NUCLEUS & CRAB Experiments

Technical Meeting on Nuclear Data Needs
for Antineutrino Spectra Applications

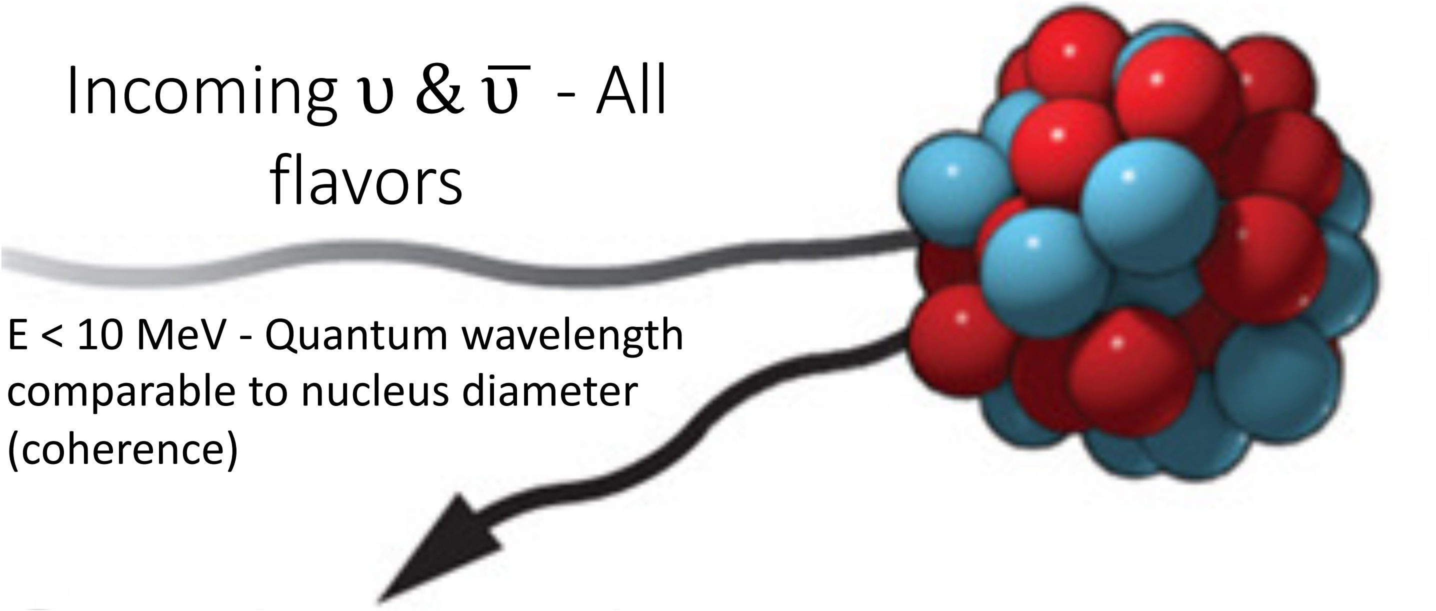
IAEA Headquater, Vienna, 16/01/2023

Thierry
Lasserre

on behalf of the NUCLEUS / CRAB collaborations

Coherent elastic neutrino nucleus scattering

Cross-section x 100-1000 with respect to other
ν detection channels → detector miniaturization

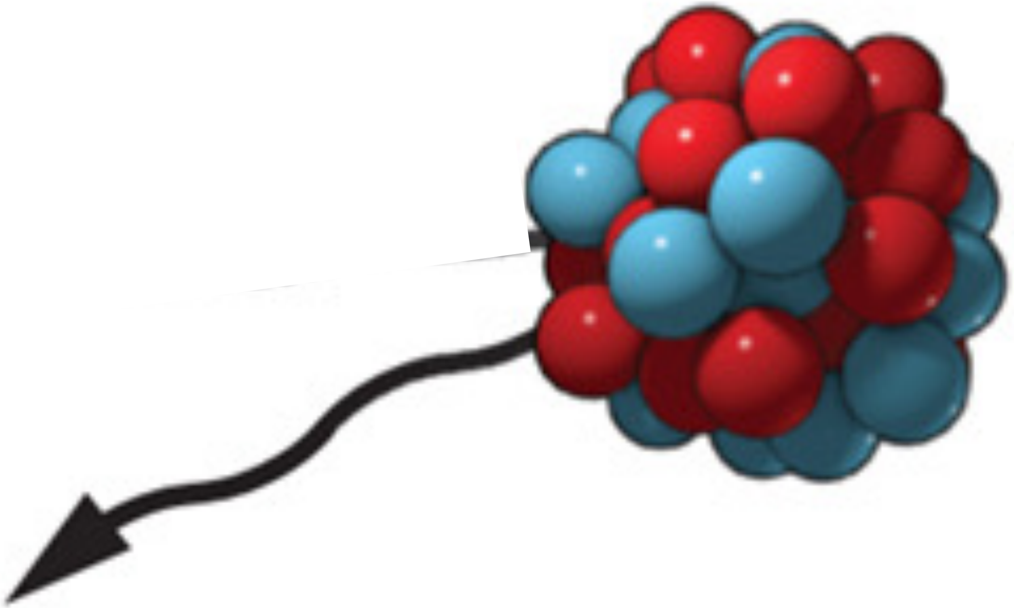


Incoming υ & $\bar{\upsilon}$ - All flavors

E < 10 MeV - Quantum wavelength comparable to nucleus diameter (coherence)

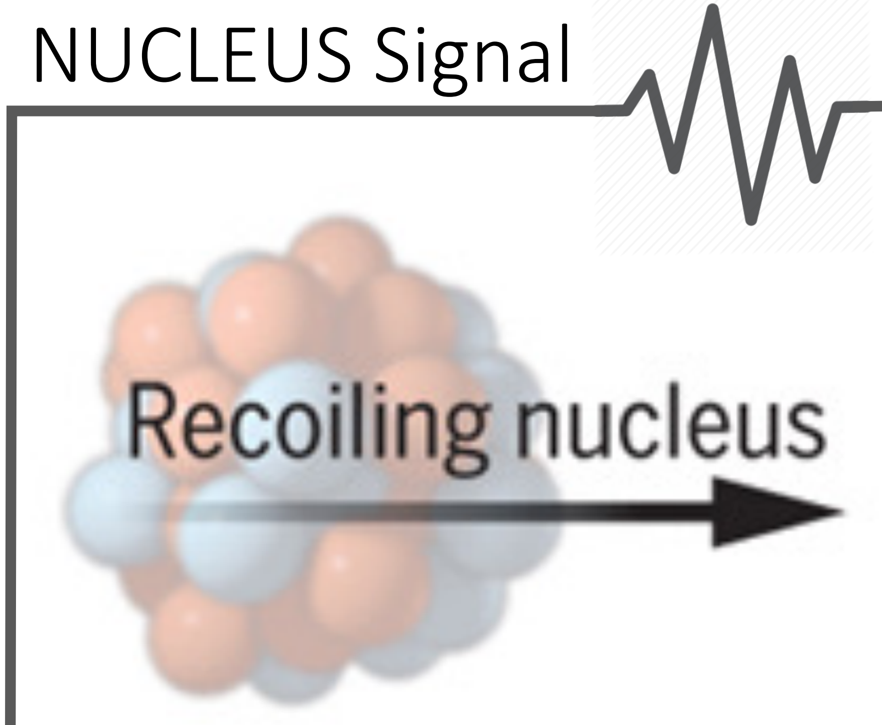
Same outgoing υ

Coherent elastic neutrino nucleus scattering



Same outgoing υ

NUCLEUS Signal



Nucleus recoils as a solid body

- → O(100 eV) energy deposition: faint signal
- → Hard to discriminate against backgrounds
- → Not yet observed for reactor neutrinos !

EXPERIMENT nu cleus

NUCLEUS Collaboration

DE LA RECHERCHE À L'INDUSTRIE cea

Technische Universität München TUM

MAX-PLANCK-INSTITUT FÜR PHYSIK

INFN

SAPIENZA UNIVERSITÀ DI ROMA

eDF

cea

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

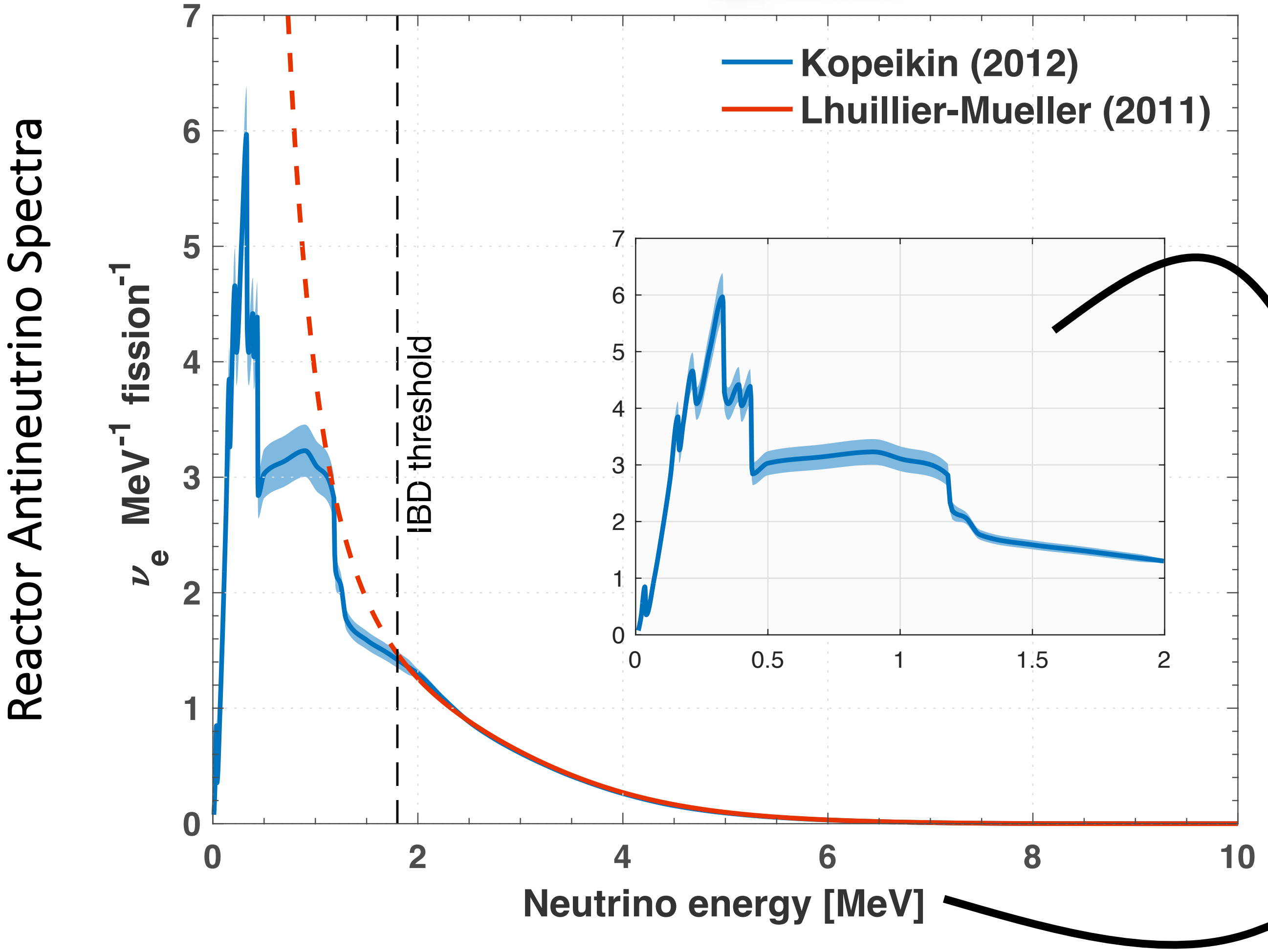
P2IO Physique des 2 Infinis et des Origines

erc European Research Council Established by the European Commission

TUM LMU ORIGINS Excellence Cluster ESO lrz

SFB 1258 Neutrinos Dark Matter Messengers

Reactor Antineutrinos Source

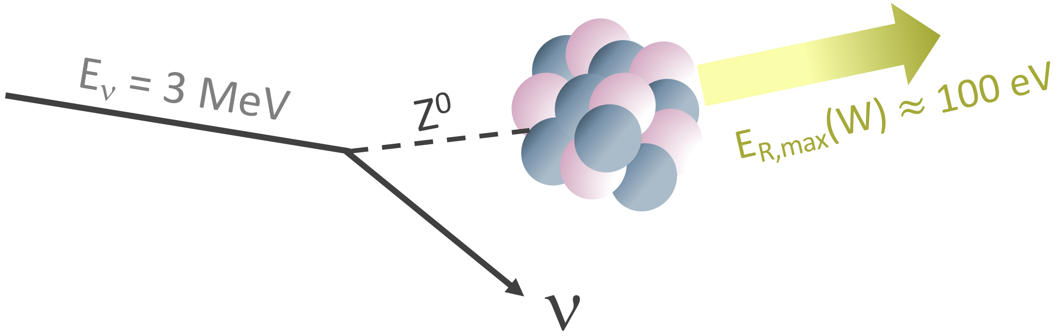


E<1.8 MeV region
→ Not yet explored!

MeV energies
→ full coherence
→ O(100eV) nuclear recoils

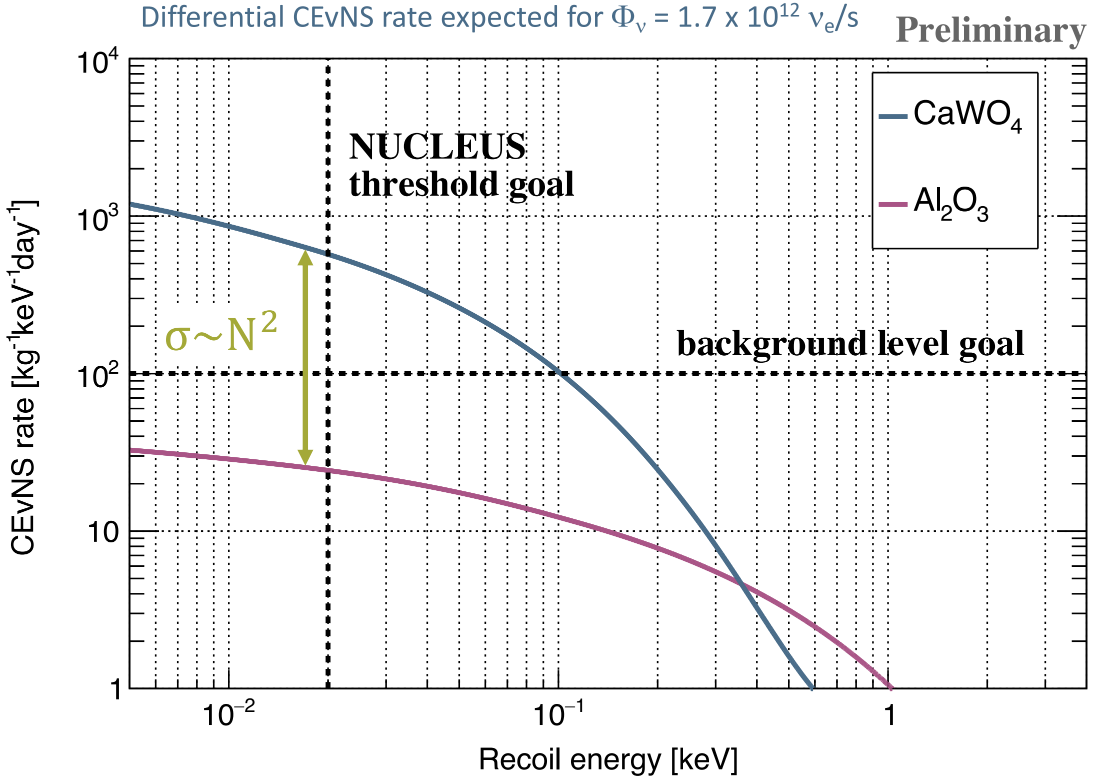
In NUCLEUS, less than the 10% of the neutrino detected will originated from E_ν<1.8 MeV

CEvNS @ reactor anti-neutrinos

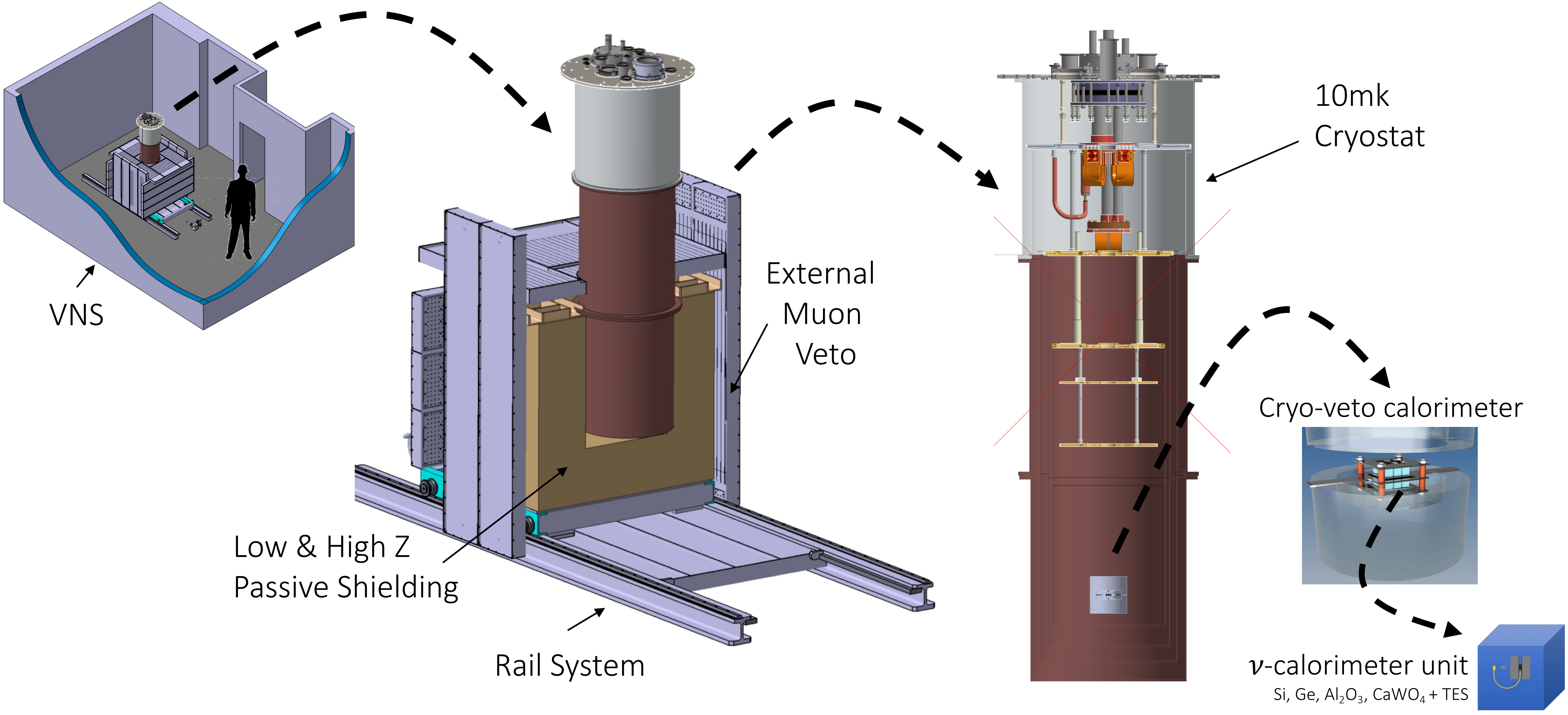


- E_ν < 8 MeV → fully coherent regime
- Induced nuclear recoil in sub-keV range
- Energy threshold and low background level are key parameters
- CEvNS of reactor anti-neutrinos has not been observed yet

Differential CEvNS rate expected for $\Phi_\nu = 1.7 \times 10^{12}\ \nu_e/s$



NUCLEUS Detector in a Nutshell



VNS

External Muon Veto

Low & High Z Passive Shielding

Rail System

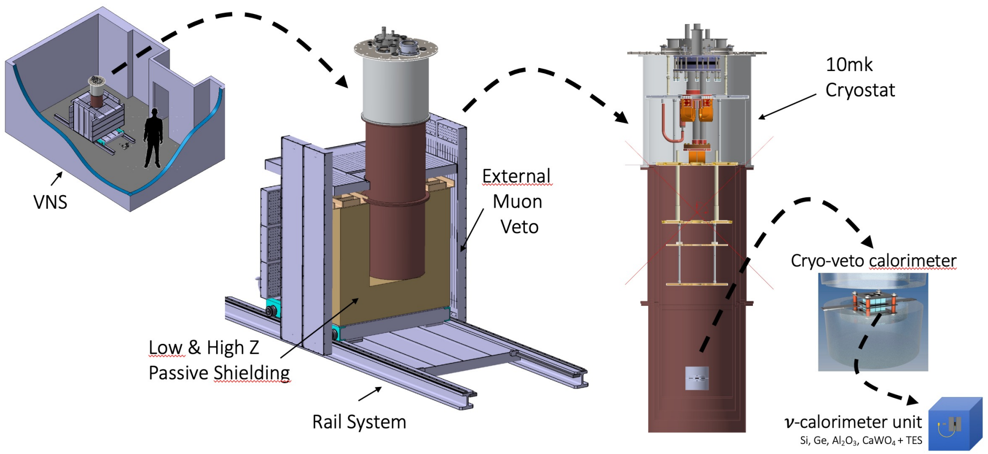
10mk Cryostat

Cryo-veto calorimeter

ν-calorimeter unit

Si, Ge, Al_2O_3, $CaWO_4$ + TES

Deployement Strategy



UL Garching, TUM

Blank Assembly – Background Validation

CNPE Chooz

Neutrino detection + First physics run

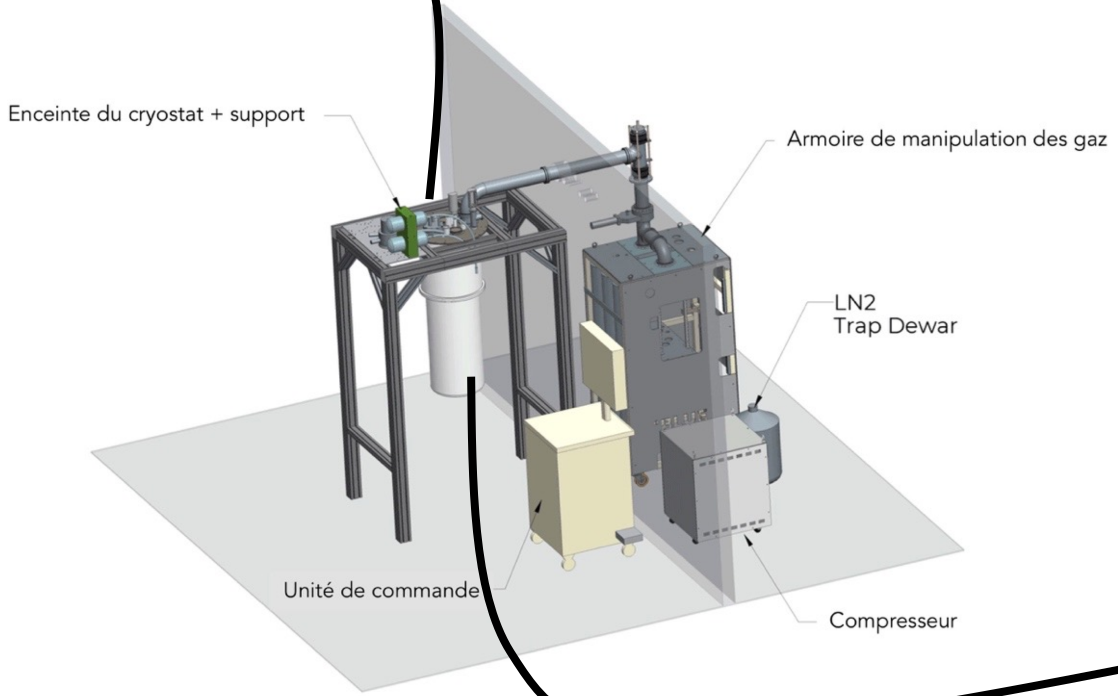
Background

≈

Cryostat Infrastructure (BlueFors)

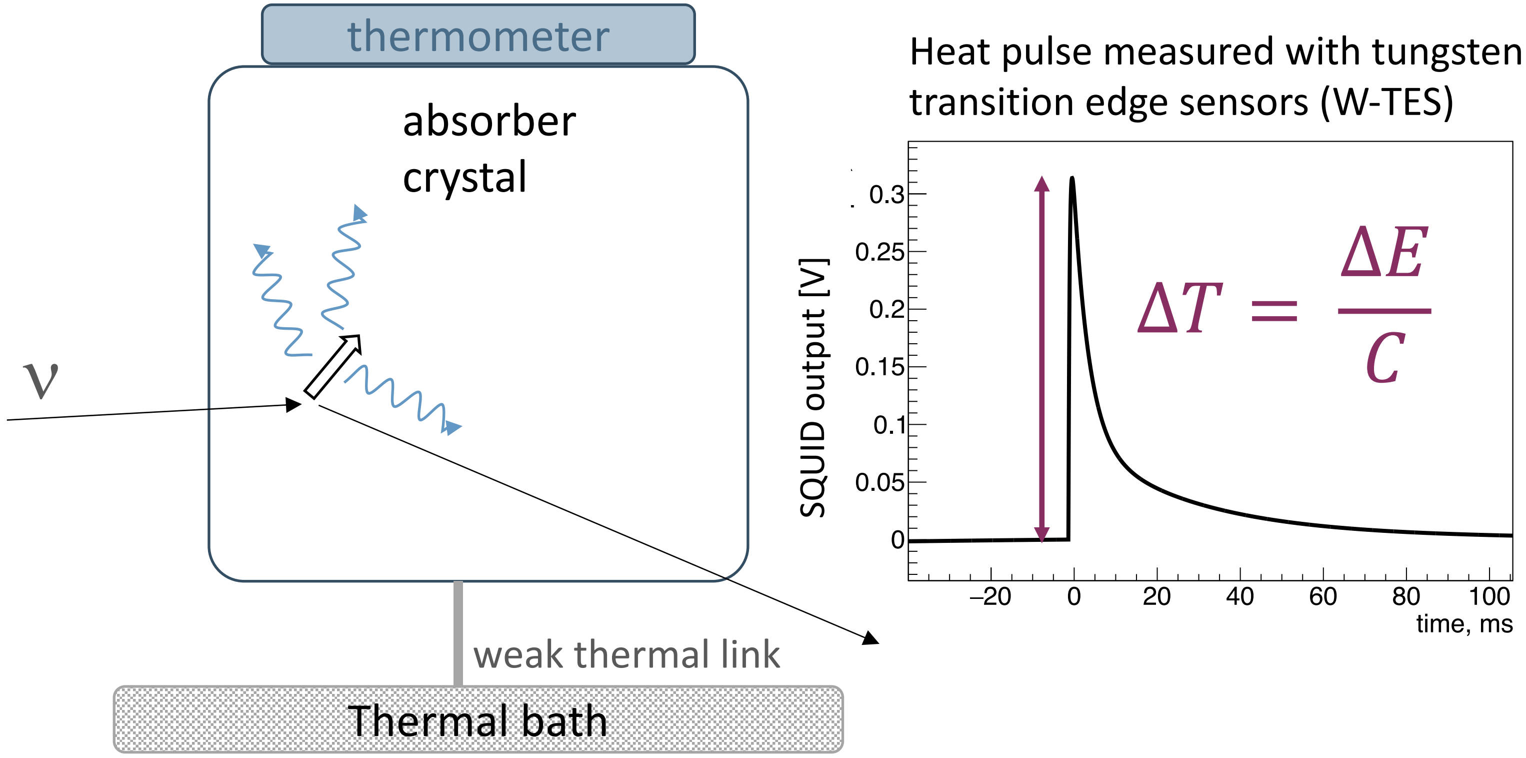
Vibration Decoupling System

mK Cryostat BlueFors LD400



Cryostat and auxillary systems

Cryogenic detectors



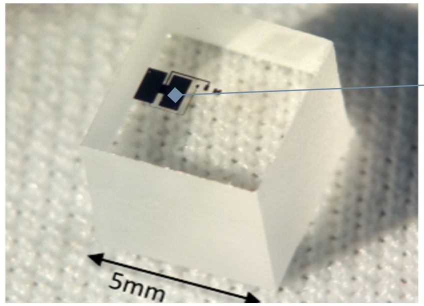
Heat pulse measured with tungsten transition edge sensors (W-TES)

- ✓ Achieve very low thresholds & excellent energy resolution
- ✓ Measure full recoil energy
- ✓ Independent of particle type
- ✓ Wide range of target materials
- ✓ Synergy with light-dark matter search: NUCLEUS is based on CRESST technology

NULCEUS Neutrino Targets

Target detectors

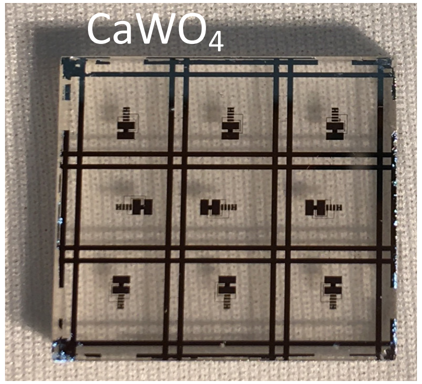
- ✓ $CaWO_4$ and Al_2O_3 crystals read-out with W-TES
- ✓ Based on CRESST technology
- ✓ Al_2O_3 prototype with threshold **$E_{th} = (19.7 \pm 0.8)\ eV_{nr}$**

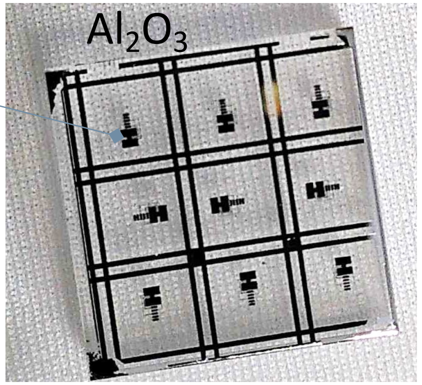


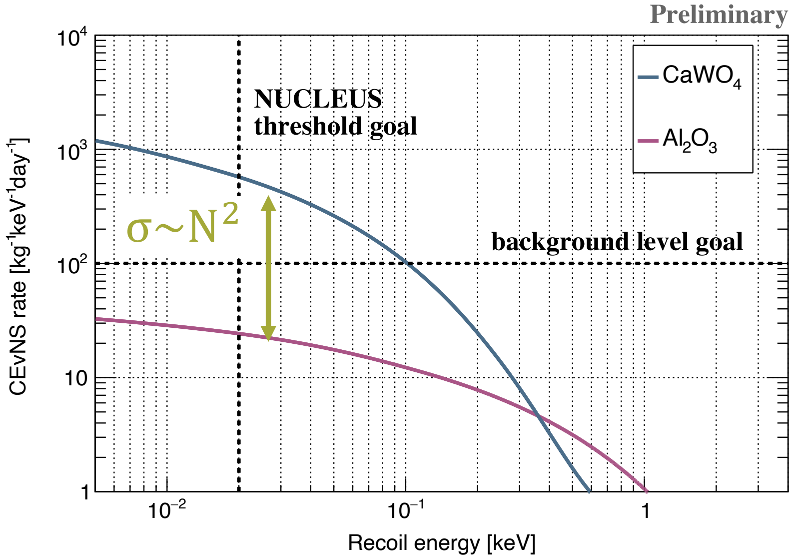
Phys. Rev. D **96**, 022009 (2017)

W-TES

Arrays before cutting with W-TES (20x20x5) mm³







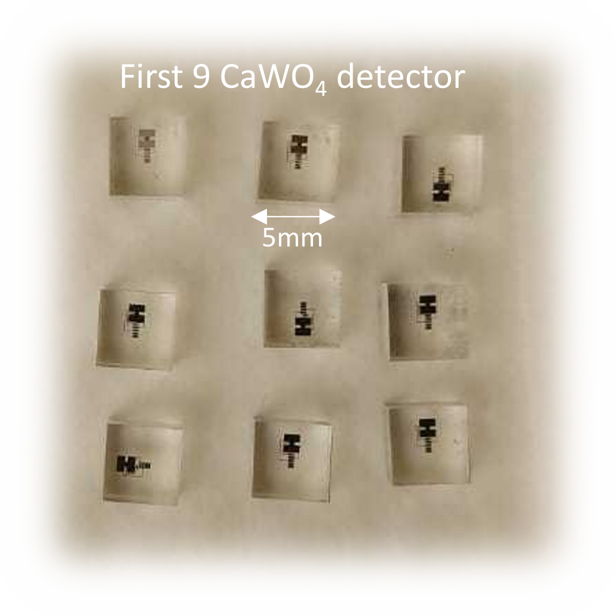
Multi-target approach

- $CaWO_4$: Background + CEνNS
- Al_2O_3 : Essentially background-only measurement

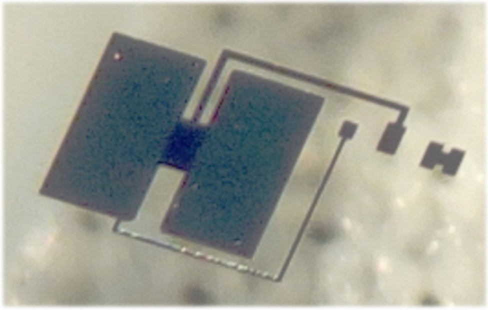
CaWO4 crystals operated at 15 mK

- ✓ 18 $CaWO_4$ crystals equipped with W-TES have been tested:
  sensitive TES has low transition temperature due to $\Delta T = \Delta E/C(T)$

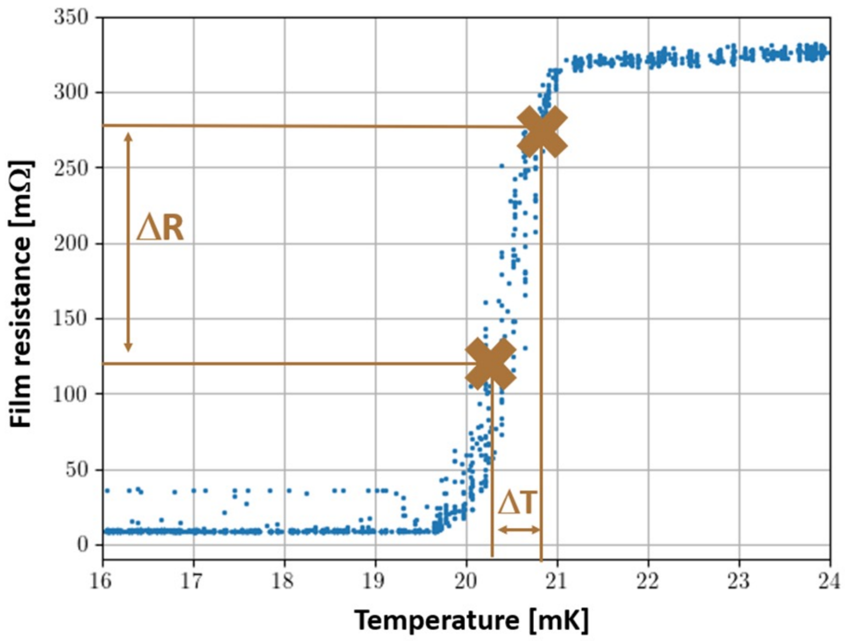
First 9 $CaWO_4$ detector



W-TES

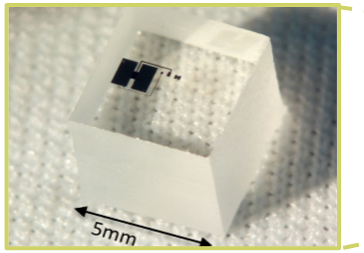


Transition of W-TES

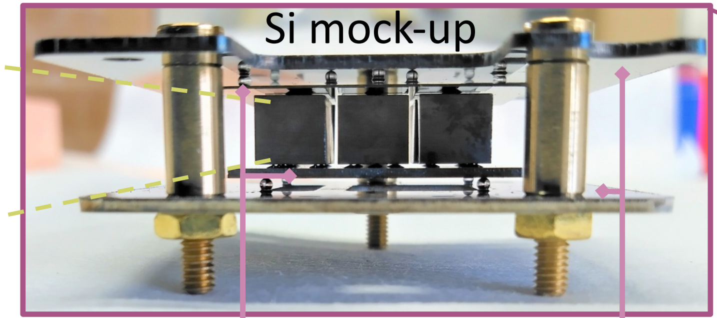


Target detectors enclosed in 4π active vetos

Target crystals:
Two 3x3 arrays with a total mass of
6g ($CaWO_4$) + 4g (Al_2O_3)



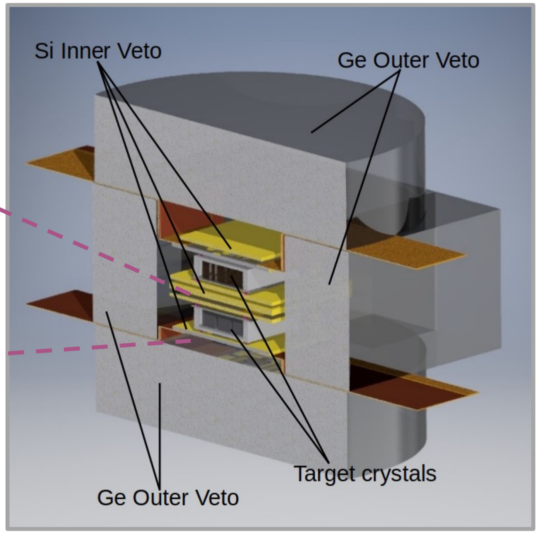
Inner veto: TES-instrumented holder
to reject surface backgrounds and holder-related events



Si wafer
+ W-TES

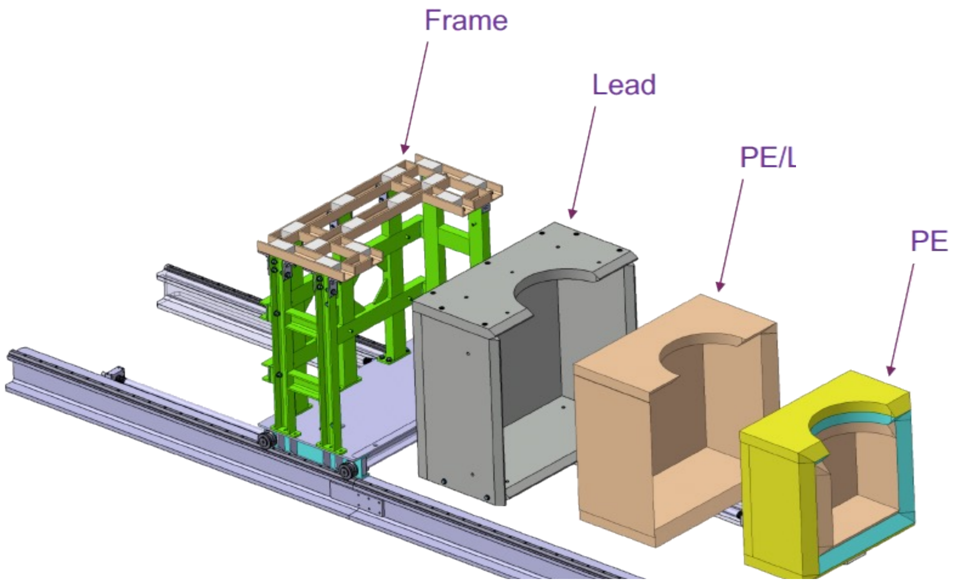
Holding plates
with electrical &
thermal contacts

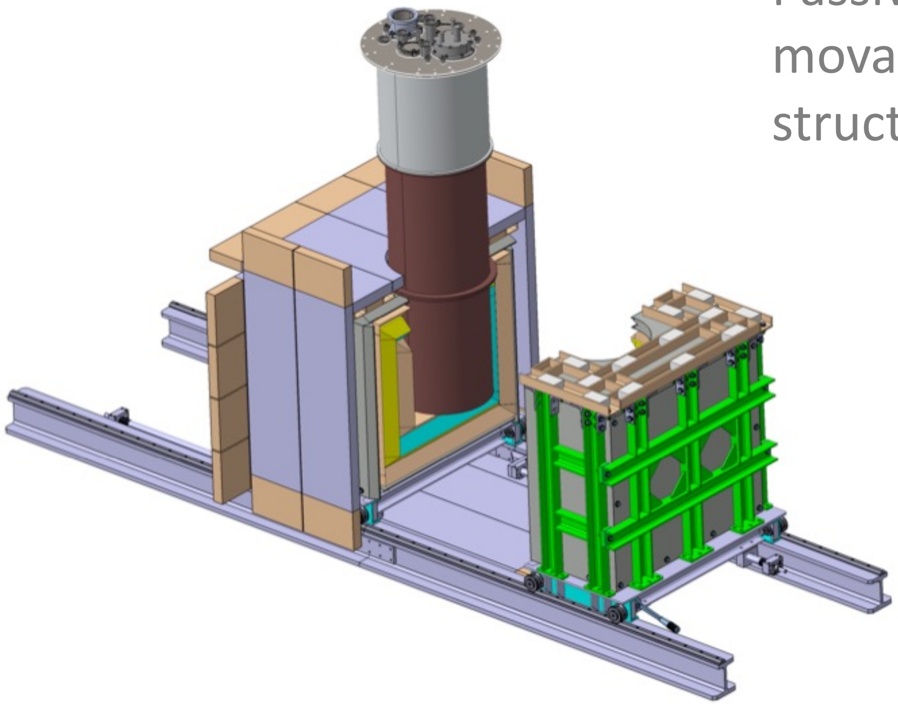
Germanium outer veto
for active γ/n background rejection



Multi-layer shielding background rejection

- Compact passive shielding with footprint of $\sim 1\ \mathrm{m}^2$

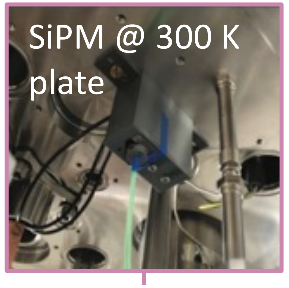




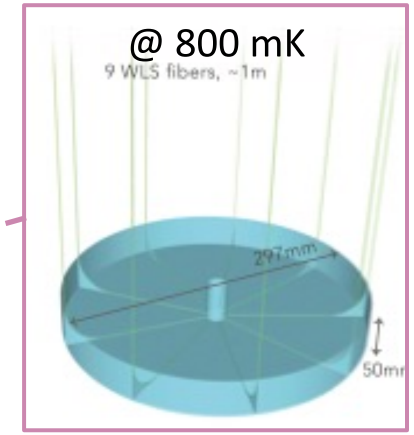
Passive shielding on movable mechanical structure

Muon Veto

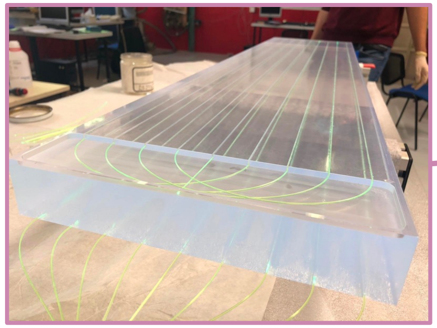
- Compact passive shielding with footprint of $\sim 1\ \text{m}^2$
- At 3 m.w.e, a muon veto with $\varepsilon > 99\%$ is needed



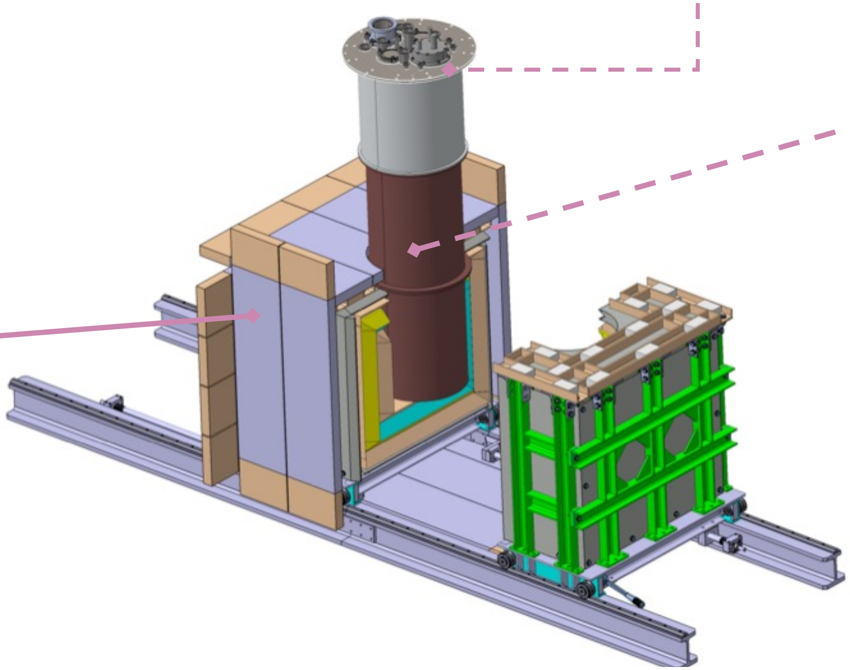
Cryogenic muon veto



Self-made muon veto



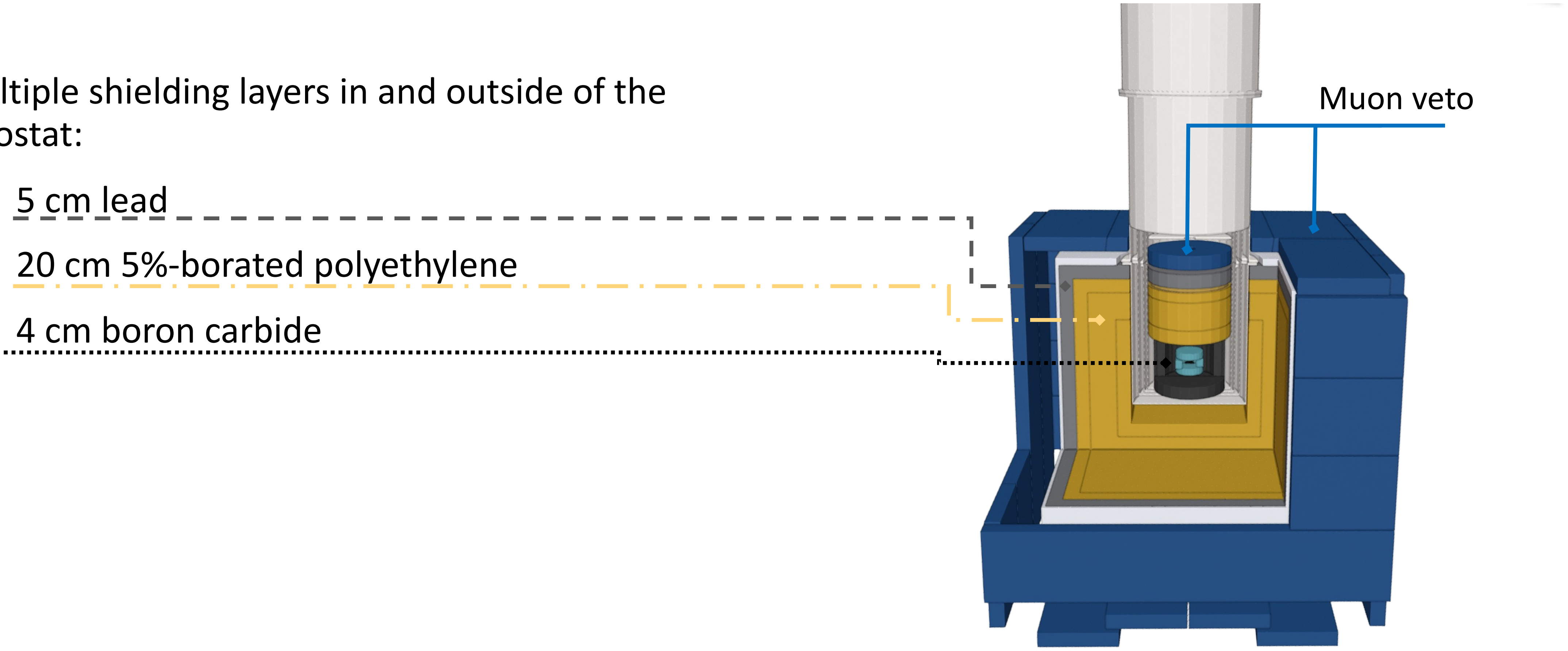
✓ Prototypes finished
arXiv:2202.03991



✓ Proof of principle shown in first measurements
arXiv:2205.01718

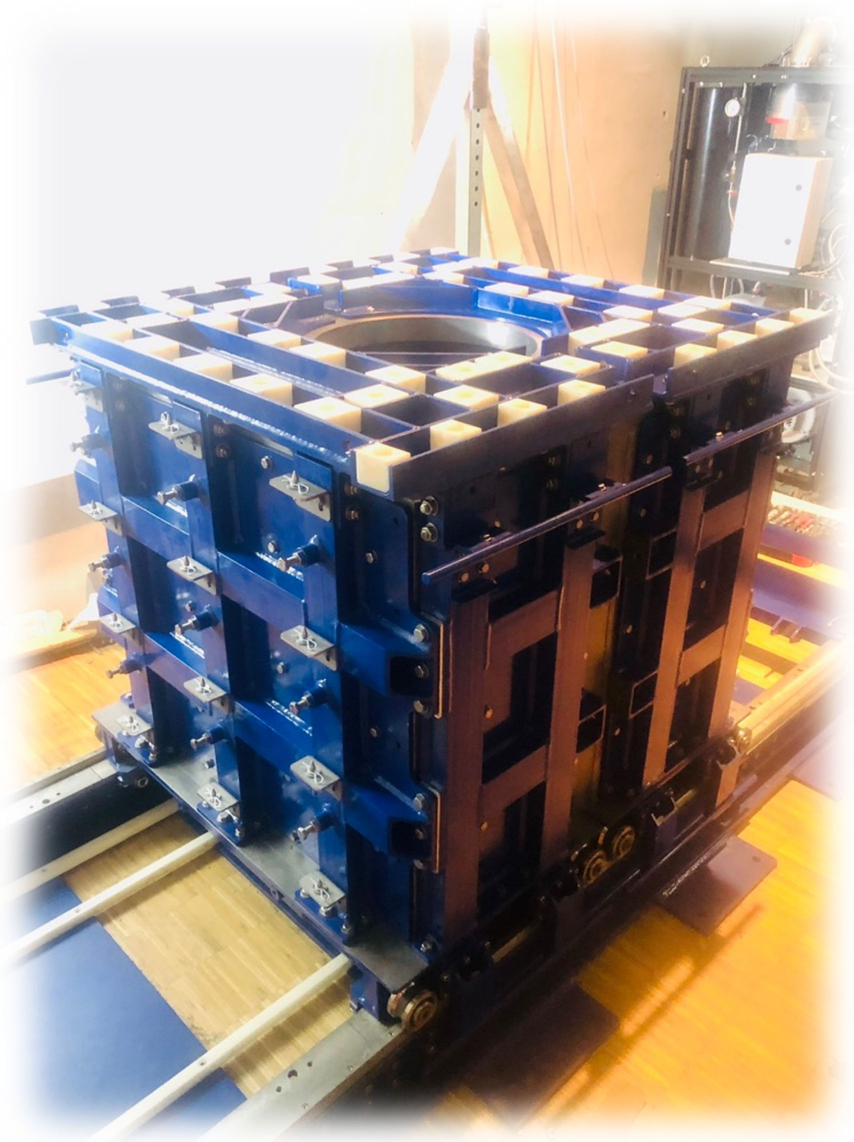
Muon Veto installed at TUM (2022)

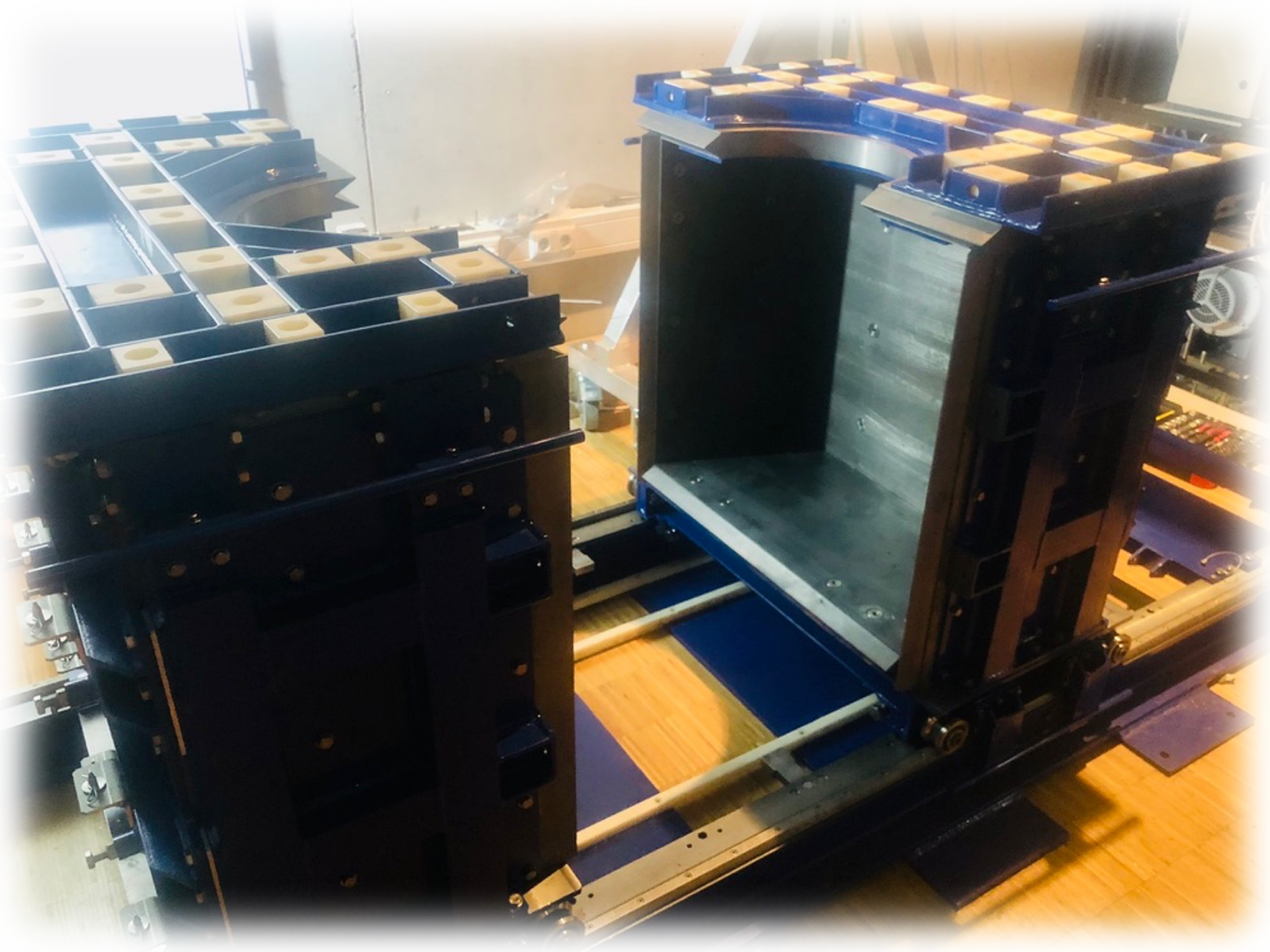
Passive Shielding



- Multiple shielding layers in and outside of the cryostat:
  - 5 cm lead
  - 20 cm 5%-borated polyethylene
  - 4 cm boron carbide

Passive Shielding installed at TUM (2022)



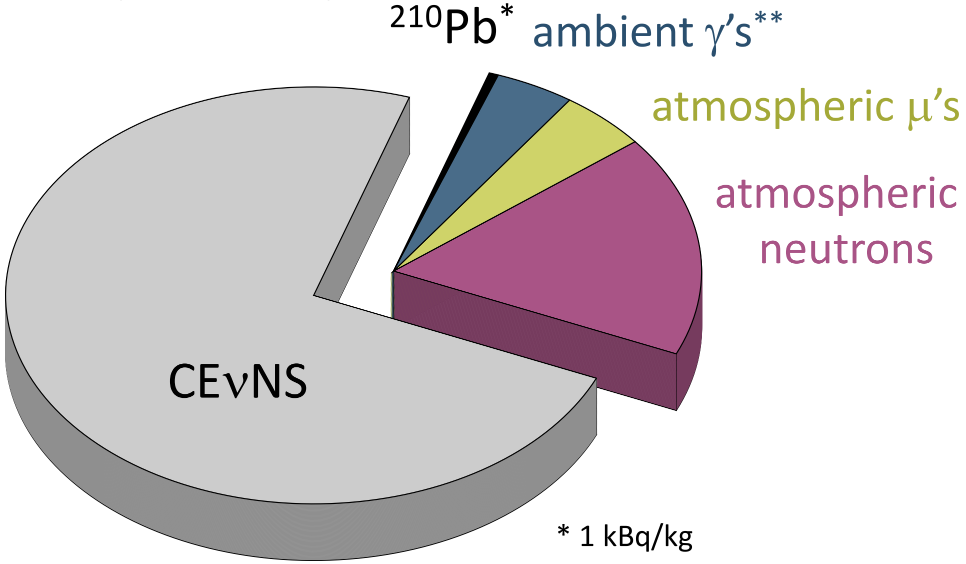


Background forecast: O(100 counts/ (keV kg d))

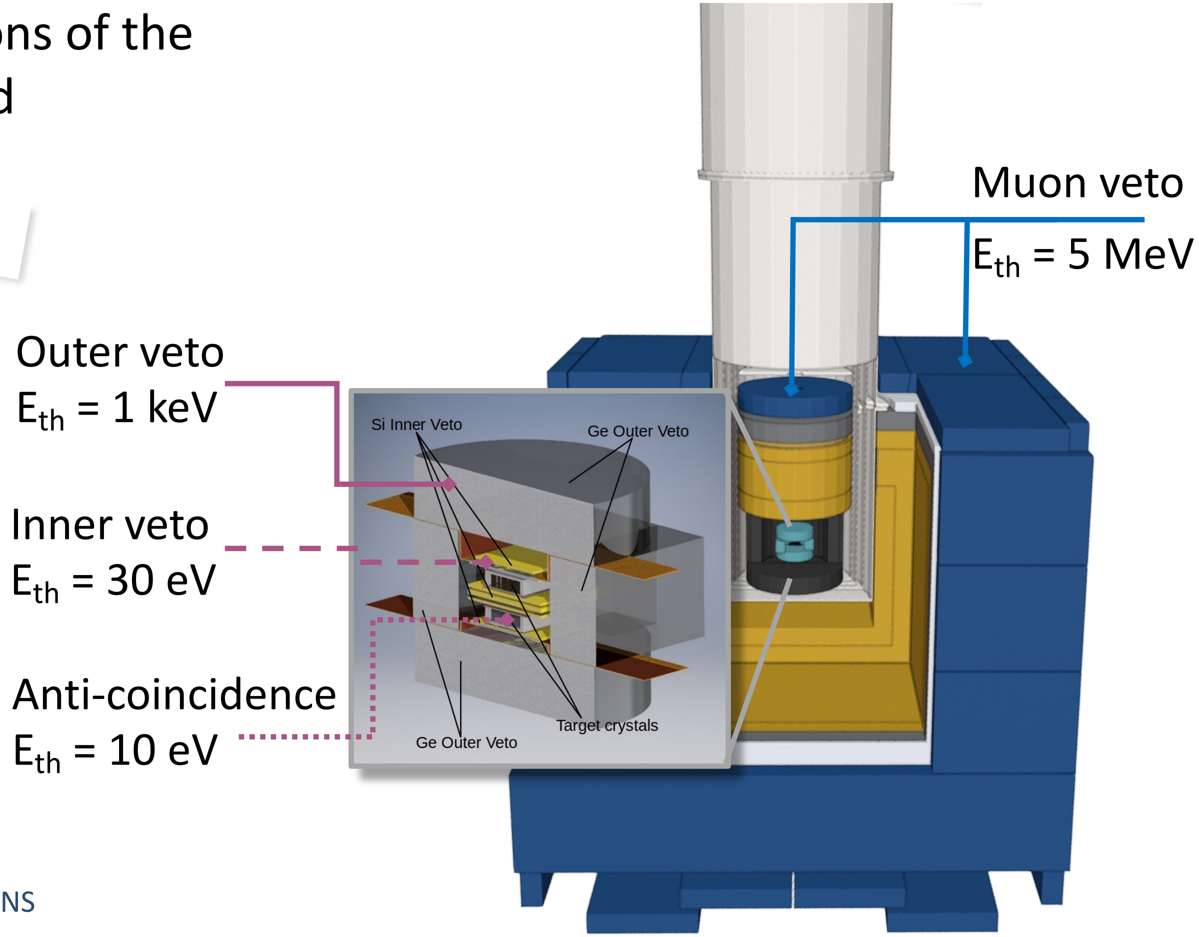
- ✓ Extensive GEANT4 Monte Carlo simulations of the full NUCLEUS setup have been performed

PRELIMINARY

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



* 1 kBq/kg
** γ-bck based on measurements @ VNS



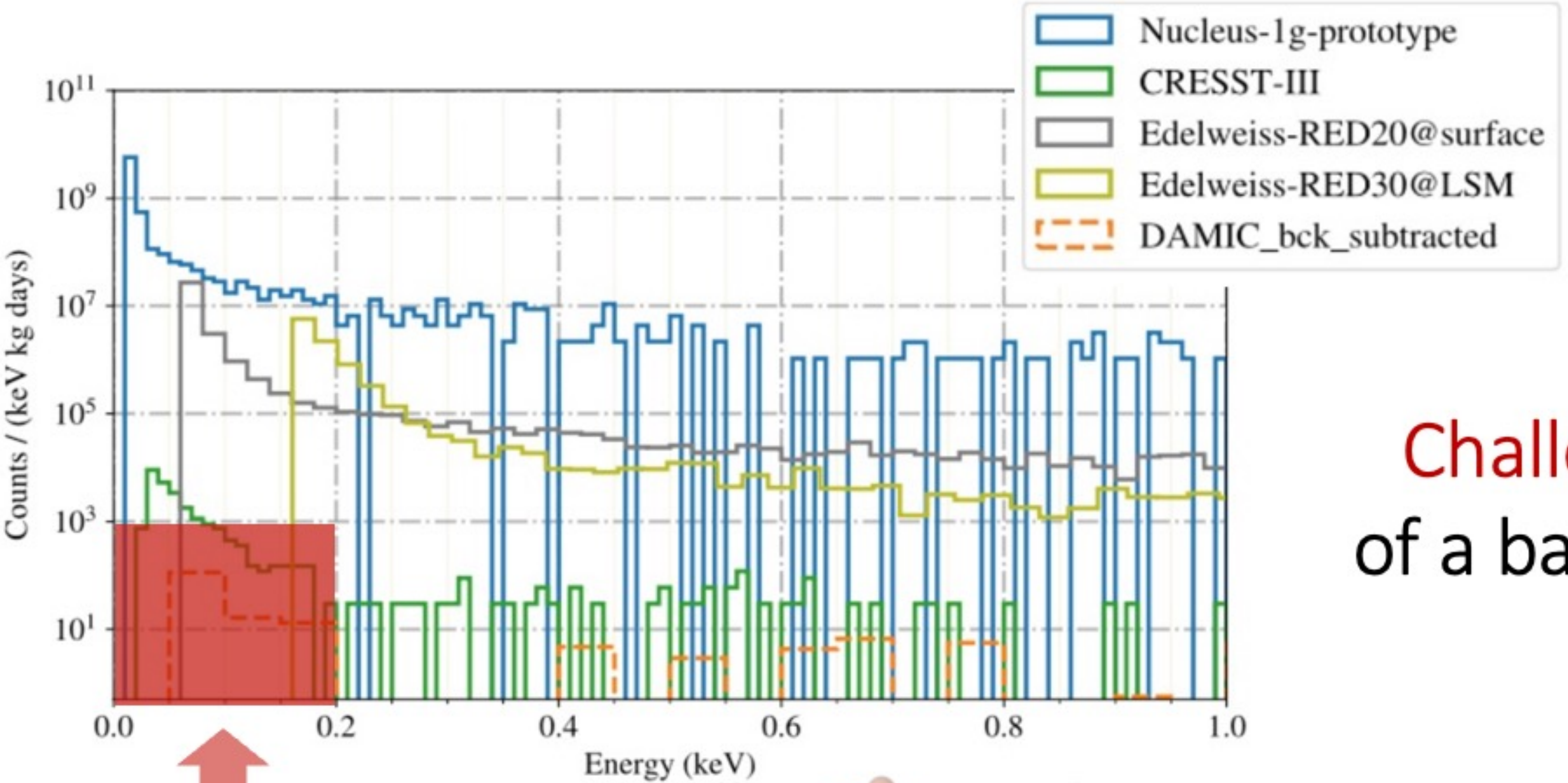
Muon veto
E_{th} = 5 MeV

Outer veto
E_{th} = 1 keV

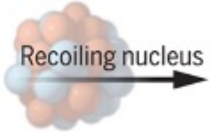
Inner veto
E_{th} = 30 eV

Anti-coincidence
E_{th} = 10 eV

The Critical “Excess” at very low energy (<100eV)



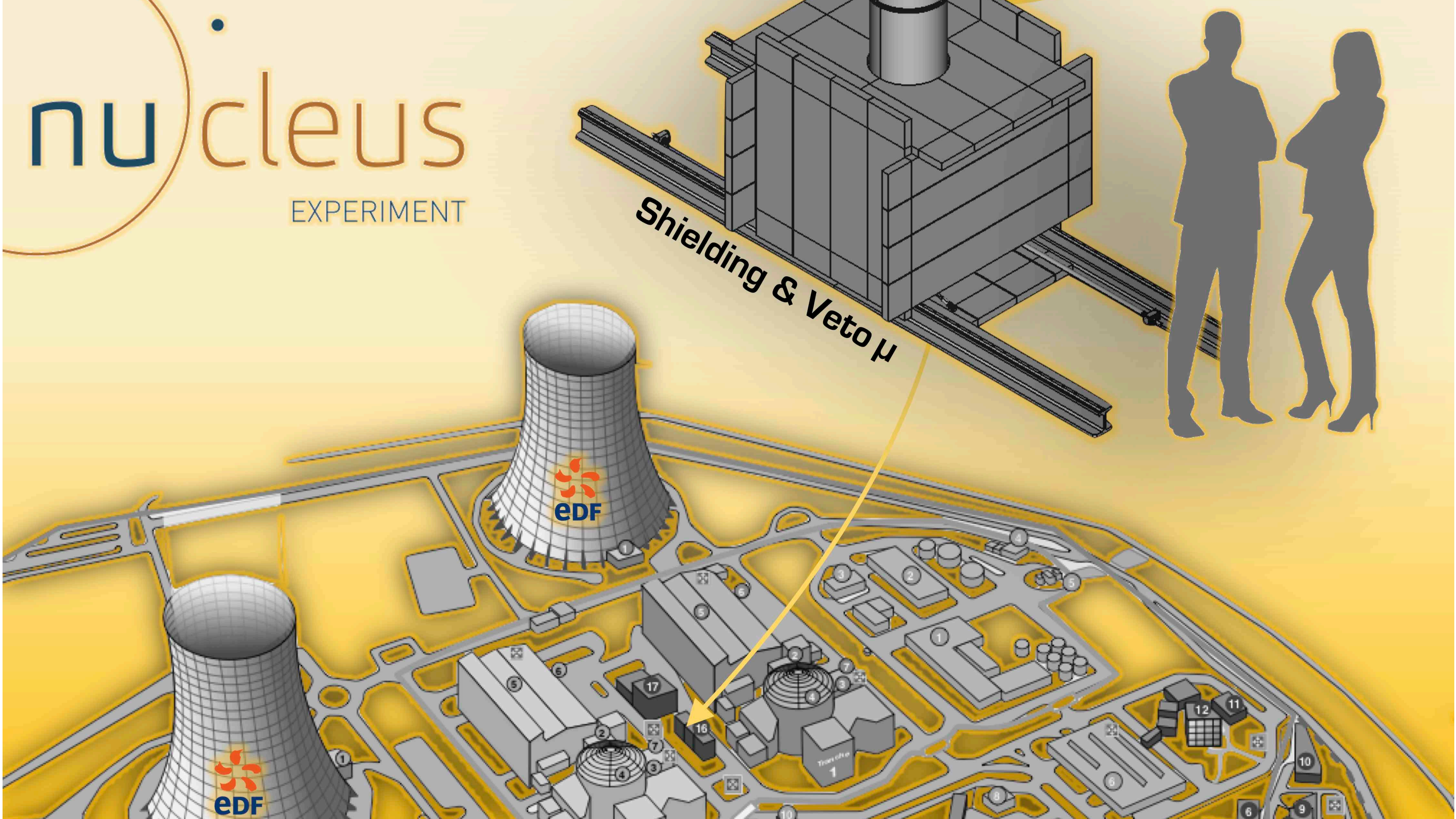
CEvNS signal



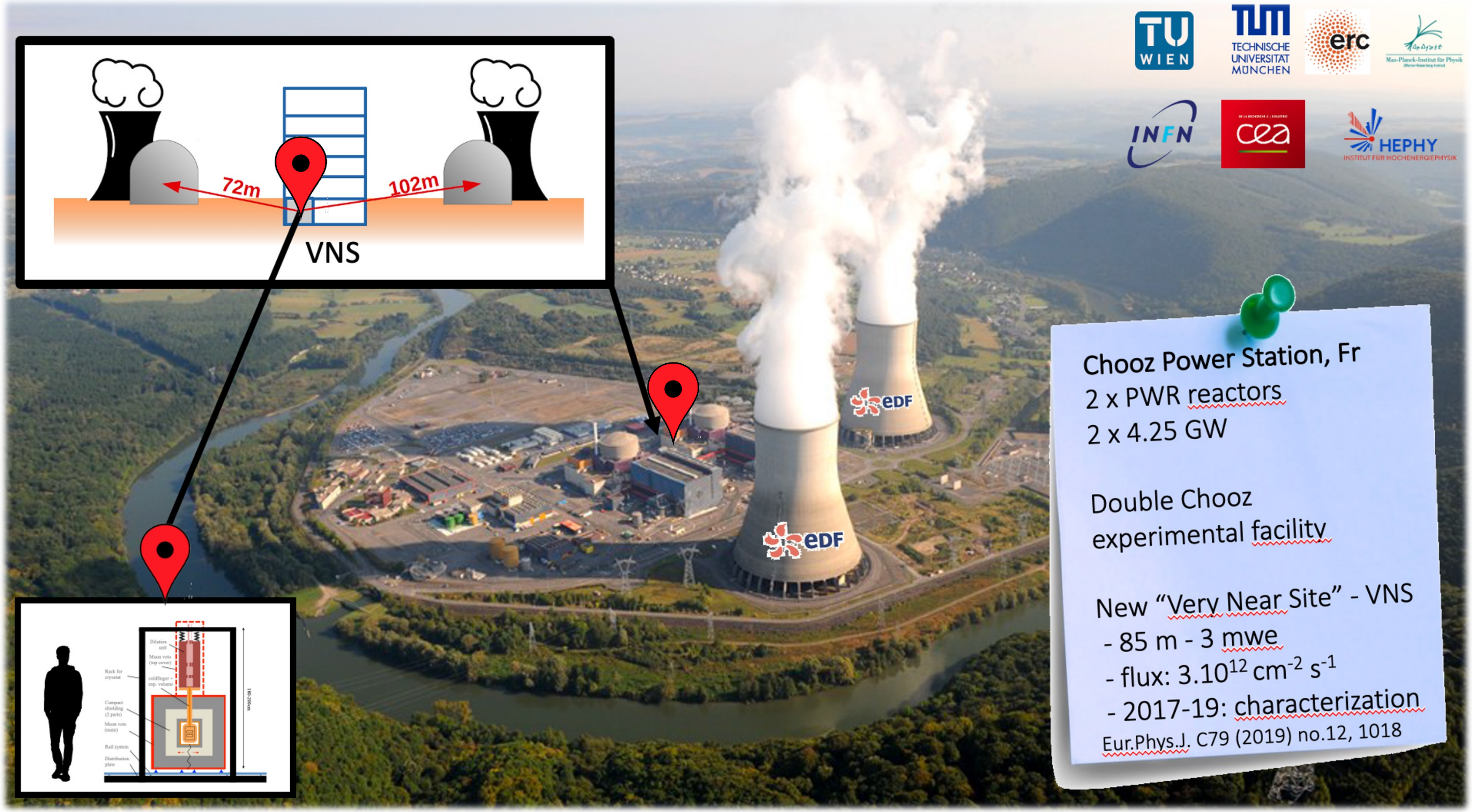
Workshop,
15.-16.06.21
https://indico.cern.ch/event/1013203/

Challenge: many observations of a background rise at E<100 eV
Unknown origin…

nucleus
EXPERIMENT



Deployment at the Chooz Nuclear Power Station



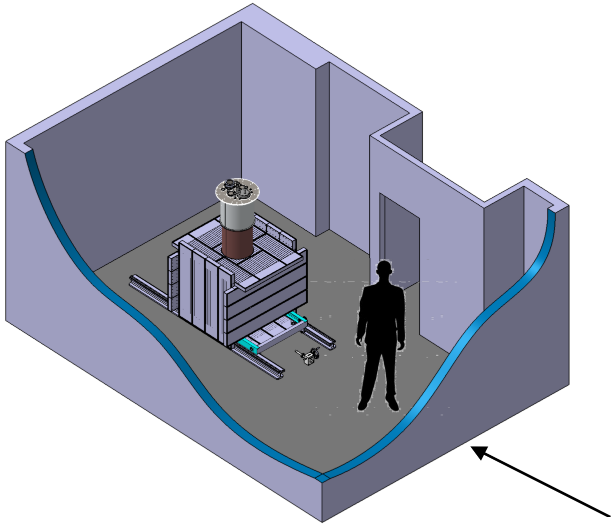
Chooz Power Station, Fr
2 x PWR reactors
2 x 4.25 GW

Double Chooz
experimental facility

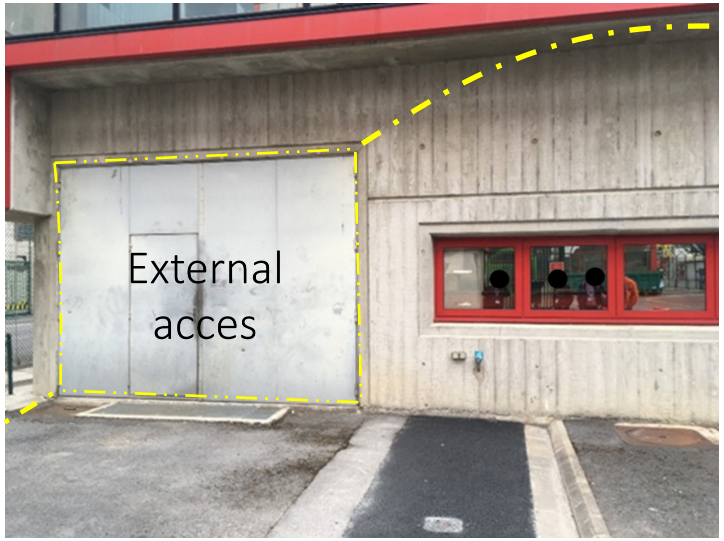
New “Very Near Site” - VNS
- 85 m - 3 mwe
- flux: 3.10^{12} cm^{-2} s^{-1}
- 2017-19: characterization

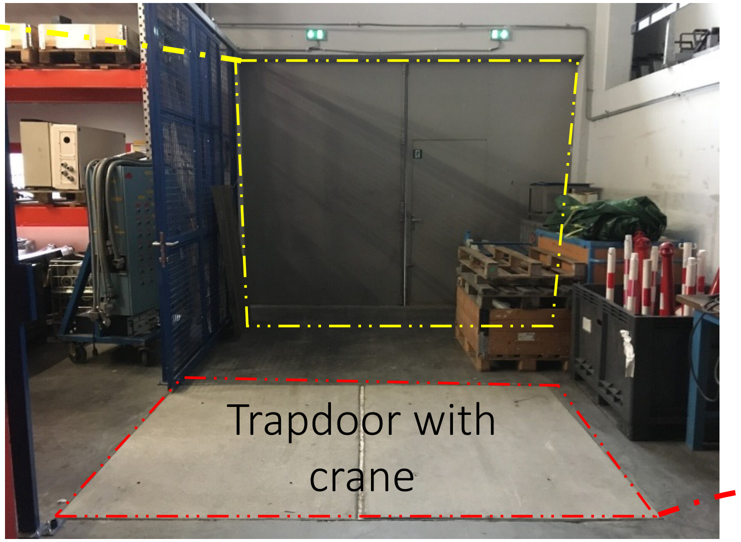
Eur.Phys.J. C79 (2019) no.12, 1018

Very Near Site at Chooz Nuclear Power Plant



VNS



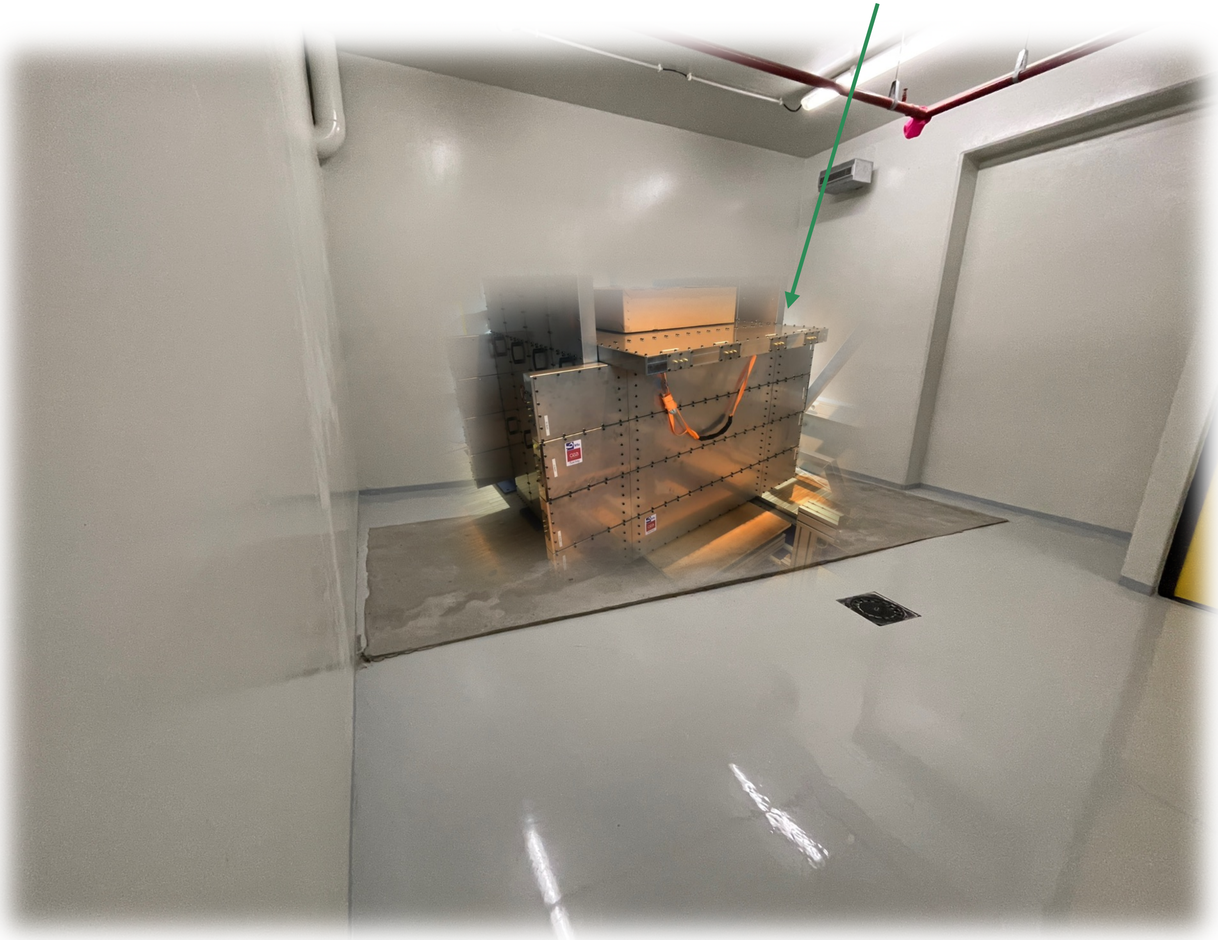


Deployment at the Chooz Nuclear Power Station

VNS room almost ready – Integration in 2024

Deployment at the Chooz Nuclear Power Station

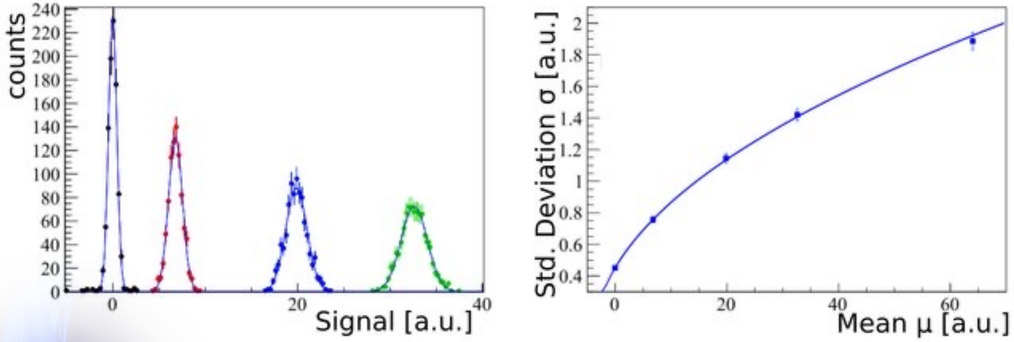
VNS room almost ready – Integration in 2024



Target Detector Calibration

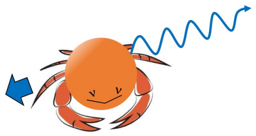
In-situ LED Calibration

- LED bursts with N photons of E_γ = 4.9 eV
- Calibration based on Poissonian photon statistics
- Cross-calibration with new X-ray fluorescence source planned



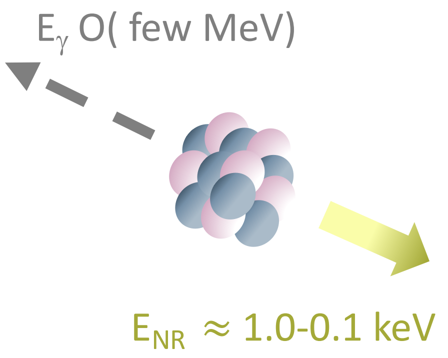
L. Cardani et al, Supercond. Sci. Technol. 31 (2018) 075002

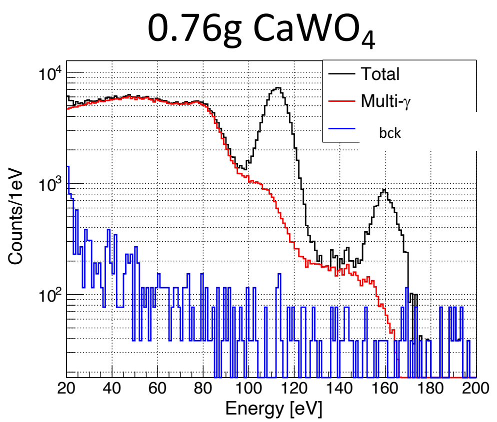
Nuclear recoil calibration with CRAB



Calibrated **R**ecoils for **A**ccurate **B**olometry

- sub-keV nuclear recoils induced by the emission of MeV γ-rays following thermal neutron capture

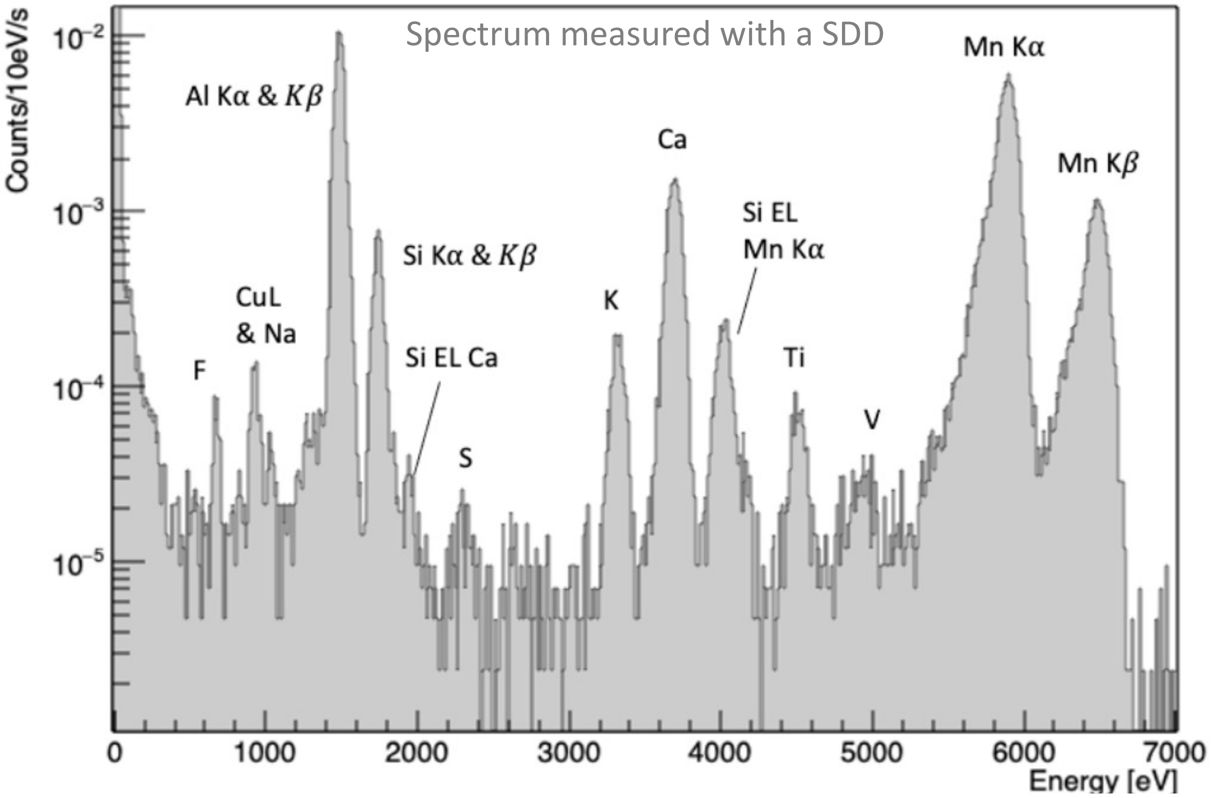




XRF Calibration

- Commonly used:
    - ^{55}Fe with lines at 5.9 keV and 6.4 keV
    - Heater pulses of different amplitudes used to extrapolate
    - cosmogenic activation of ^{182}W with lines at 2.6 keV and 11.3 keV
- LED calibration system
- X-ray fluorescence sources with broad line spectrum between 677 eV and 6.4 keV

K. von Mirbach, master thesis (TUM, 2021)



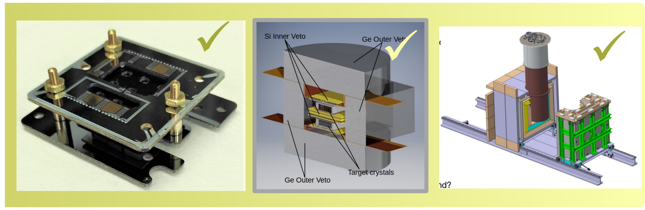
Spectrum measured with a SDD

Schedule

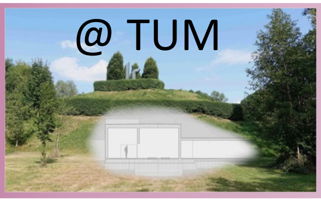
2022-2023

2024

Design phase



Blank assembly & Commissioning

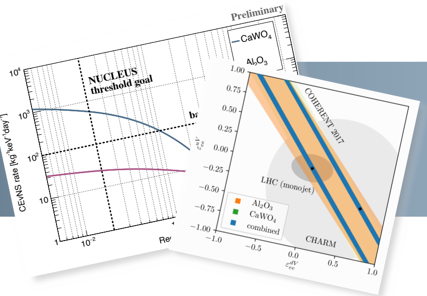


- Performance
- Calibration
- Background

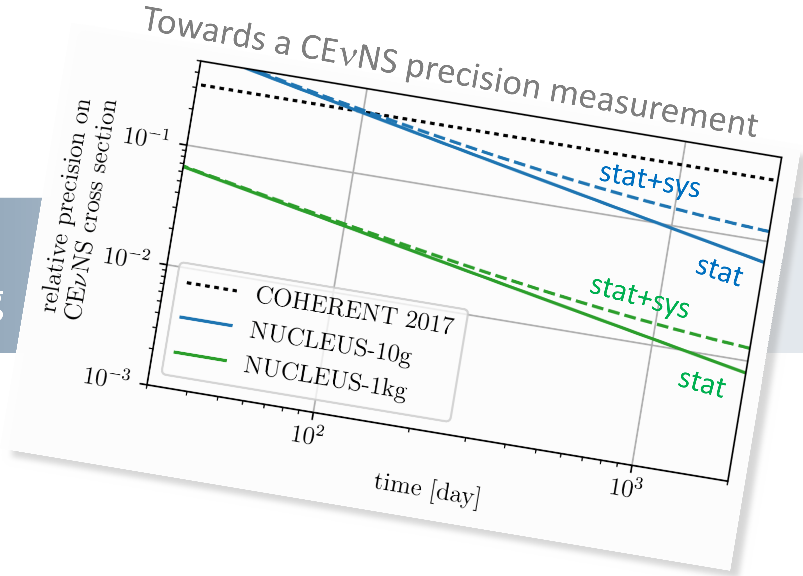
On-site installation

2024-2025

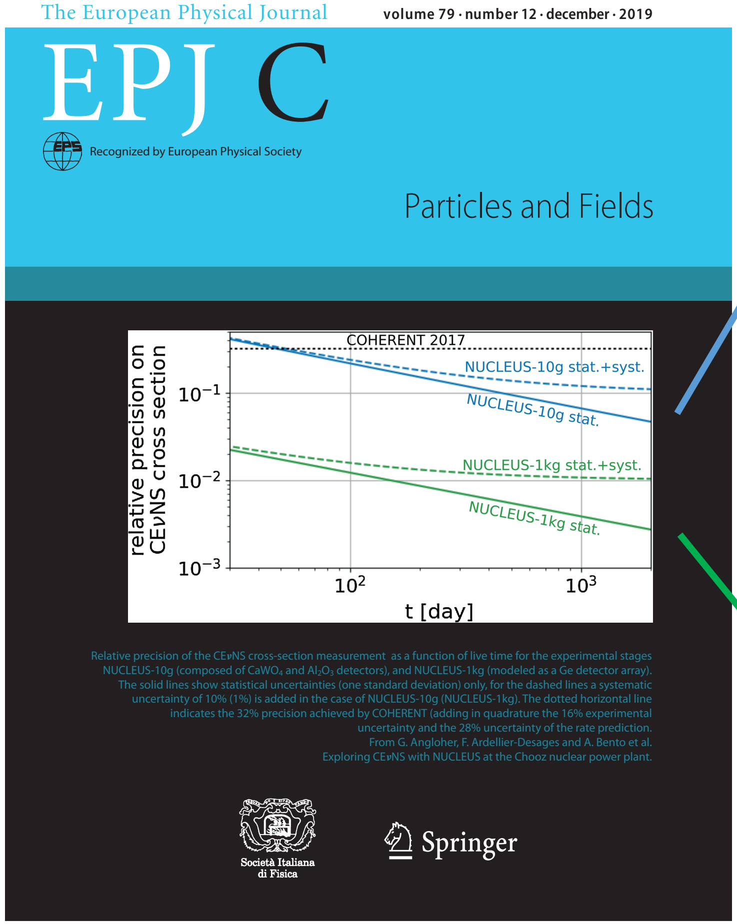
Physics Run
NUCLEUS-10g



Towards
NUCLEUS-1kg


Towards a CEνNS precision measurement

NUCLEUS Physics Reach


The European Physical Journal volume 79 · number 12 · december · 2019

EPJ C

Recognized by European Physical Society

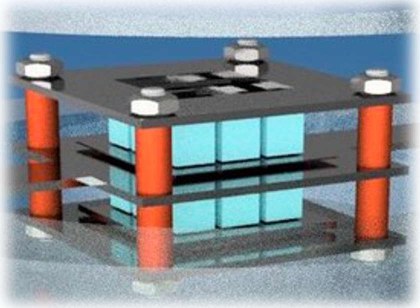
Particles and Fields

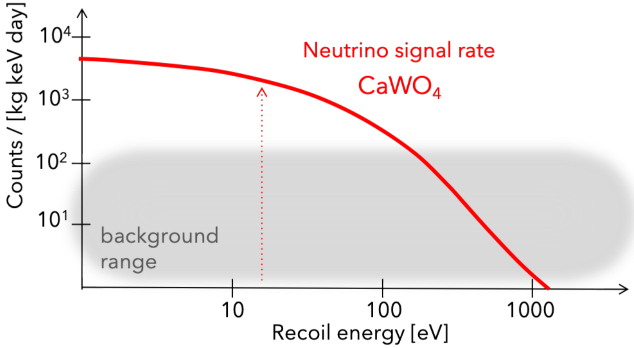
Relative precision of the CEνNS cross-section measurement as a function of live time for the experimental stages NUCLEUS-10g (composed of $CaWO_4$ and Al_2O_3 detectors), and NUCLEUS-1kg (modeled as a Ge detector array). The solid lines show statistical uncertainties (one standard deviation) only, for the dashed lines a systematic uncertainty of 10% (1%) is added in the case of NUCLEUS-10g (NUCLEUS-1kg). The dotted horizontal line indicates the 32% precision achieved by COHERENT (adding in quadrature the 16% experimental uncertainty and the 28% uncertainty of the rate prediction.
From G. Angloher, F. Ardellier-Desages and A. Bento et al.
Exploring CEνNS with NUCLEUS at the Chooz nuclear power plant.

Società Italiana di Fisica

Springer

Phase I: NUCLEUS-10g – 2024-2025

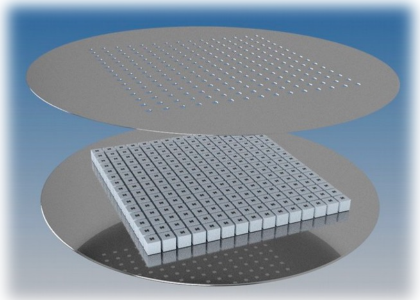

9 x $CaWO_4$ + 9 x Al_2O_3



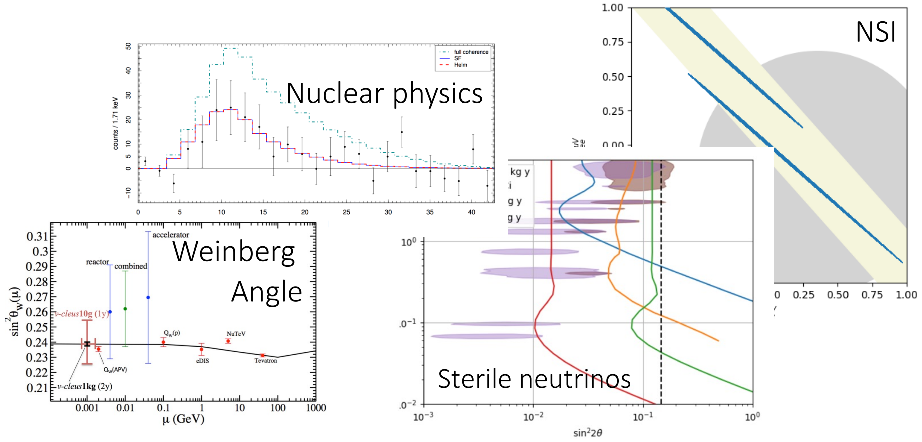
S = 150 counts / year

B < 300 counts / year

Phase II : NUCLEUS-1kg – 2026 – SM & BSM


Ge, Multi-target ?

S > 10^{3-4} counts / year



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The CRAB Calibration & Collaboration

TECHNISCHE UNIVERSITÄT MÜNCHEN

TU WIEN

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

INFN

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

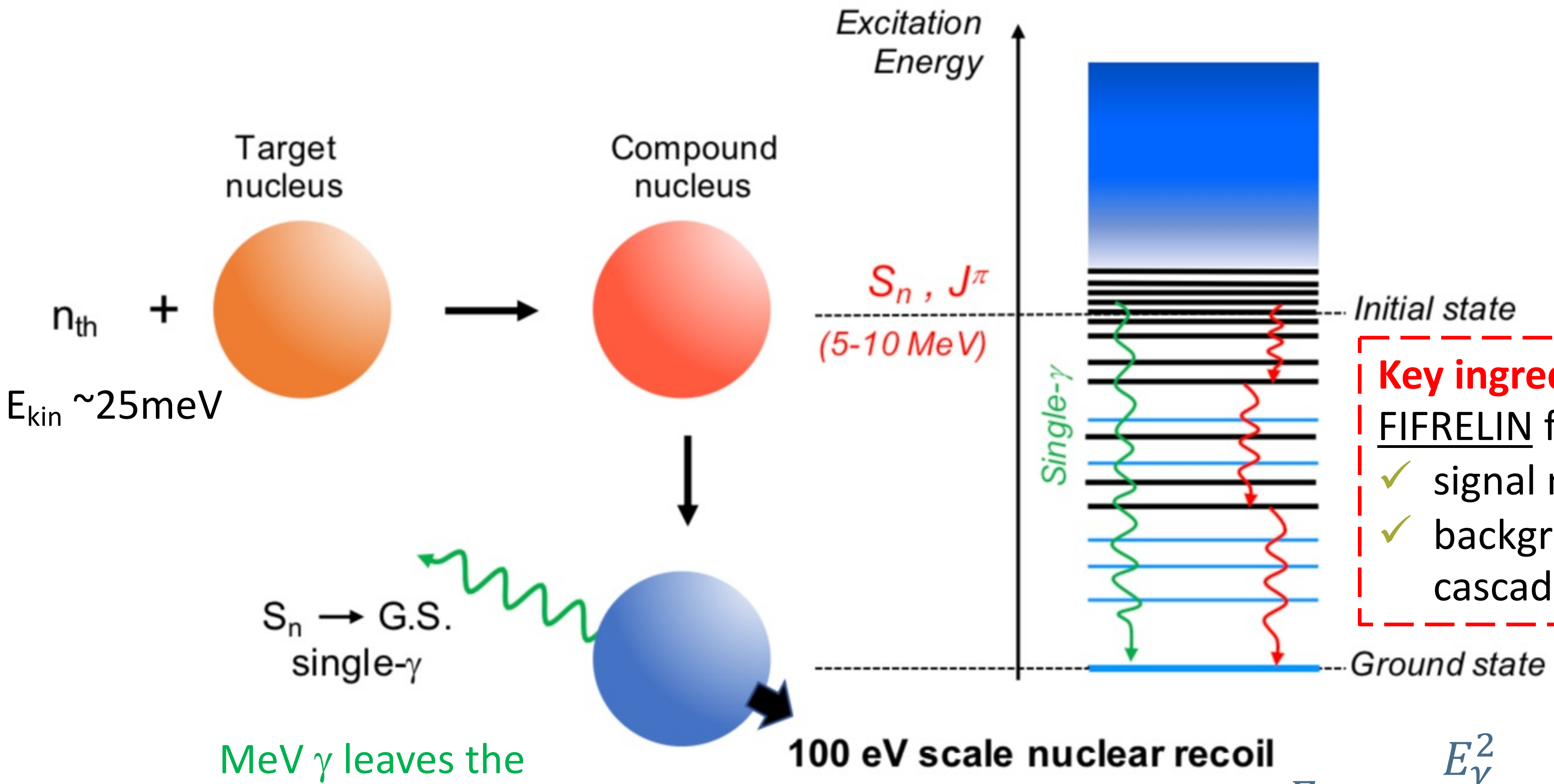
SFB 1258 Neutrinos Dark Matter Messengers


First collaboration meeting April ‘22 @TUM

Strong overlap with nucleus EXPERIMENT

The CRAB Concept

Calibrated Recoils for Accurate Bolometry



MeV γ leaves the cm-scale detector

Key ingredient: simulation code FIFRELIN for prediction of

- ✓ signal nuclear recoils
- ✓ background induced by multi-γ cascades

$$E_{nr} = \frac{E_\gamma^2}{2M}$$

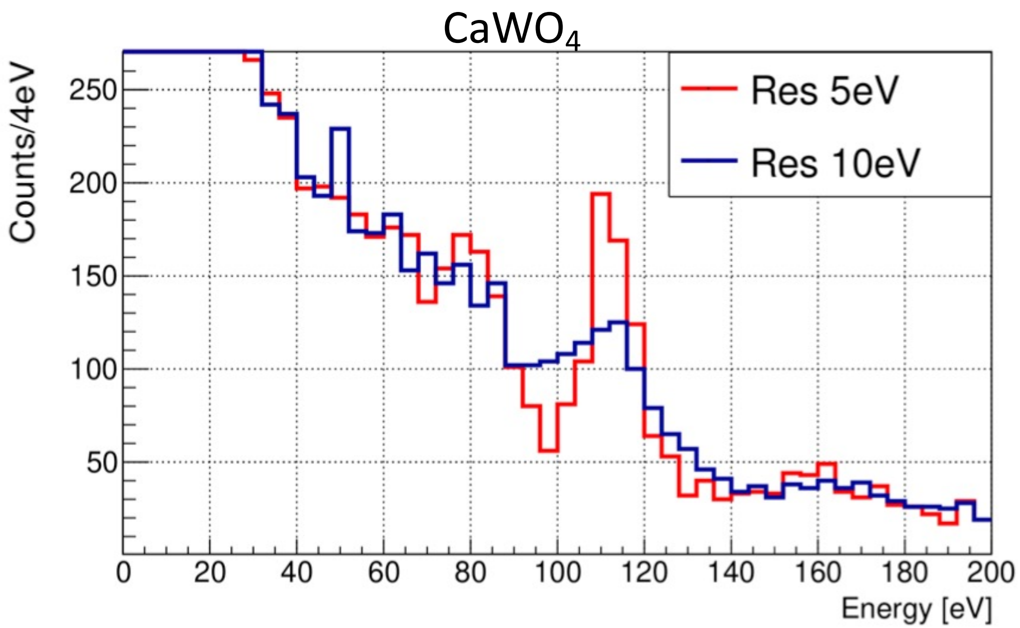
O. Litaize et al., Eur. Phys. J. A 51, 1 (2015)

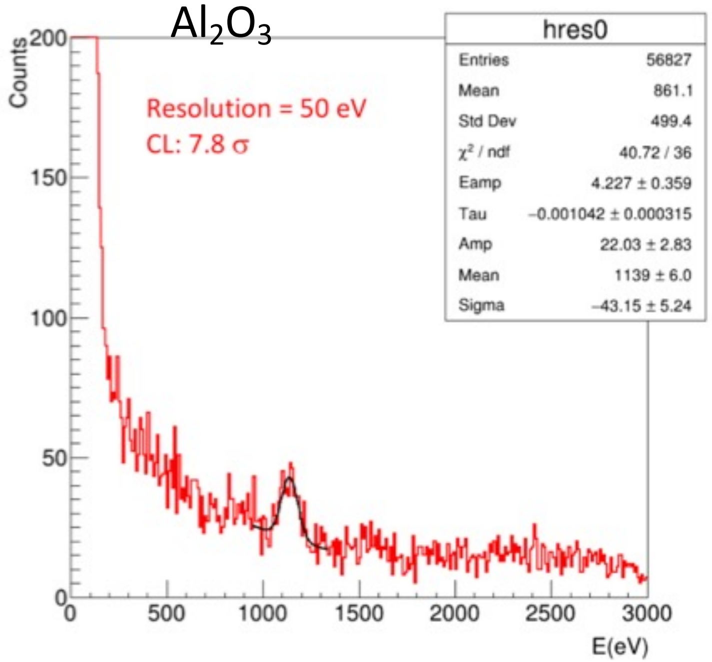
L. Thulliez, D. Lhuillier et al 2021 JINST 16

The CRAB Method for Different Targets

	Target nucleus (A)			Compound nucleus (A+1)			
Cryo detector	Isotope	Y_{ab} [%]	$\sigma_{n,\gamma}$[barn]	I_γ^S[%]	S_n [keV]	**Recoil [eV]**	FoM
$CaWO_4$	^{182}W	26.5	20.32	13.94	6191	**112.5**	7506
	^{183}W	14.3	9.87	5.83	7411	**160.3**	823
	^{186}W	28.4	37.89	0.26	5467	**85.8**	281
Ge	^{70}Ge	20.5	3.05	1.95	7416	**416.2**	122
	^{74}Ge	36.5	0.53	2.83	6506	**303.2**	54
Al_2O_3	^{27}Al	100	0.23	26.80	7725	**1145**	616
Si	^{28}Si	92.2	0.18	2.17	8473	**1330**	36

Proof of Concept at TUM: simulation



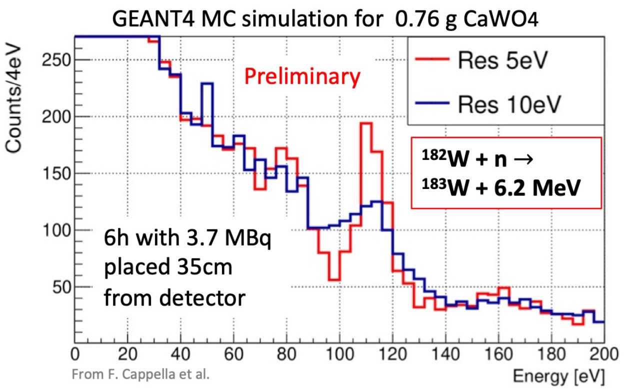


Target nucleus (A)			Compound nucleus (A+1)		
Isotope	Y_{ab} [%]	$\sigma_{n,\gamma}$[barn]	I_γ^S[%]	S_n [keV]	Recoil [eV]
^{182}W	26.50	20.32	13.94	6191	112.5
^{27}Al	100	0.23	26.81	7725	1145

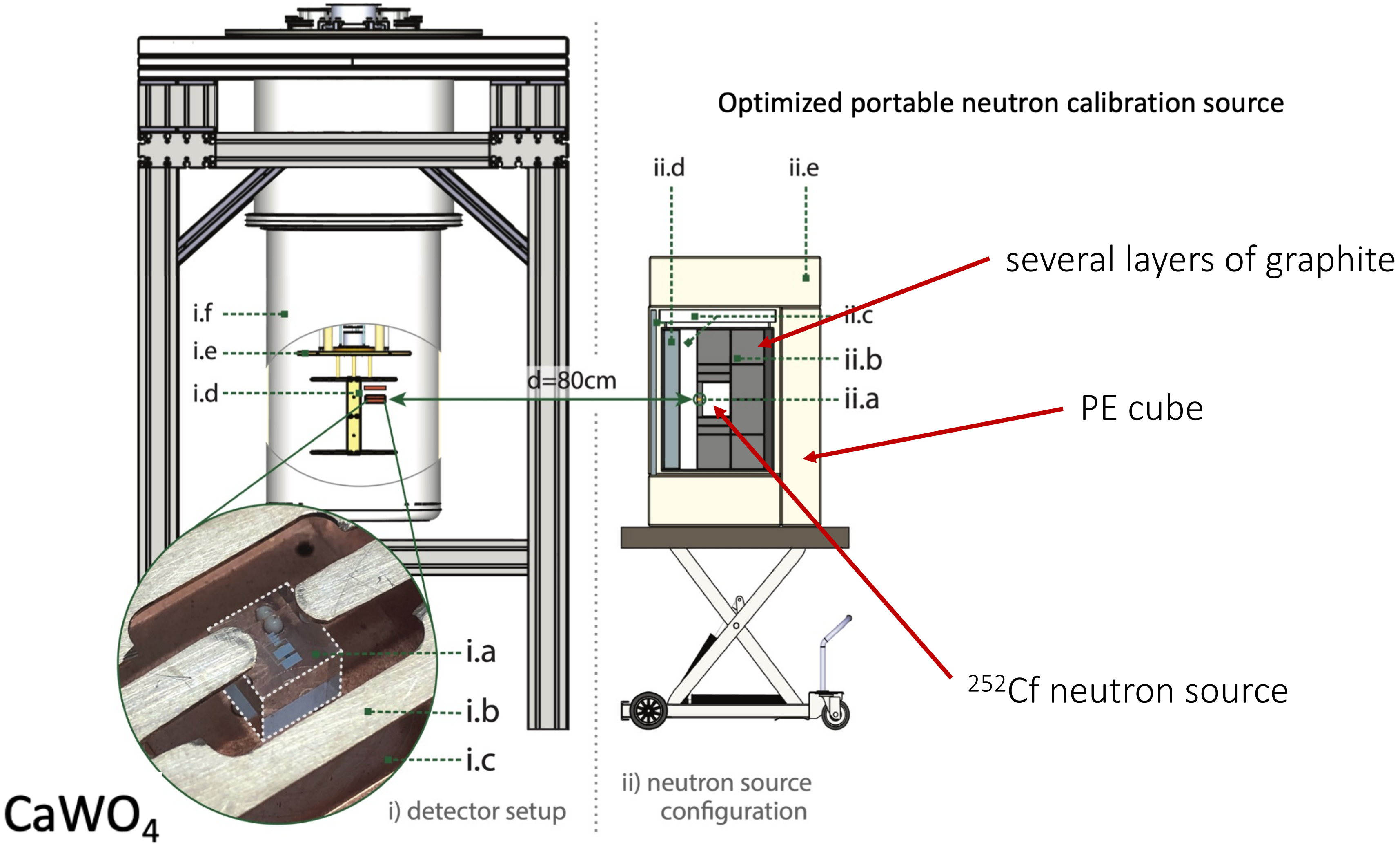
Proof of Concept at TUM – few days of data

Two data sets were acquired:

- Background data (lifetime 18.9 h)
- ^{252}Cf source data (lifetime 40.2 h).



From F. Cappella et al.



several layers of graphite

PE cube

^{252}Cf neutron source

Proof of Concept at TUM - results

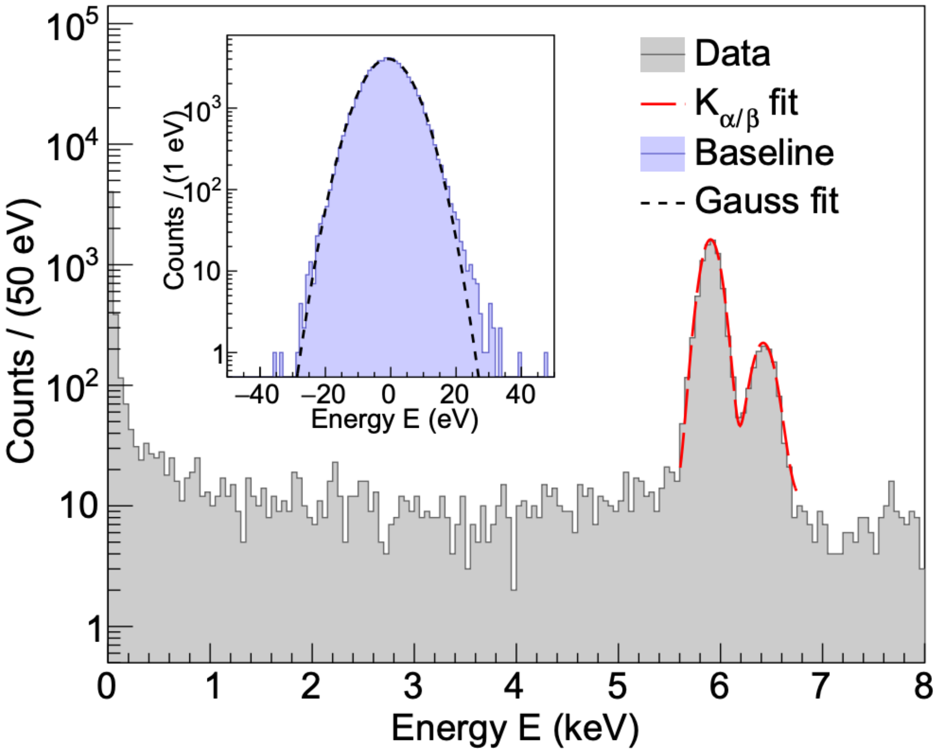
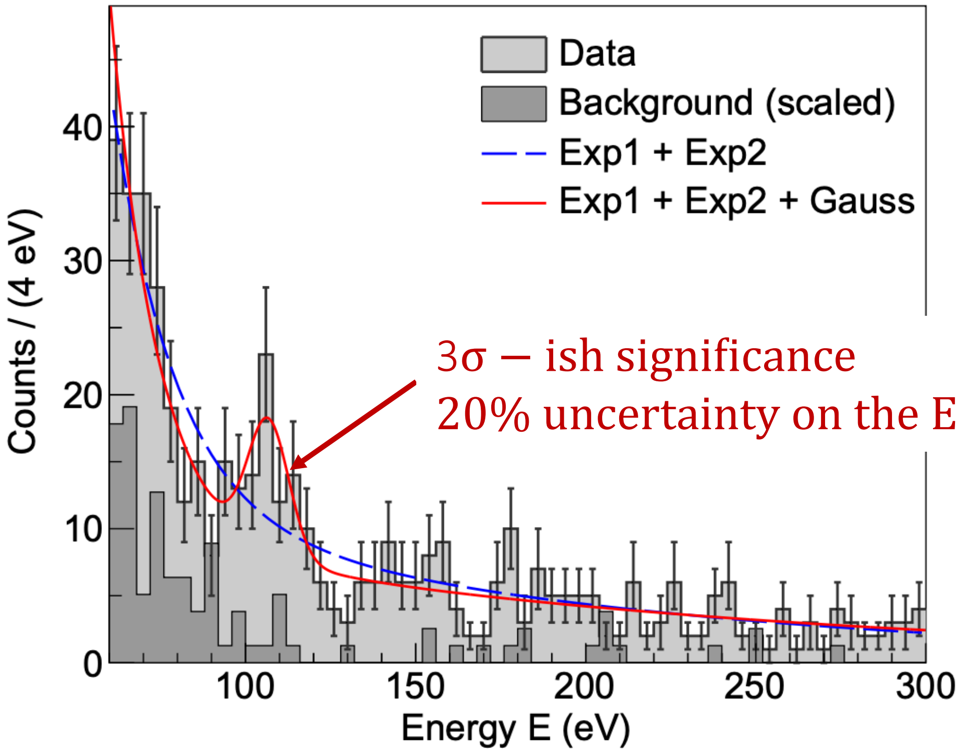


FIG. 2. Energy spectrum recorded during the *source* measurement. The two peaks from the ^{55}Fe source are used to set the energy scale of the detector (see text). The inset shows the distribution of filtered baselines after quality cuts.

arXiv:2211.03631

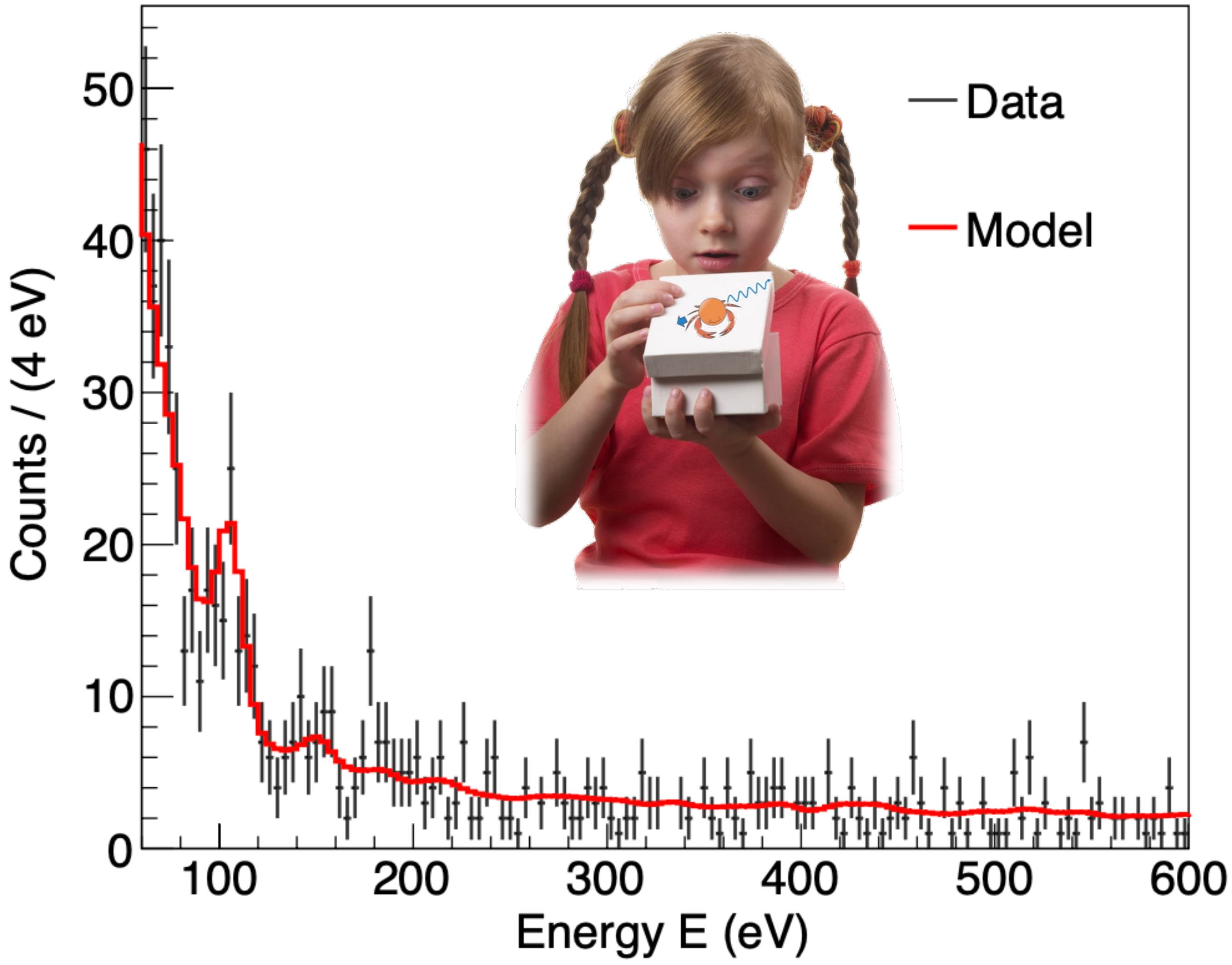


3σ – ish significance

20% uncertainty on the E – scale

FIG. 3. Energy spectra (from 60 to 300 eV) measured by the Nucleus detector for the *source* and *background* (scaled to source exposure) measurements. The error bars represent the Poissonian uncertainties. The red solid and blue dashed lines illustrate the best fit with and without the Gaussian contribution, respectively.

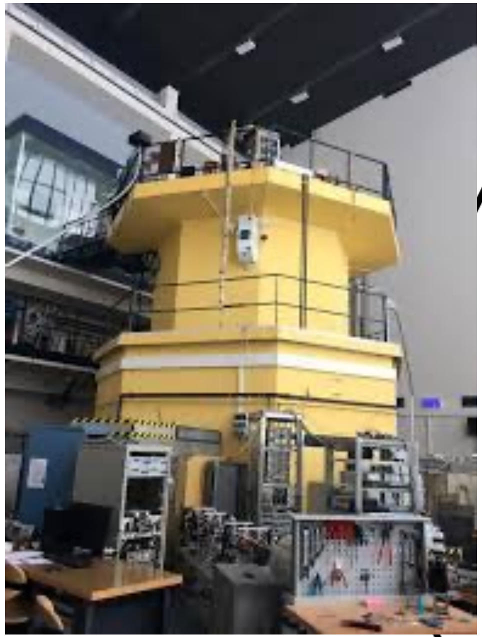
Proof of Concept at TUM – results/simulation

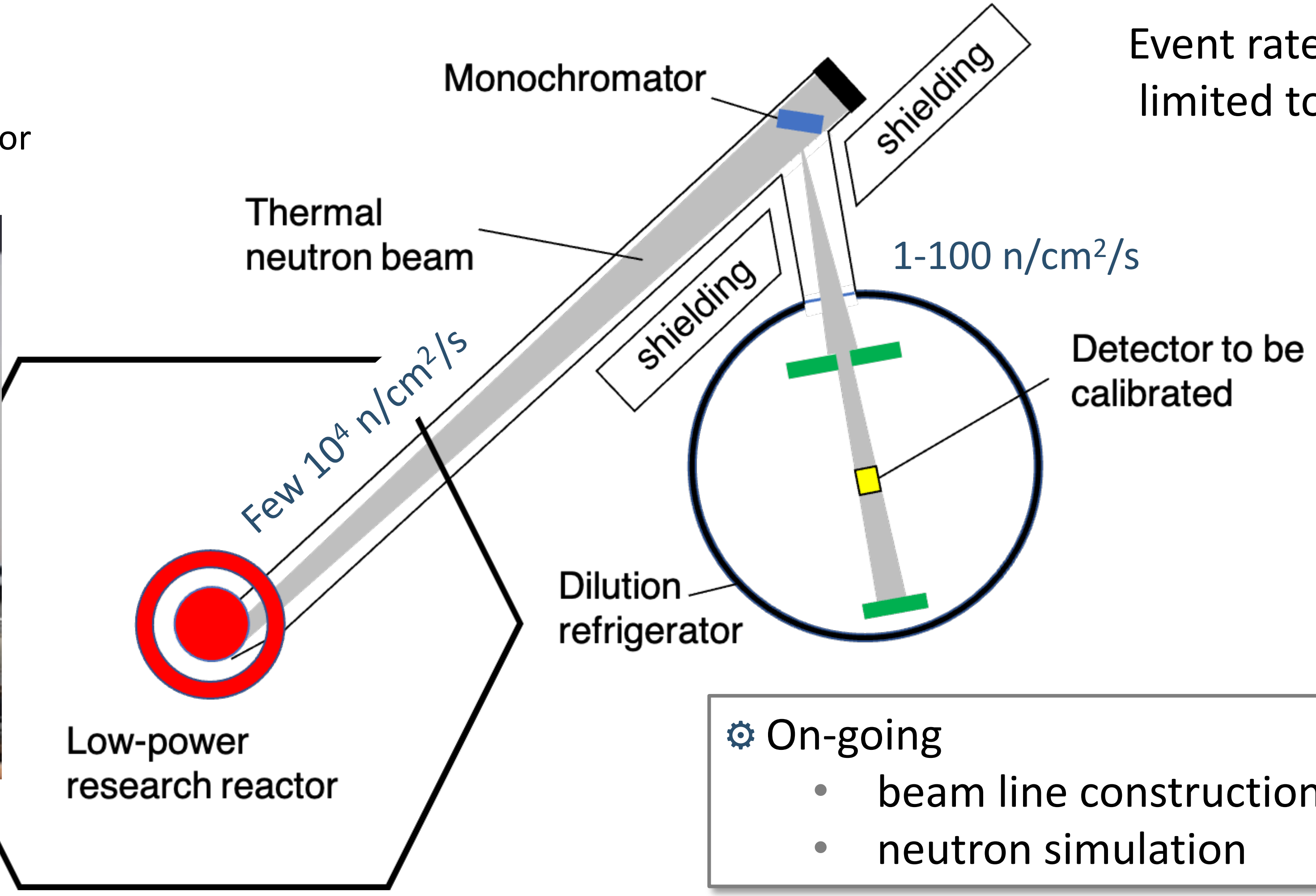


- Recoil spectrum measured with the neutron source in place **(black points)**
- Expected spectrum built from the measured ambient background and the simulation (red line)
- The simulation (red) is fitted on the data in the 60 – 300 eV range with free normalization, energy scale, and energy resolution

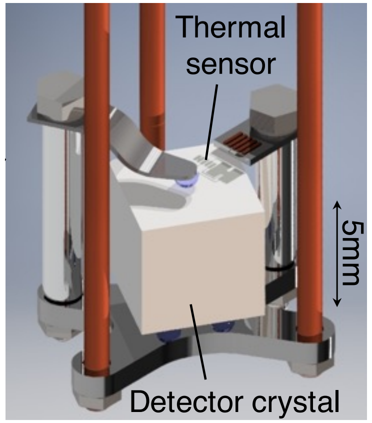
Final Calibration at Vienna TRIGA-Mark-II reactor

Vienna TRIGA-Mark-II reactor
Low Power: 250 kW





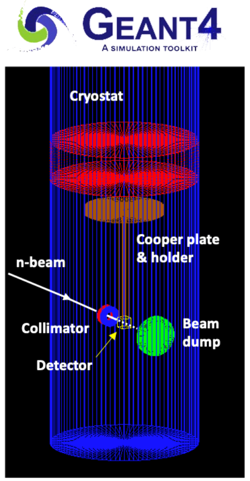
Event rate in cryo detectors limited to **O(few Hz)**



Low-mass detector holder

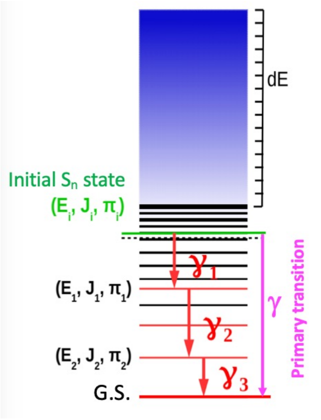
⚙ On-going
- beam line construction
- neutron simulation

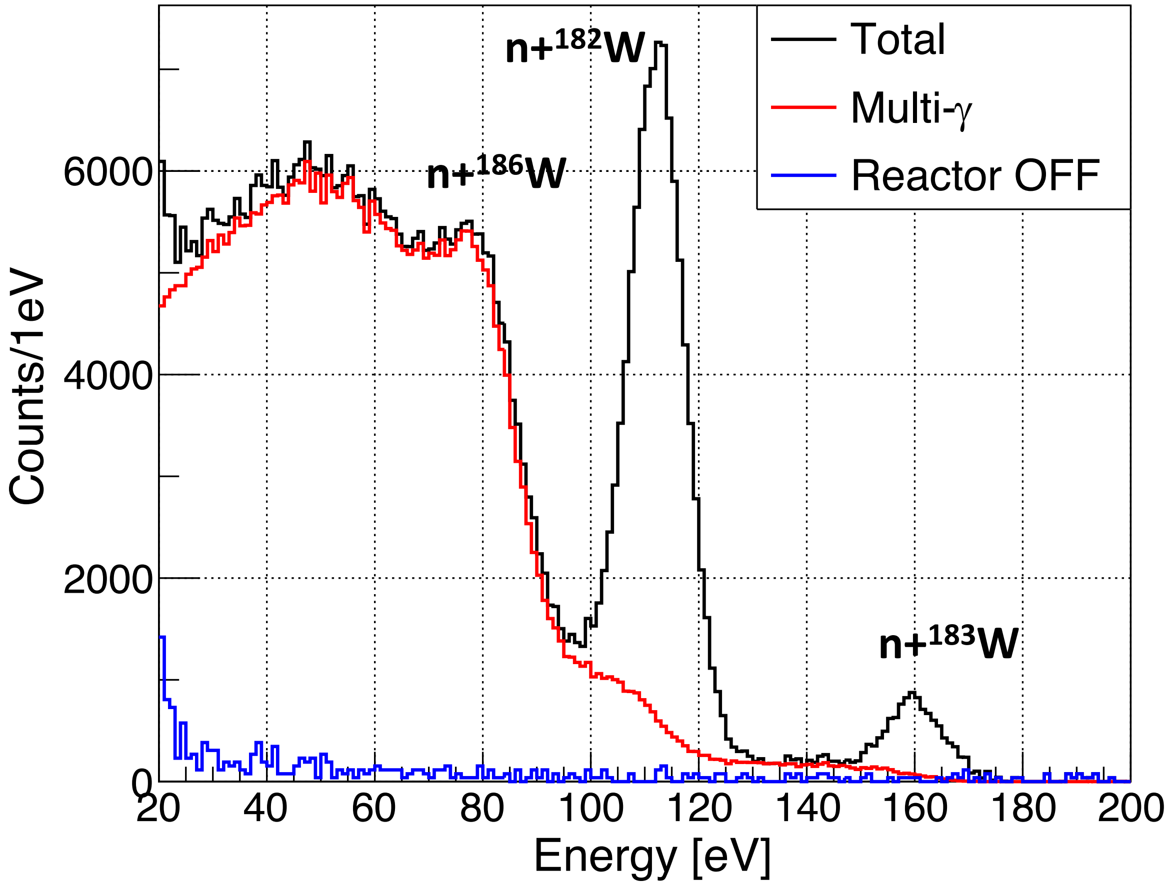
Final Calibration at Vienna TRIGA-Mark-II reactor



&

FIFRELIN

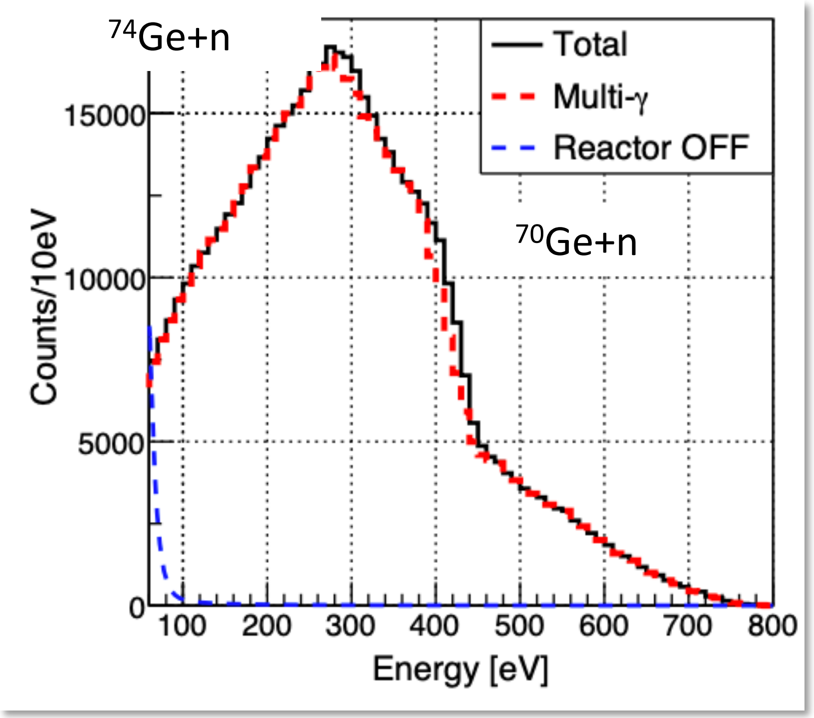




- Full GEANT4 simulation of the exp. setup coupled with FIFRELIN
- Run: 3.4 days with 270 n/cm²/s
- Detector performance and background as taken in surface lab (*Phys. Rev. D96, 022009 (2017)*)
- Energy resolution σ = 5eV

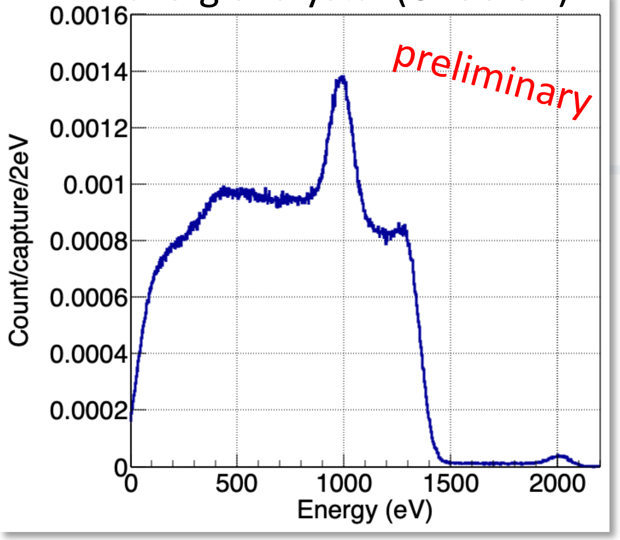
CRAB as a facility for the community

33g Ge crystal (σ=20 eV),
7 days with 6 n/cm^2/s



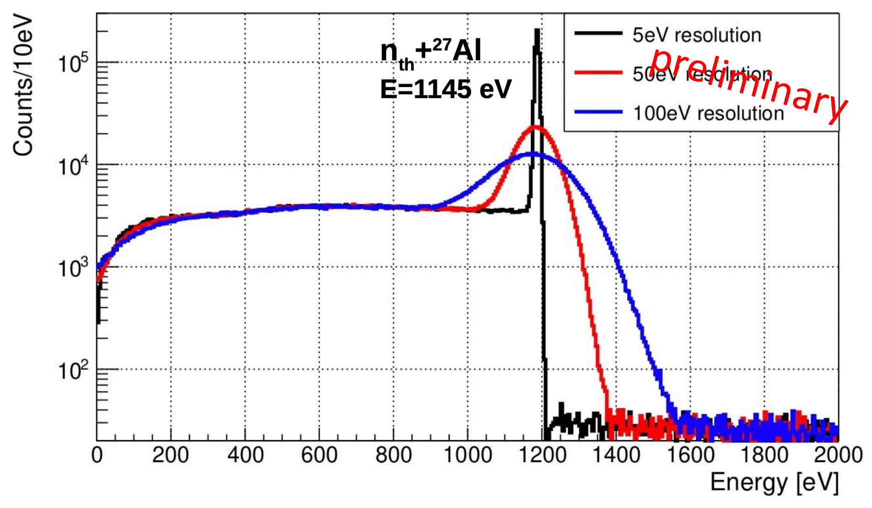
EDELWEISS R&D *Phys. Rev. D99, 082003 (2019)*

619 g Si crystal (σ=50 eV)



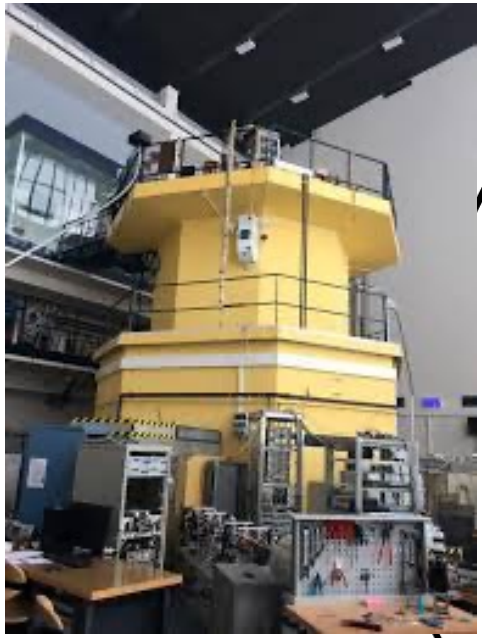
https://arxiv.org/pdf/2110.02751.pdf

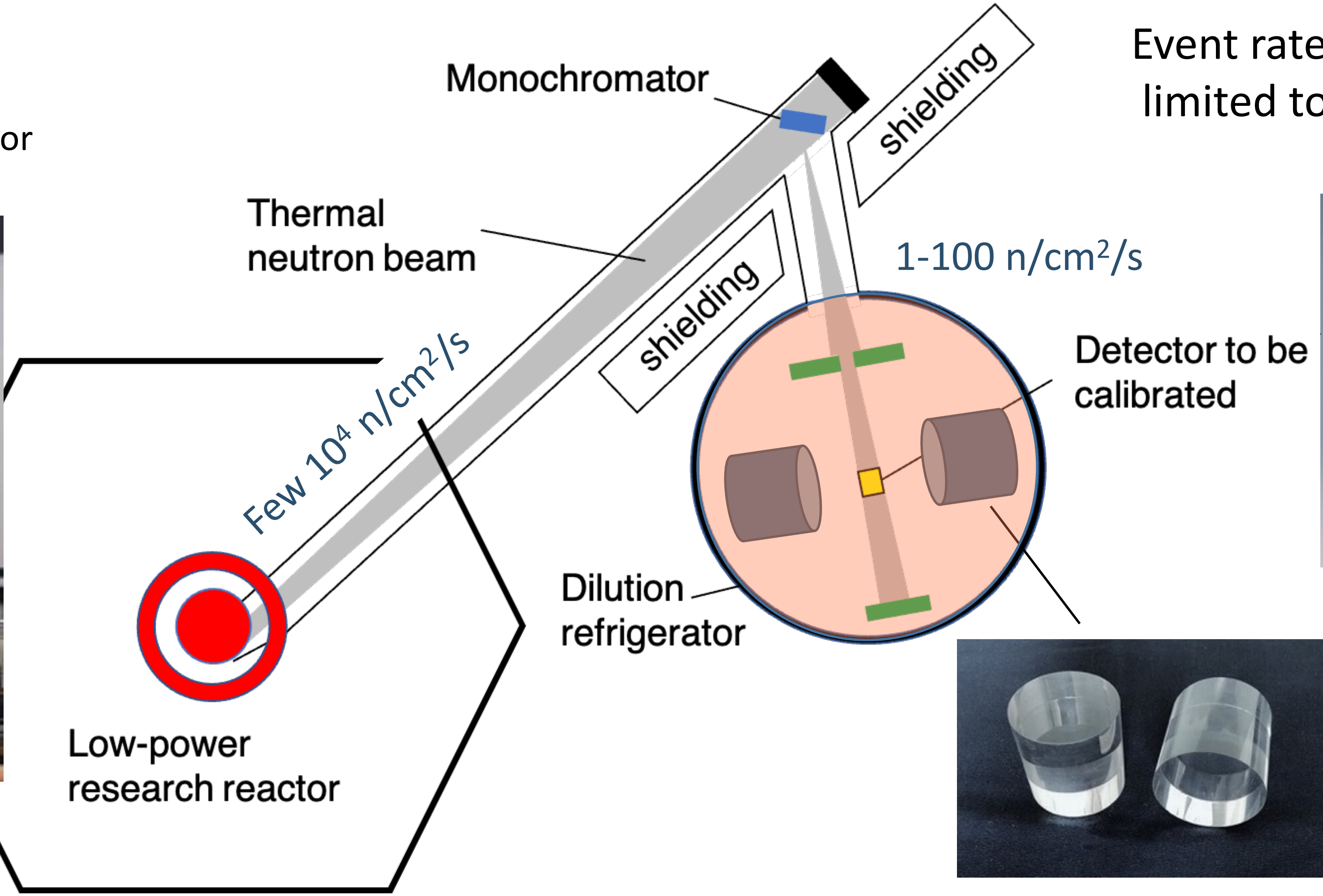
NUCLEUS 0.4 g Al_2O_3 crystal



Improvement using gamma-tagging

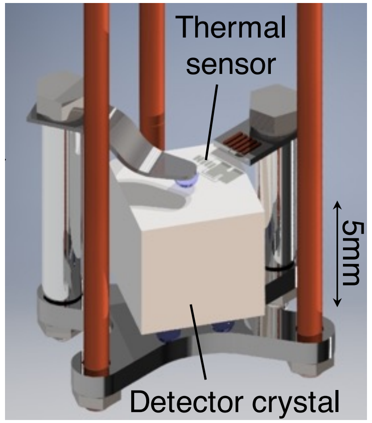
Vienna TRIGA-Mark-II reactor
Low Power: 250 kW





3"x 3" BGO

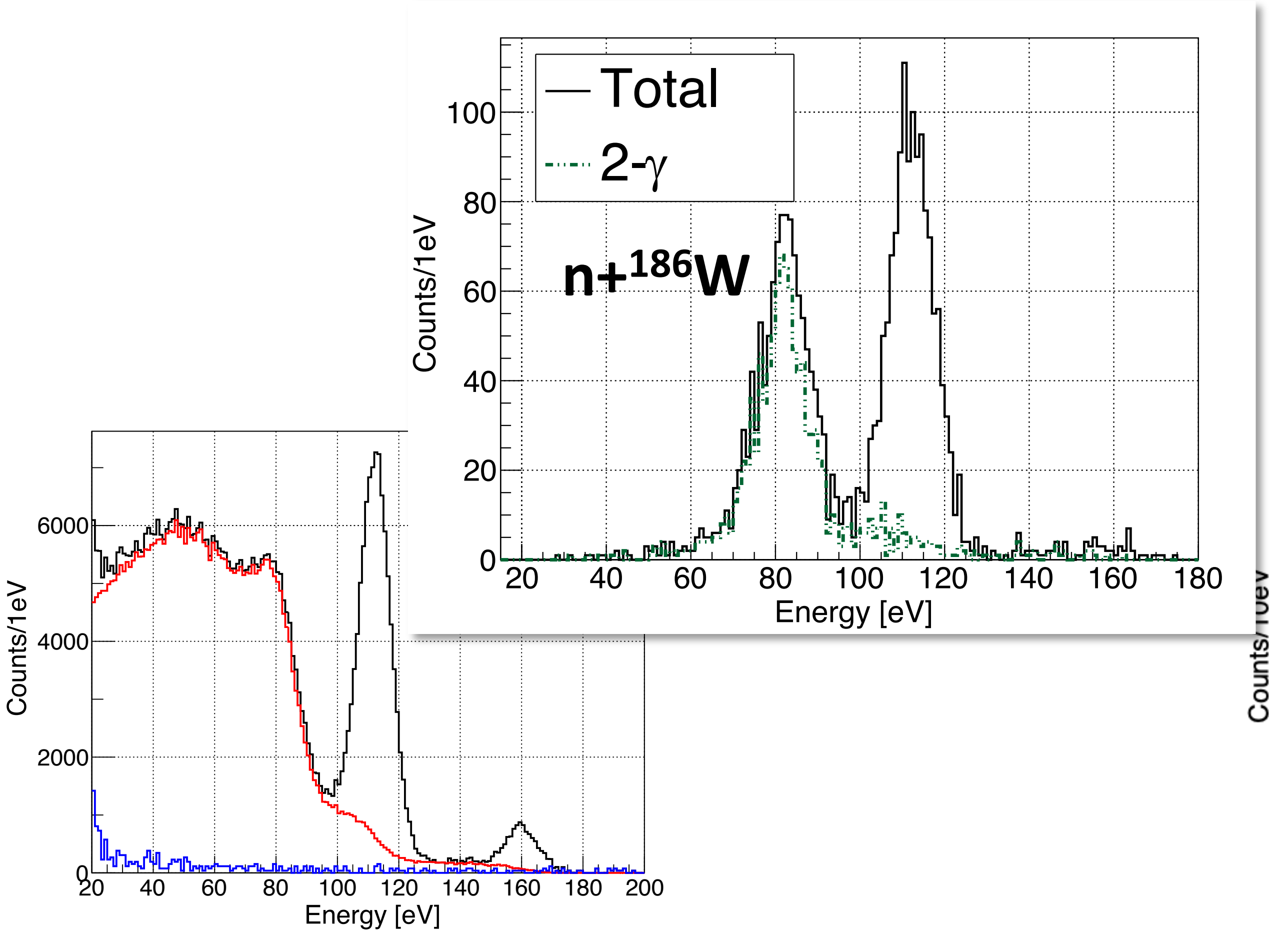
Event rate in cryo detectors limited to **O(few Hz)**



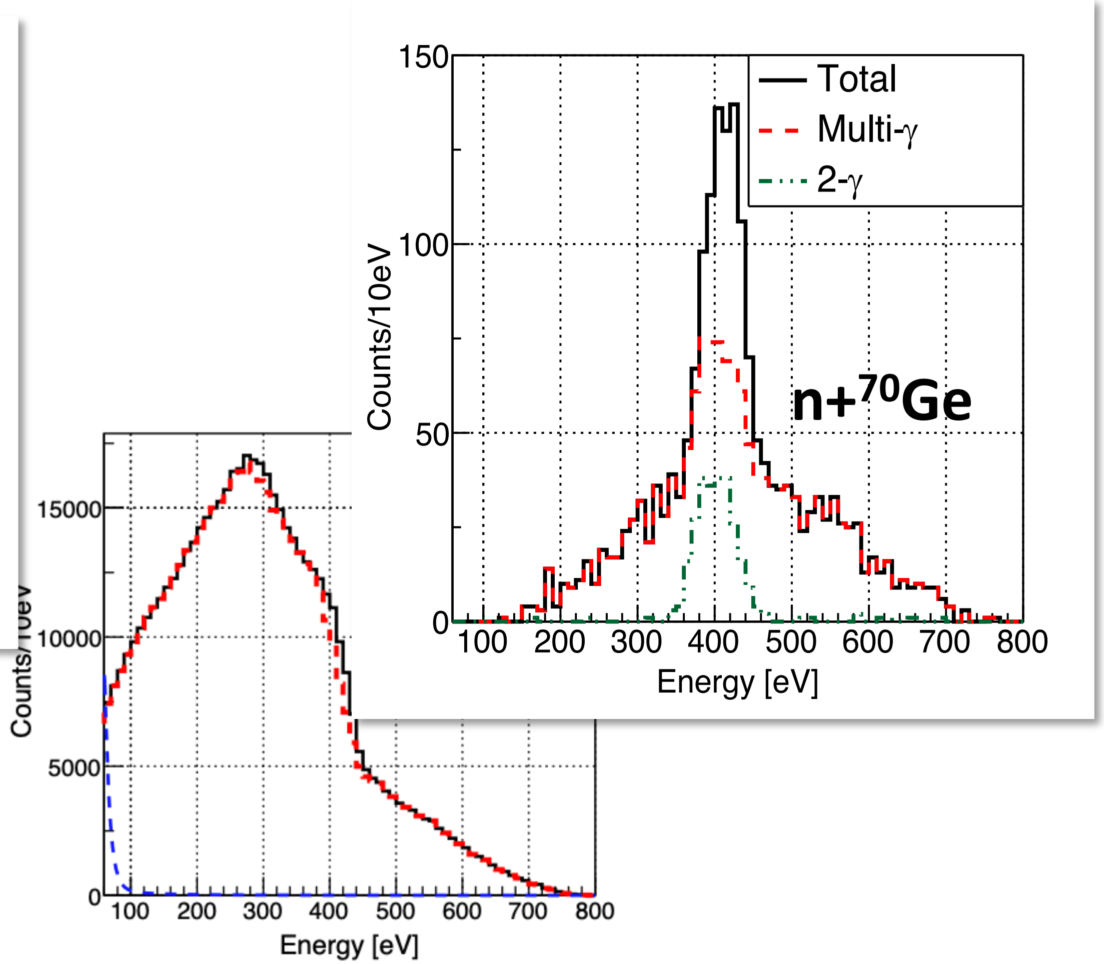
Low-mass detector holder

Improvement using gamma-tagging

NUCLEUS 0.76g $CaWO_4$ + (5.47 ± 0.2) MeV coincidence



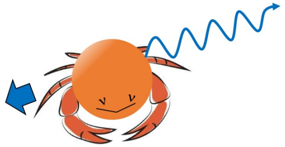
33 g Ge detector + [7.2-7.6] MeV coincidence



CRAB Timeline

2022-2023

- Calibration of NUCLEUS detectors (CaWO$_4$ & Al$_2$O$_3$)



>2024

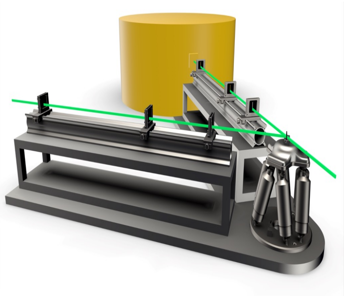
- Study **linearity**
- Application to **other materials** beyond CaWO$_4$
- Measurement of **quenching factor at sub-keV**
- Sensitivity **to lattice defects**

Proof of principle

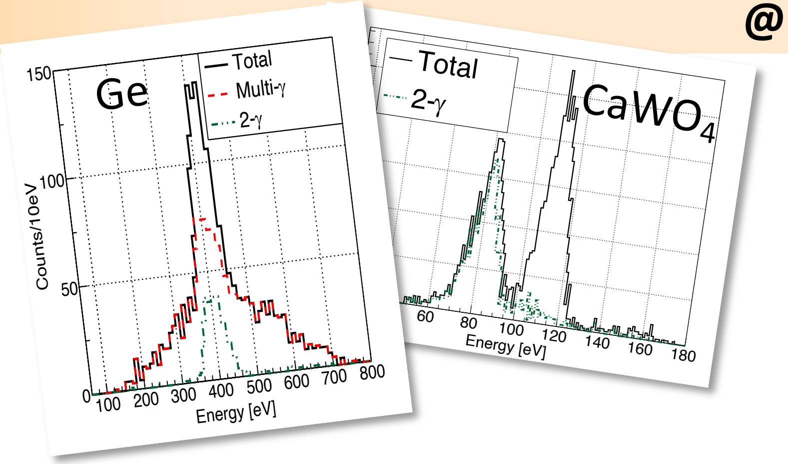
Installation &
first measurements
@TU Wien

Upgrade: γ-tagging

Solid state &
Nuclear physics
@100 eV



2024



Thanks for your attention