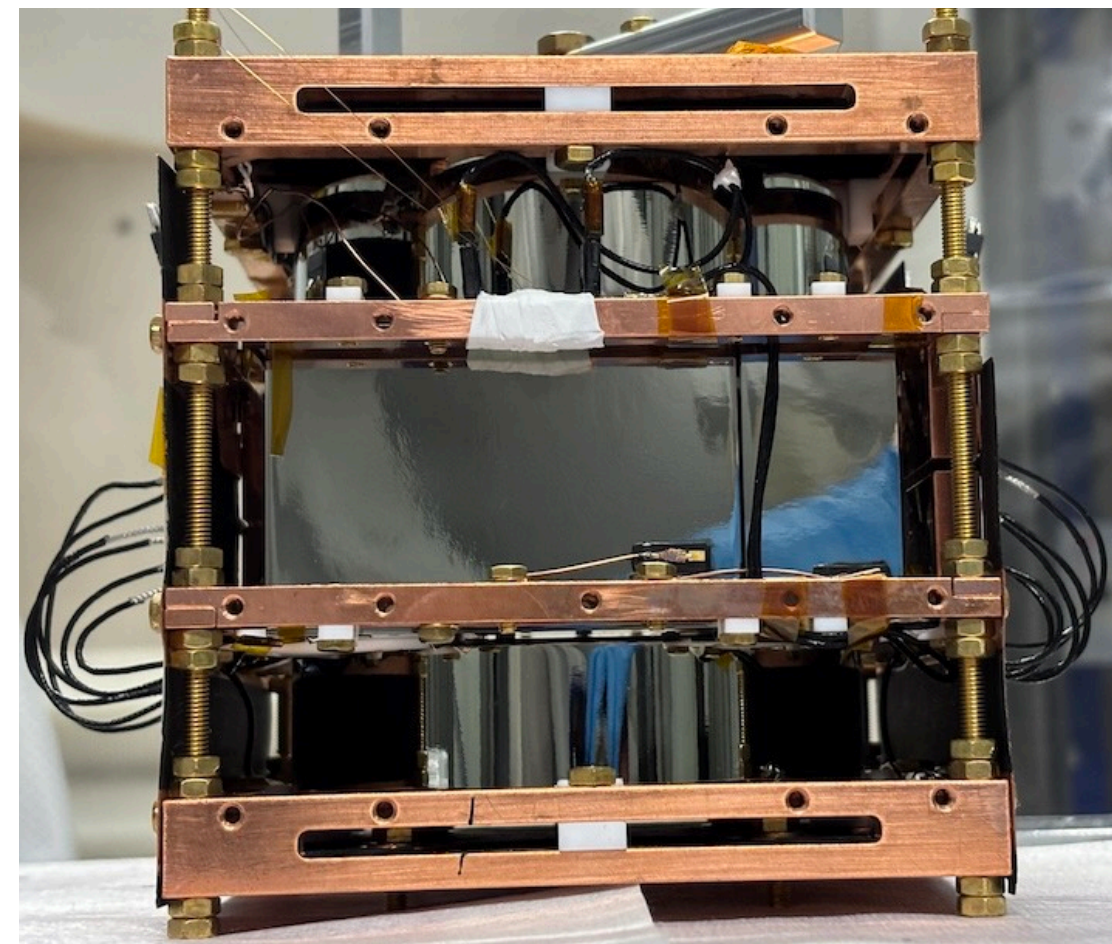
[ArXiv 2026]
[JINST 2026]

Technical Run at Chooz: Status

DPhP
DPhN
DEDIP
DIS

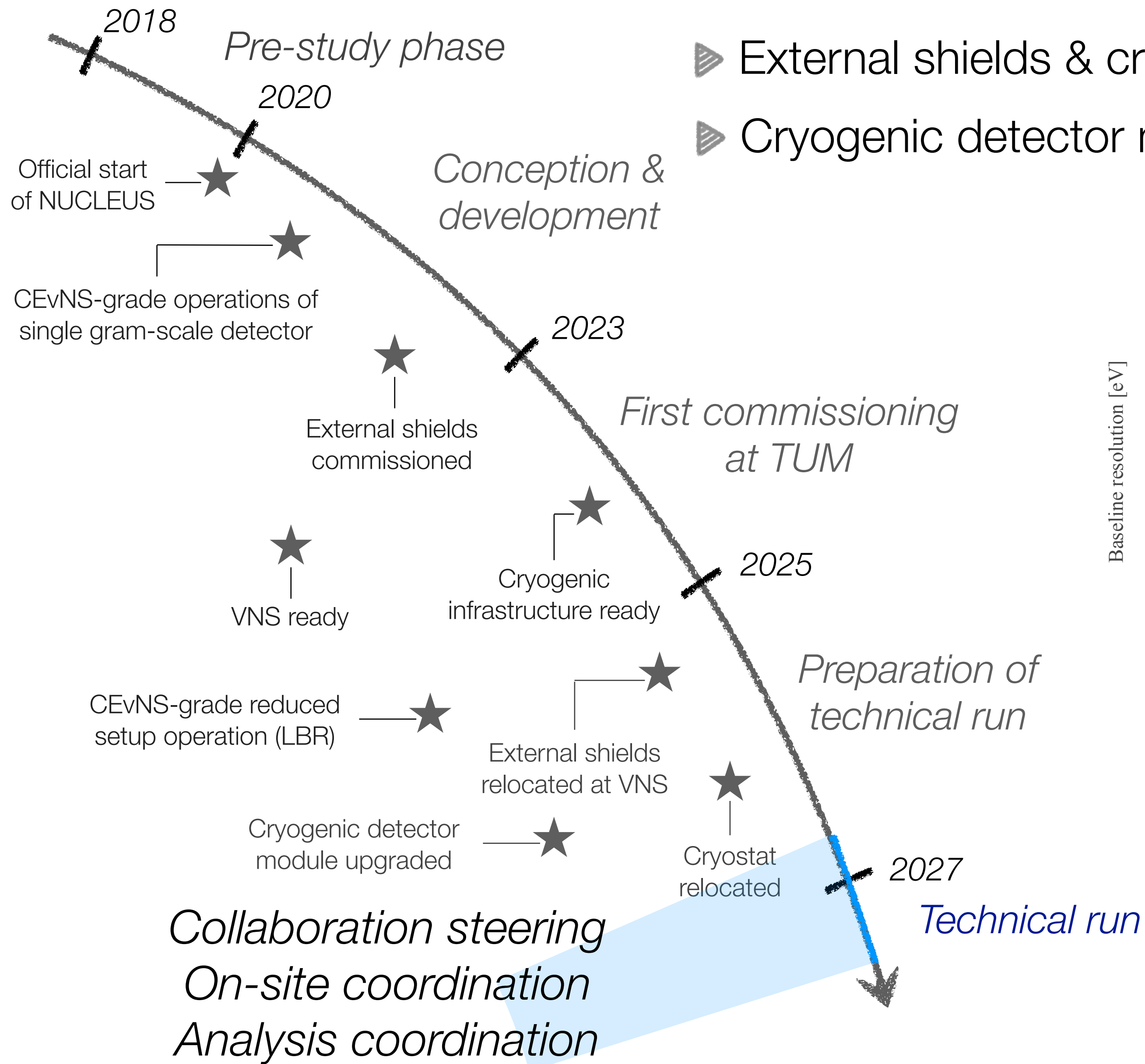


- ▶ External shields & cryogenic facility fully operational
- ▶ Cryogenic detector module commissioning on-going



Technical Run at Chooz: Status

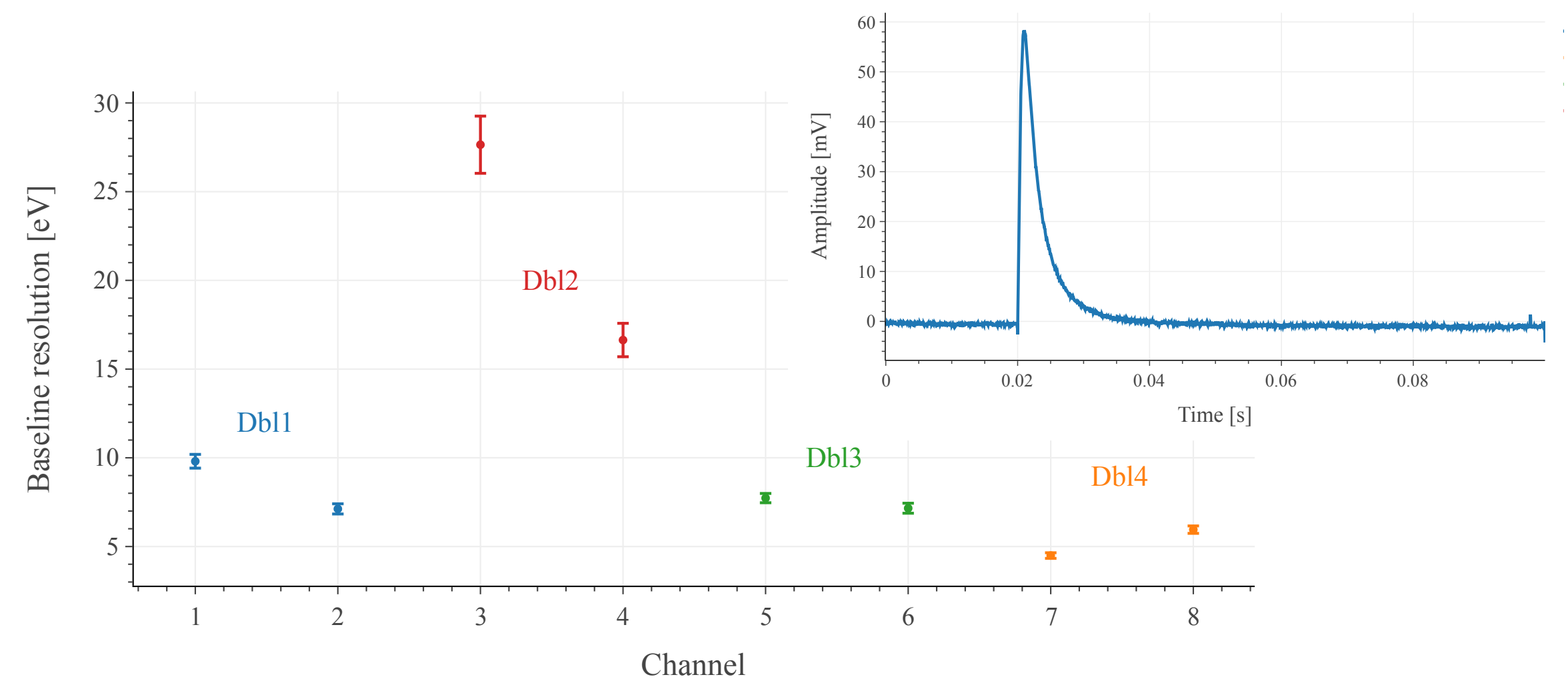
DPhP
DPhN
DEDIP
DIS



- ▶ External shields & cryogenic facility fully operational
- ▶ Cryogenic detector module commissioning on-going



First TES signals at Chooz

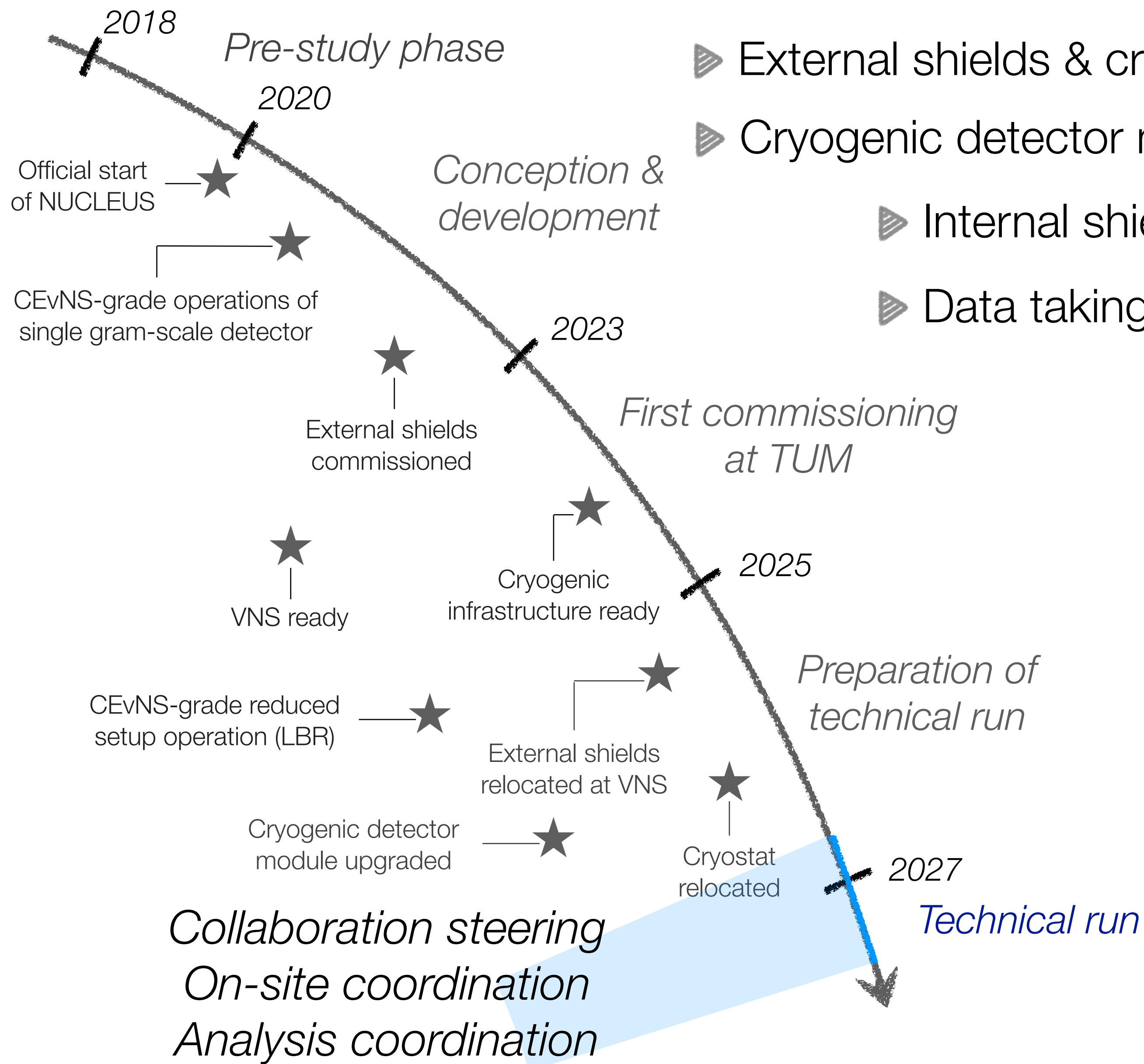


Commissioning status

- Successful thermalization < 10 mK
- TES detectors nearly on specs
- Remaining issues with COV (thermalization + electronics)...

Technical Run at Chooz: Next Steps

DPbP
DPbN
DEDIP
DIS



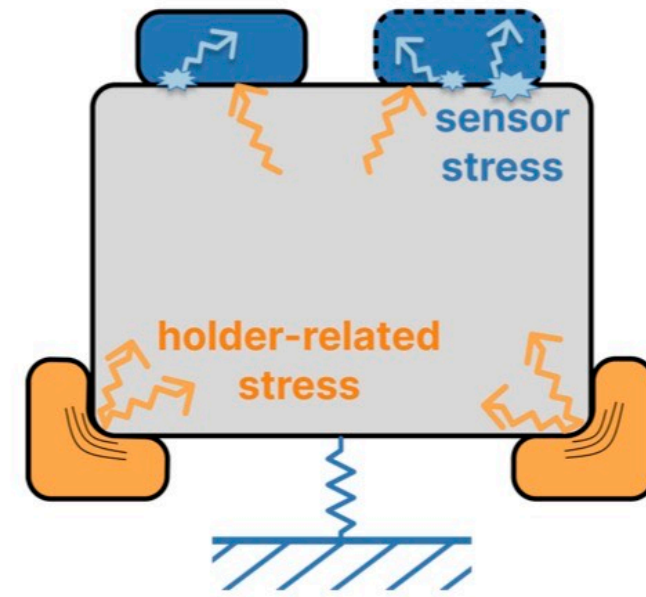
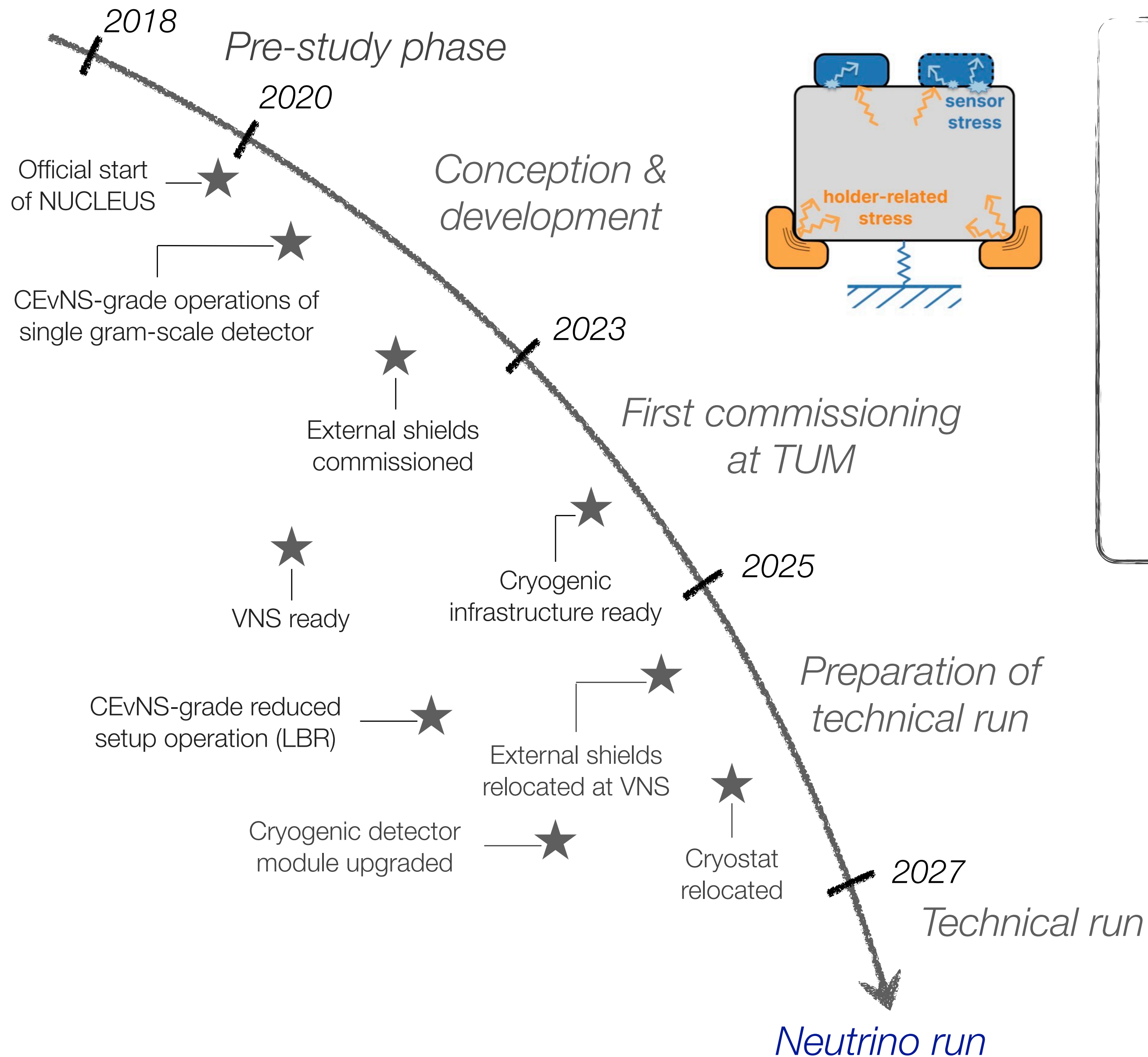
- ▶ External shields & cryogenic facility fully operational
- ▶ Cryogenic detector module commissioning on-going
 - ▶ Internal shield installation (October)
 - ▶ Data taking start (planned in November)



Goals

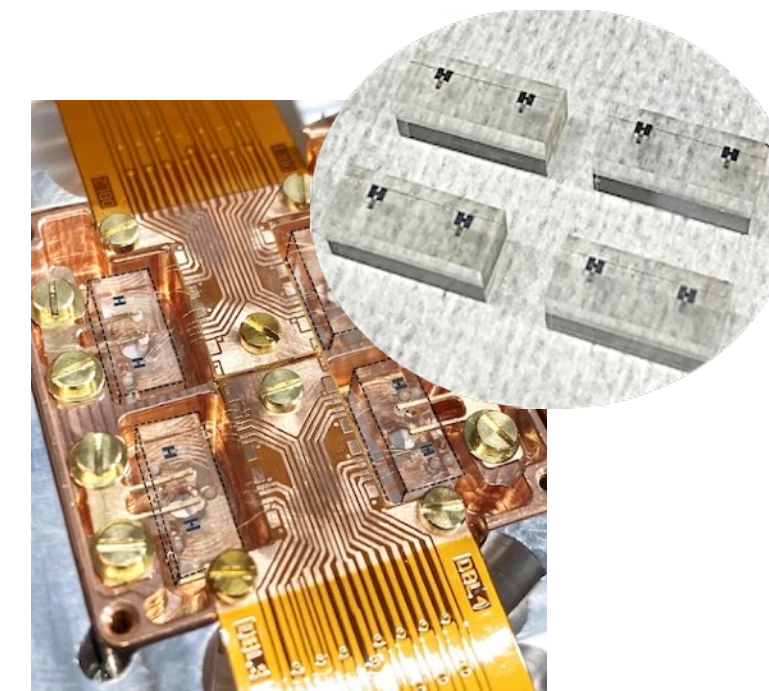
- ▶ Run in “experiment mode”
 - Demonstrate experimental infrastructure at Chooz
 - Practice data-taking over month-long periods (reactor ON & OFF)
 - Coordinated analysis and simulation effort
- ▶ Fine characterization of backgrounds
 - Particle backgrounds + test of shielding strategy
 - LEE
- ▶ Prepare for neutrino run

Toward Neutrino Run

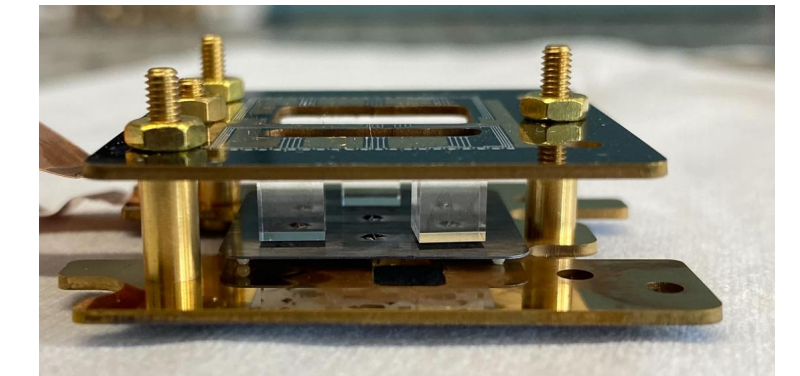
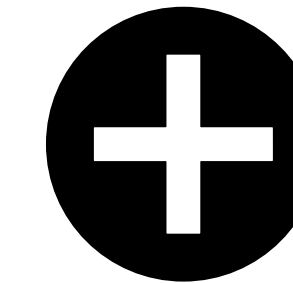
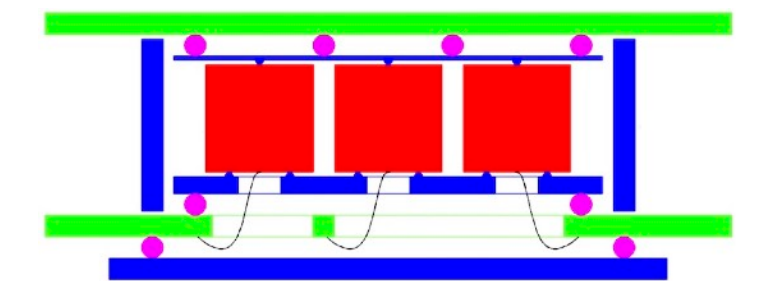


LEE rejection strategy

Double-TES detectors
(sensor-related)



Inner veto = 2 Si wafers with TES
(holder-related)

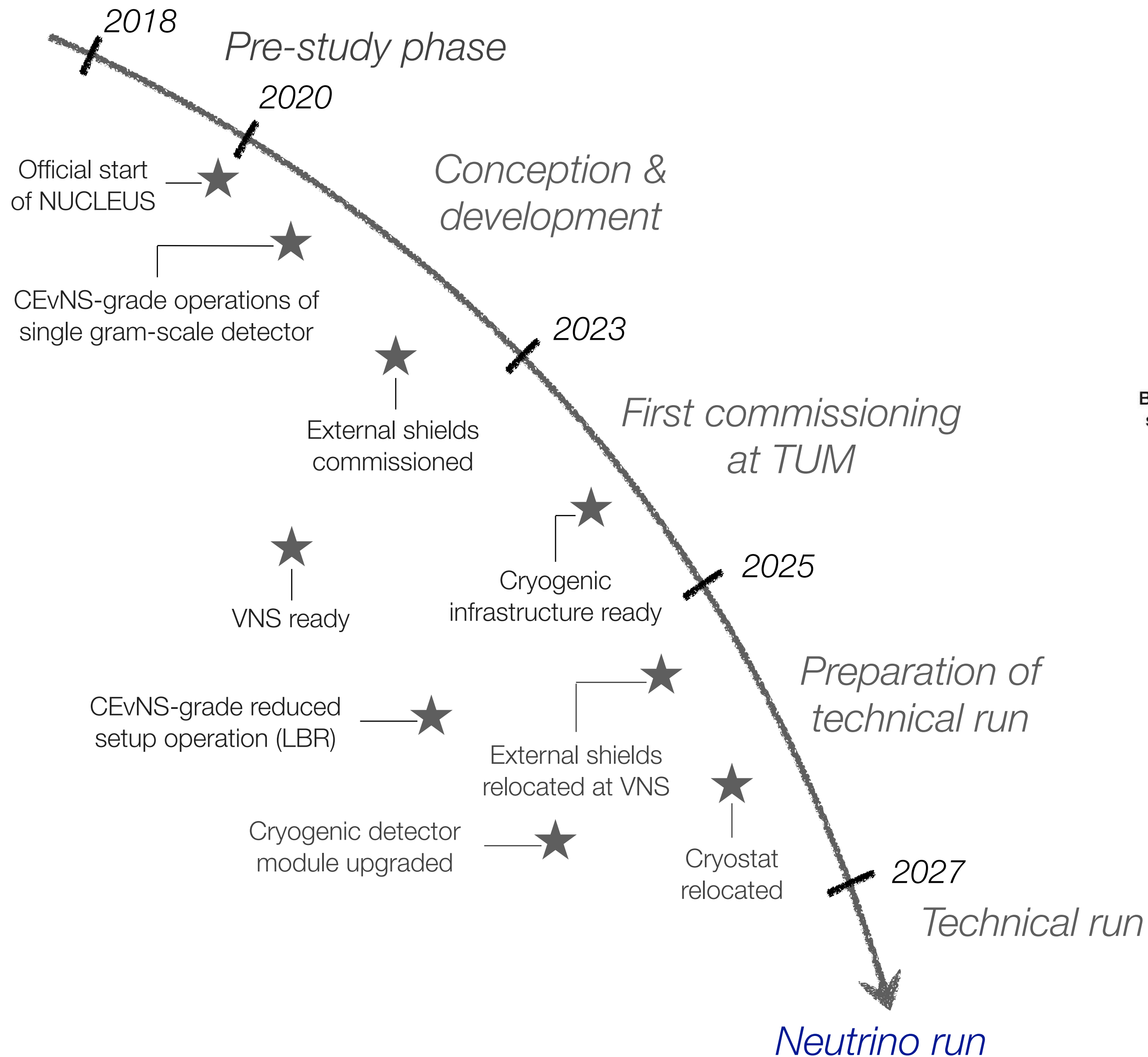


Development work on-going at TUM

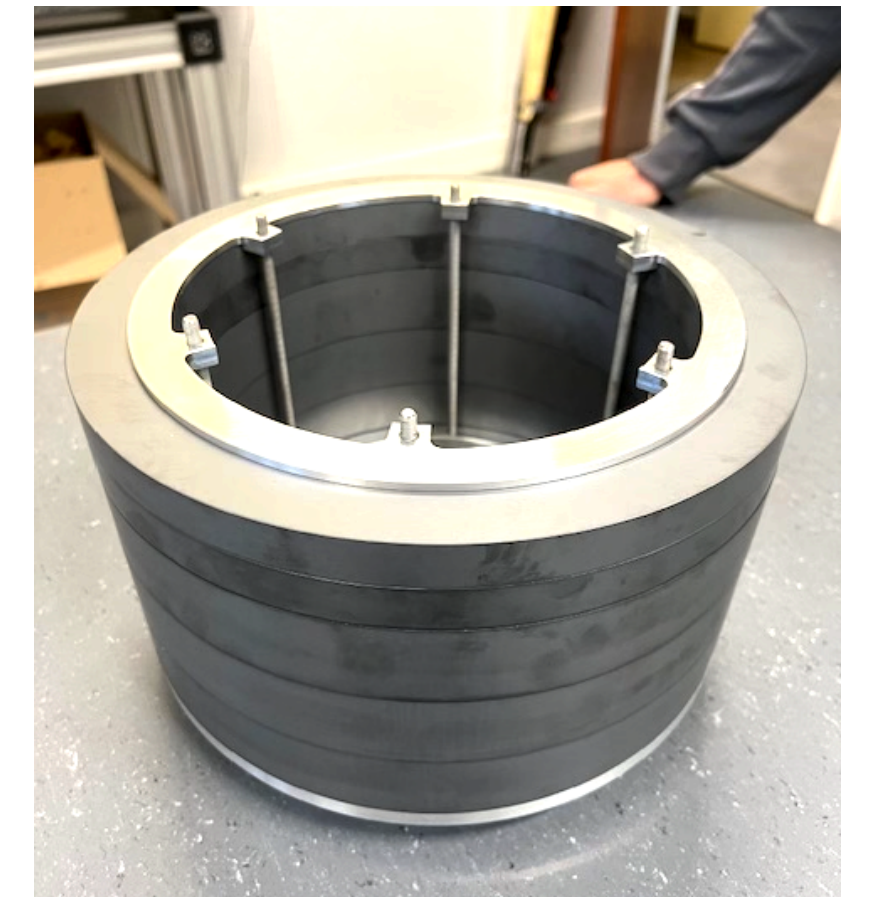
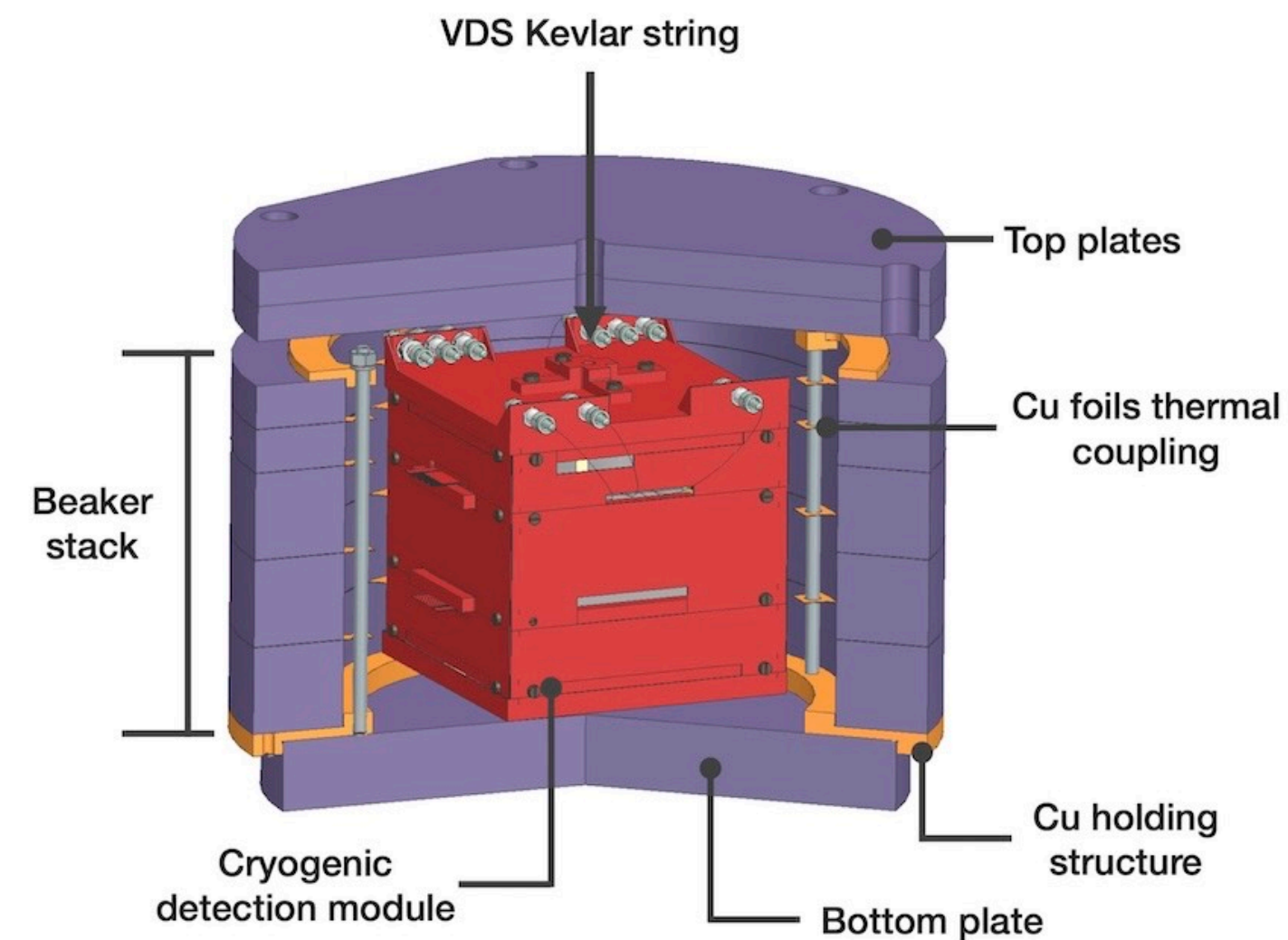
- Mechanical and thermalization concept demonstrated
- First version with one CaWO_4 detector operational → characterization & optimization on-going
- Second version with 4 CaWO_4 detectors in preparation
- Upgrade of detection module with IV system after technical run (end of 2027)

Toward Neutrino Run

DPhP
DIS
DEDIP



Integration of the B₄C cryogenic neutron shield



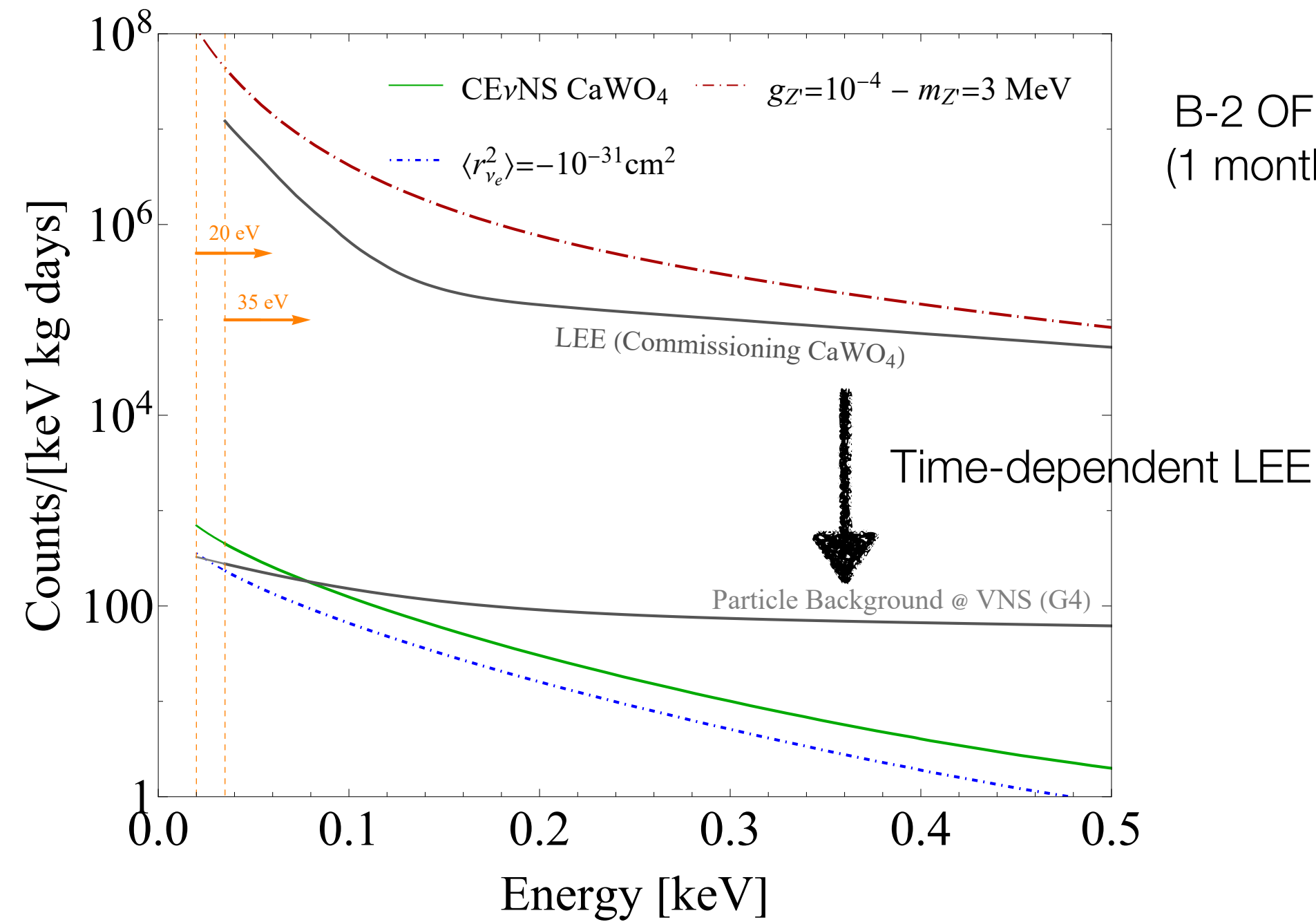
- Design proposed by CEA/Irfu
- Integration work after technical run:
 - ◉ Demonstration of mechanical & thermalization concept
 - ◉ Validation of interfaces with cryogenic detection module (very tight spatial constraints!)

Phase-I Sensitivity Projections

DPhP

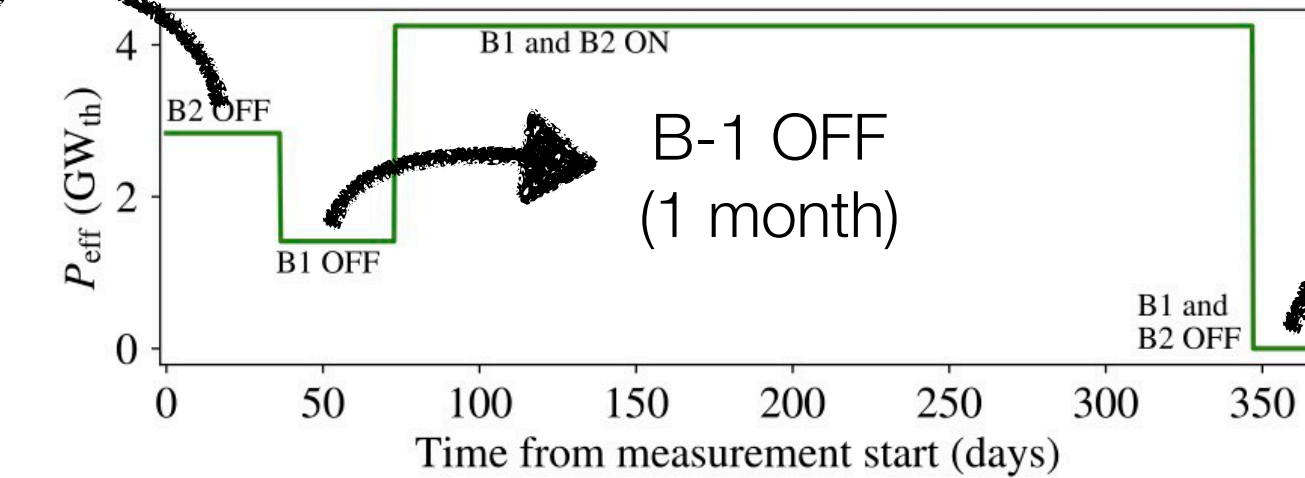
Signal & background modeling at VNS

[PRD 2026]

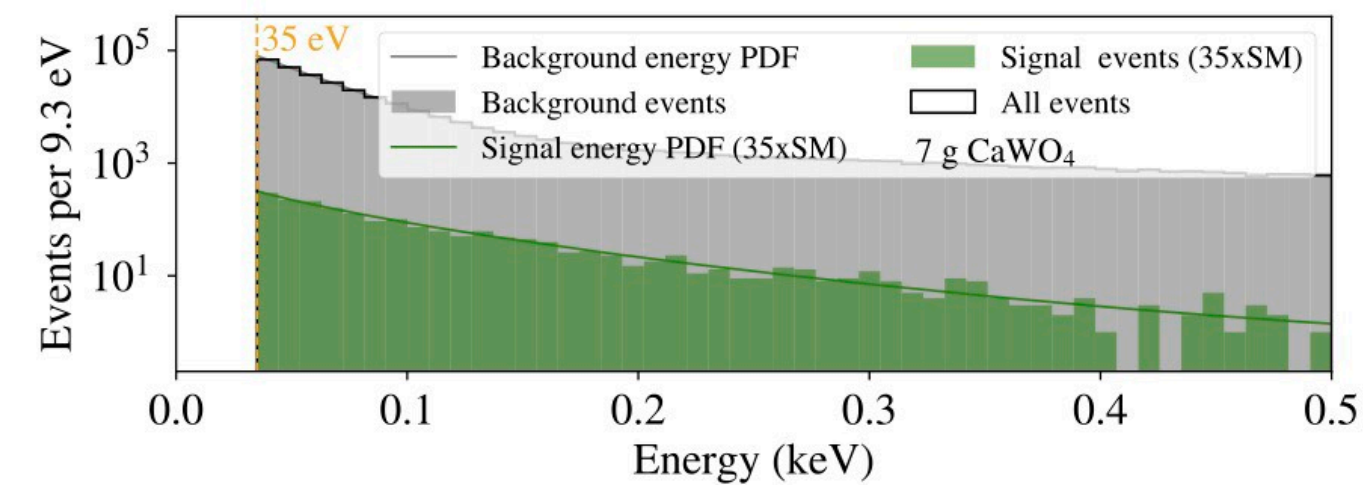
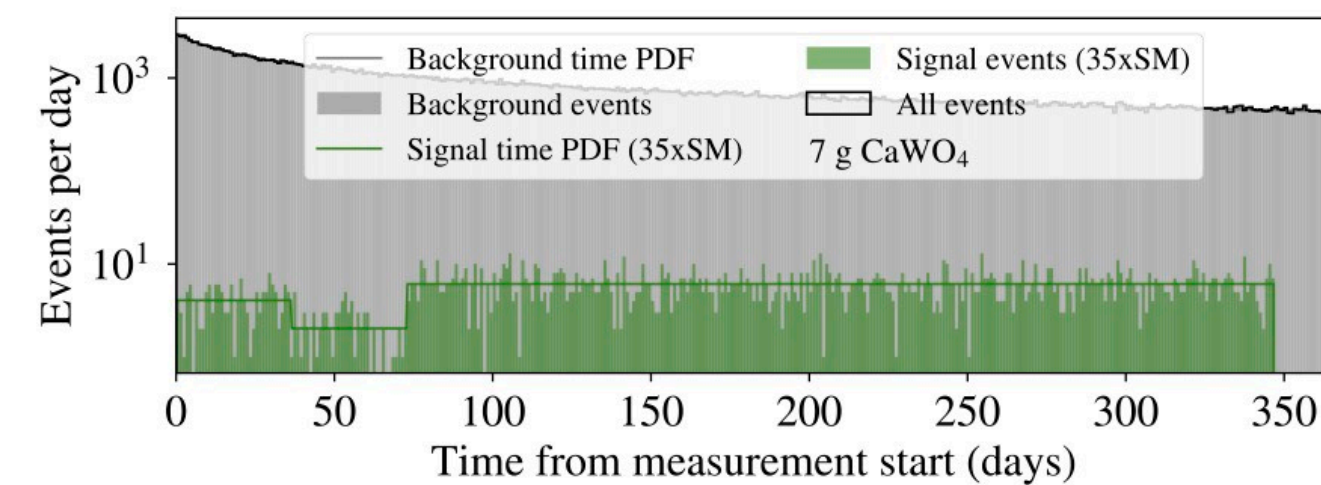


Reactor rate modulation + spectral shape analysis

B-2 OFF
(1 month)

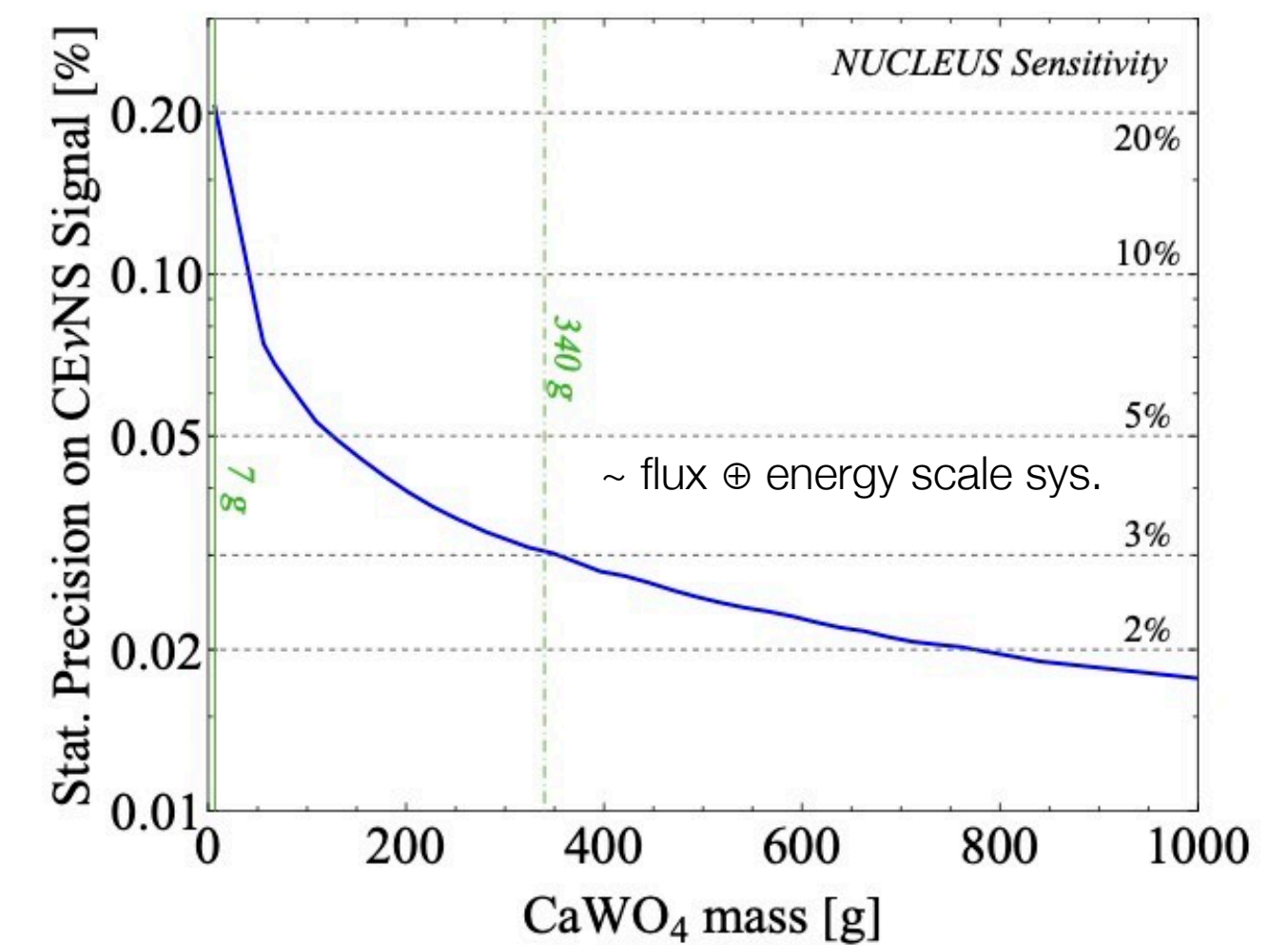


OFF-OFF
(15 days)



Sensitivity estimates

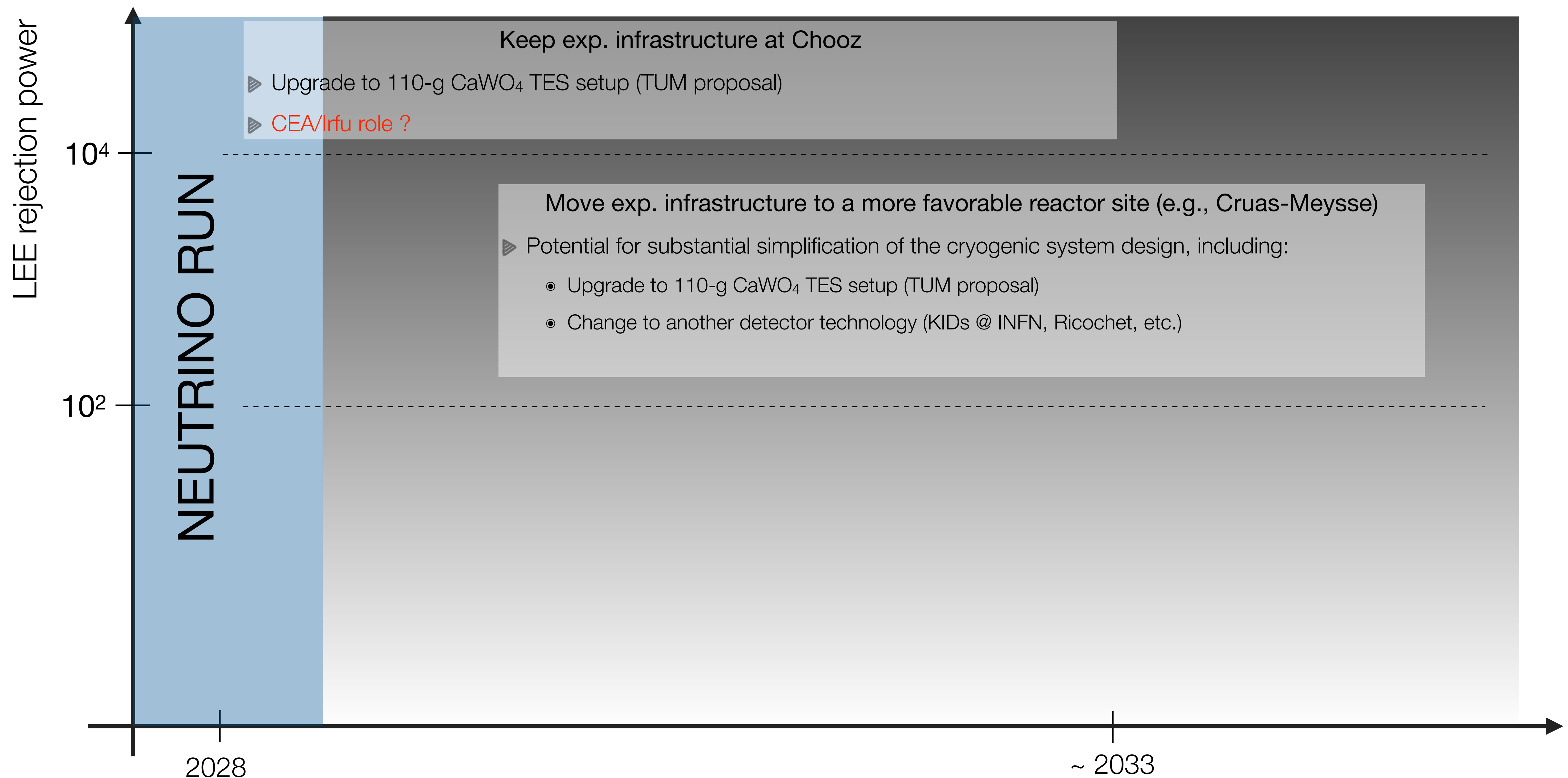
- Technical run: $< 35 \times \text{SM}$ (90% C.L.)
- Neutrino run: 4.7σ median discovery



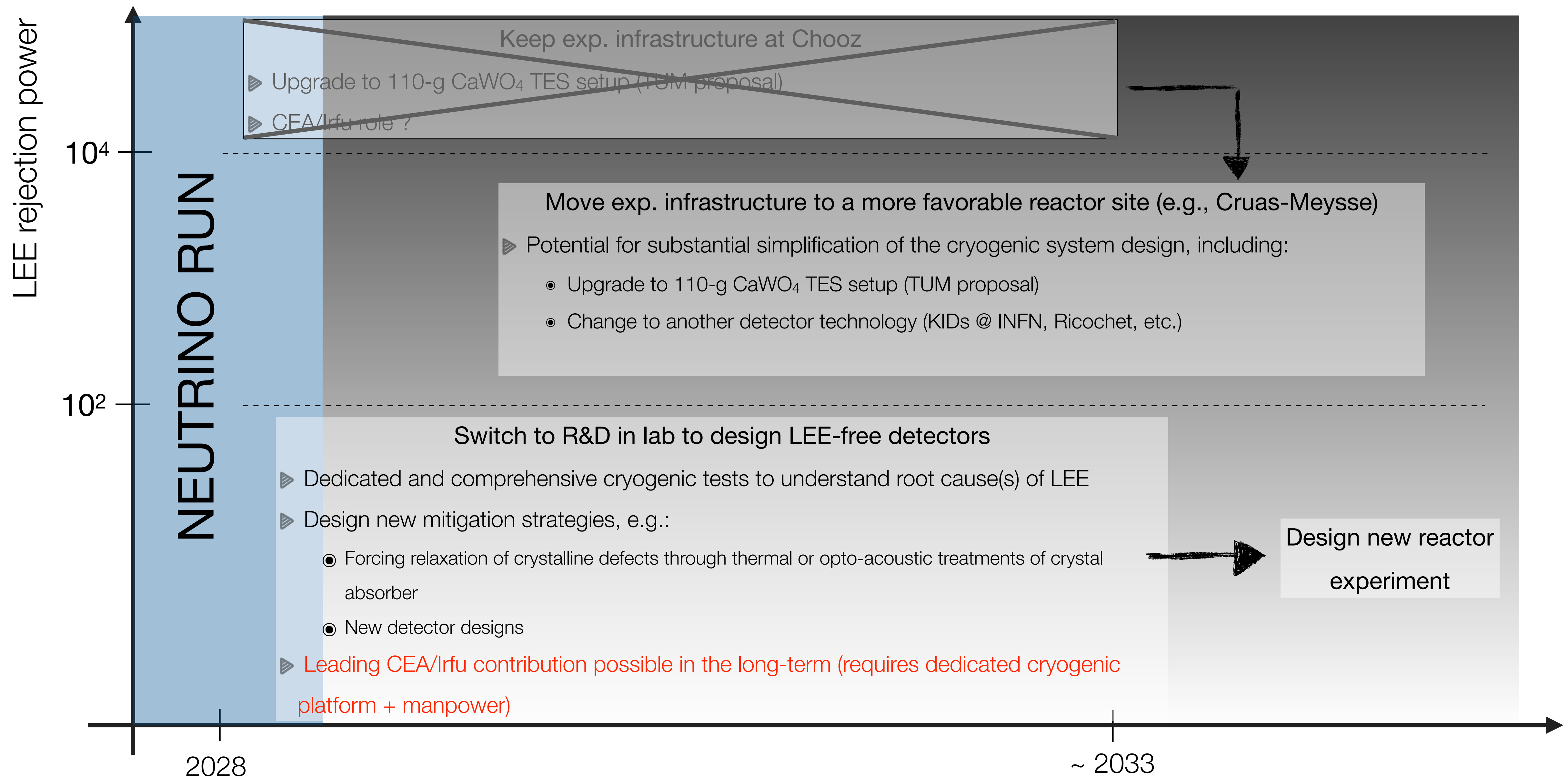
Bounding scenarios

- 7-g CaWO_4 + full shielding + 1 year of data taking
 1. Technical run: no LEE mitigation + LBR thr. (35 eV)
 2. Neutrino run: full LEE mitigation + 20 eV thr.

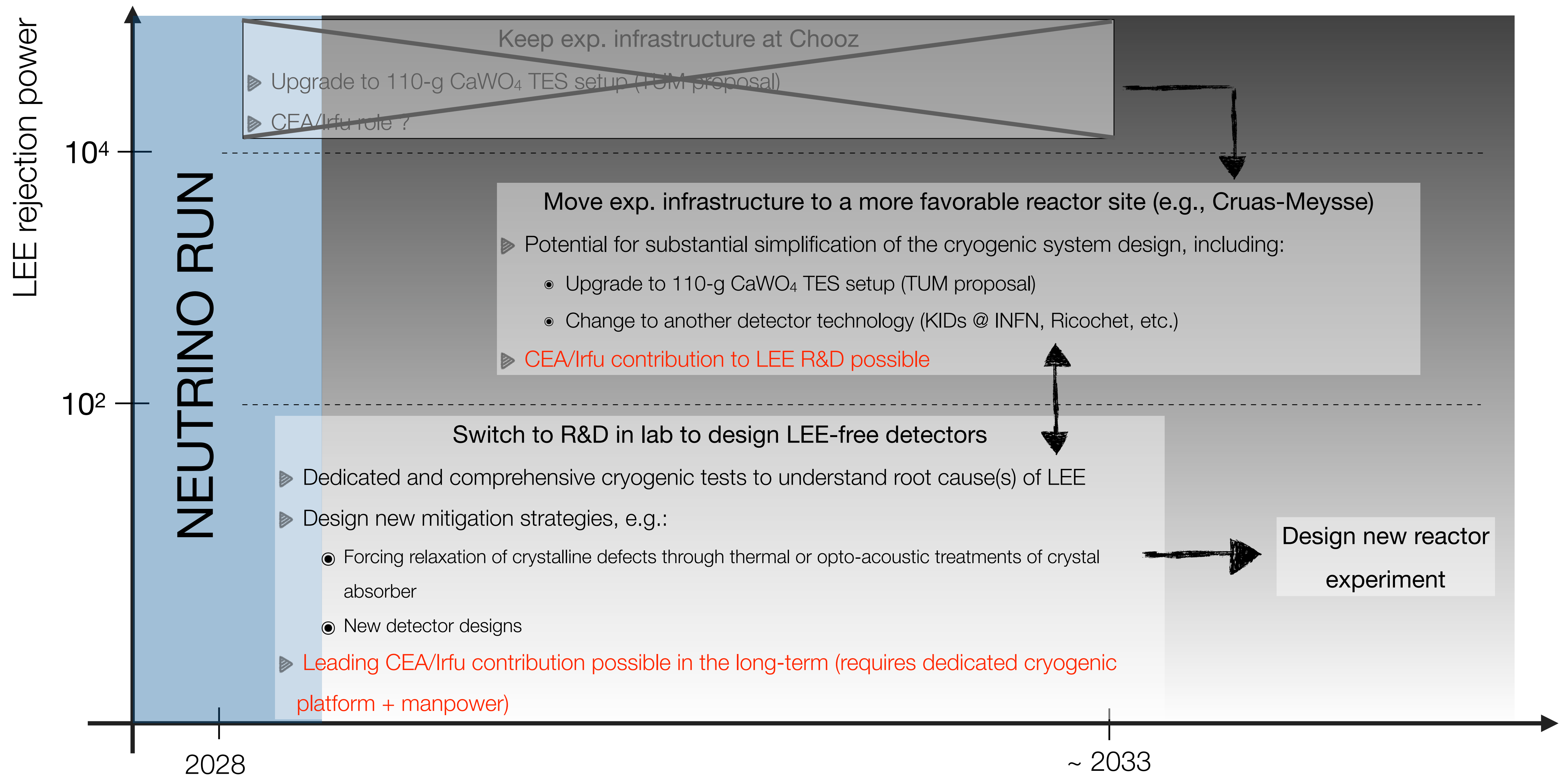
Possible steps after phase-I ?



Possible steps after phase-I ?

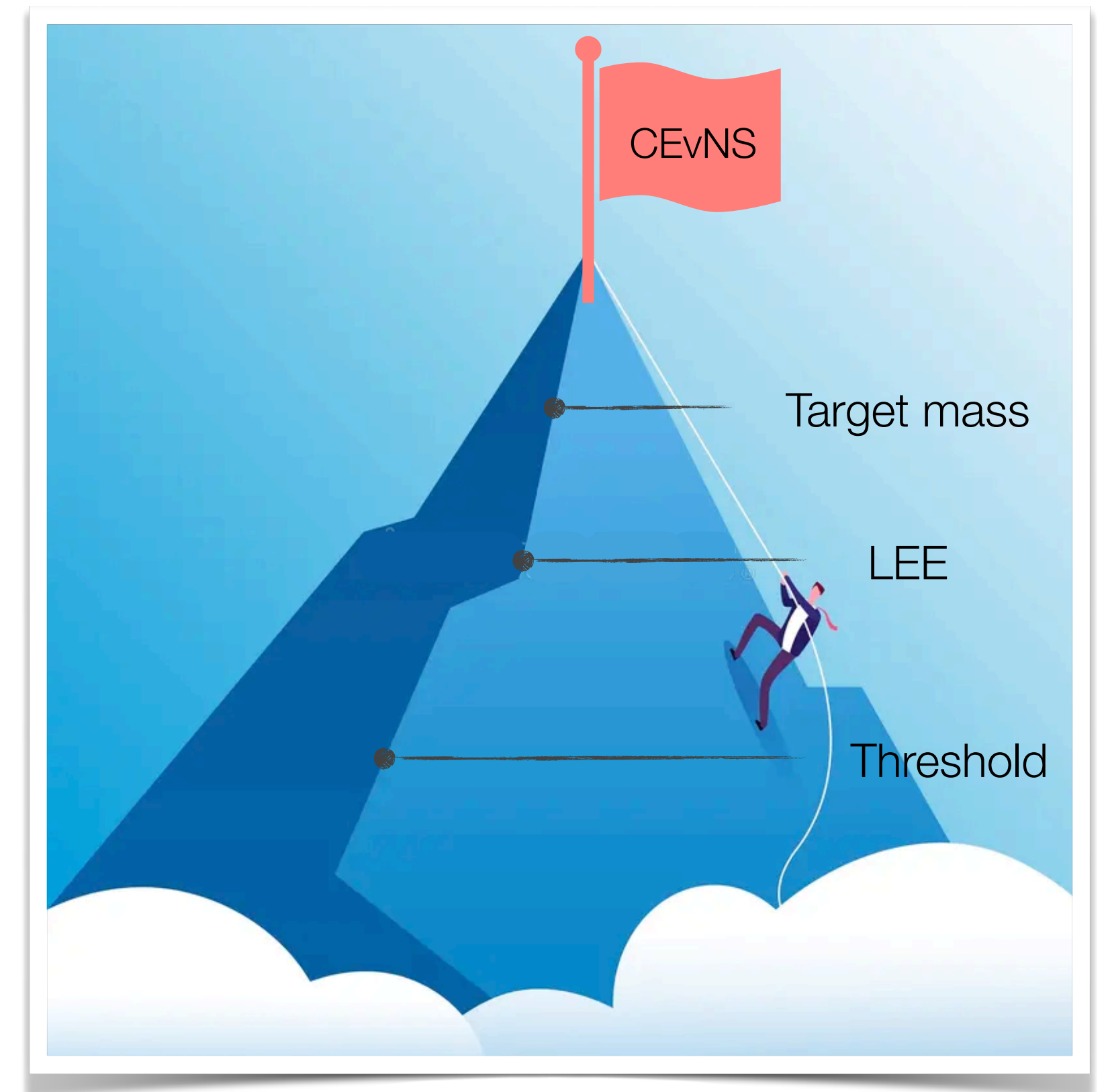


Possible steps after phase-I ?



Summary and Outlooks

A long climb still ahead...



Summary and Lessons Learned

- ▶ NUCLEUS = technological pathfinder for the cryogenic detection of reactor neutrinos through CEvNS
 - ▶ Much progress has been made despite highly sophisticated design and subsequent technical challenges → soon first reactor data at Chooz !
 - ▶ Neutrino signal currently hindered by LEE background → final setup to be upgraded with inner veto concept (and B₄C neutron shield) in 2027
 - ▶ Neutrino run planned in 2028 meant to assess rejection of LEE and detectability of neutrinos with TES technology
 - ▶ No clear positioning on the future of the experiment possible until then, even though discussions with key actors in the field (Ricochet, CONUS) have started
-
- ▶ Highly complex (cryogenic) system → many technical issues + lot of delays
 - ▶ Cryogenic detector development centralized at TUM + almost no handle on the associated work packages & plannings → many frustrations despite efforts to diagnose problems and propose solutions

Outlooks for CEA/Irfu

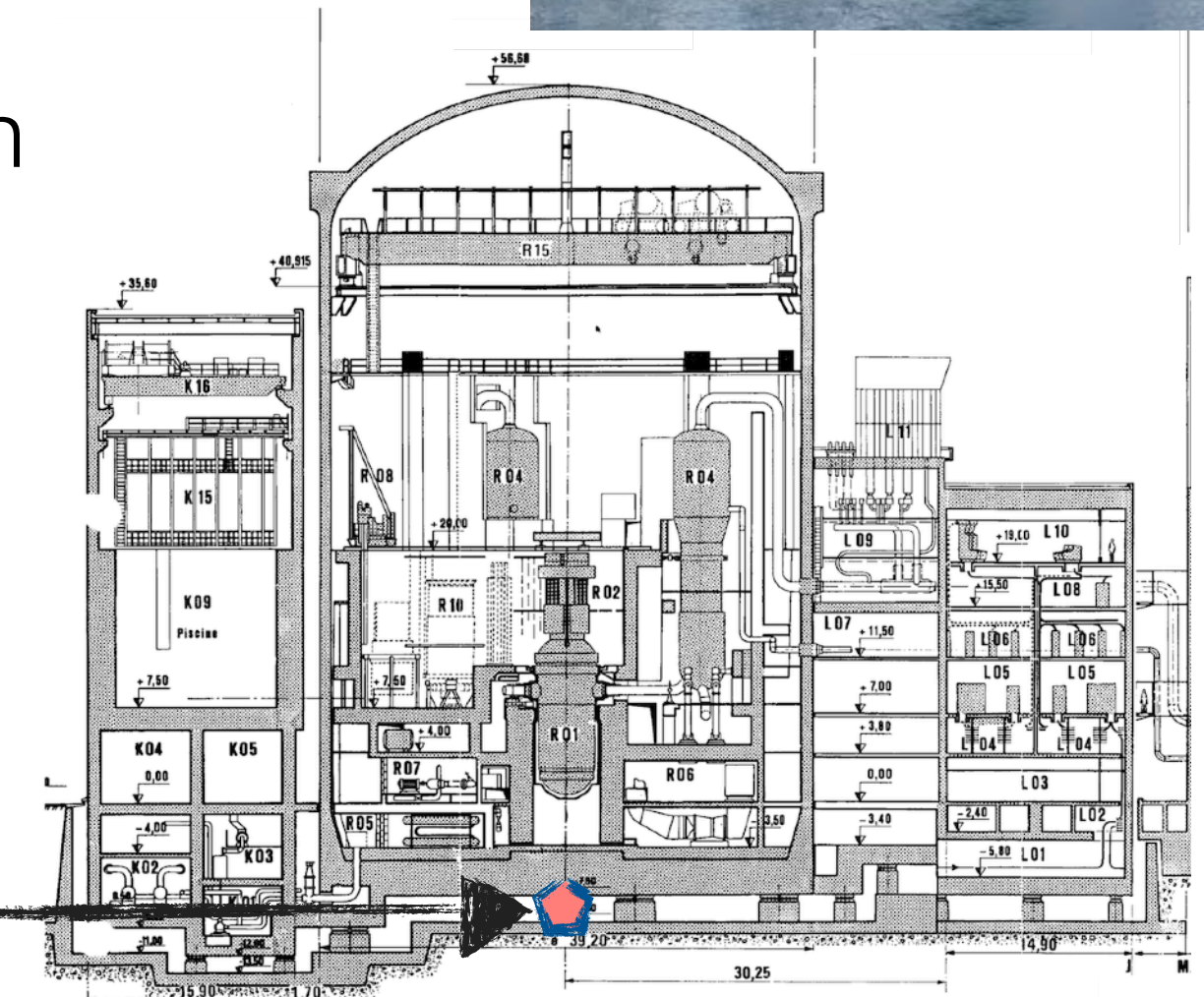
- ▶ Even though not yet successful, CEvNS detection of reactor antineutrinos is of strategic interest for CEA/Irfu:
 - SM model test at unprecedented low-energies + BSM searches in the Neutrino sector
 - Obvious applications for nuclear energy and non-proliferation, which falls within CEA's core missions
- ▶ Demonstrating and implementing the technique at nuclear reactor is a long-term (> 10 yr) effort
- ▶ Cryogenic resources & manpower very limited, with two consequences:
 1. No handle on the cryogenic detector work package along the NUCLEUS project
 2. Need to go back to a well-defined and organized instrumentation R&D in our lab

Cruas-Meyssse (Ardèche)



- ▶ Emerging ideas for innovative detector developments using the IBD technique, with a focus on nuclear energy and non-proliferation applications
- ▶ Recent and promising opportunity with the Cruas-Meyssse nuclear power plant
- ▶ Clear and motivated synergy with DPhN

Promising neutrino sites !



Backup slides

NUCLEUS publications with leading CEA/Irfu contrib.

[ArXiv 2026] : “Development and Commissioning of the Cryogenic Target Detectors for the Technical Run of the NUCLEUS Experiment”, N. Schermer et al. (2026)

[JINST 2026] : “Sensitivity enhancement techniques for cryogenic calorimeters in the NUCLEUS experiment”, M. Cappelli et al. (2026)

[PRD 2026] : “Prospect of the NUCLEUS experiment at Chooz for coherent elastic neutrino-nucleus scattering and new physics searches“, H. Abele et al. (2026)

[EPJC 2026b] : “Characterization of the low energy excess using a NUCLEUS Al₂O₃ detector”, H. Abele et al. (2026)

[EPJC 2026a] : “Particle background characterization and prediction for the NUCLEUS reactor CEvNS Experiment”, H. Abele et al. (2026)

[PRD 2025] : “Commissioning of the NUCLEUS Experiment at the Technical University of Munich”, H. Abele et al. (2025)

[JLTP 2025] : “Sub-keV Electron Recoil Calibration for Macroscopic Cryogenic Calorimeters Using a Novel X-ray Fluorescence Source”, H. Abele et al. (2025)

[NIM A 2024] : “Prototyping a High Purity Germanium cryogenic veto system for a bolometric detection experiment”, C. Goupy et al. (2024)

[PRL 2023] : "Observation of a Nuclear Recoil Peak at the 100 eV Scale Induced by Neutron Capture”, H. Abele et a. (2023)

[JINST 2022] : “Development of a compact muon veto for the Nucleus experiment”, V. Wagner et al. (2022)

[EPJC 2019] : “Exploring CEvNS with NUCLEUS at the Chooz nuclear power plant”, G. Angloher et al. (2019)

NUCLEUS team at CEA/Irfu

DPhP

- M. Vivier (PI)
- T. Lasserre (2020-2026)
- C. Nones (2020-2023)
- E. Mazzucato (2022-2023)

DEDIP

- F. Jeanneau (project manager)
- M. Lefèvre (2020-2025)
- F. Popieul

DIS

- L. Scola
- H. Neyrial
- G. Coulloux (2020-2023)

DPhN

- D. Lhuillier

Non-permanent

- V. Wagner (post-doc, 2018-2020)
- R. Rogly (PhD, 2019-2022)
- C. Goupy (PhD, 2021-2024)
- R. Martin (PhD, 2022-2025)
- E. Bossio (post-doc, 2023-2026)
- L. McCallin (PhD, 2024-2027)